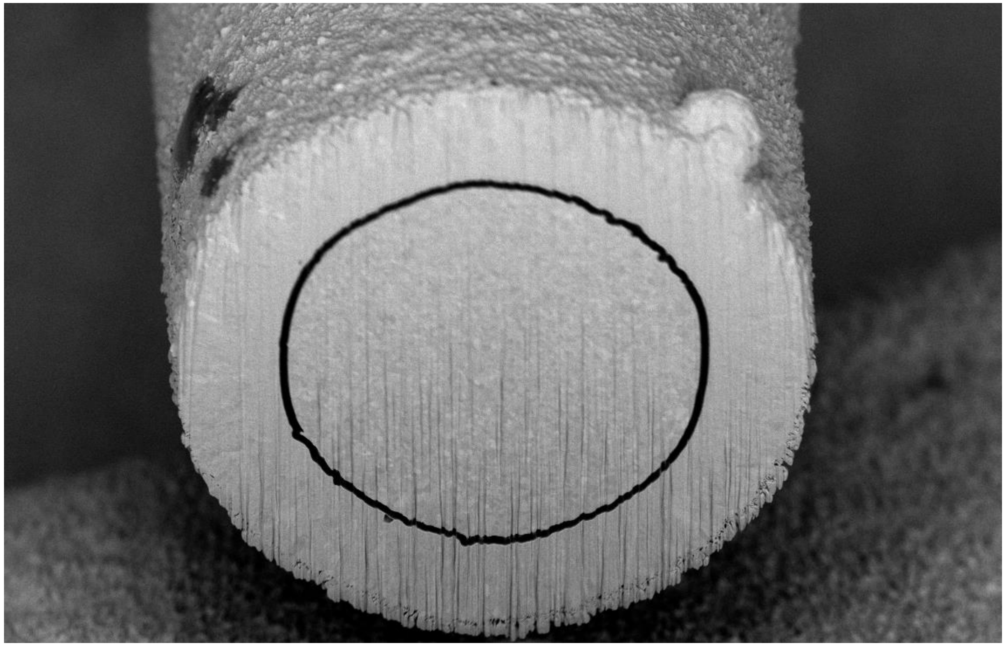
An In-Situ Microcoaxial Fabrication and Attachment Strategy

Daniela Torres

iMAPS NE

MEMS Session

May 1st 2018



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Outline of Presentation

Introduction

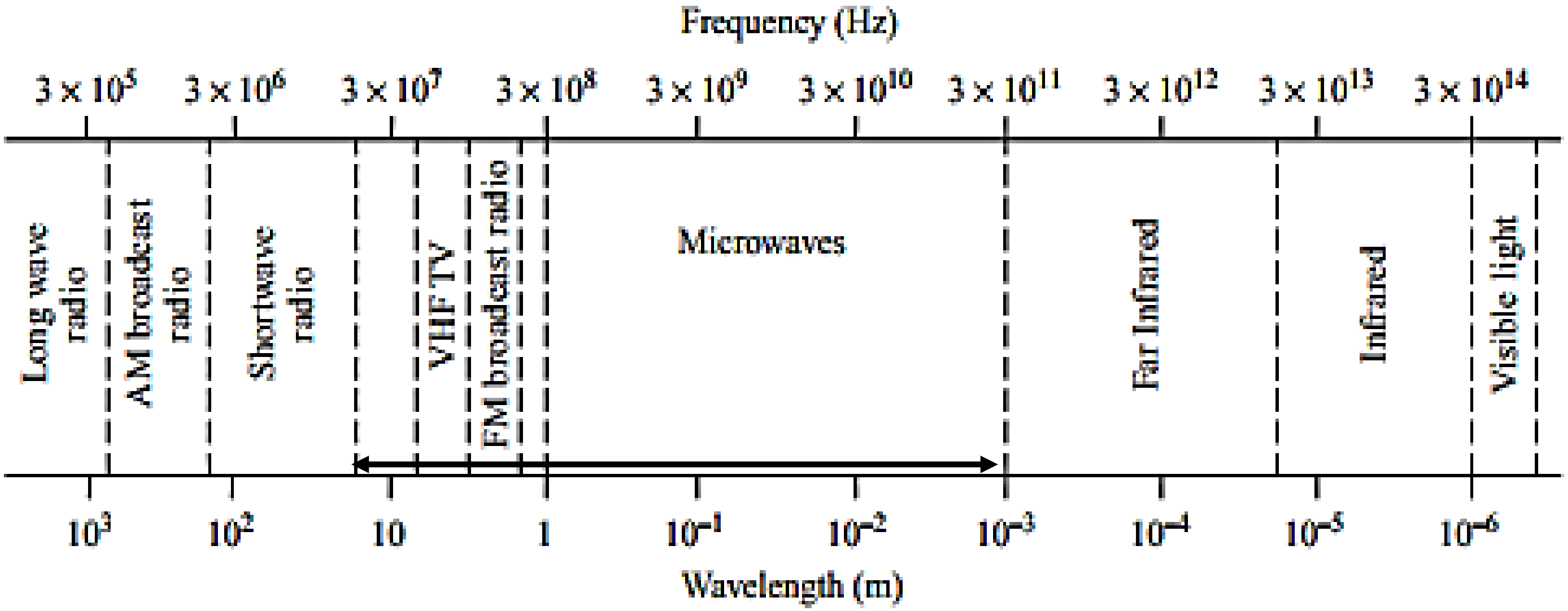
- High Frequency Band, Modules, & Advantages
- Packaging RF Modules
- Microcoaxial Cables for RF Modules
- Thesis Contributions

Methods & Results

- Microcoaxial Fabrication
- 2-Port RF Characterization
- 4-Port Cross-Talk Tests

Conclusions & Future Work

RF and Microwave Frequencies



RF: 30 MHz – 300 MHz

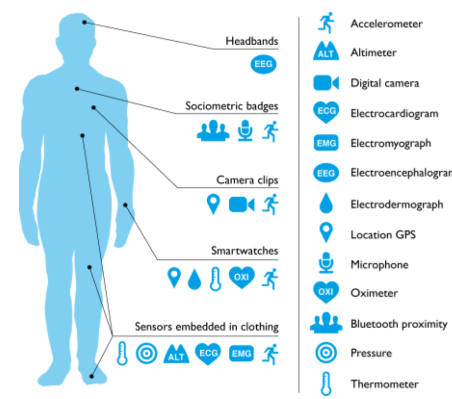
Microwaves: 300 MHz – 300 GHz

D. M. Pozar, Microwave Engineering, Addison-Wesley, 1990.

RF and Microwave Applications

Application	Example	Frequency
Communication Systems	FM, TV, Cell	88 MHz – 960 MHz
Communication Systems	ISM	902 MHz – 5.85 GHz
Antenna and Radar	UWB Imaging	3.10-10.6 GHz
Antenna and Radar	L-F Bands	1-140 GHz
Navigation & Weather	GPS	1227.6-1575.42 MHz
Medical	Diagnostics & Wearables	30-300 GHz



D. M. Pozar, Microwave Engineering, Addison-Wesley, 1990.

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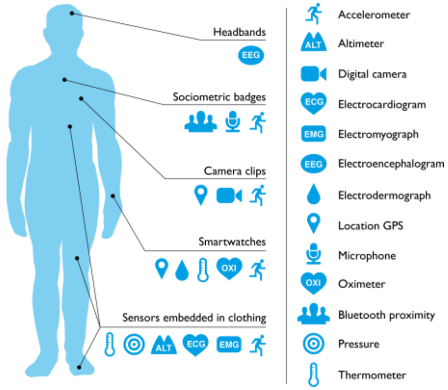
RF and Microwave Advantages

Application	Advantage
Communication Systems	Higher Bandwidth
Antenna and Radar	Target Detection
Navigation & Weather	Penetration Through Ionosphere
Medical	Sense Molecular Resonances

RF Modules Make up 66% of System in Package (SiP) Components

Yole, "Status of Advanced Packaging Industry 2017," Sonoma, 2017.



D. M. Pozar, Microwave Engineering, Addison-Wesley, 1990.

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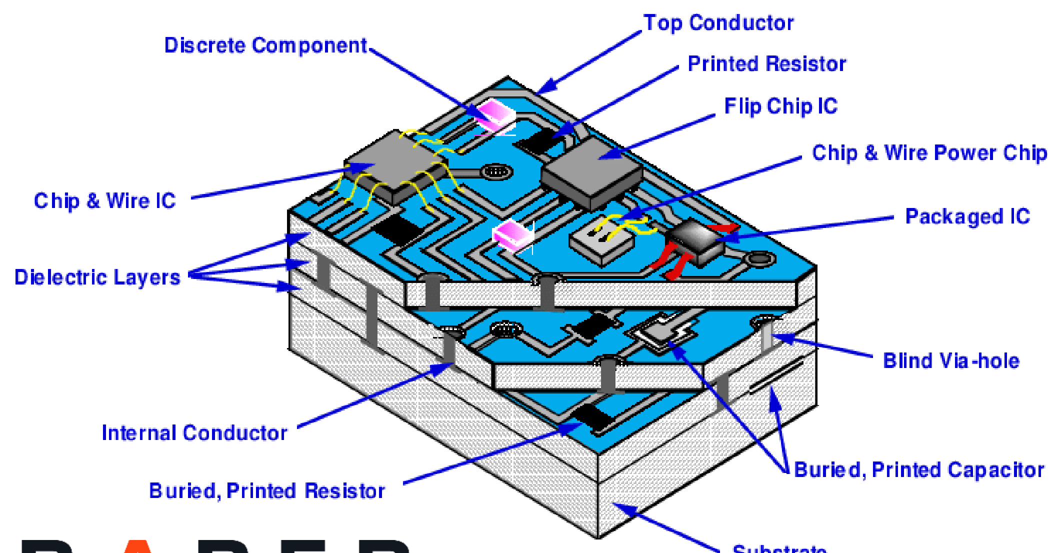
Challenges of Packaging RF Modules

Key Challenge	Why?
Packaging Introduces Parasitics	Unwanted inductance at high frequencies
Impedance Mismatch	Inability to distribute power or signals efficiently
Electromagnetic Interference	Cross-talk contamination
Heterogeneous Integration	Desire rapid methods for complex miniature systems (SiP)

Arun Chandrasekhar, "Characterization, Modeling and Design of Bond-Wire Interconnects for Chip-Package Co-Design," in European Microwave Conference , Munich, 2003.

E. A. Sanjuan and S. S. Cahill, "Scaling Quad-Flat No-Leads Package Performance to E-Band Frequencies," in IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS2013), Tel Aviv, 2013.

S. H. J. DeLaCruz, "Improvements of System-in-Package Integration and Electrical Performance Using BVA Wire Bonding," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 7, no. 7, pp. 1020-1034, July 2017.



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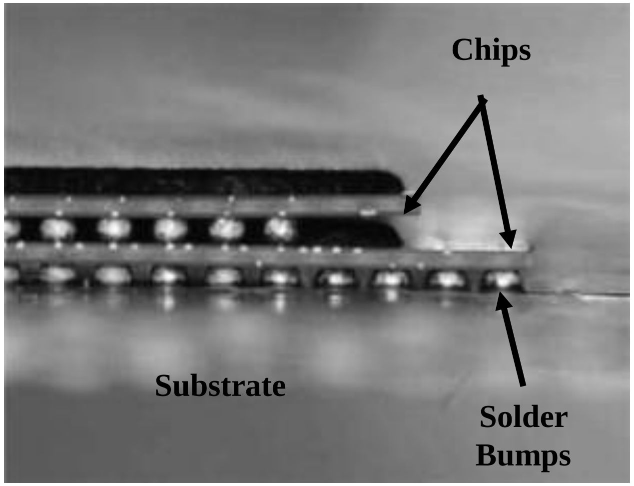
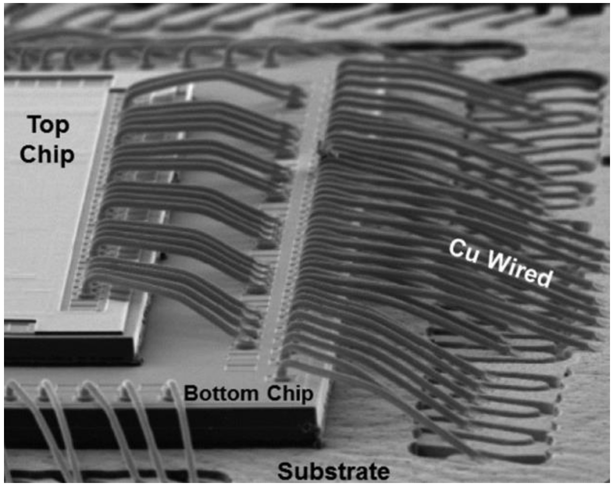
Current Packaging Techniques for RF Modules

Method	Advantage	Disadvantage
SiGe	Common in Semiconductor Industry Good Electrical Performance	Slow integration
GaAs	Better RF properties than Si >250 GHz Good thermal properties	Expensive, no native oxide, Slow integration
Flip Chip	Good for Multi-Chip Modules (MCMs)	May introduce up to 0.4 dB of insertion loss (IL)
Wire Bonding	Good for MCMs More rapid and easy to integrate	May introduce up to 2.2 dB of IL, 0 to -20 dB cross-talk up to 14 GHz

C. H. J. Poh, "Packaging Effects of Multiple X-Band SiGe LNAs Embedded in an Organic LCP Substrate," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 2, no. 8, pp. 1351-1360, 2012

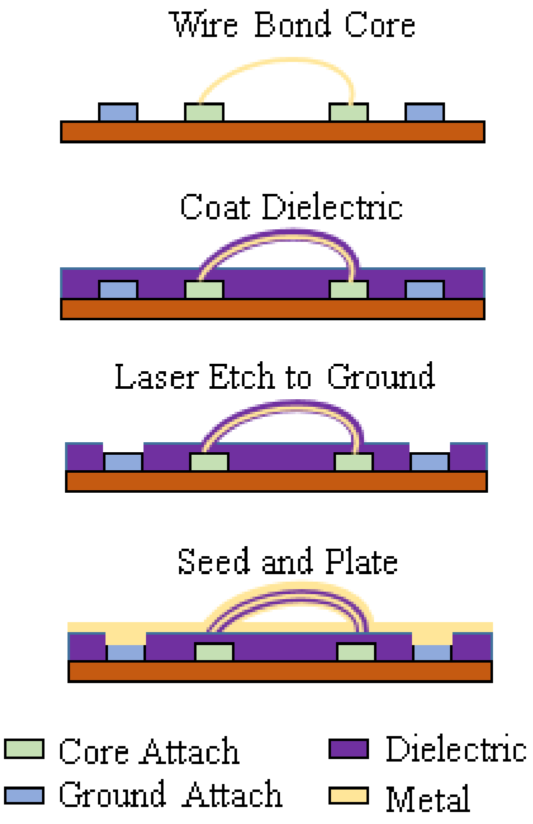
B. Goettel, "Packaging Solution for a Millimeter-Wave System-on-Chip Radar," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 8, no. 1, pp. 73-81, 2018





Microcoaxial Cables for RF Modules

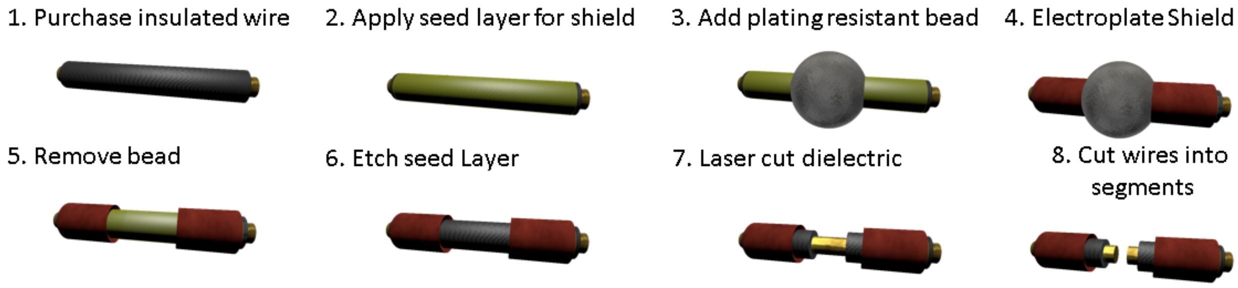
- Utilizes wire bonding and existing fabrication methods to integrate microcoax for signal distribution
- Fabricated micro-coax with target impedances of 40-50Ω
- Cross-talk did not exceed -40 dB up to 26.5 GHz
- Total wire diameters ~100µm

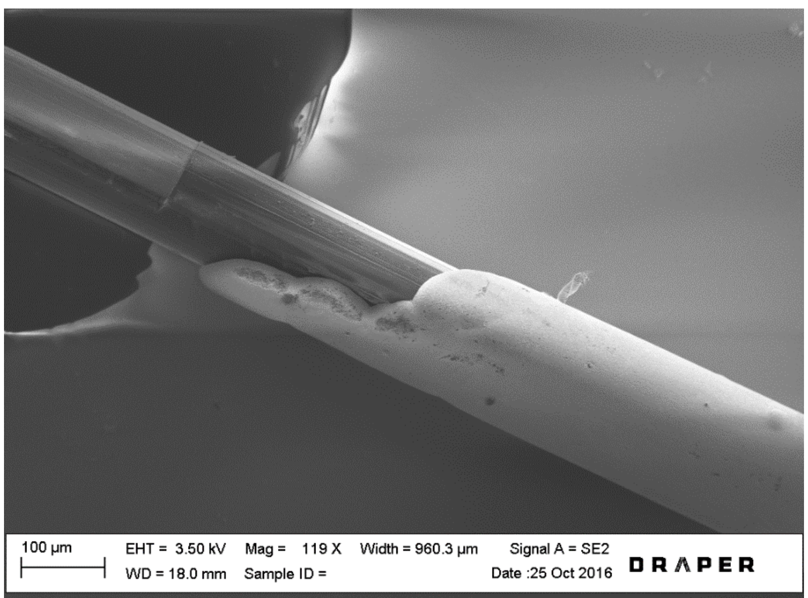


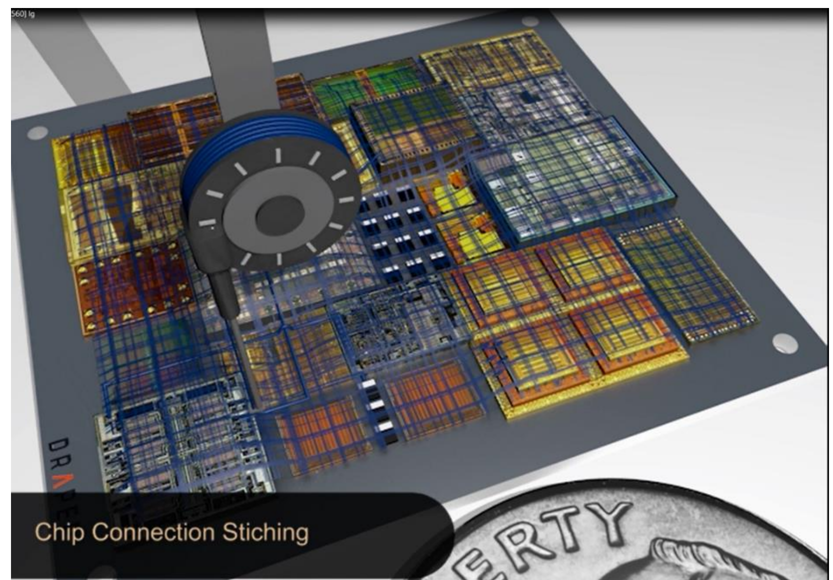
Fabrication Process First Introduced in: S. S. Cahill, E. A. Sanjuan and L. Levine, "Development of 100+ GHz High-frequency MicroCoax Wire Bonds," in iMAPS, 2006.

Microcoaxial Cables for RF Modules

Utilizes new fabrication methods and attachment strategies to integrate microcoax for power and signal distribution. Power coax has not been explored yet in literature.







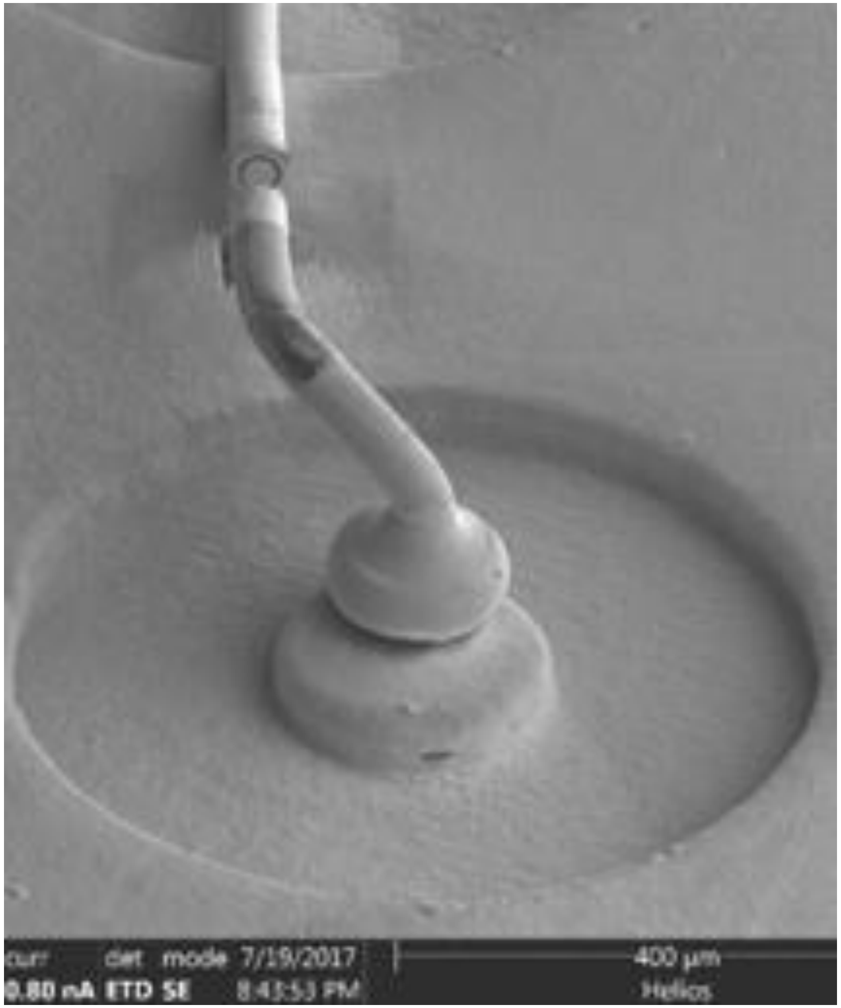
Thesis Contributions

Goals

- Expedite integration and characterization of micro-coaxial cables for MMS.
- Rapid and uses existing technology.

Accomplishments

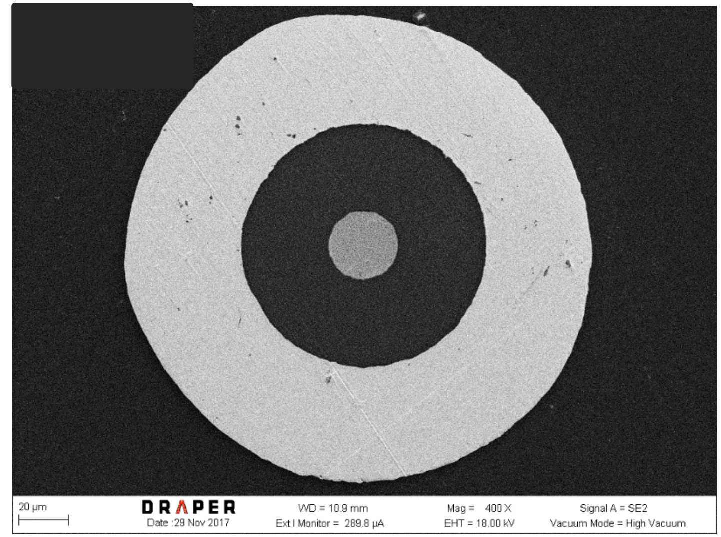
- Fabricated coax for power and signal distribution
- Explored new dielectric options such as ALD HfO_2 for thin (100 nm) dielectrics
- Determined theoretical electrical properties of different cables from fabrication process and compared to RF measurements
- Cross-Talk Analysis of different wires



Types of Microcoax for MMS System

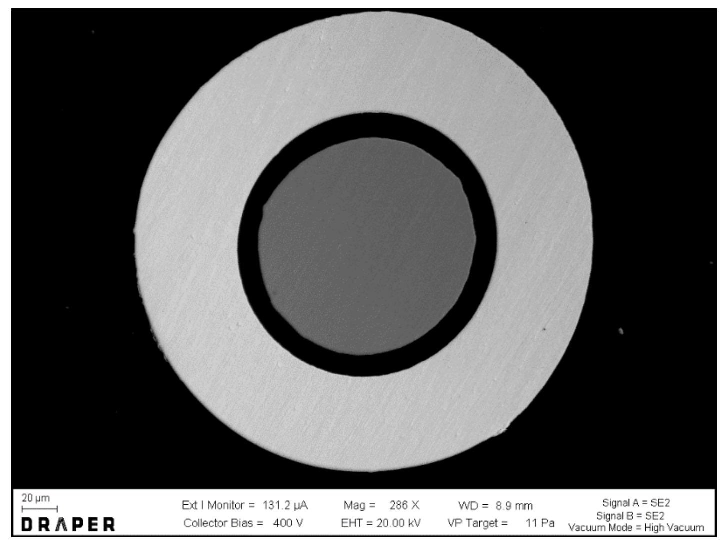
Signal Coax

- Previously explored in literature
- Target Impedances Between 30-70Ω
- Impedance determined by matching



Power Coax

- Not previously explored
- Target Low impedances <10Ω
- Impedance determined by Power Distribution Network (PDN)



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Types of Microcoax for MMS System

Core Radius (r_c)

- In-Situ Fabrication – Determined by existing wire bond core
- MMS – Determined by wire manufacturers

Dielectric Thickness (t_d)

- Determined by target impedance
- Assume for now lossless cable

$$t_d = r_c(e^{Z_0\sqrt{k}/60} - 1)$$

Shield Thickness (t_s)

- For now assume that core and shield resistances are equal
- Neglect frequency dependence for preliminary design

$$t_s = \sqrt{r_c^{\,2}(\frac{\sigma_c}{\sigma_s}) + (r_c + t_d)^2} - (r_c + t_d)$$

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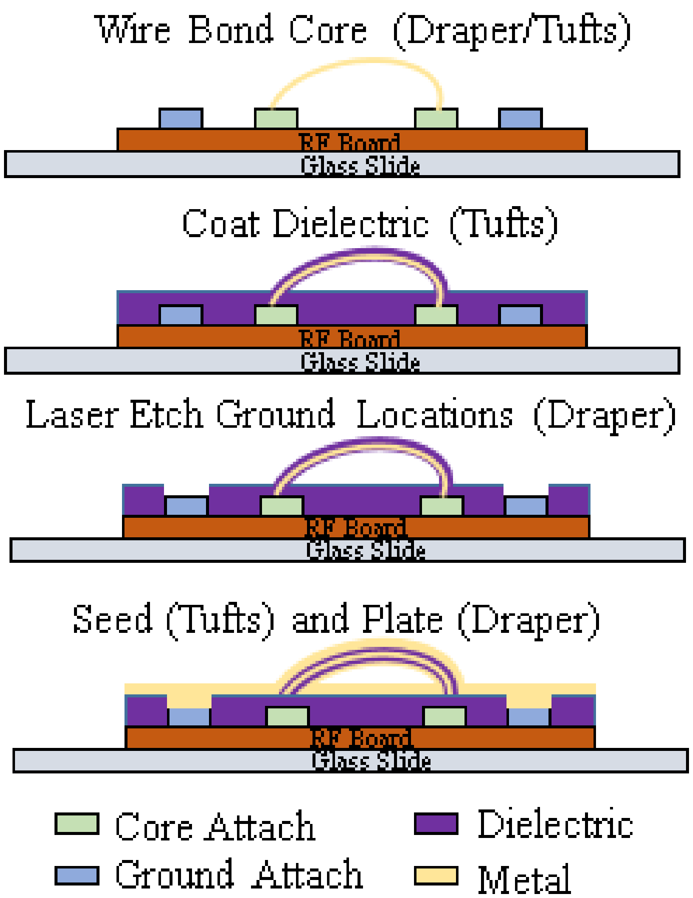
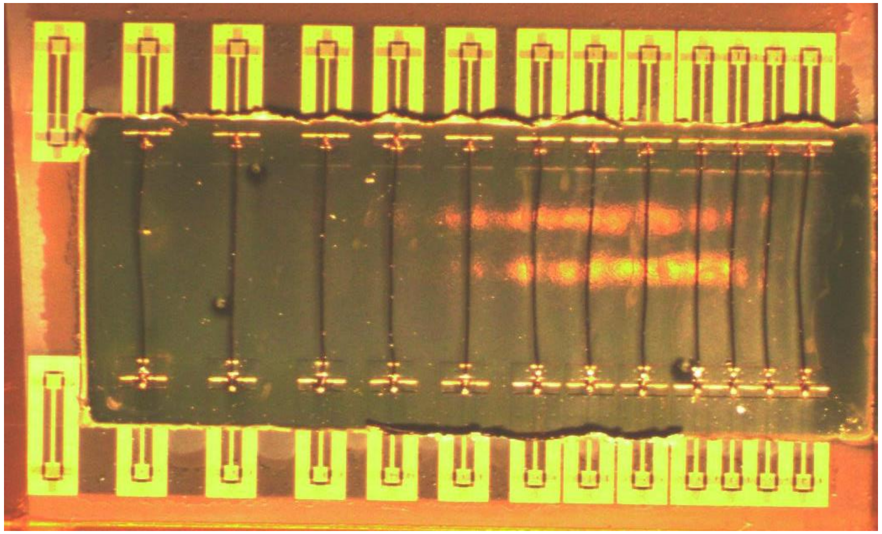
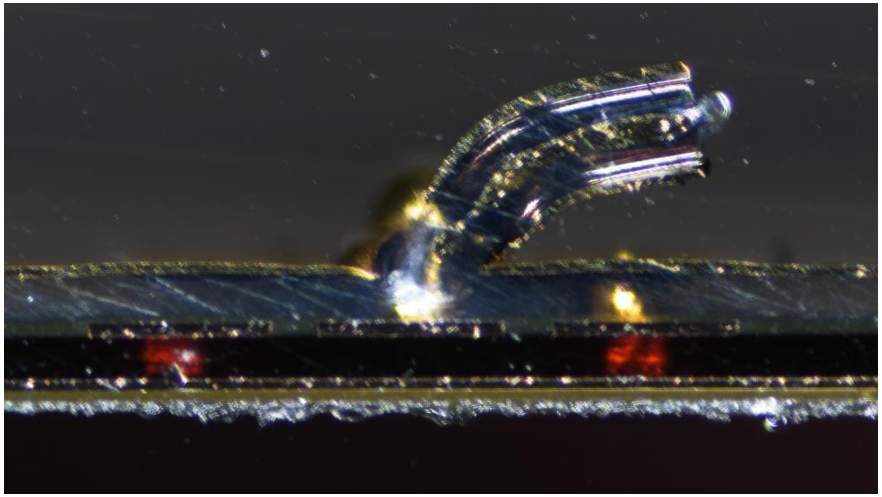
In-Situ Attachment and Fabrication of Microcoax







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Power Coax With HfO_2 Dielectric

Core

25.4 µm Diameter Au Ball Bonded Wire

Dielectric

100 nm HfO_2 Deposited by Atomic Layer Deposition (ALD)

Laser

0.220 W and 248 nm wavelength

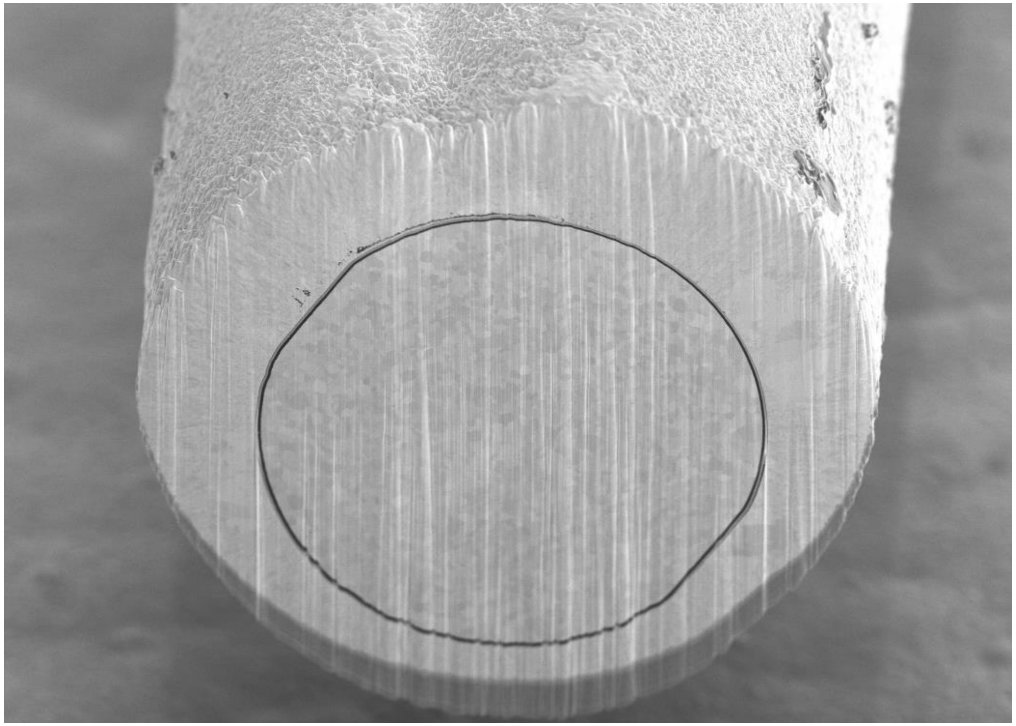
with 10 Pulses

Adhesion Layer

Sputtered 20 nm Cr & 200 nm Au (x2)

Shield

5.0 µm Electroplated Au



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Power Coax With Parylene C Dielectric

Core

25.4 µm Diameter Au Ball Bonded Wire

Dielectric

1.0 µm Vapor Coated Parylene C

Laser

0.220 W and 248 nm wavelength

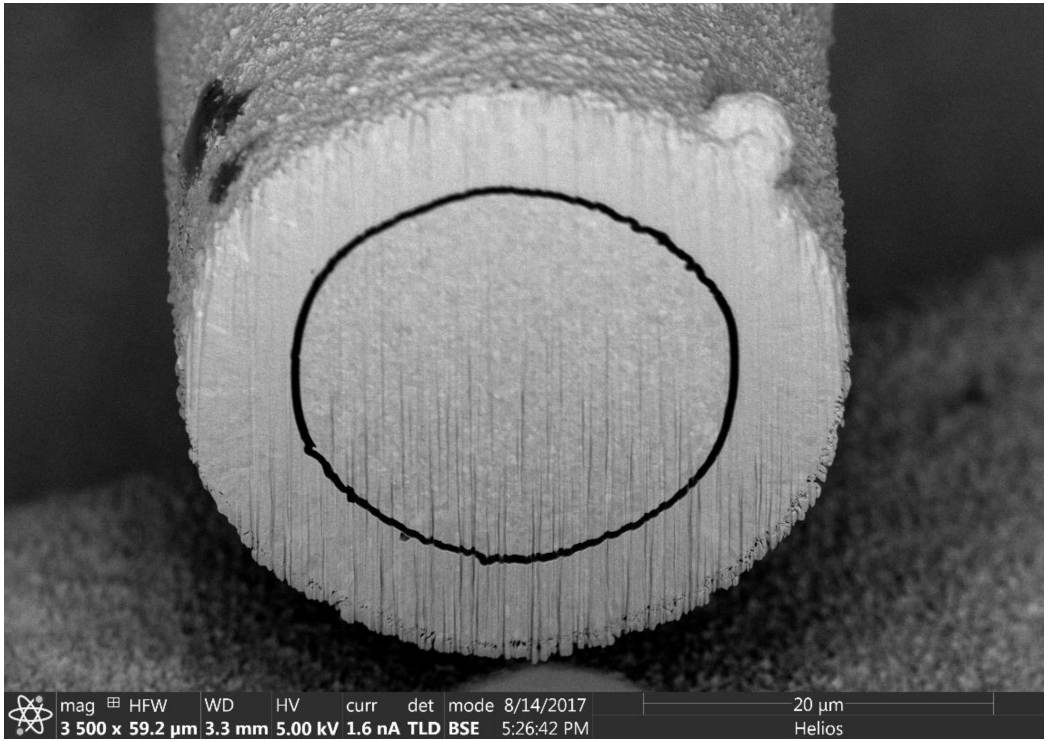
with 20 Pulses

Adhesion Layer

Sputtered 20 nm Cr & 200 nm Au (x2)

Shield

5.0 µm Electroplated Au



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Signal Coax With Parylene C Dielectric

Core

25.4 µm Diameter Au Ball Bonded Wire

Dielectric

38 µm Vapor Coated Parylene C

Laser

0.220 W and 248 nm wavelength

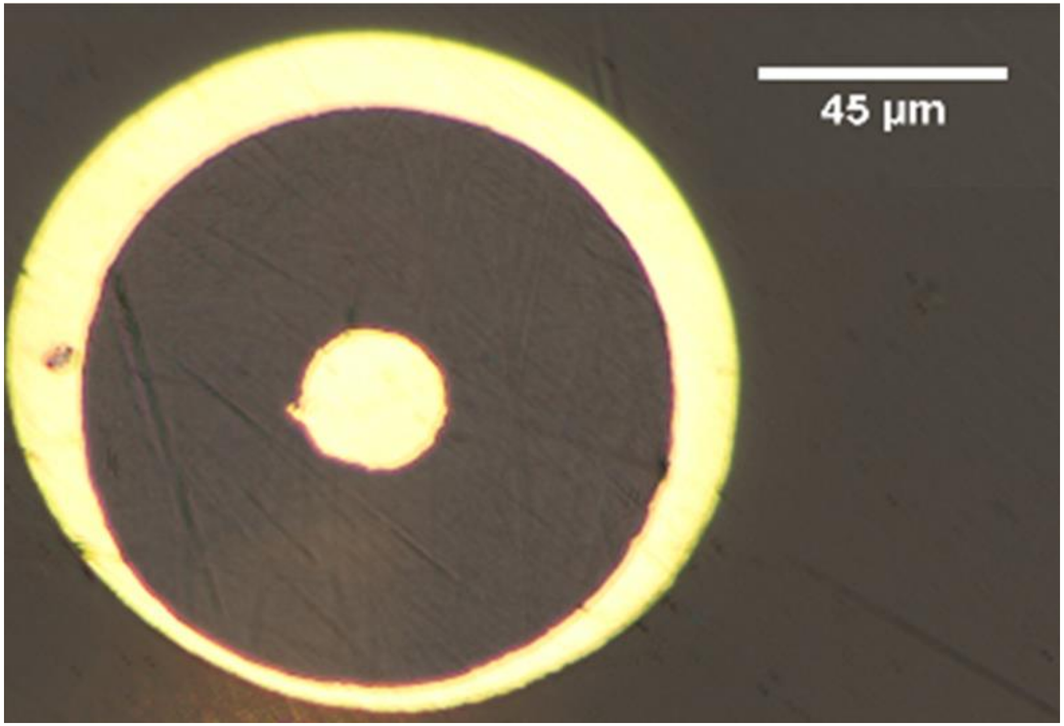
with 420 Pulses

Adhesion Layer

Sputtered 20 nm Cr & 200 nm Au (x2)

Shield

5.0 µm Electroplated Au



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Fabrication Summary

	Core Thickness (µm)	Shield Thickness (µm)	Wire Length - x (mm)
All Wires	24-25	5-6	3.5-3.7

Dielectric	Dielectric Const. (ε_r)	Magnetic Permeability (μ_r)	Thickness (µm)	Wave Speed (m/s)	Freq. for ¼ Wavelength (GHz)
Parylene C	2.95-3.15 (~<1GHz)	1	Power: 0.8-1.2 Signal: 37-46.5	$1.70\text{-}1.75 \cdot 10^8$	~12
HfO2	16-40 (~<1GHz)	1	Power: 0.10	$4.74\text{-}7.50 \cdot 10^7$	~5

Thickness measurements taken from ellipsometer, profilometer, and FIB measurements. Dielectric constants taken from literature and from pinhole measurements.

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Expected C, L, Z_0 From Fabrication

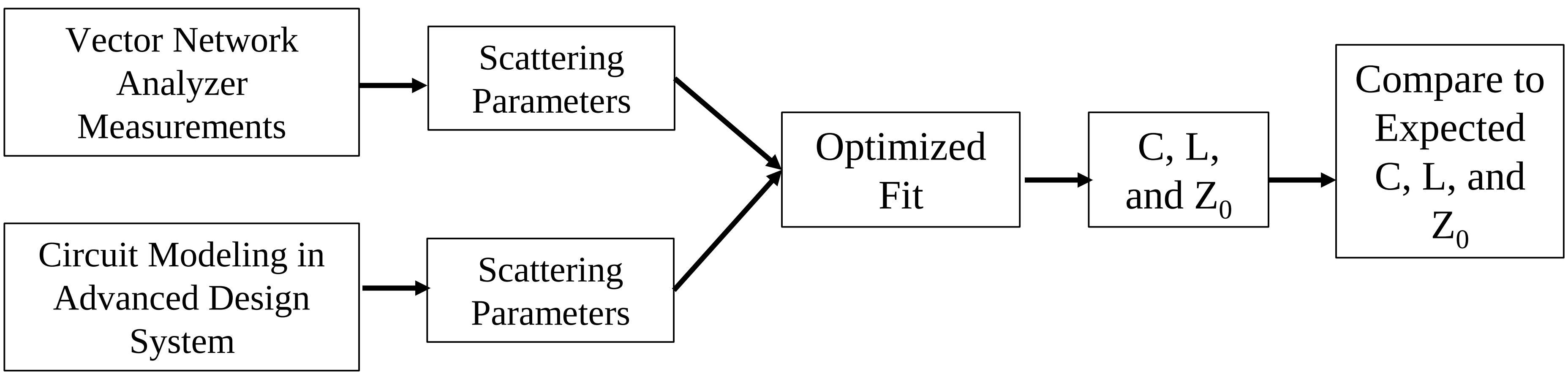
Dielectric	Capacitance (pF)	Inductance (pH)	Z_0 (Ω)
Parylene C	Power: 5.63-9.29 Signal: 0.36-0.48	Power: 48.87-75.56 Signal: 943-1172	Power: 2.29-3.66 Signal: 44-57
HfO2	Power: 375-1074	Power: 5-6	Power: 0.07-0.13

$$\frac{C}{l} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{r_c + t_d}{r_c}\right)} \qquad \frac{L}{l} = \frac{\mu_0\mu_r}{2\pi}\ln\left(\frac{r_c + t_d}{r_c}\right) \qquad Z_0 \cong \sqrt{\frac{L}{C}}$$

D. M. Pozar, Microwave Engineering, Addison-Wesley, 1990.

Overall, low inductance and low characteristic impedance is expected for power coax. For signal coax a characteristic impedance of 50Ω is expected.

Electrical Characterization Process Flow



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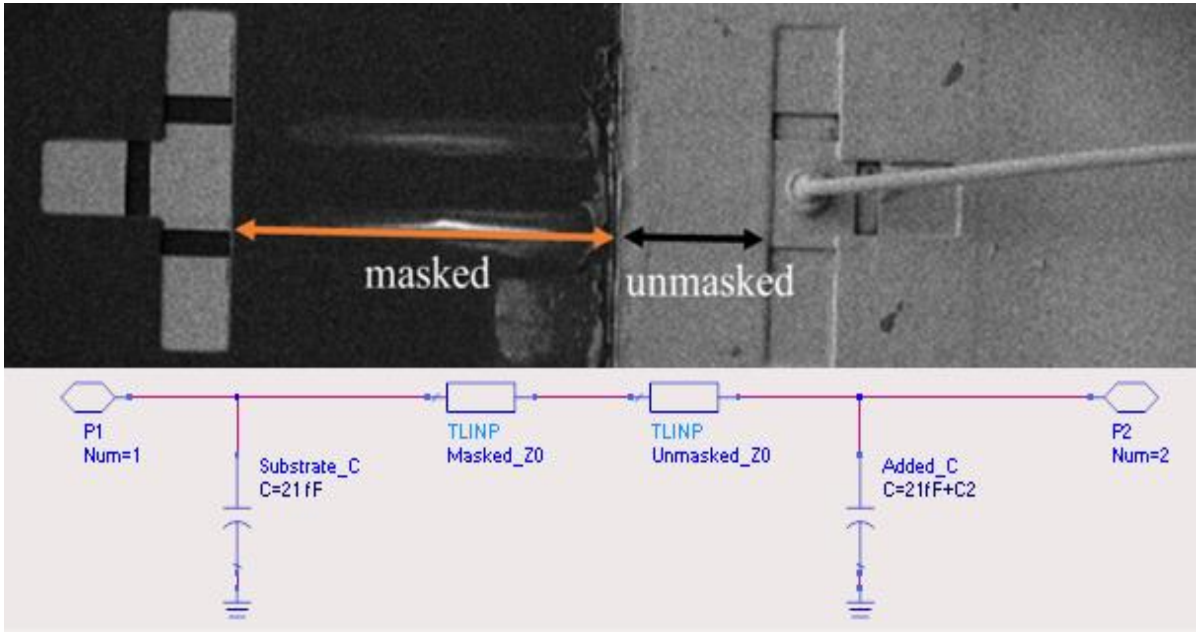
De-Embedding

For Now Result to Modeling Substrate and Fitting $S_{Measured}$ to Models.



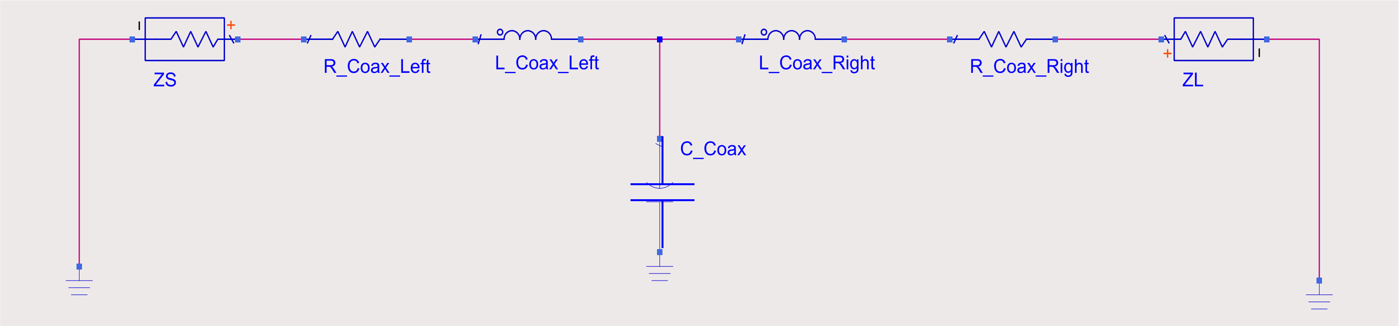
$$[S_{Measured}] = [S_{FA}][S_{DUT}][S_{FB}]$$

HP, "S-Parameters Theory and Applications"

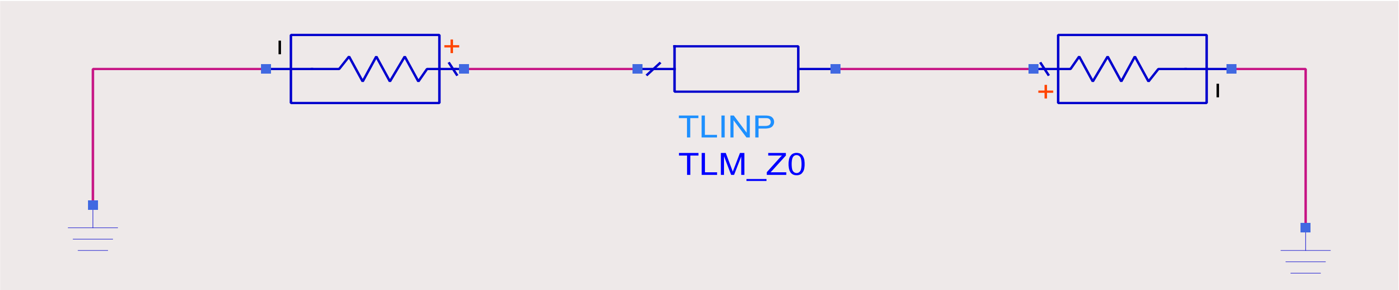
Advanced Design System (ADS) Circuit Modeling

Wire Type	C, L, and R	TLM	C, L, and R De-embedded	TLM De-embedded
Power Coax Parylene C	✓	✓	✓	✓
Power Coax HfO2	✓	✓	✓	✓
Signal Coax Parylene C		✓		✓

C,L and R Model



TLM Model



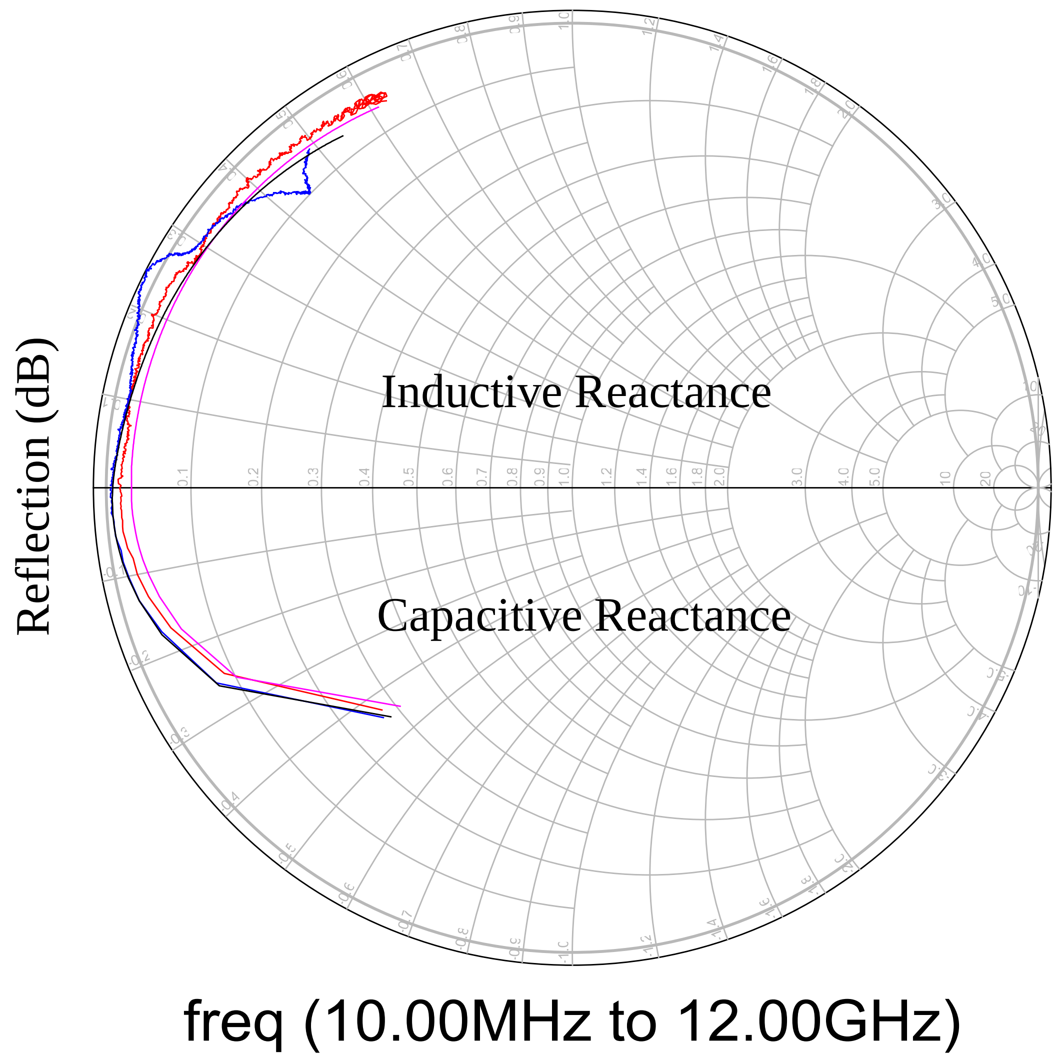
2 Port RF Results Power Coax With HfO_2

S_{11} - Reflection Coefficient at Measured Port 1

S_{22} - Reflection Coefficient at Measured Port 2

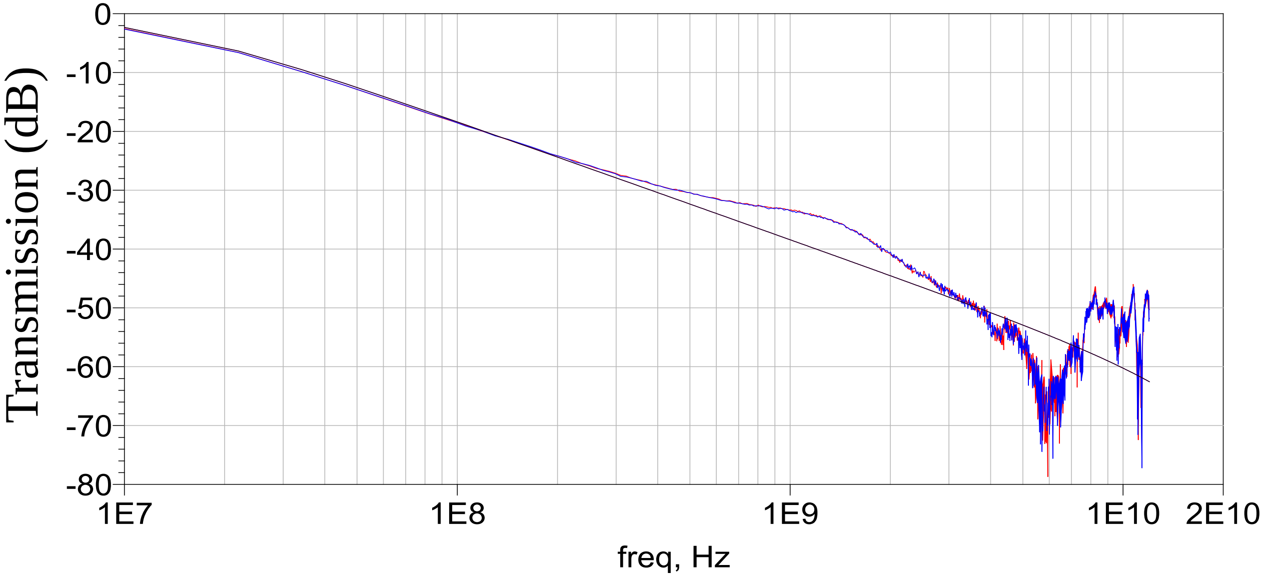
S_{11} - Reflection Coefficient at Simulated Port 1

S_{22} - Reflection Coefficient at Simulated Port 1



2 Port RF Results Power Coax With HfO_2

S_{12} – Reverse Transmission Coefficient at Measured Port 1
S_{21} – Forward Transmission Coefficient at Measured Port 2
S_{12} – Reverse Transmission Coefficient at Simulated Port 1
S_{21} – Forward Transmission Coefficient at Simulated Port 2



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2 Port RF Results Power Coax With HfO_2

Measured Set of 3 Wires

Method	C/l (pF/mm)	Z_0 (Ω)	L/l (pH/mm)
Analytical	104-298	0.07-0.13	1.40-1.70
Non-De-embedded	145±3.0 (LM)	0.17±0.00 (TL)	214±20 (LM)
De-embedded	139±3.0 (LM)	0.12±0.00 (TL)	48±56 (LM)

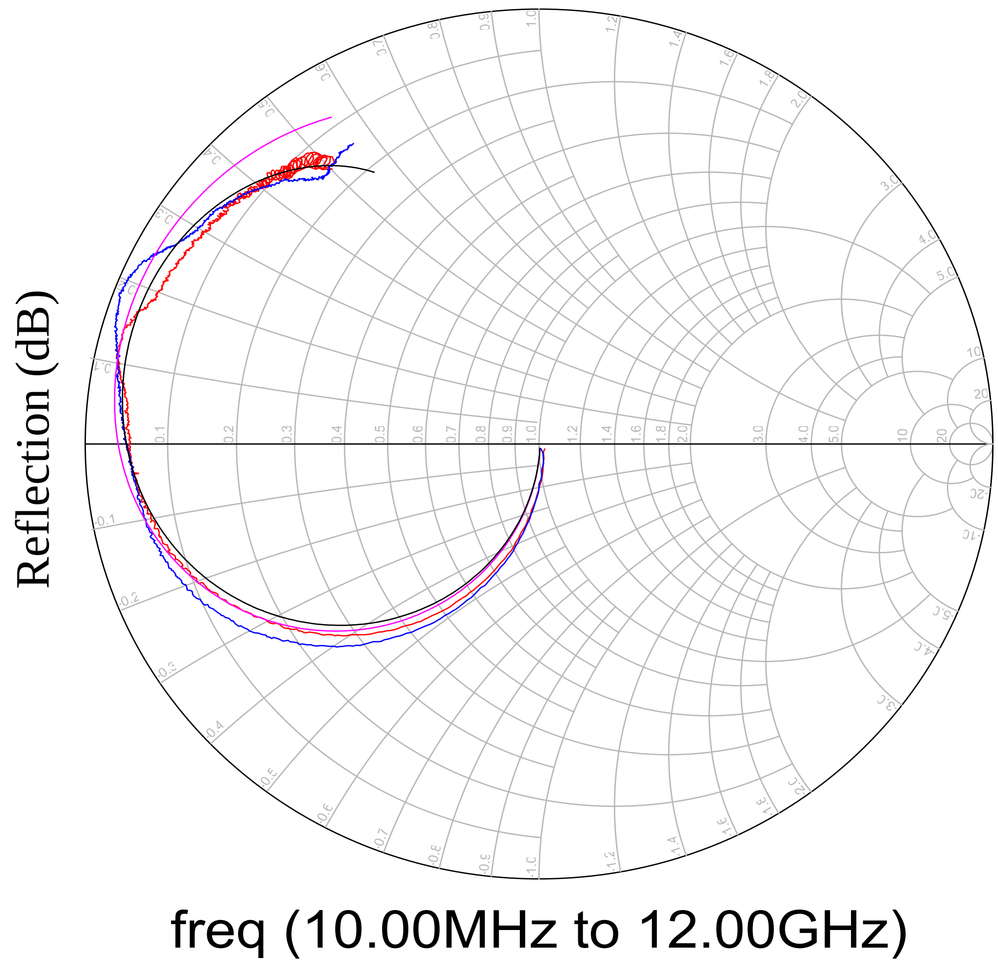
2 Port RF Results Power Coax With Parylene C

S_{11} - Reflection Coefficient at Measured Port 1

S_{22} - Reflection Coefficient at Measured Port 2

S_{11} - Reflection Coefficient at Simulated Port 1

S_{22} - Reflection Coefficient at Simulated Port 1



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2 Port RF Results Power Coax With Parylene C

S_{12} – Reverse Transmission Coefficient at Measured Port 1
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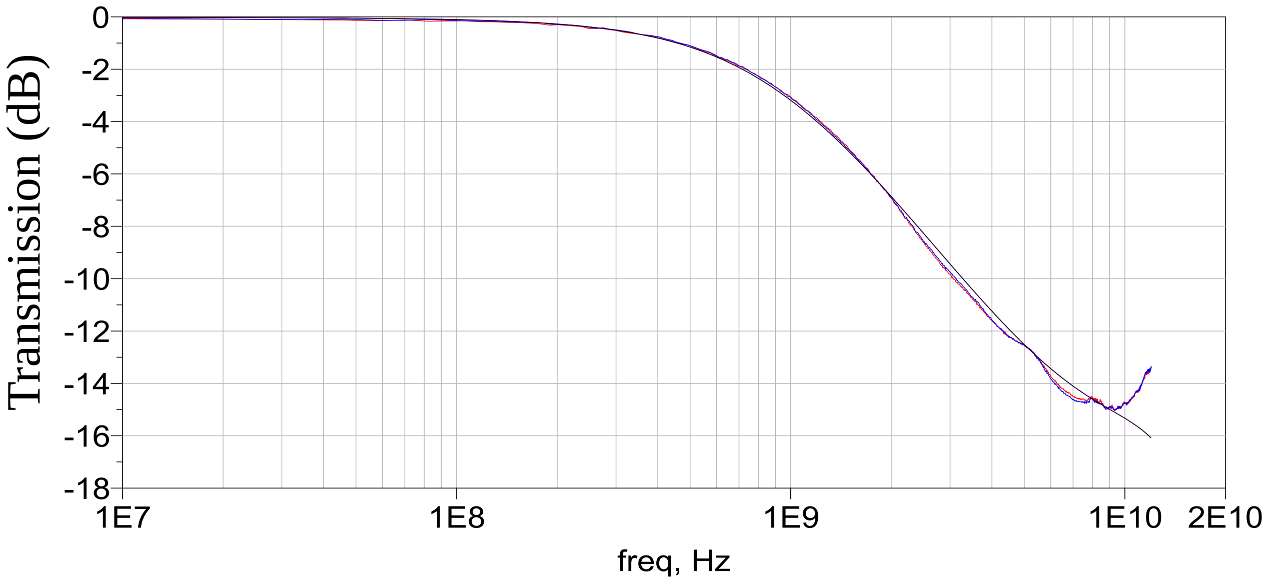
S_{12} – Reverse Transmission Coefficient at Simulated Port 1
S_{21} – Forward Transmission Coefficient at Simulated Port 2



2 Port RF Results Power Coax With Parylene C

Measured Set of 13 Wires

Method	C/l (pF/mm)	Z_0 (Ω)	L/l (pH/mm)
Analytical	1.60-2.60	2.30-3.70	13.6-21.0
Non-De-embedded	1.80±0.06 (LM)	3.40±0.10 (TL)	223±15 (LM)
De-embedded	1.50±0.07 (LM)	4.20±0.75 (TL)	97±38 (LM)

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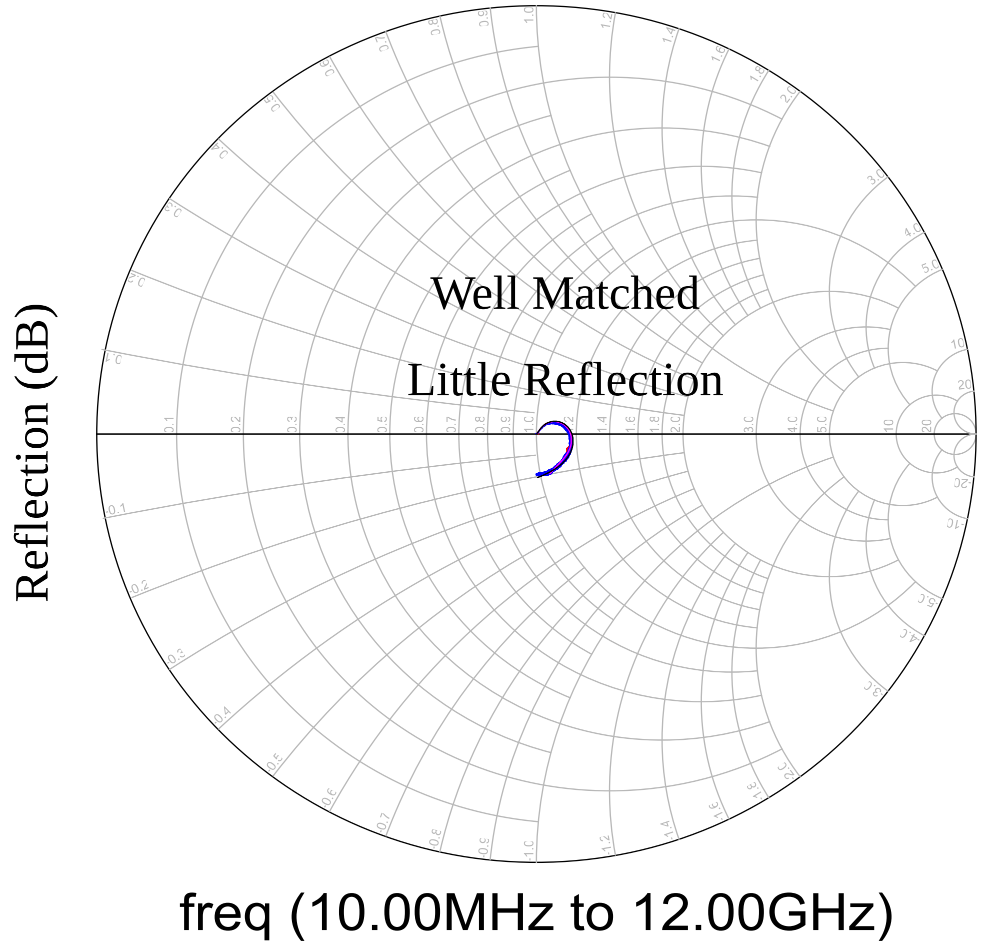
2 Port RF Results Signal Coax With Parylene C

S_{11} - Reflection Coefficient at Measured Port 1

S_{22} - Reflection Coefficient at Measured Port 2

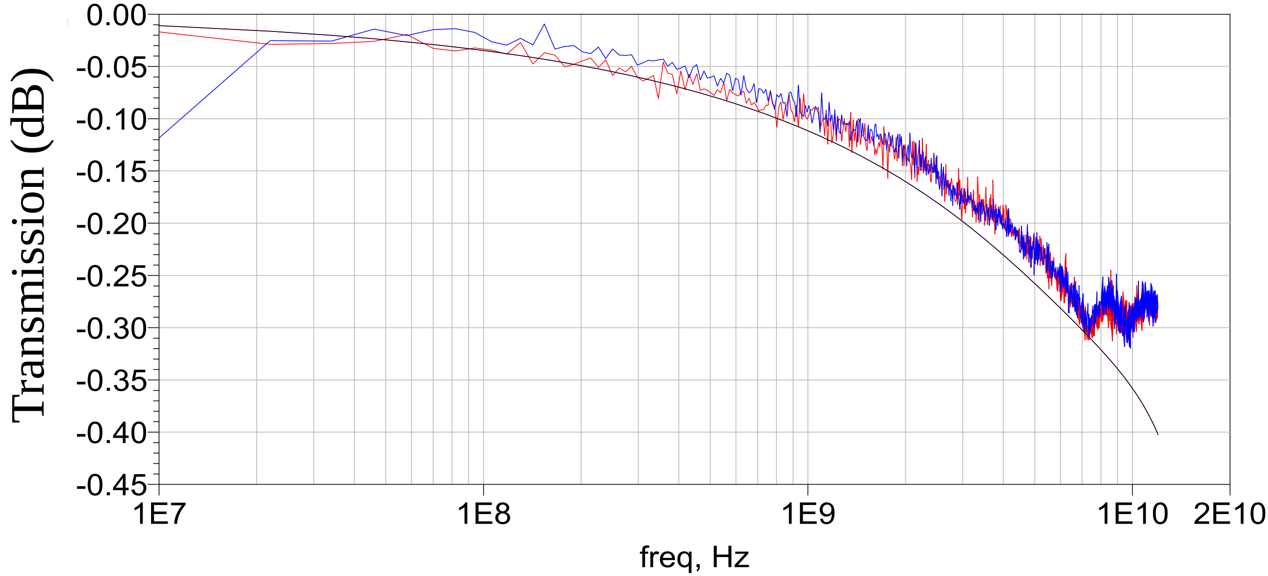
S_{11} - Reflection Coefficient at Simulated Port 1

S_{22} - Reflection Coefficient at Simulated Port 1



2 Port RF Results Signal Coax With Parylene C

S_{12} – Reverse Transmission Coefficient at Measured Port 1
S_{21} – Forward Transmission Coefficient at Measured Port 2
S_{12} – Reverse Transmission Coefficient at Simulated Port 1
S_{21} – Forward Transmission Coefficient at Simulated Port 2



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2 Port RF Results Parameters

Measured Set of 9 Wires

Method	**Z_0 (Ω)**
Analytical	44-57
Non-De-embedded	42±1.0 (TL)
De-embedded	63±3.0 (TL)

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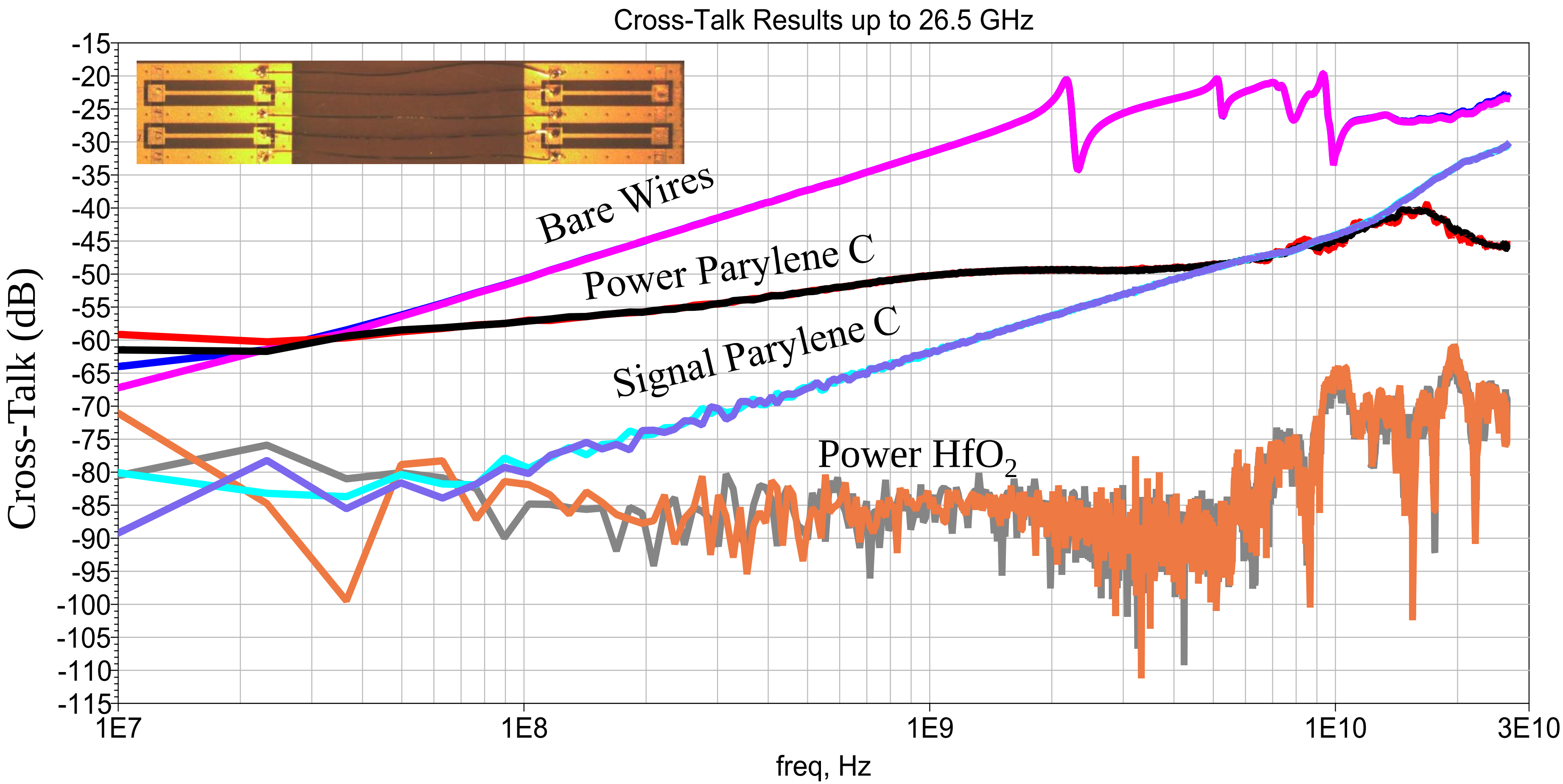
Cross-Talk Results



All Wire Pairs Have a Pitch of 0.5 mm

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Conclusions

Fabrication

- Fabricated power and signal coax with conformal film layers and targeted geometry
- Yield per board > 3 wires, higher (>9 wires) for thicker dielectrics

2-Port RF Characterization

- Good fit between measured s-parameters and simulated s-parameters
- Met impedance requirements for both power (<10Ω) and signal wires (~50Ω)

Wire Type	Meas. C (pF/mm)	Anal. C (pF/mm)	Meas. Z_0 (Ω)	Anal. Z_0 (Ω)
Power HfO_2	139-145	104-298	0.12-0.17	0.07-0.13
Power Parylene C	1.50-1.80	1.60-2.60	3.40-4.20	2.30-3.70
Signal Parylene C	--	0.36-0.48	42-63	44-57

- Large deviation for inductance by ~100 pH/mm between measured and analytical

4-Port Cross-Talk Measurements

- Cross-talk decreased up to 50 dB for shielded wires compared to GSG bare wires at 1 GHz
- Cross-talk did not exceed -35 dB for shielded wires up to 26.5 GHz

Future Work

Fabrication

- Explore other conformal films or introduce new fixturing in sputter tool
- Further optimize fabrication cleaning, electroplating, and masking

2-Port RF Characterization

- Remove wires and 2-port test substrate
- Compare electromagnetic simulations to analytical and measured results
- Consider simpler RF board
- Include inductance effects of board and wire joints

4-Port Cross-Talk Measurements

- Test wires with varying shield quality
- Study resonant modes of cable and substrate

Other

- Characterize thermal effects on CTE mismatch or wire impedance
- Characterize mechanical reliability through wire pull and shear tests

Acknowledgements

Thank you to:

Robert White – Tufts ME Advisor

Caprice Gray – Draper Advisor & MMS PI

Marc Hodes – Thesis Committee

Tony Kopa – MMS RF Task Lead

Peter Lewis – MMS Integration Team

Sara Baron – MMS Wire Fabrication Task Lead

Brian Smith – Heterogeneous Microsystems Group Leader

Yen Wah – Wire Bonding Technician

Mark Singleton – Lab Manager

Prasit Sricharoenchaikit – External Contractor

Lab Group: Kevin Ligonde, Niko Kastor, Henry Shi, Jim Vlahakis

Questions?

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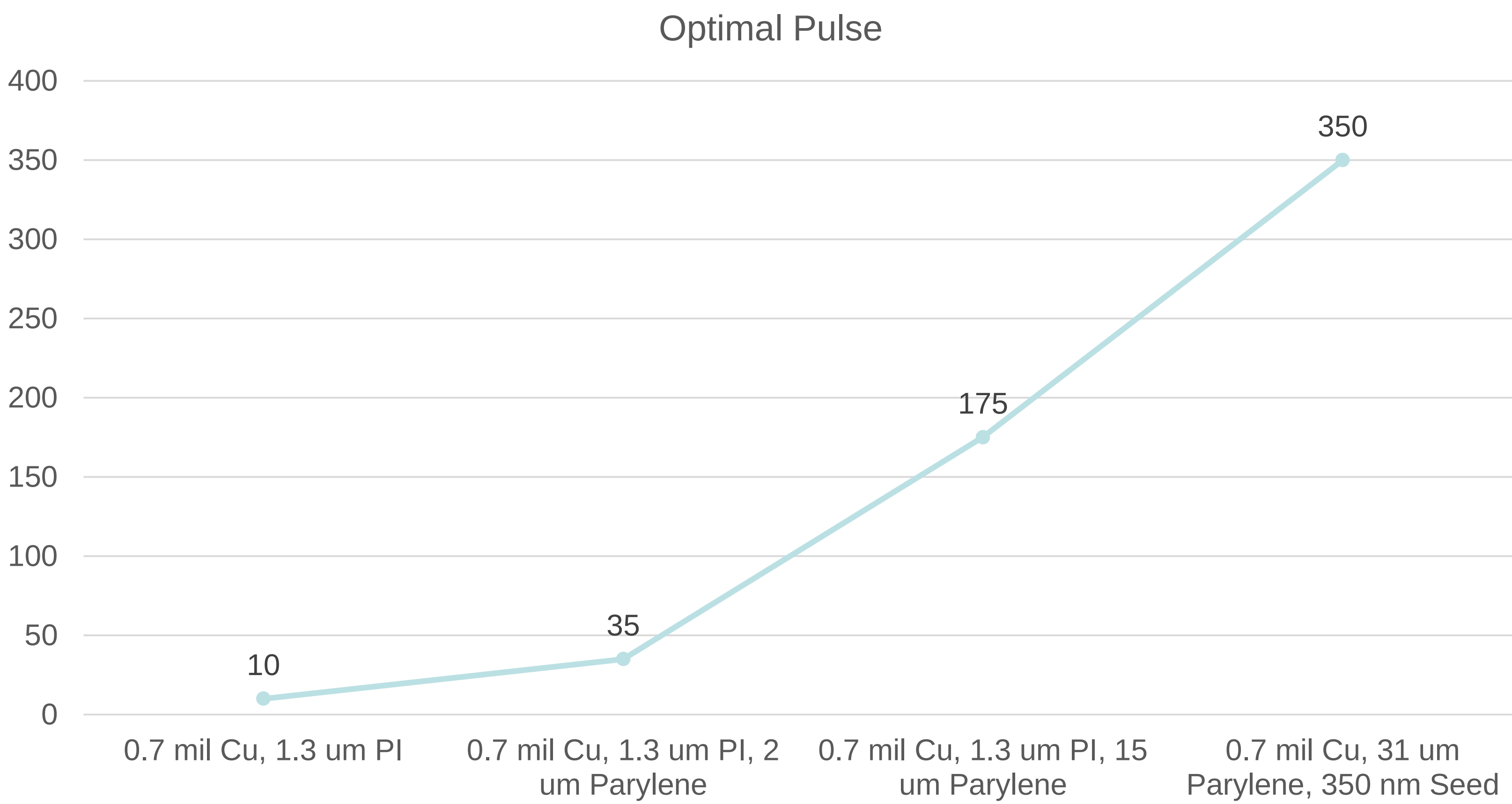
Appendix A – Laser Etching Pulse Optimization



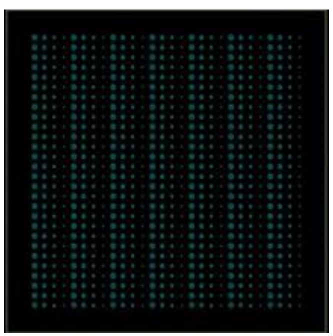
By: Tara Sarathi

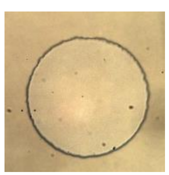
Appendix B – Pinhole Tests Parylene C

Tested 112 electrodes

Expected Diameter (µm)	Measured Diameter (µm)	Measured Radius (µm)	Measured Area (A) (µm^2)	Measured Thickness (d) (µm)	Measured Area (A) (m^2)	Measured Thickness (d) (m)	Theoretical Capacitance (F)	Theoretical Capacitance (pF)	Theoretical – Measured Capacitance (pF)
127	141.94	70.97	15823.39	3.138	1.58E-08	3.14E-06	1.41E-13	0.141	0.224
254	278.23	139.115	60799.19	3.138	6.08E-08	3.14E-06	5.40E-13	0.54	0.227
381	398.39	199.195	124654.1	3.138	1.25E-07	3.14E-06	1.11E-12	1.11	0.27
508	530.65	265.325	221159.8	3.138	2.21E-07	3.14E-06	1.97E-12	1.97	0.23

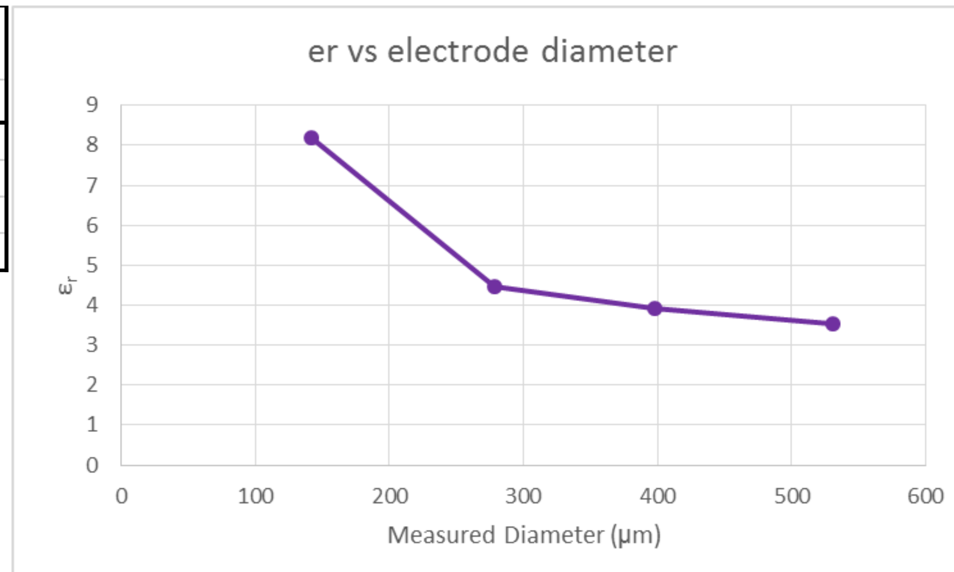
Expected Diameter	Measured Capacitance (pF)	Std Dev	Measured Resistance (GΩ)	Measured ε_r
5 Mil	0.365	0.033	21.73	8.18
10 Mil	0.767	0.025	6.06	4.47
15 Mil	1.38	0.026	2.65	3.92
20 Mil	2.2	0.026	1.58	3.53





$$C = \frac{e_0 e_r A}{d}$$

$$8.85\times10^{-12} F/m$$



Stray may be due to:

- Parallel Capacitors
- Additional Diameter (mask)
- Thinned Dielectric (Probing)

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Appendix C – TLM Parameters ADS

Board	Z_0 Coax (Ω)	K Coax	A Coax (dB/m)	TanD Coax	Z_0 Masked Sub (Ω)	K Masked Sub	A Masked Sub (dB/m)	TanD Masked Sub	Z_0 unmasked Sub (Ω)	K unmasked Sub	A unmasked Sub (dB/m)	TanD unmasked Sub
Power Parylene (MMS003)	4.21	3.80	236.3	0.0005	53.60	4.22	5.46	0.3462	51.07	8.21	306.16	0.0384
Power HfO2 (MMS004)	0.120	20.82	0.2	0.1	42.18	5.27	40.8	0.2333	49.59	5.92	19	0
Signal Parylene (MMS007)	63.2	2.69	11.8	0.0005	91.83	1.61	7.19	0.0409	61.60	3.25	22.30	0.0039

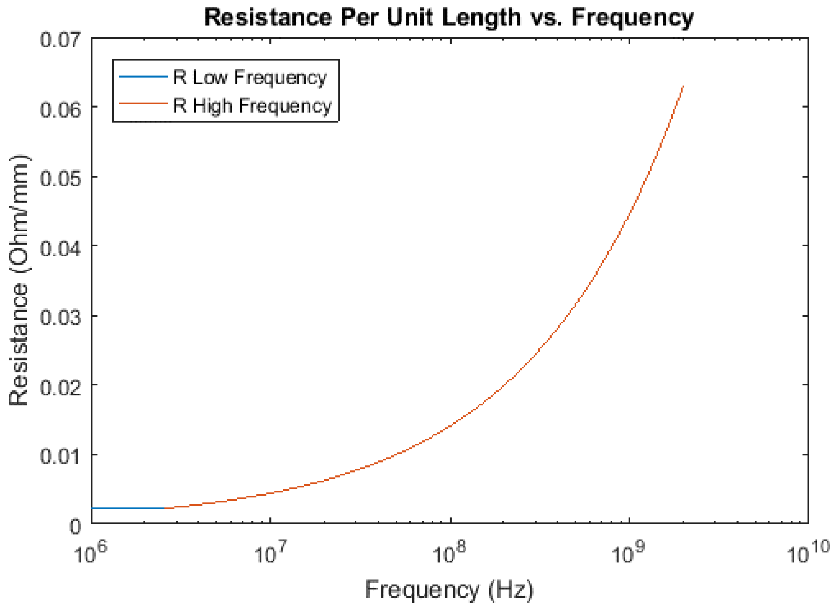
Appendix D– Frequency Dependence on R and L

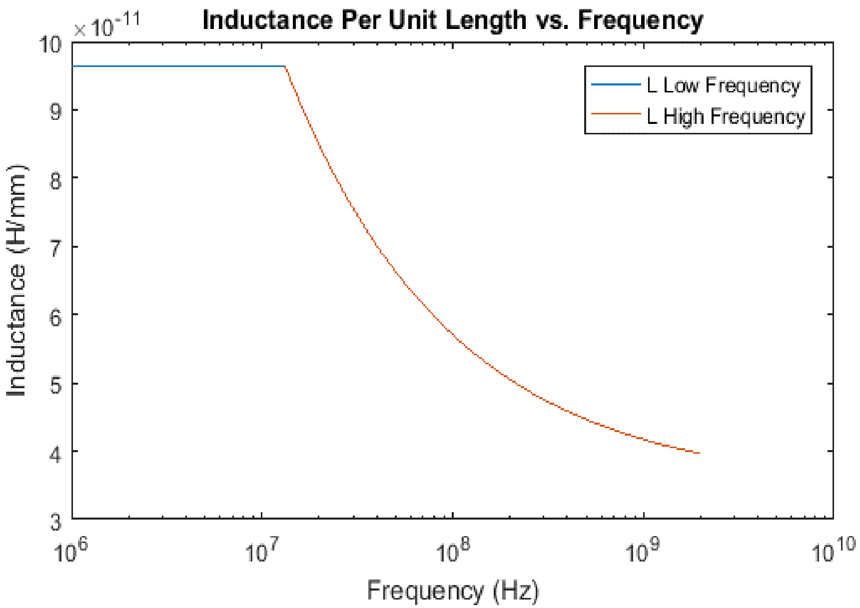
Parameter	Value	Units
r_c	Core Radius	m
t_d	Dielectric thickness	m
t_s	Shield thickness	
ρ_c	Core Resistivity	Ωm
ρ_s	Shield Resistivity	Ωm
μ_0	Magnetic Permittivity Free Space = $4\pi \cdot 10^{-7}$	H/m
μ_r	Magnetic Permittivity Constant = 1	
ε_0	Electric Permittivity Free Space = $8.85 \cdot 10^{-12}$	F/m
ε_r	Dielectric Constant	
f	Frequency	Hz
σ_c	Core Conductivity	S/m
σ_s	Shield Conductivity	S/m
l	Wire Length	m

Appendix E– Frequency Dependence on R and L (Cont.)

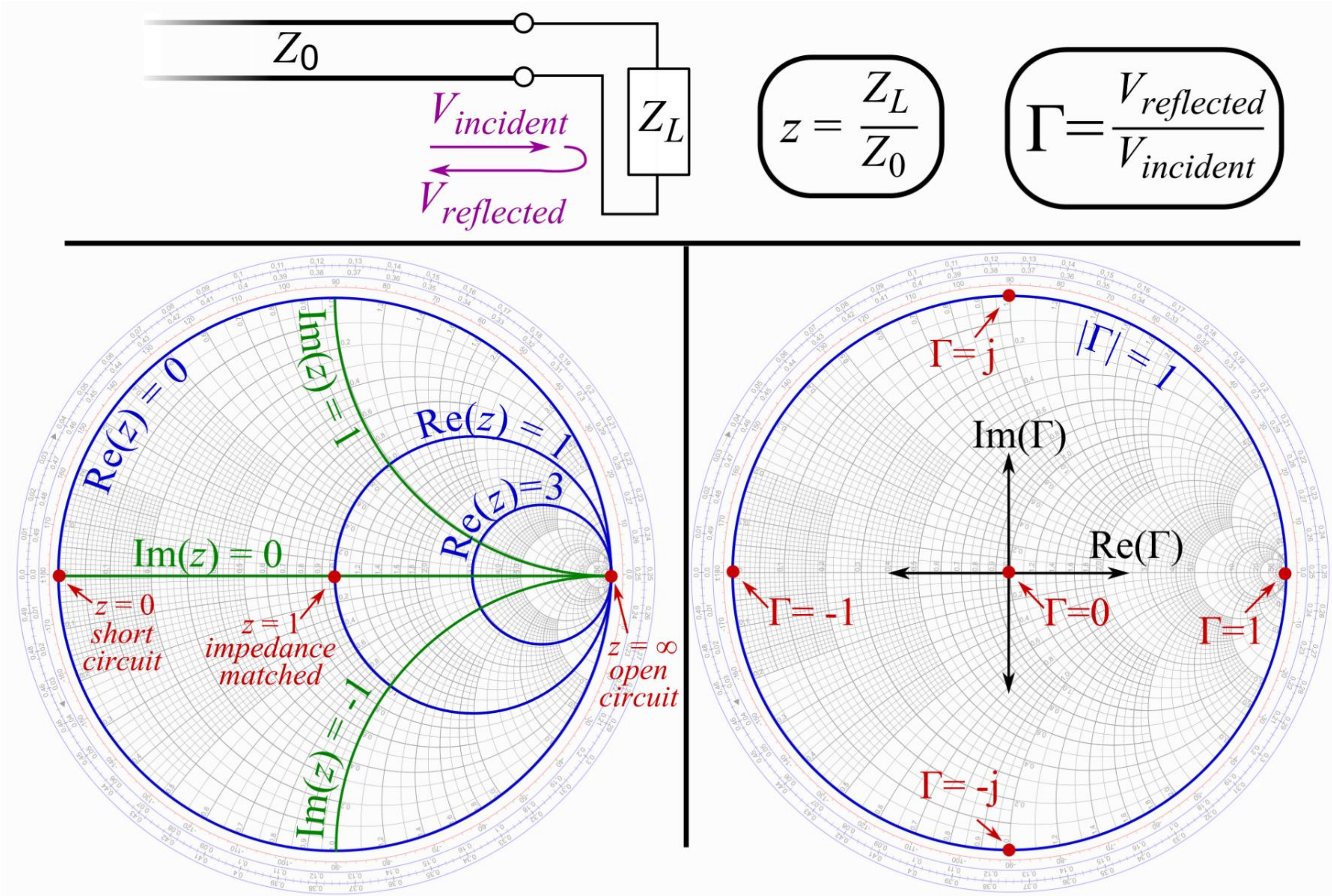
$$\frac{R_{high\_freq}}{l} = \frac{R_{core}}{l} + \frac{R_{shield}}{l} = \frac{1}{2\pi r_c}\sqrt{\frac{\pi f \mu_0}{\sigma_c}} + \frac{1}{2\pi (r_c + t_d)}\sqrt{\frac{\pi f \mu_0}{\sigma_s}}$$

$$\frac{L_{External}}{\ell_{wire}} = \frac{\mu_0}{2\pi}\ln\left(\frac{r_{core} + t_d}{r_{core}}\right) \quad \frac{L_{core}}{\ell_{wire}} = \frac{\sqrt{\mu_0}}{2\pi r_{core}\sqrt{4\pi f \sigma_{core}}} \quad \frac{L_{shield}}{\ell_{wire}} = \frac{\sqrt{\mu_0}}{2\pi (r_c + t_d)\sqrt{4\pi f \sigma_{shield}}}$$



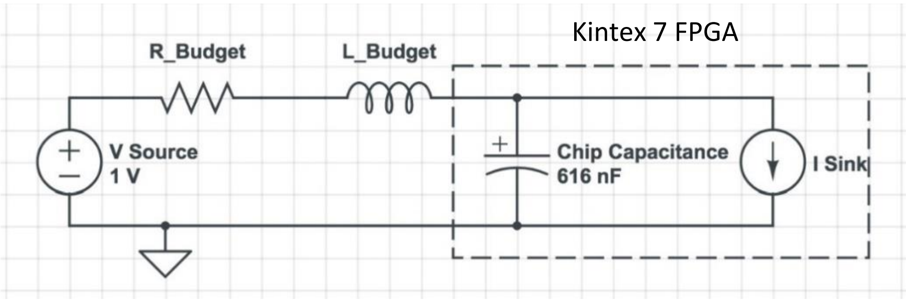


Appendix F– Smith Chart



Appendix G – Power Distribution Network

- PDN is essentially a circuit model of important contributing components to power distribution
- MMS has done case studies on several PDN
- A PDN is shown to the right that was used as a preliminary analysis
- Chip capacitance and R and L of microcoax were the only components considered
- Power requirements of the Kintex 7 FPGA were known to be 30 mV voltage ripple and max current draw of 3.4 A
- ADS circuit models were used to determine limits for R and L



$$Z_{pdn} < \frac{V_{ripple}}{\Delta I}$$

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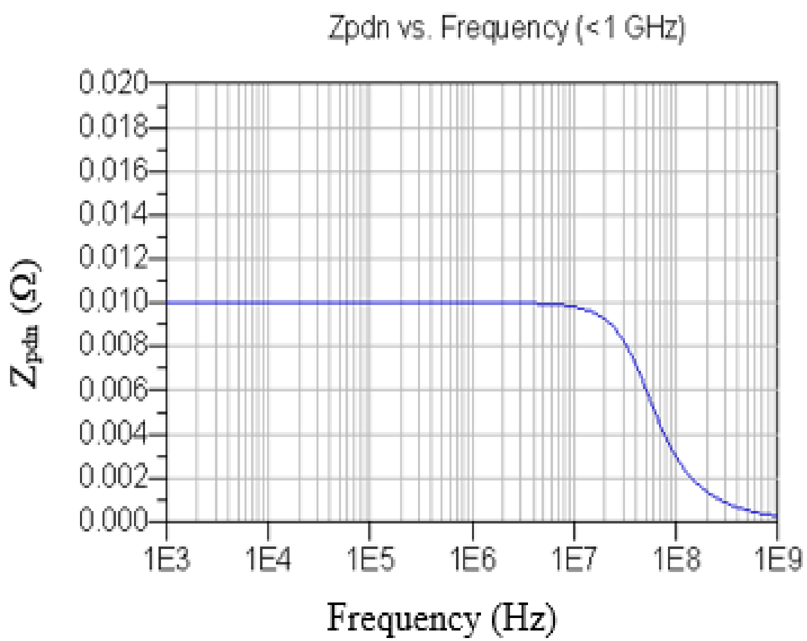
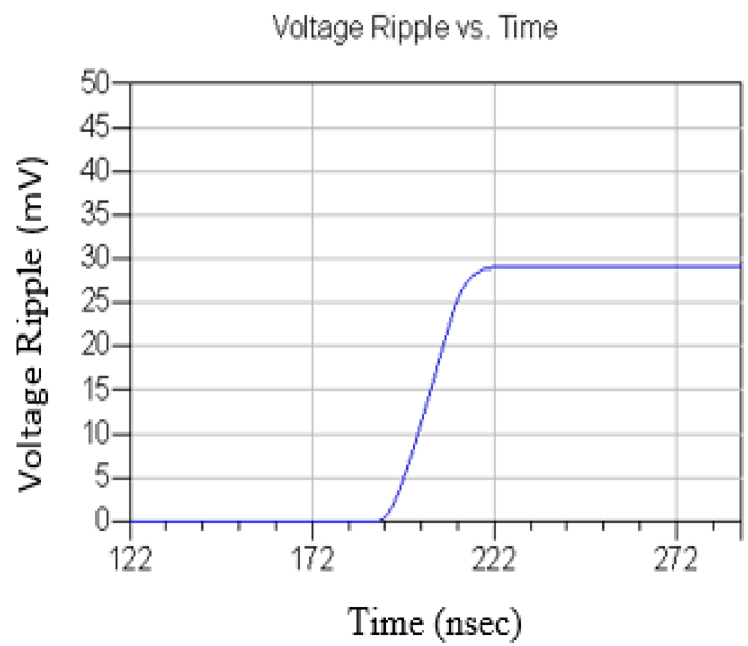
Appendix H – Power Distribution Network

Given power requirements and 16 connections needed to package a Kintex 7 FPGA total allowable Zpdn may not exceed 10mΩ

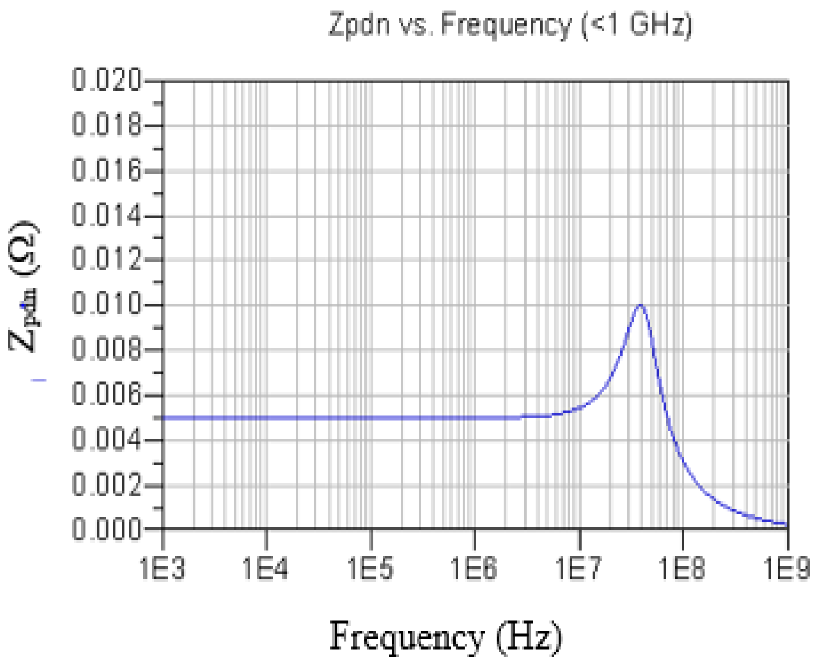


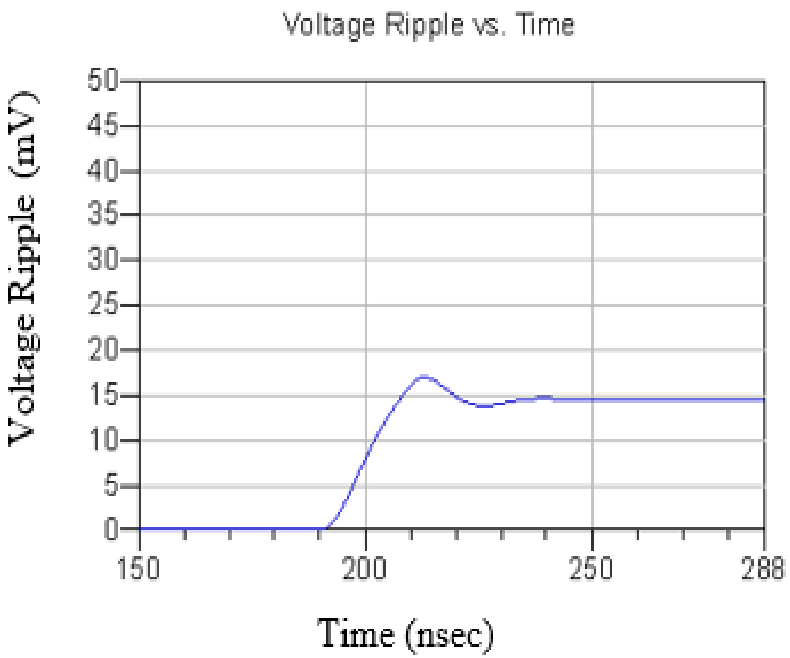


R per wire is 160 mΩ and L per wire is 320 pH

Appendix I – Power Distribution Network

Second analysis shows that if we lower R per wire we can tolerate a higher wire inductance but a higher L introduces new resonances



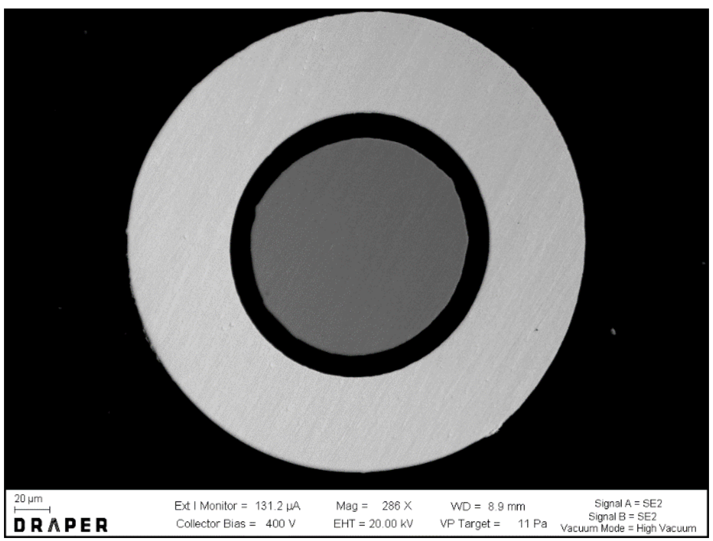


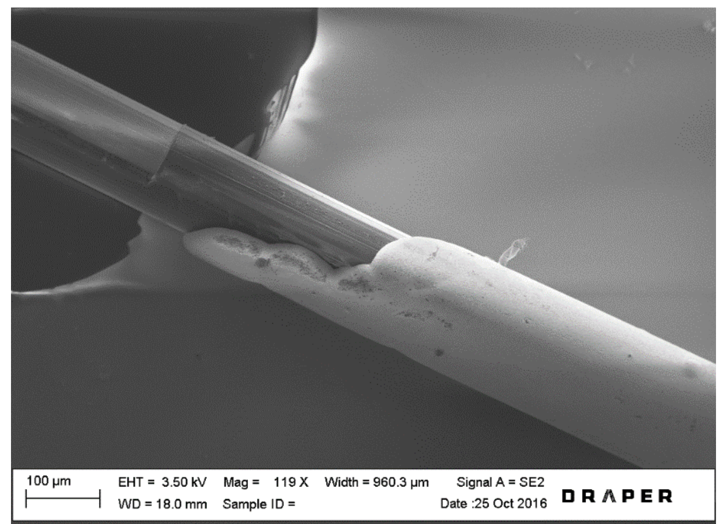
R per wire is 80 mΩ and L per wire is 380 pH

Target R and L from both cases are 3.2-3.6 mΩ/mm and 12.8-15 pH/mm

Appendix J – Power Distribution Network

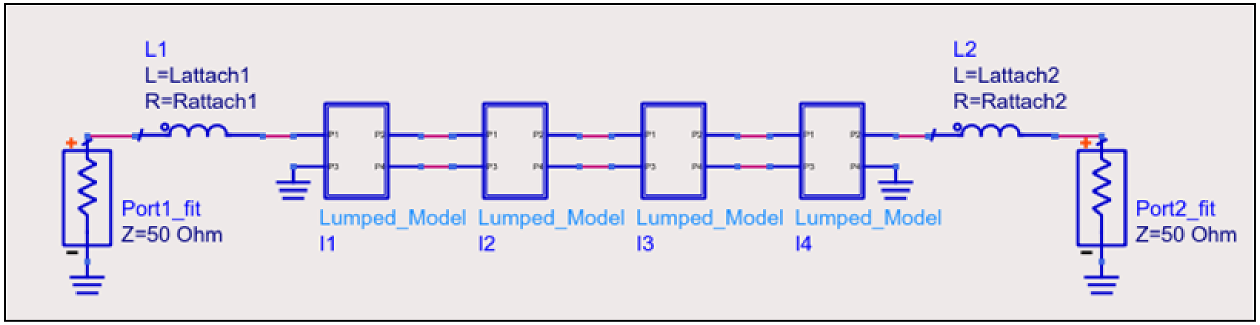
Parameter	Target Value	Actual Value	Notes
r_c	41µm	62.5 µm	Determined using a core resistance of 3.20 mΩ/mm, **copper core** material,
t_d	3.0 µm	12 µm	Determined using L_{Budget} of 15 pH/mm
t_s	28 µm	55 µm	Determined using a shield resistance of 3.20 mΩ/mm, gold shield material



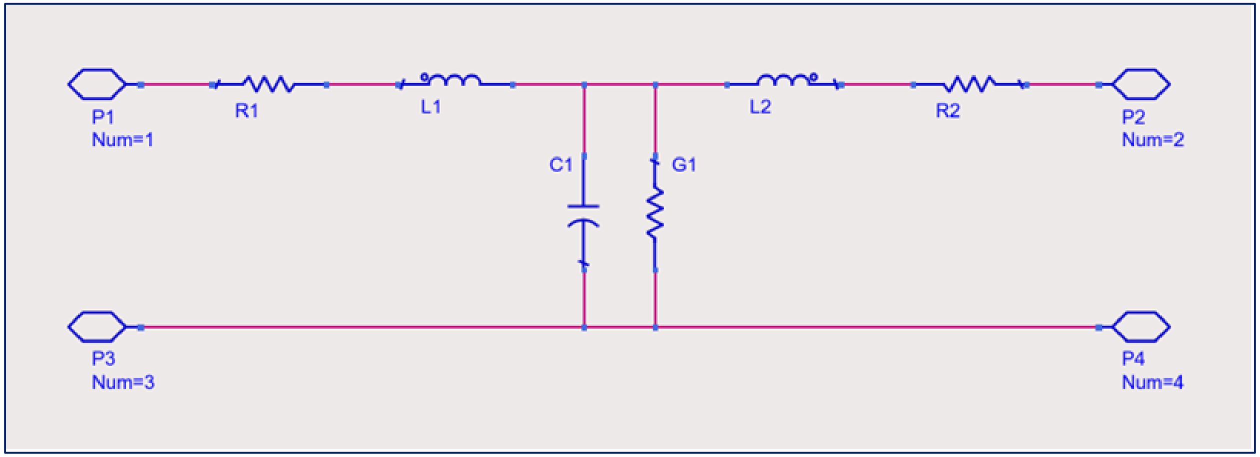


Appendix K – RF Results on Other MMS Wires

Quasi Distributed Model 20 mm long wire



Individual Cell Model 5 mm long



By: Tony Kopa

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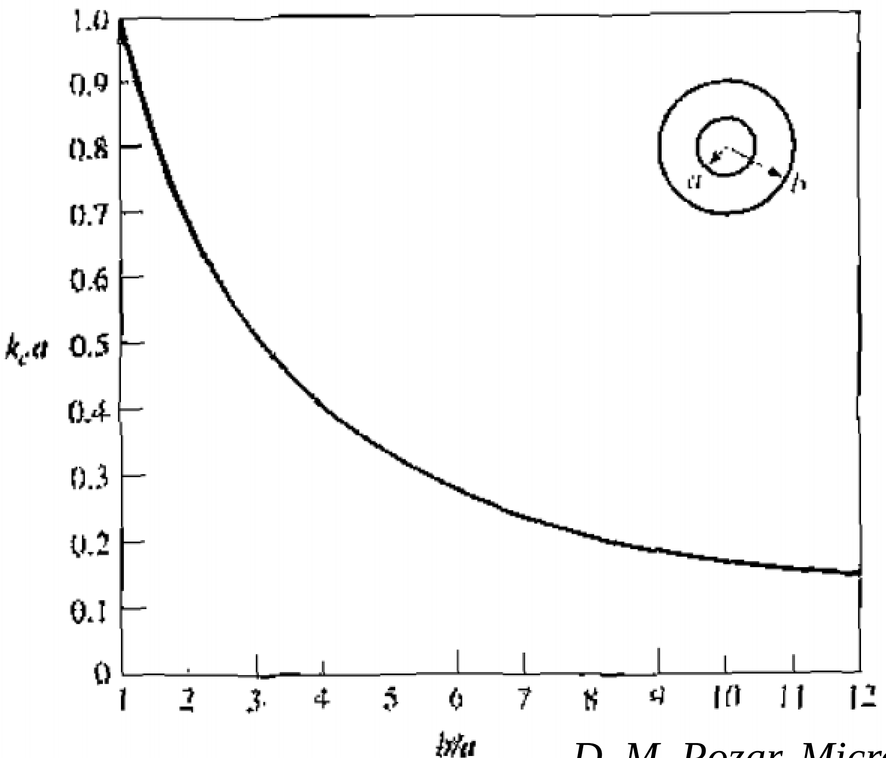
Appendix L – RF Results on Other MMS Wires

	L (pH/mm)	C (pF/mm)	Z_0 (Ω)	R(mΩ/mm)
Analytical	40	0.98	5.98	2.30
Measured (VNA)	40	0.93	6.56	2.00
Simulated (HFSS)	50	0.94	7.30	--

Inductance target exceeded and resistance may be exceeded at higher frequencies. Thinner dielectric is needed.

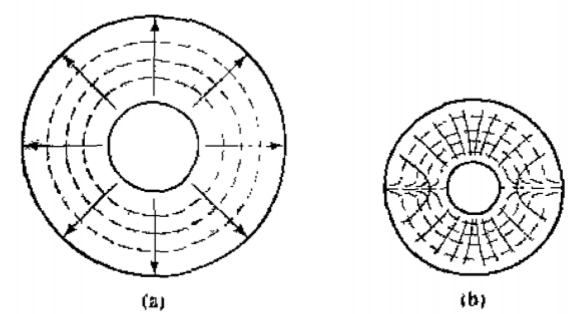
By: Tony Kopa

Appendix M – TEM Mode of Cable



Cut off Frequency

$$k_c = \frac{2}{a+b} \qquad f_c \approx \frac{c k_c}{2\pi\sqrt{\varepsilon_r}}$$



Field lines for the (a) TEM and (b) TE_{11} modes of a coaxial line.

D. M. Pozar, Microwave Engineering, Addison-Wesley, 1990.

Wire	b/a	kc	c (m/s)	v_f	er	fc
HfO2	1.007874	78431.37	61200000	0.16	28	1.44E+11
Parylene C Power	1.07874	75757.58	172500000	0.45	3.05	1.19E+12
Parylene C Signal	3.992126	31545.74	172500000	0.45	3.05	4.96E+11

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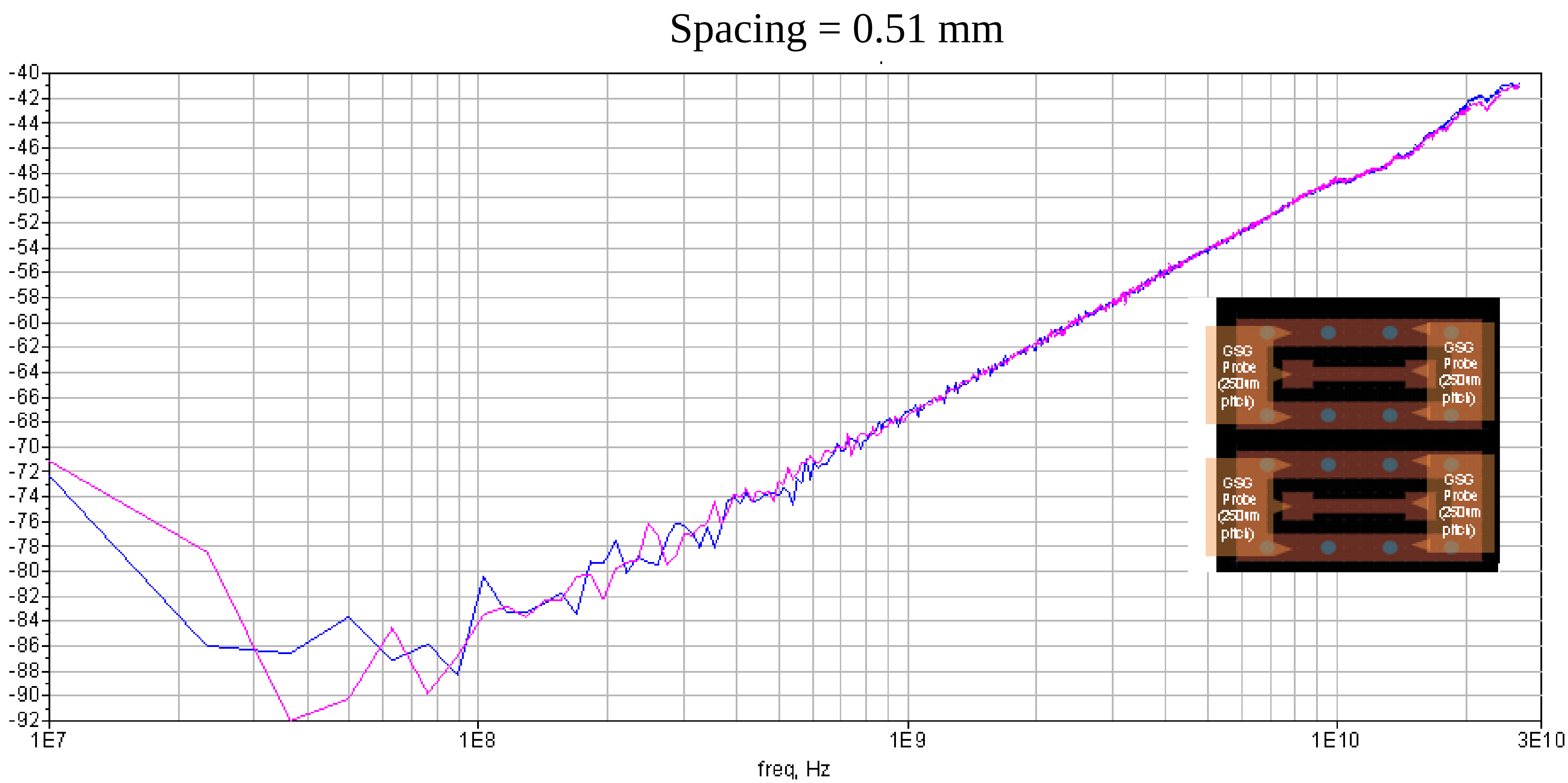
Resonances in data may be from substrate only

Appendix N – Crosstalk Adjacent Empty Launches



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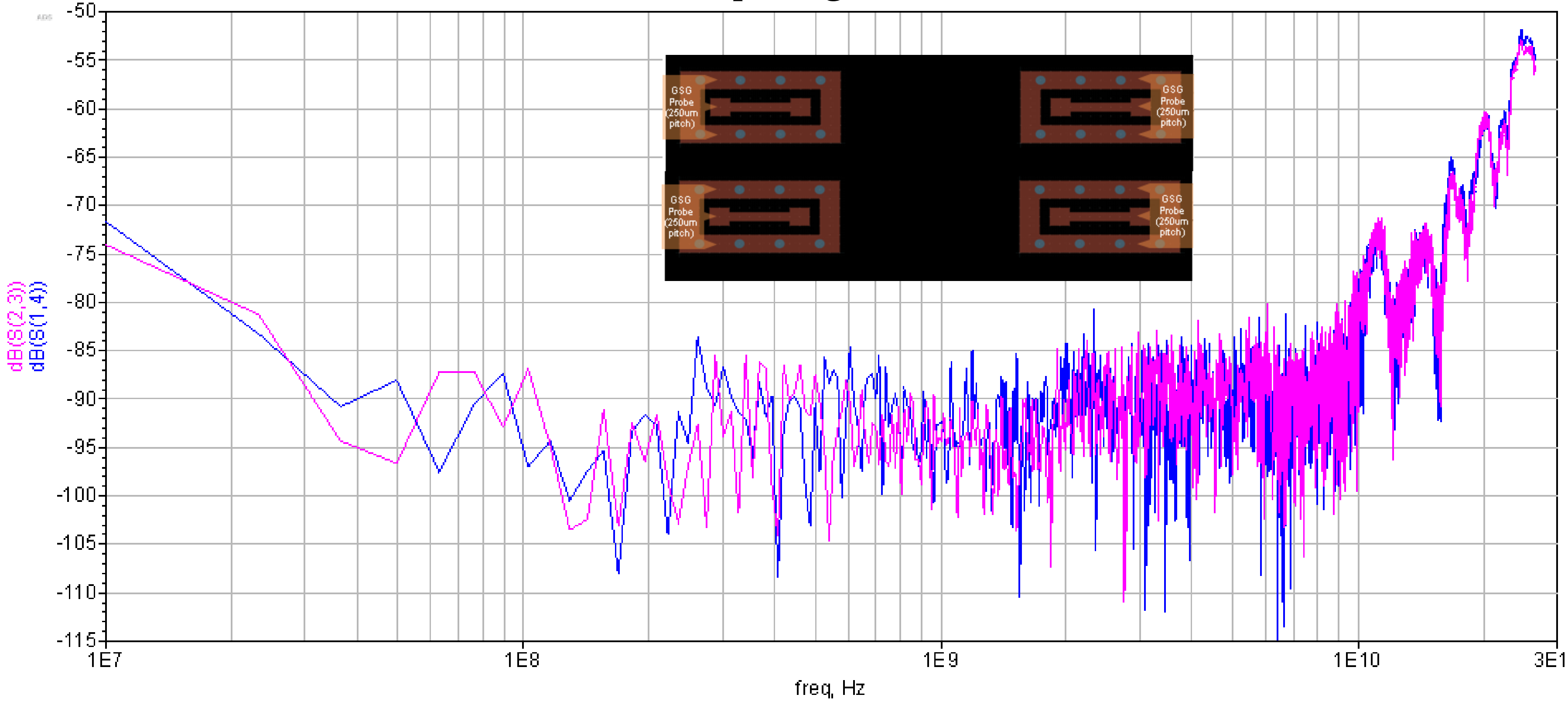
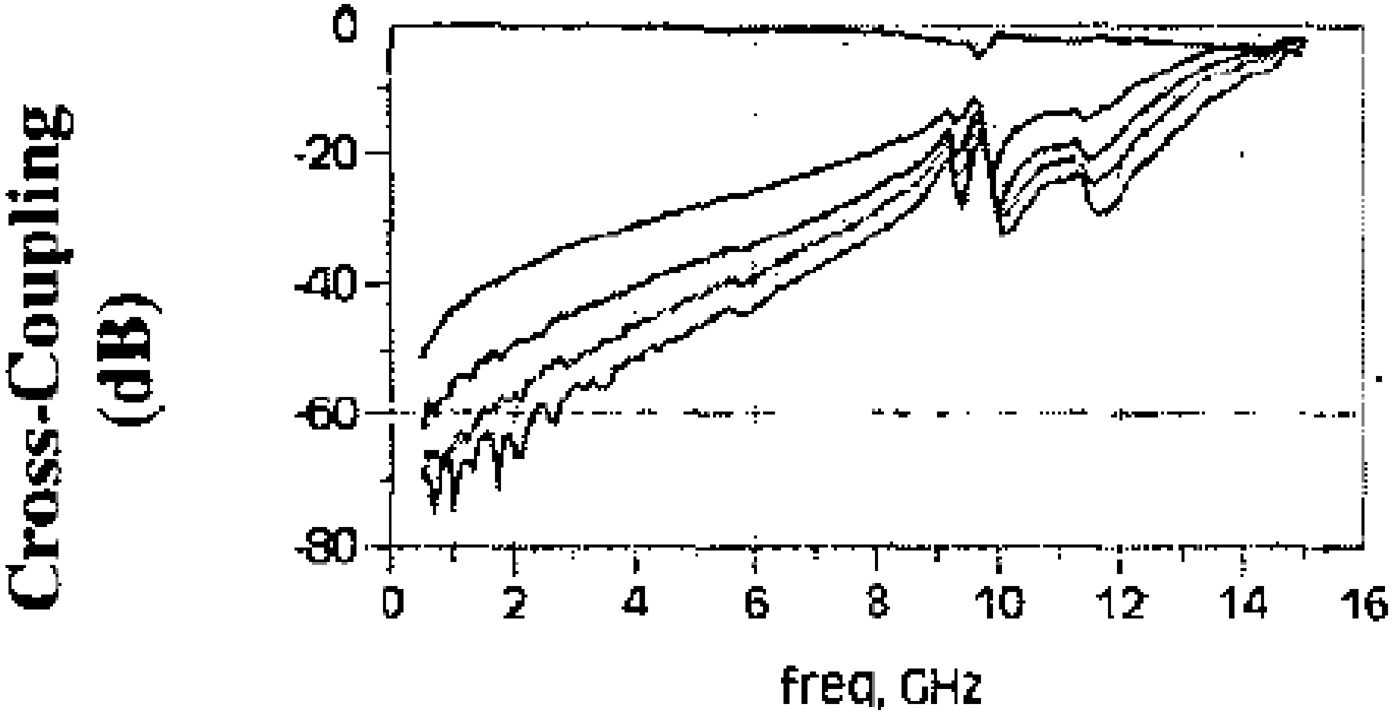
Appendix N – Crosstalk Across Empty Launches

Spacing = 3.5 mm



Cross-Talk Results Bare Wires – Prior Art

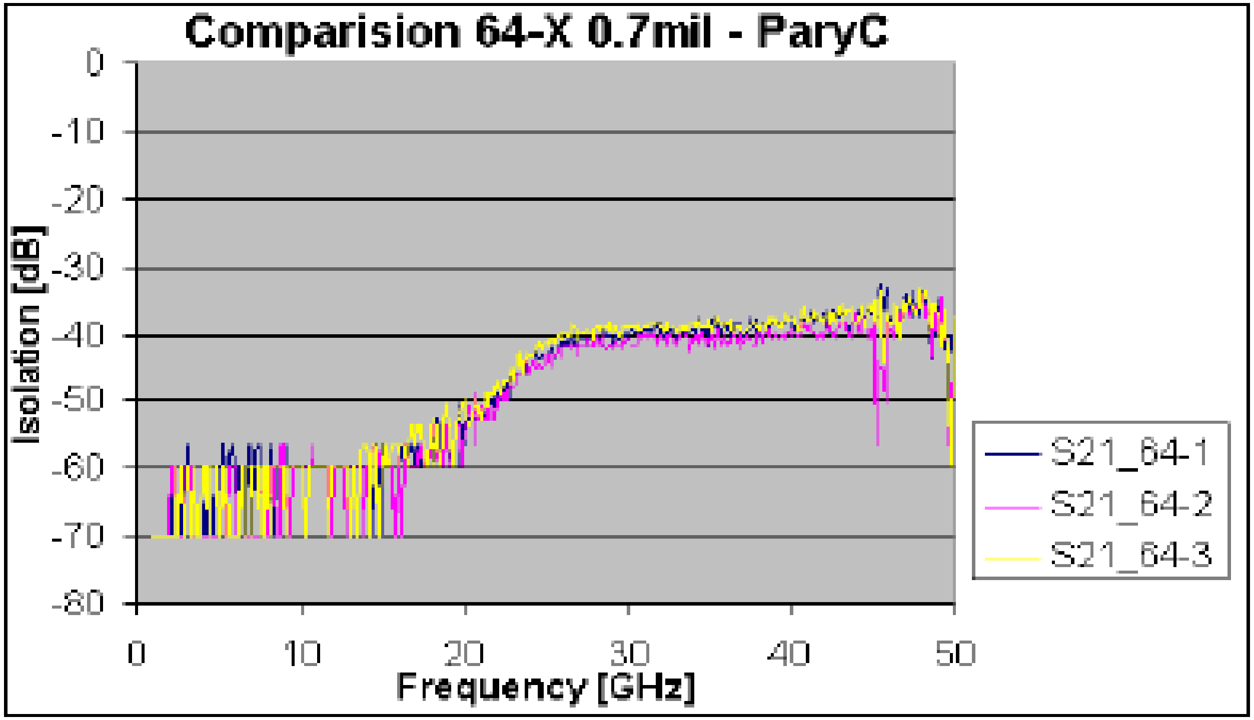
2 mm long Au Wire Bonds in GSG Configuration



Arun Chandrasekhar, "Characterization, Modeling and Design of Bond-Wire Interconnects for Chip-Package Co-Design," in European Microwave Conference , Munich, 2003

Cross-Talk Results Microcoax Wires – Prior Art

3 mm long 40 Ω Signal Coax
160 µm Wire Pitch



S. S. Cahil, E. A. Sanjuan and L. Levine, "Development of 100+ GHz High-Frequency Micro Coax Wire Bonds," iMAPS

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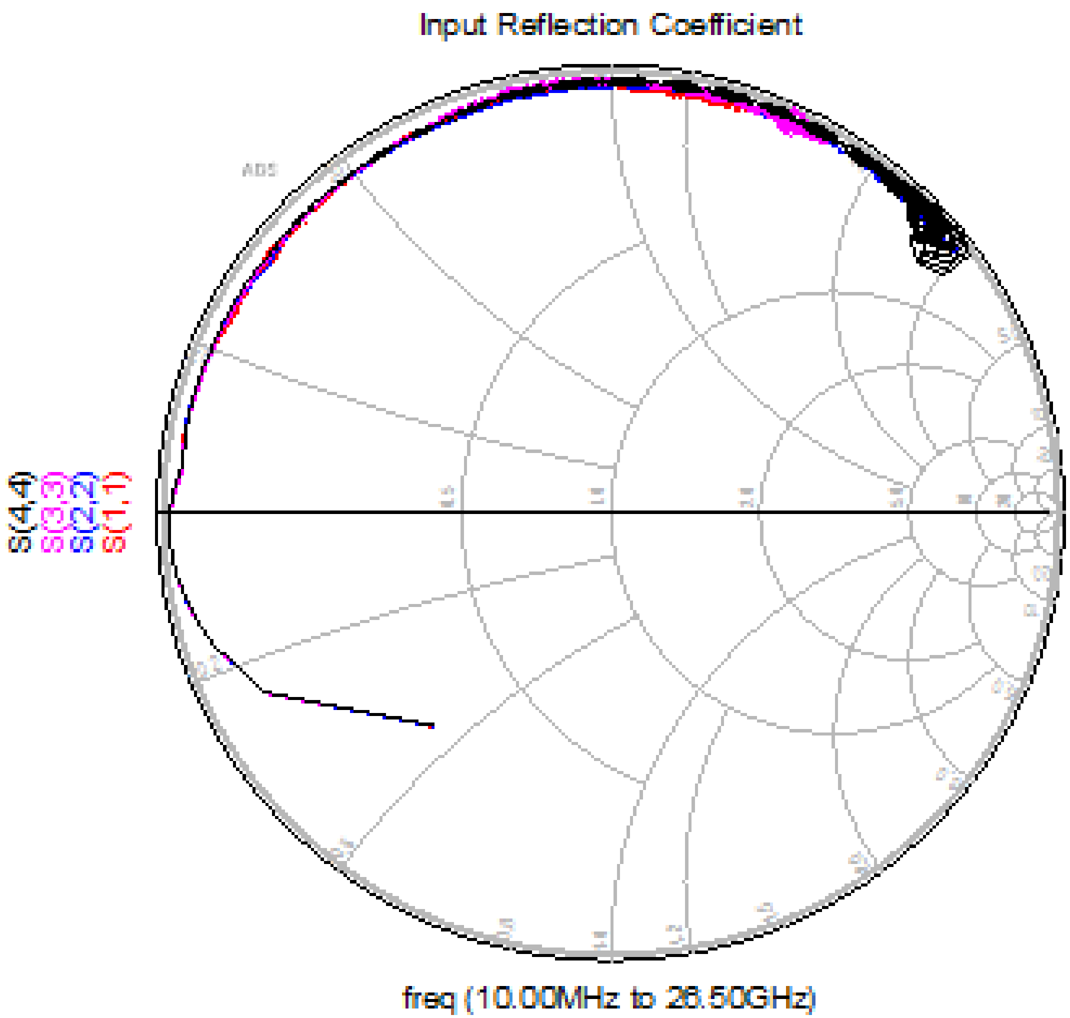
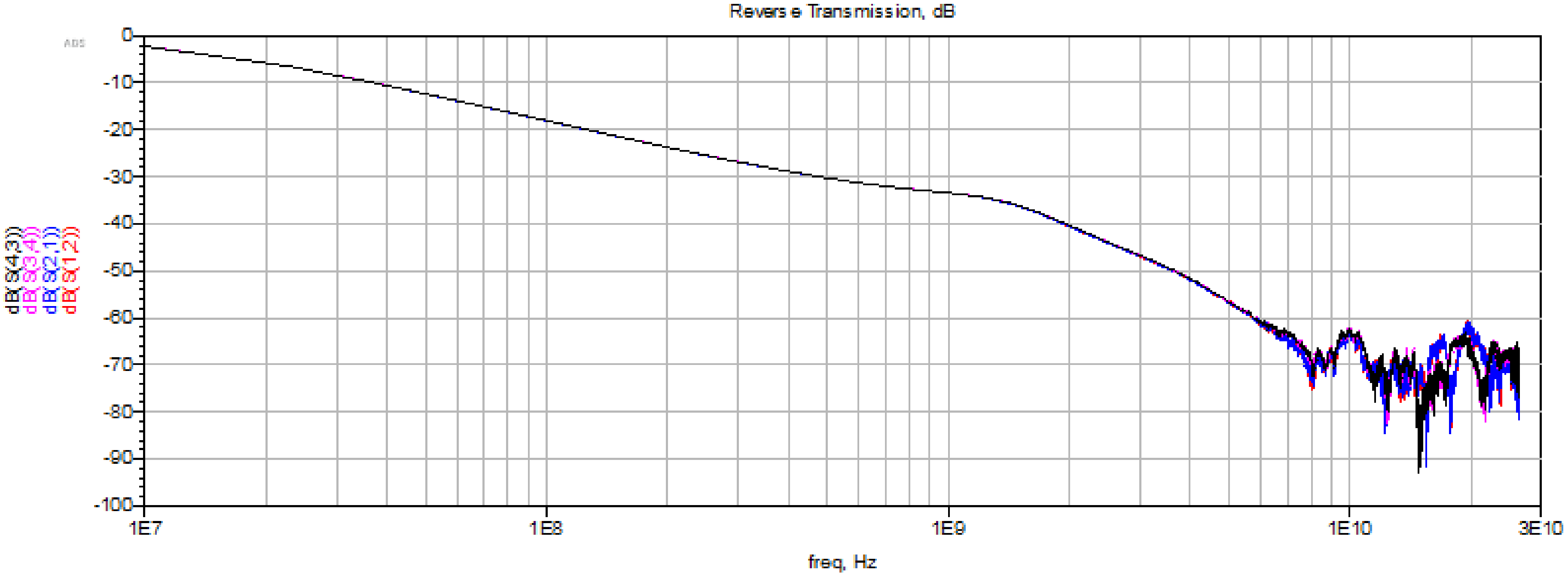
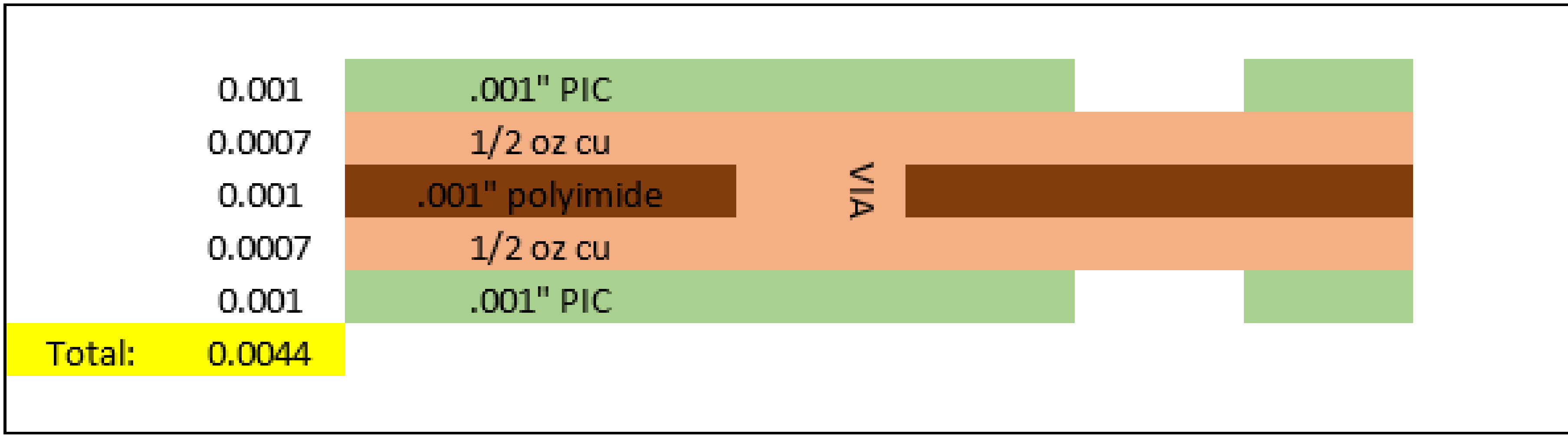
Appendix O – 4 Port Test HFO_2



Appendix O – 4 Port Test HFO_2



Appendix P – RF Board



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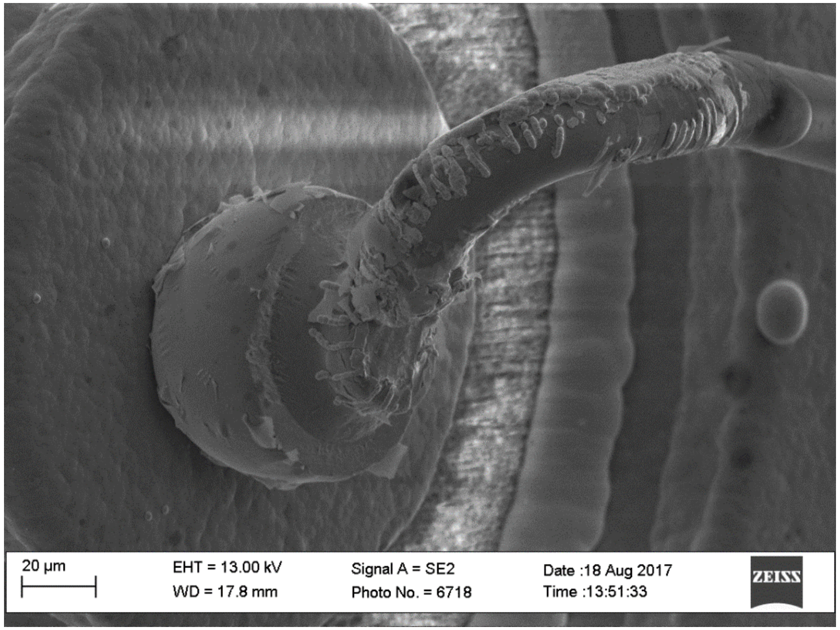
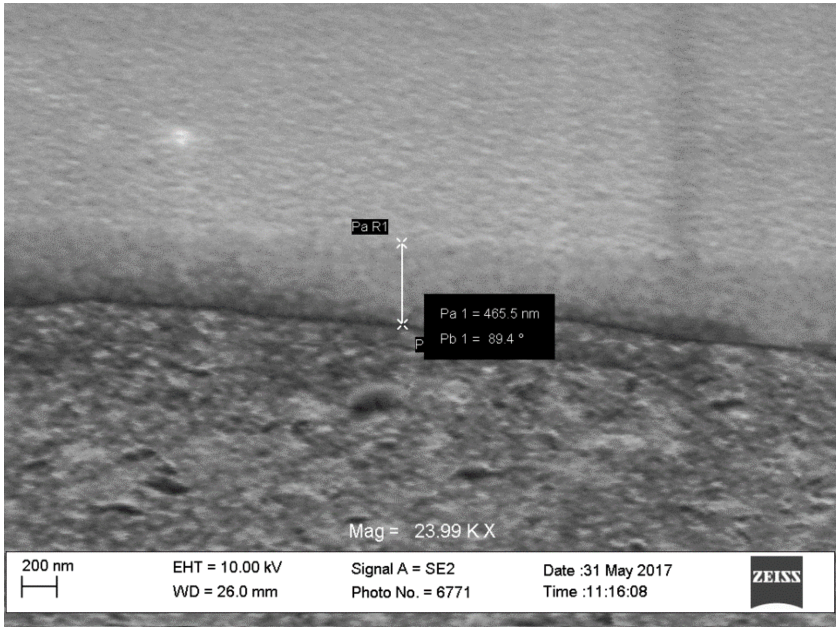
Appendix Q - Other Fabrication Challenges

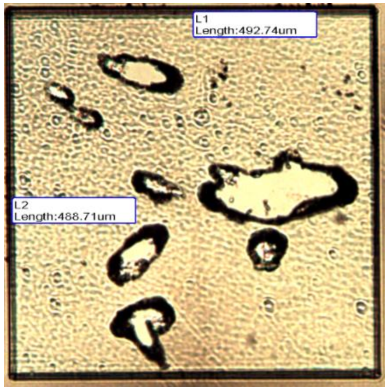
ALD Pt as a Seed Layer

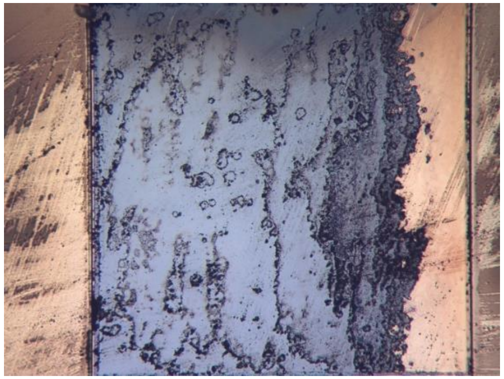


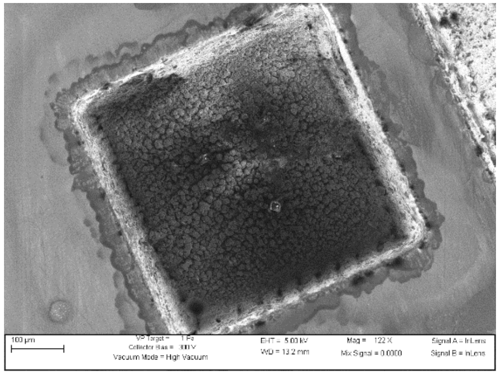
Lift Off Thin Films with PR



Optimizing Laser Etching and Pinhole Tests

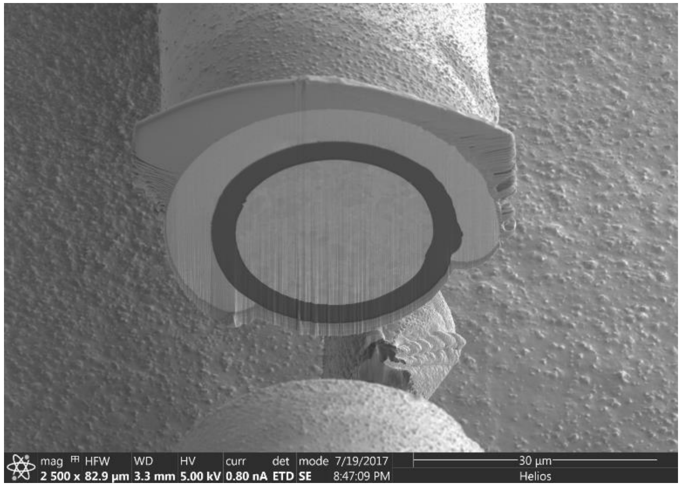




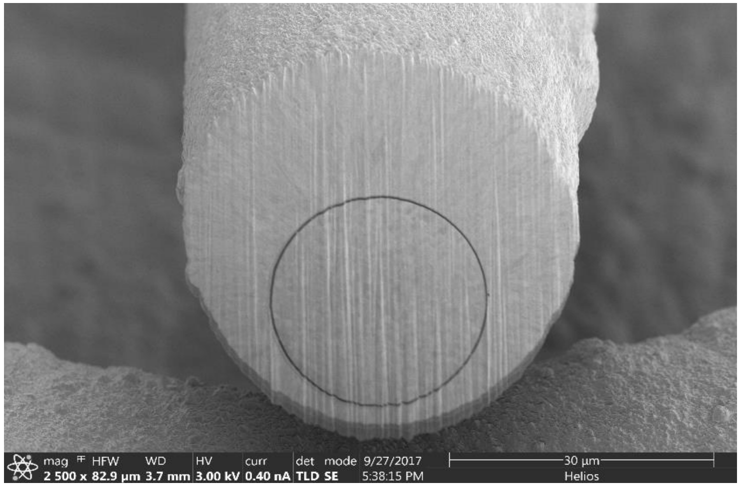


Importance of Conformal Adhesion Layers

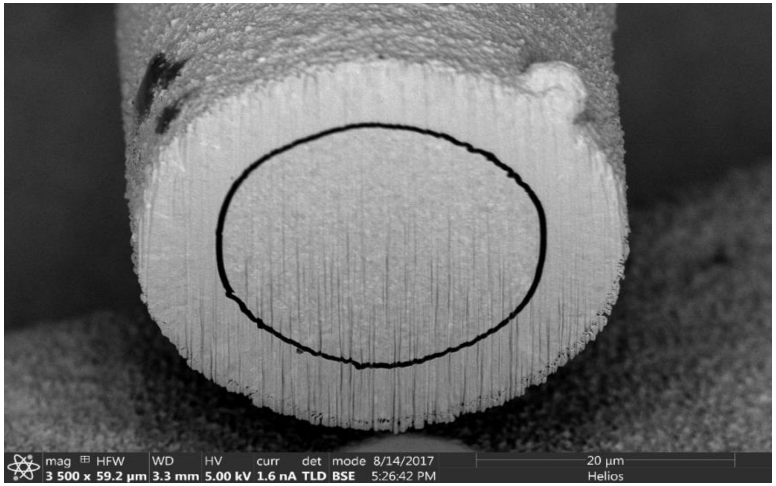
Evaporated Seed Layer



Sputtered Seed Layer (x1)



Sputtered Seed Layer (x2)



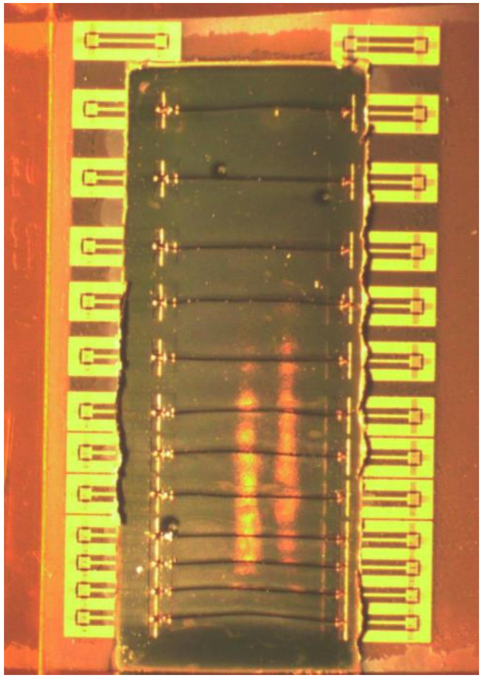
Signal Coax Fabrication Challenges

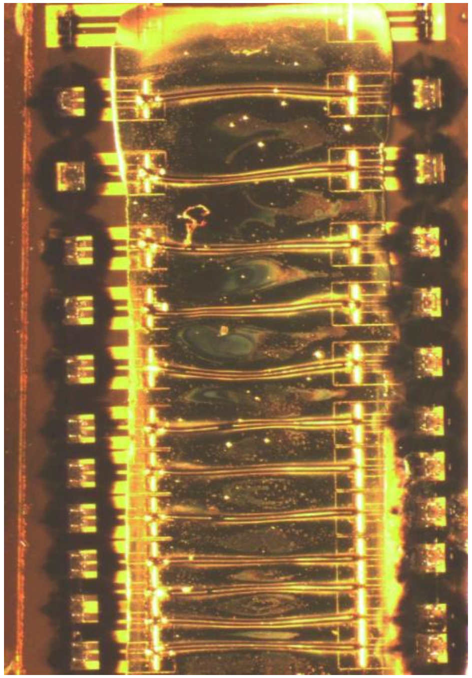
Laser Etching

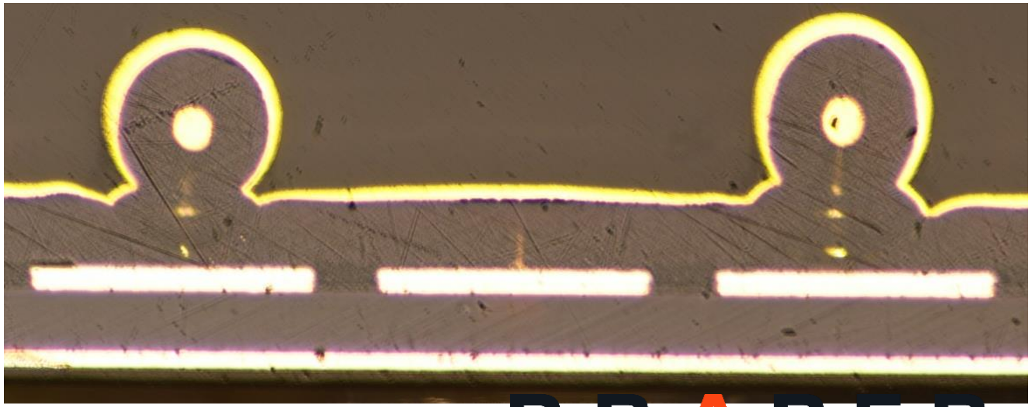
- Masking thick parylene C is challenging
- Residue formed due to heat spreading of laser and re-deposition of material onto surface

Non Suspended Wires

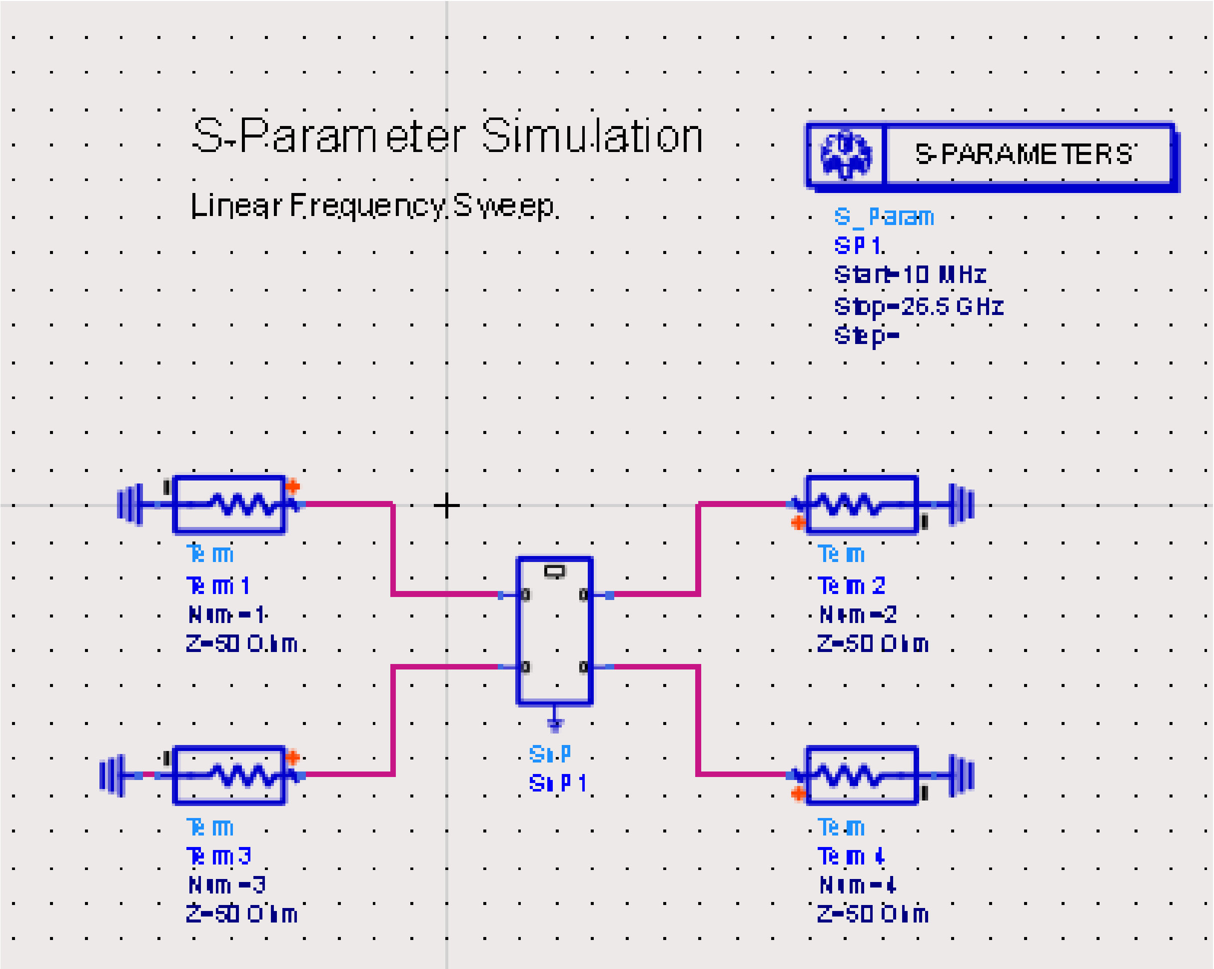
- Some wires are not suspended
- Asymmetric coaxial shield







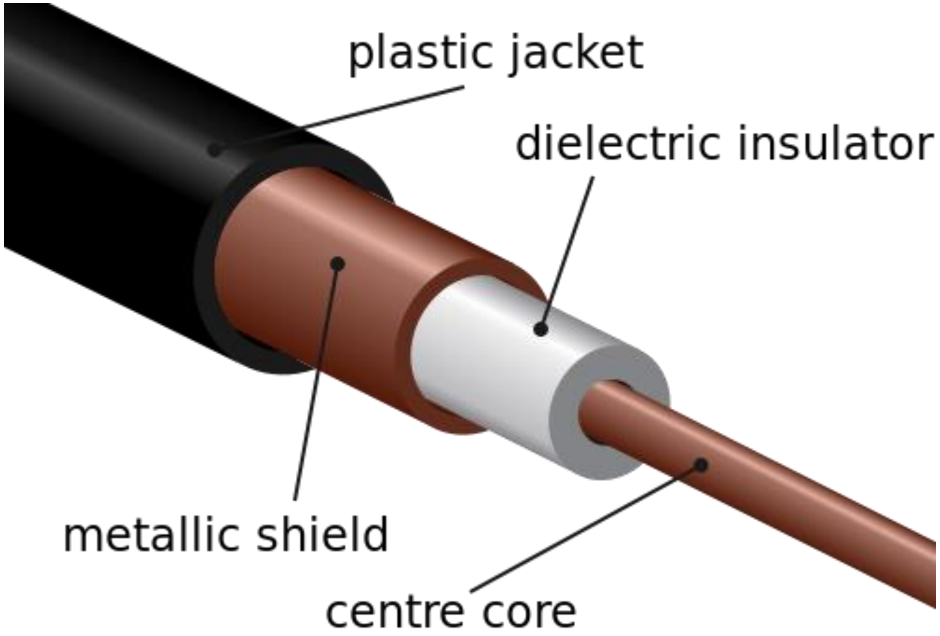
4 Port Cross-Talk ADS Simulation



Microcoaxial Cables for RF Modules

Main Components

- Core metal – signals or power
- Dielectric – insulate core
- Shield metal – ground
- Jacket – protect further handling (not a focus in this work)



Advantages

- Electric and magnetic fields kept within dielectric
- Protection from external fields
- Correlation between coaxial geometry and dielectric properties to desired impedance

D. M. Pozar, Microwave Engineering, Addison-Wesley, 1990.

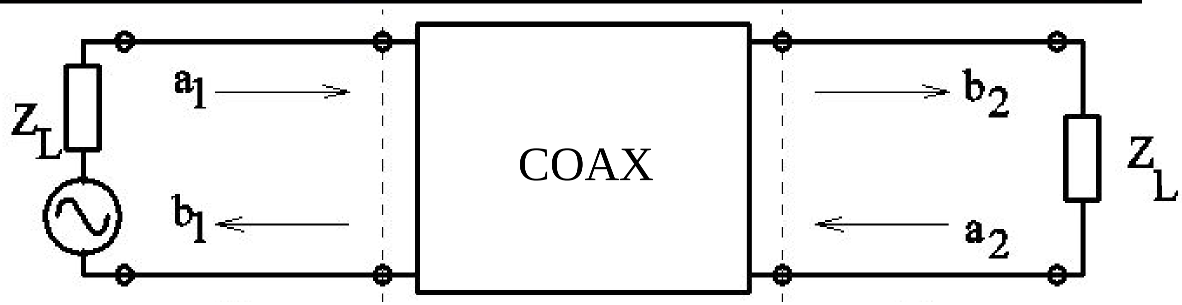
2 Port Vector Network Analyzer and S-Parameters

2-Port Network Used to Characterize RF Components up to 12 GHz

Port 1

Port 2

Port 1



Port 2

Voltage Behave as Waves at High Frequency

$$a_i = \frac{Voltage\ wave\ incident\ at\ port\ i}{\sqrt{Z_0}} = \frac{V_i + I_i Z_0}{2\sqrt{Z_0}}$$

$$b_i = \frac{Voltage\ wave\ reflected\ at\ port\ i}{\sqrt{Z_0}} = \frac{V_i - I_i Z_0}{2\sqrt{Z_0}}$$

HP, "S-Parameters Theory and Applications"

2 Port Vector Network Analyzer and S-Parameters

Relate Reflected and Transmitted Waves With S - Parameters

$$b_1 = s_{11}a_1 + s_{12}a_2$$

$$b_2 = s_{21}a_1 + s_{22}a_2$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

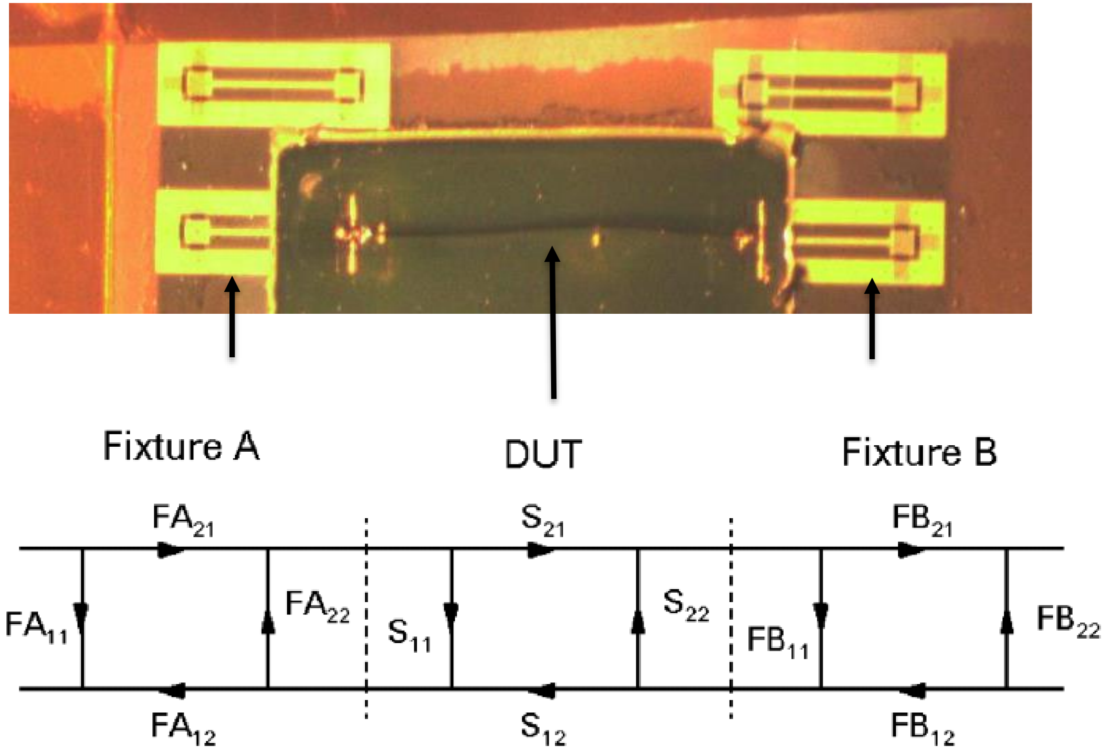
S-Parameters May be Related Back to Complex Impedances

$$s_{11} = \frac{b_1}{a_1} = \frac{\frac{V_1}{I_1} - Z_0}{\frac{V_1}{I_1} + Z_0} = \frac{Z_1 - Z_0}{Z_1 + Z_0}$$

HP, "S-Parameters Theory and Applications"

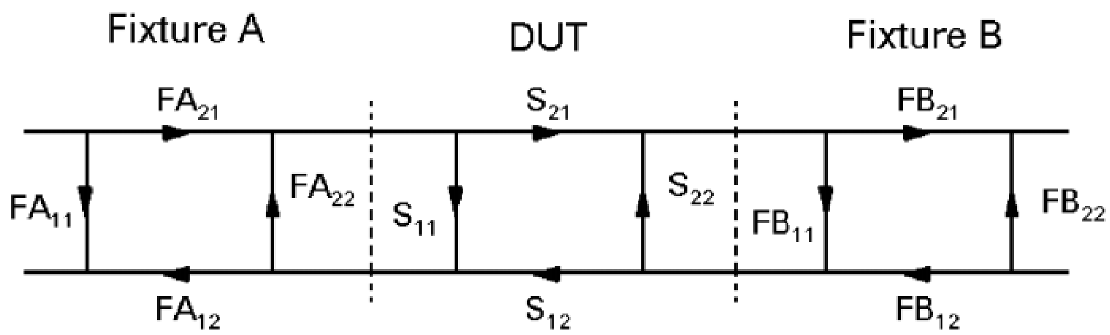
De-Embedding

S-Parameter Matrix Gathered from VNA are that of the Substrate and Wire. De-Embedding is Necessary to Remove Substrate Effects.



HP, "S-Parameters Theory and Applications"

De-Embedding



$$\left[S_{Measured}\right]=\left[S_{FA}\right]\left[S_{DUT}\right]\left[S_{FB}\right]$$

$$\left[S_{FA}\right]^{-1}\left[S_{Measured}\right]\left[S_{FB}\right]^{-1}=\left[S_{DUT}\right]$$

Preferably S_{FA} and S_{FB} are Measured Directly Using the VNA

(Known as 2-Port De-embedding)

This Fabrication Process Makes that Difficult

HP, "S-Parameters Theory and Applications"

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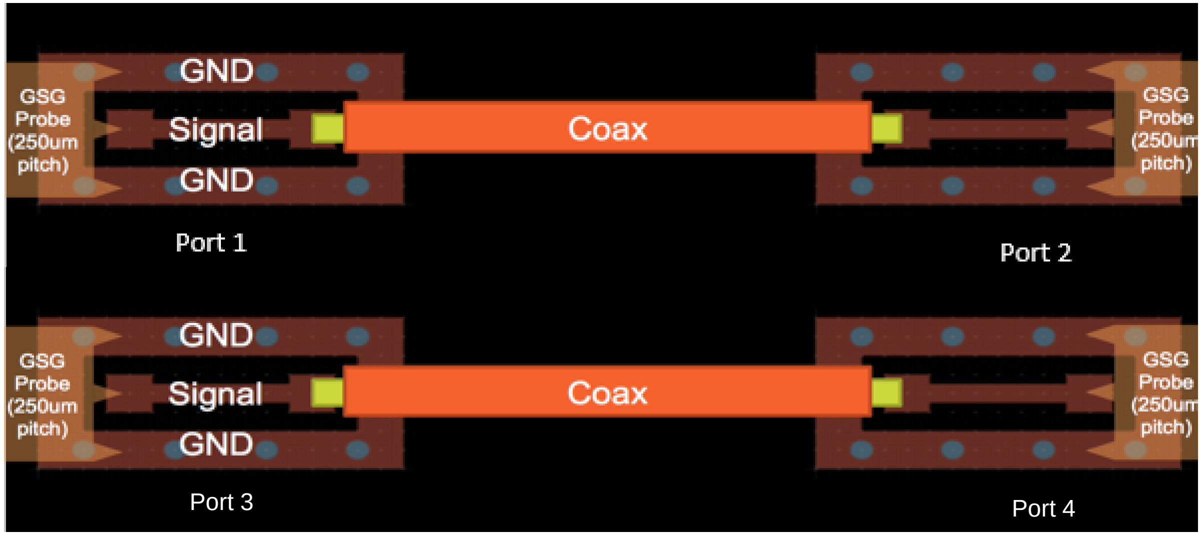
4 Port VNA Measurements

4 Port VNA Measurement 10 MHz – 26.5 GHz



Network Theory Still the Same

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

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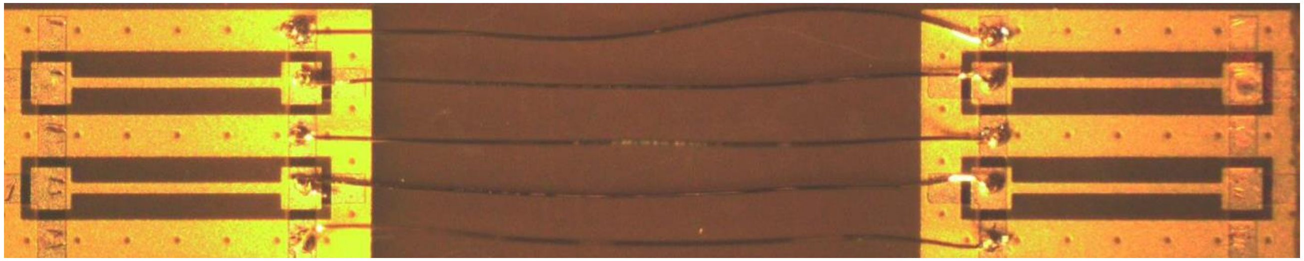
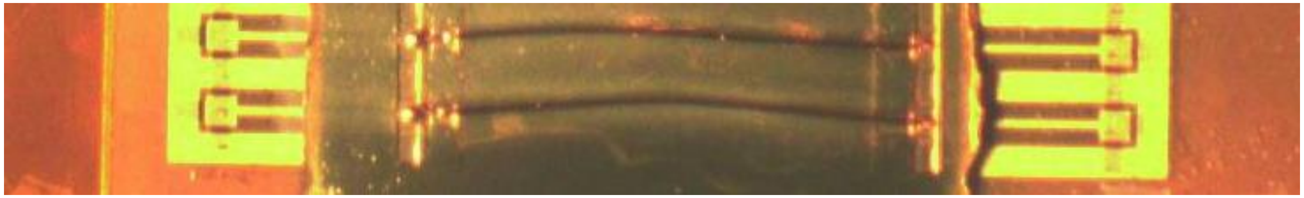
Cross-Talk Test

Bare Au Wires with 25.4 µm Core
Bonded to GSG Pads – Imitate IO on IC
Signal to Signal Pitch – 0.50 mm



Used Same RF Boards HfO_2 and Parylene Micro Coax
Signal to Signal Pitch – 0.5 mm



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