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The Effects of Probe Impedance on RF KGD Measurements

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Agenda

- **Introduction**
- **Objective**
  – The impact if increased inductance (impedance)
- **Methods / Materials / Procedures**
  – Impact of small inductance to impedance
  – Membrane emulation of different probe types
  – HFSS modeling
- **Summary**
- **Follow-On Work**

WLCSP Demands KGD

- **WLCSP is the fastest growing package type**
  – "Wafer level chip-scale packages… became the IC industry's most popular package type in 2009.
    - Yannou, Jean-Marc. "WLCSP quietly edges into #1 position" 3D Packaging, Feb 2010: 16-17
  – KGD testing
    - Die test is Final Test
  – Wider pitch probes
    - Package technology can be adapted for die level testing
      – Wider pitch (400-500 µm)
      – More compliance
      – Longer, more inductive probes

Specs – Bandwidth, Inductance

- **Datasheets consistently spec bandwidth and contact resistance**
- **Longer, more inductive probes have sufficient bandwidth for consumer RF applications in the 1-2.5 GHz range**
  - Typical socket bandwidth specs for -1 dB
    - 6.8, 11.1, 11.5, 17.17 GHz
  - Typical inductance specs
    - 1.71, 1.27, 1.1, 1.15 nH
- **From a Pyramid Probe perspective, that's a lot of inductance**

What's the Big Deal With Small Inductances?

- **Consider inductance in terms of reactance**
  - This is the frequency dependant part of impedance
- **Impedance is $Z_o = R + 1/j\omega C + j\omega L$**
  - The inductive reactance, $X_L = \omega L$
    - WLAN and Bluetooth are approximately 2.5 GHz
    - A little inductance would be 0.1 nH
  - $X_L = \omega L$
  - $X_L = 2\pi * 2.5\ \text{GHz} * 0.1\ \text{nH}$
  - $X_L = 1.6\ \Omega$
- **1 nH would be ten times as much, 16 Ω**

What's the Big Deal with Small Inductances?

- **Why do such small inductances make a difference?**
  – Contact resistance (typical values)

1.5 – 2 ohms	**Broz, J., Rincon, R. (1998). Probe Needle Wear and Contact Resistance, SWTW, p 8**
0.8 – 1.2 ohms	**Strom, J., (1998). Multi-Tier Probe Cards and Contact Resistance, SWTW, p 7**
0.5 ohms (Upper Spec Limit)	**Kister, J., (2007). Electrical Contact Resistance - The Key Parameter in Probe Card Performance, SWTW**

- **X_L =1.6 Ω for a 0.1 nH inductor**
  – For a small inductance, you have an impedance change or discontinuity equivalent to double or triple the acceptable contact resistance.
- **X_L =16 Ω for a 1 nH inductor**
  – For a large inductance, the discontinuity could be 10x the contact resistance or 1/3 of the 50 ohm trace impedance

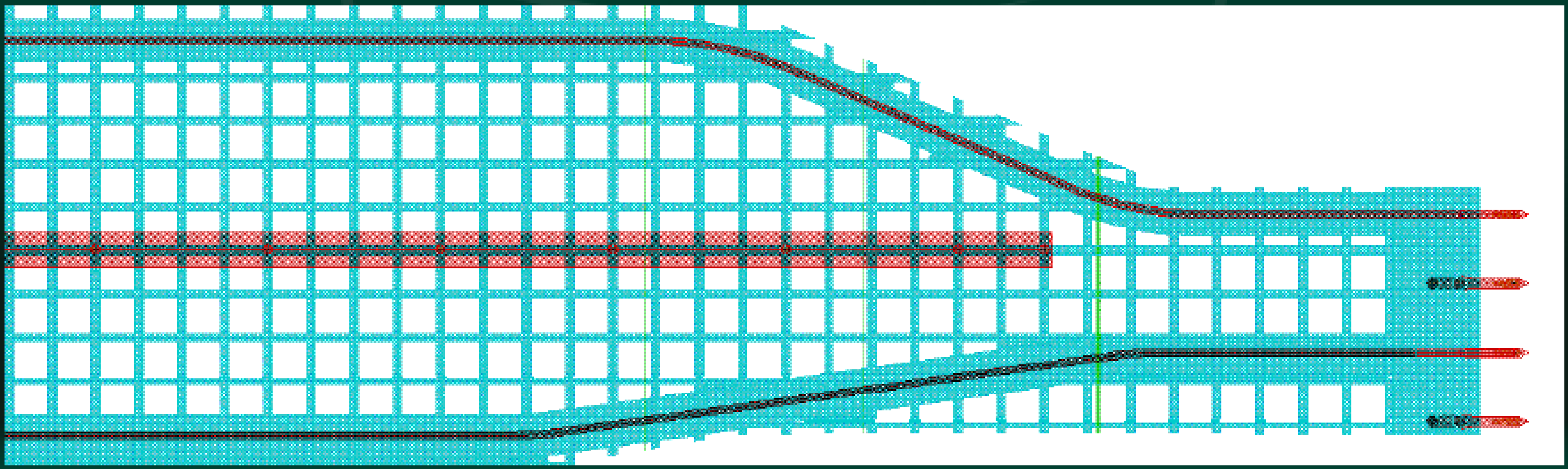
Inductance Comparison

- **Create a Pyramid Probe membrane to investigate the affect of an inductive contact**
  - Target WLCSP devices
    - Use 400 µm pitch
  - Typical inductances for three contact types
    - Standard Pyramid Probe geometries, 0.04 nH
    - Spring pin, 0.68 nH
    - MEMS vertical, 1.05 nH

Membrane Design – Pyramid Probe

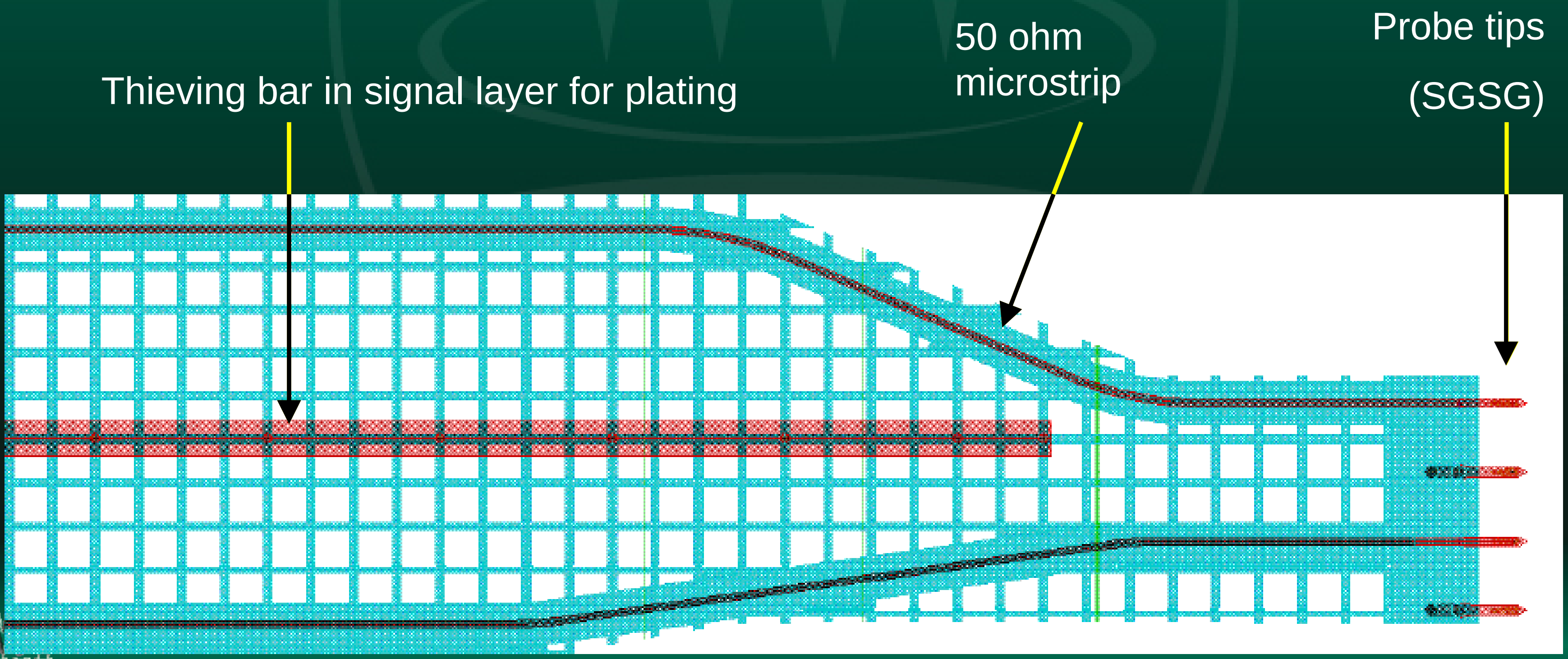
- **Pyramid Probe**

Transmission line	50 Ω
Inductance from end of transmission line to DUT	n/a
Inductance from GND plane to DUT	0.04 nH



Membrane Design – Pyramid Probe

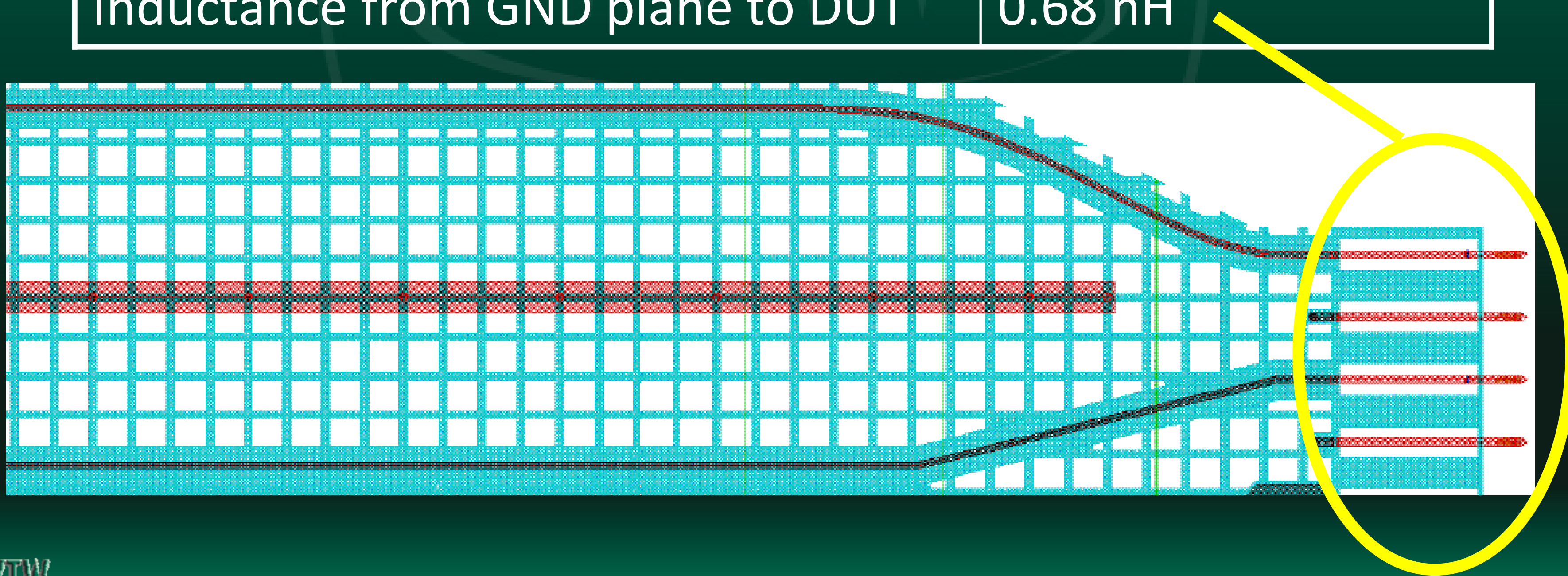
- **Pyramid Probe**
  - Two metal layers
    - Ground plane is blue; mesh and solid
    - Signal layer is red



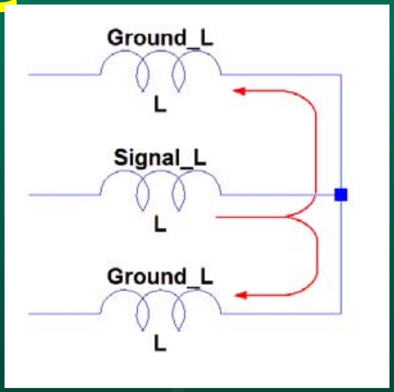
Membrane Design
Spring Pin Emulation

- **Spring Pin**

Transmission line	50 Ω
Inductance from end of transmission line to DUT	0.68 nH
Inductance from GND plane to DUT	0.68 nH



Determining Spring Pin Self-Inductance



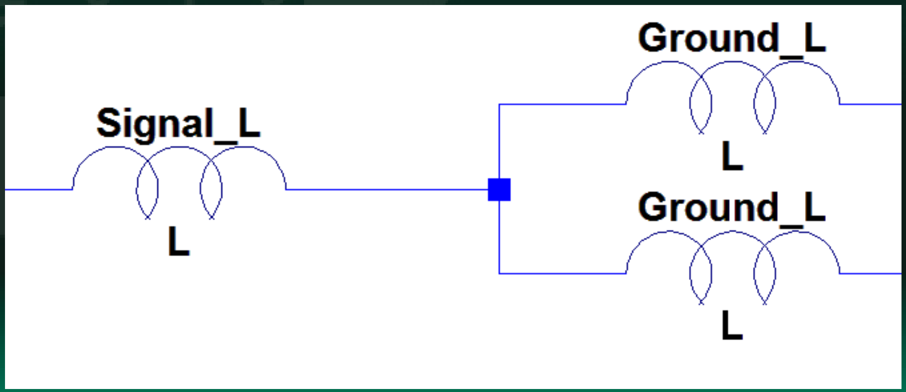
- **Datasheet**
  - GSG pattern at 400 µm pitch
  - Loop inductance of 1.02 nH
- **Three inductors with the same value**
  - Loop inductance is a single inductor in series with a pair in parallel

$L_{total} = L + (L*L)/2L$

$L_{total} = L + L/2$

$1.02\ nH = 3L/2$

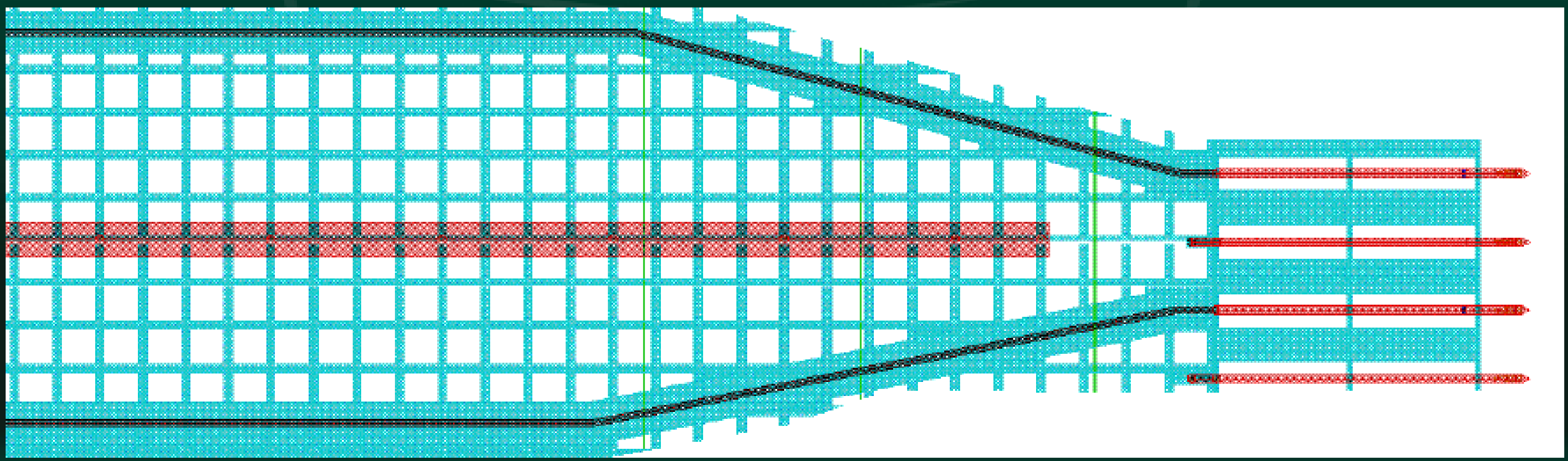
$L = 0.68\ nH$



Membrane Design
MEMS Vertical Emulation

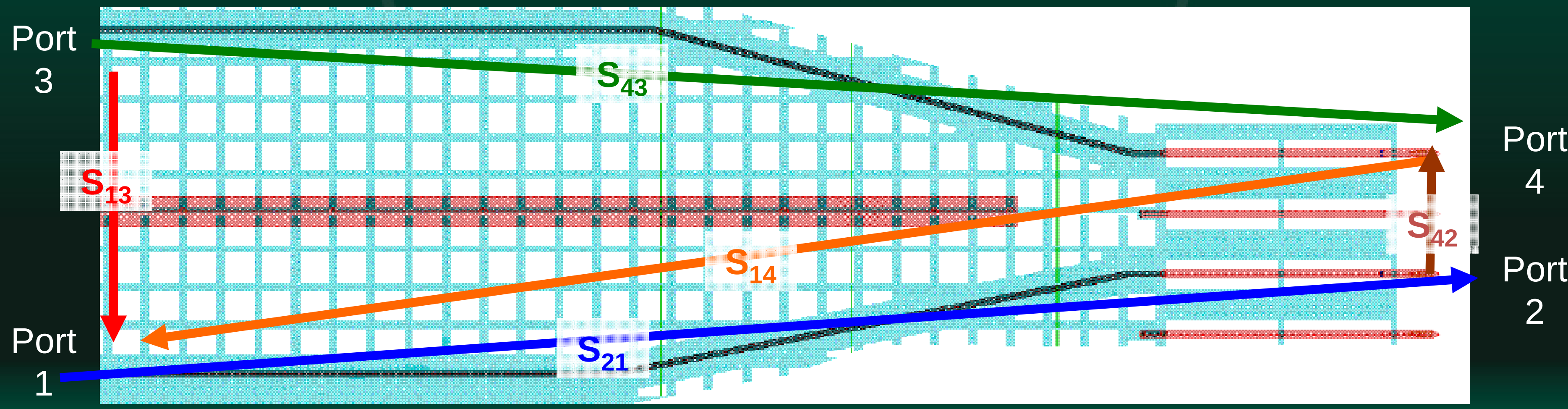
- **MEMs Vertical**

Transmission line	50 Ω
Inductance from end of transmission line to DUT	1.05 nH
Inductance from GND plane to DUT	1.05 nH



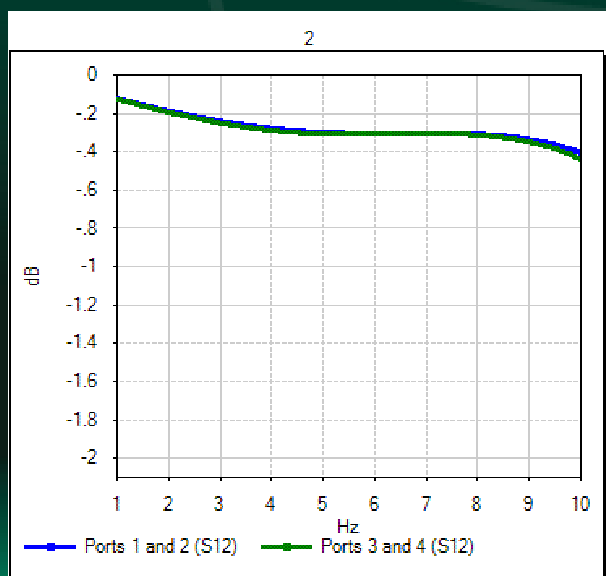
Modeling the Membrane Design

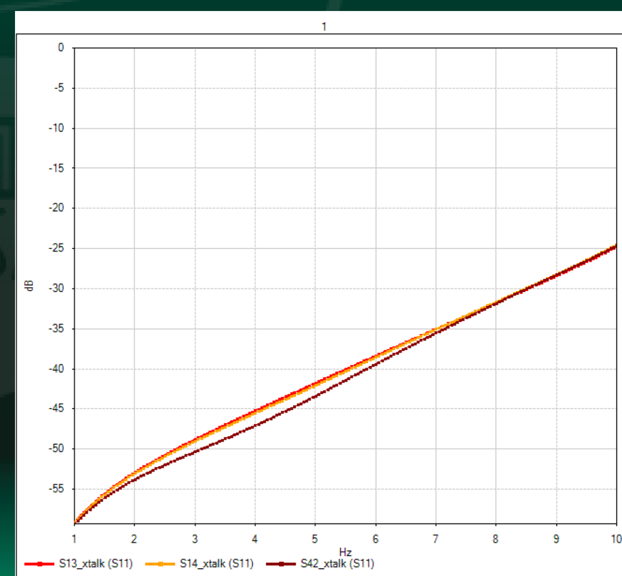
- **HFSS™ model with 4 RF ports**
  - HFSS = High Frequency Structural Simulator
  - Insertion loss; S_{21}
  - Crosstalk; S_{13} S_{14} S_{42}



Simulation Results – Pyramid Probe

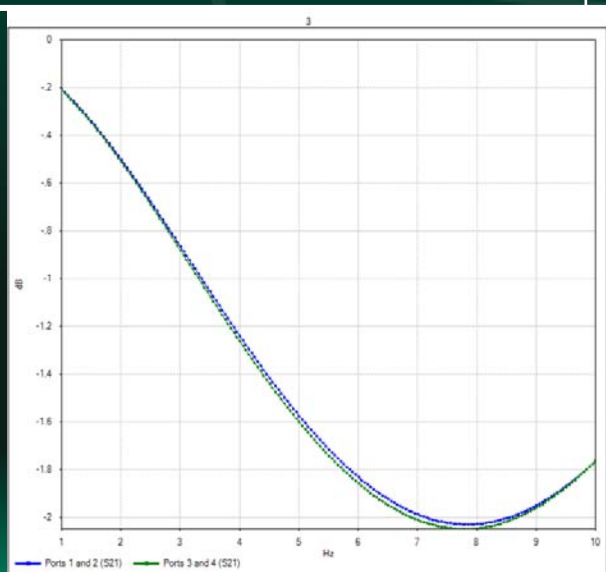
Transmission line	50 Ω
Inductances	0.04 nH, GND
Bandwidth (simulated)	-1 dB is >10 GHz
Crosstalk (simulated)	-51 to -52 dB at 2.5 GHz

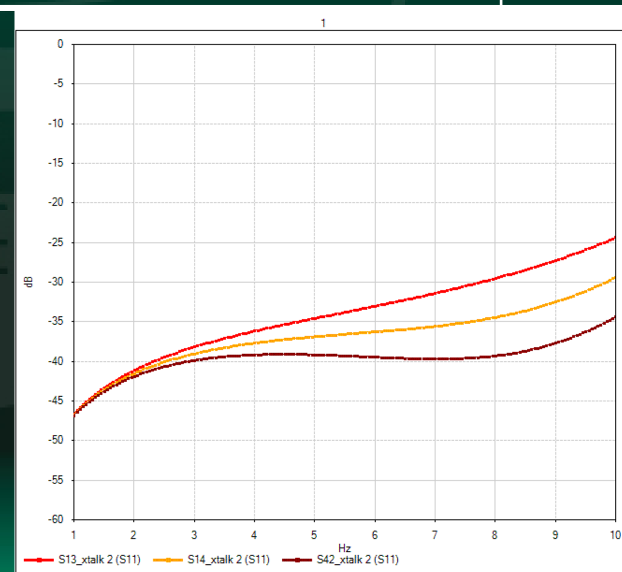




Simulation - MEMs Vertical Emulation

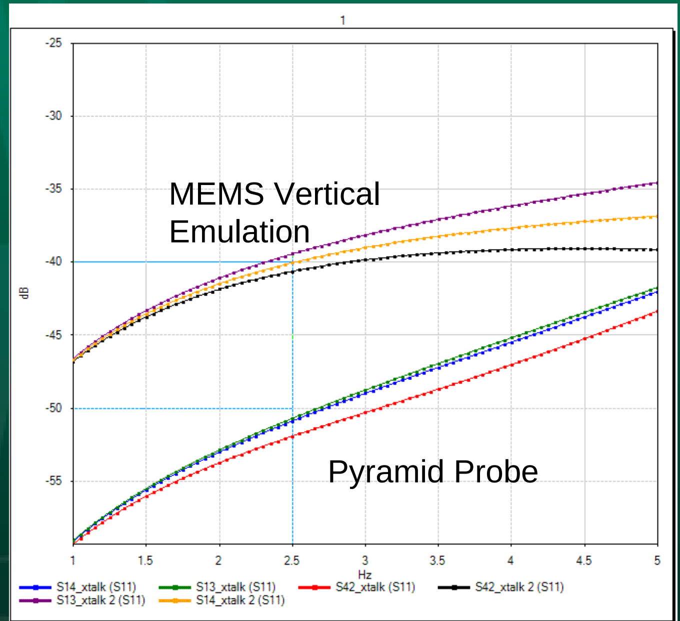
Spec	Simulation	Datasheet
Transmission line	50 Ω	
Inductances		1.05 nH
Bandwidth (-1 dB)	3.35 GHz	2.8 GHz
Bandwidth (-3 dB)	>10 GHz	6-10 GHz
Crosstalk (simulated)	-39 to 41 dB at 2.5 GHz	





Crosstalk Comparison

Simulation	Pyramid Probe	MEMS Vertical Emulation
Inductances	0.04 nH	1.05 nH
Crosstalk (2.5 GHz)	-51 to -52 dB	-39 to -41 dB



- **The frequency of operation for consumer RF devices in WLCSP often around 2.5 GHz**
- **There is a correlation between reduced inductance and improved crosstalk**
  - 10 dB better isolation at 2.5 GHz

Crosstalk – dB to mV

- **Decibel review**
  - Decibels normally refer to power
    - When considering voltages, use

      $V(dB) = 20\log(V/V_0)$
    - Each -10 dB is a reduction in the voltage by square root of 10, which is 3.162

0 dB	1 V
-10 dB	0.316 V
-20 dB	0.100 V
-30 dB	0.032 V
-40 dB	0.010 V
-50 dB	0.003 V

Crosstalk – dB to mV

- **In the simulations, there is an improvement in isolation from -40 dB to -50 dB**
  - What's the big deal? Those are both a lot of isolation
- **A -40 dB crosstalk system would put 10 mV on the victim for every 1 V on the aggressor**
- **A -50 dB crosstalk system would put 3.2 mV on the victim for every 1 V on the aggressor**
  - That's a better than a 3x improvement is crosstalk!
    - At 1.8 V, that's 18 vs. 5.7
    - At 3.3 V, that's 33 mV vs. 10.4
- **This is enough to push a marginal part over the limit, causing false failures and lower yield!**

Summary

- **Look beyond bandwidth for RF WLCSP**
  - Impedance/reactance
  - Crosstalk
  - Noise margin

Simulation	**Pyramid Probe**	**MEMS Vertical**
Inductances	0.04 nH	1.05 nH
Bandwidth (-1 dB)	>10 GHz	3.35 GHz
Bandwidth (-3 dB)	>10 GHz	>10 GHz
Crosstalk (2.5 GHz)	-51 to -52 dB	-39 to -41 dB
X_L at 2.5 GHz	0.6 Ω	16 Ω

Further Work

- **Simulate the third design**
- **Measure all three configurations on the completed membrane**
  – Refine the model to more closely match the measurements

Mutual Inductance Rule of Thumb

- **When can you ignore mutual inductance?**
- **Rule of thumb**
  - If the spacing between two conductor segments is farther apart than their length, their partial mutual inductance is less than 10% of the partial self-inductance of either one and can often be ignored.
    - Signal Integrity: Simplified by Eric Bogatin
- **Apply the inverse**
  - For a given pitch, mutual inductance cannot be ignored if the conductors are shorter than the pitch.
- **Mutual inductance IS crosstalk**

Acknowledgments

- **Special thanks to Mike Fredd, RF Product Applications Manager, for model creation and HFSS simulations**