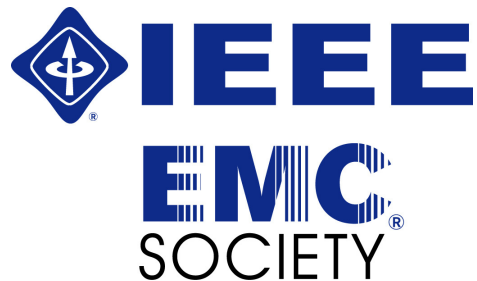


IEEE SCV-EMC 2011 Mini-Symposium May 19, 2011

Brought to you by:



Santa Clara Valley Chapter

WELCOME!

Thank you for attending this special one-day Mini-Symposium and exhibition brought to you by the Santa Clara Valley chapter of the IEEE Electromagnetic Compatibility Society.

We hope you enjoy our special guest speaker Dr. Eric Bogatin's full-day presentation "**A Practical Guide to Measuring and Modeling PDN Components.**" The goal of this regional event is to bring technical education to IEEE members who do not have the opportunity to attend the annual international symposium on EMC. Quite often, travel costs and time away from the office prohibit engineers from attending these large, week long, conferences. Our hope is that you will learn practical information that you can bring back to your work place from this Mini-Symposium. We also hope you will have the opportunity to talk to Dr. Eric Bogatin in person. There will be vendor exhibits throughout the day so please visit vendor booths to find out what EMC solutions they have to offer.

Special **THANK YOUS** to those who made this event a big success, including all the vendors, companies, individuals, all volunteers and officers.

Please plan on staying for the reception with our guest speaker Dr. Bogatin following the technical presentation. There will be appetizers, wine and beer served and several raffles. Enjoy the Mini-Symposium and exhibition!

Please visit us at <http://ewh.ieee.org/r6/scv/emc/index.html>

Monthly meeting on the 2nd Tuesday except June/July and August
@ Applied Materials Bowers Cafeteria, free admission

September Event

Date: Tuesday, September 13, 2011

5:30pm: Networking/light dinner

6:30pm: Presentation

7:45pm: Adjourn

Title: PCB stackup design

Speaker: Lee Ritchey, Speeding Edge

2011 Mini-Symposium Program Outline

7:00 AM – 8:00 AM	Registration, Breakfast & Vendor Exhibits
8:00 AM – 9:30 AM	Module 1: Measuring Low impedance with a 2-port VNA
9:30 AM – 10:00 AM	Morning Break & Vendor Exhibits
10:00 AM – 12:00 PM	Module 2: Building Models from S-parameter Measurements
12:00 PM – 1:30 PM	Lunch & Vendor Exhibits
1:30 PM – 3:00 PM	Module 3: Interpreting the Complex Behavior of Planes
3:00 PM – 3:30 PM	Afternoon Break & Vendor Exhibits
3:30 PM – 5:00 PM	Module 4: Interpreting Plane properties with Capacitors
5:00 PM – 6:00 PM	Reception, Vendor Exhibits & Raffle

What Have You Done For Me Lately? Plenty!



16,000 Watts of Pure Power

Stand back! We've exceeded our old limits with the new 16000A225 amp. It covers 10 kHz to 225 MHz and delivers 16,000 watts of power.

We've Pushed The Technology Envelope

We ripped that envelope wide open with our small, lightweight Solid State Hybrid Power Modules. They deliver high output power (up to 5 watts) across an ultra-wide instantaneous bandwidth (4 to 18 GHz).



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Our two newest laser-powered E-Field probes, FL7040 – 2 MHz to 40 GHz and FL7060 – 2 MHz to 60 GHz; each do the work of multiple probes, with outstanding accuracy and linearity.

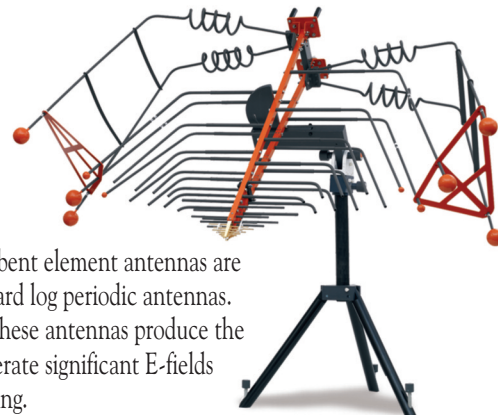


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They're smaller and lighter. Yet our new "S" Series amps are available from 0.8 to 4.2 GHz, 20 to 1200 watts and everything in between.

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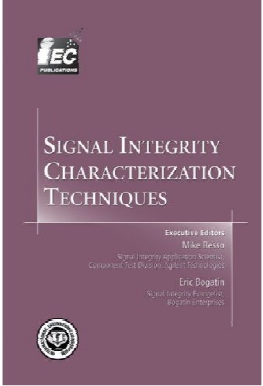
In Europe, call ar United Kingdom 441-908-282766 • ar France 33-1-47-91-75-30 • emv GmbH 89-614-1710 • ar Benelux 31-172-423-000



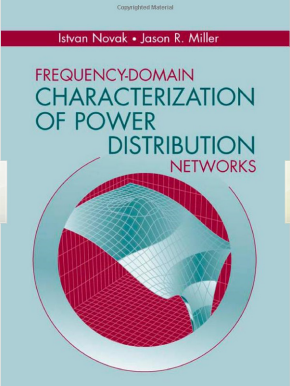
EMC 01 Measuring low Z Slide -1

Be The Signal 

A Practical Guide to Measuring and Modeling PDN Components



Dr. Eric Bogatin,
Signal Integrity Evangelist,
Bogatin Enterprises
www.beTheSignal.com



5/19/2011

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EMC 01 Measuring low Z Slide -2

Be The Signal 

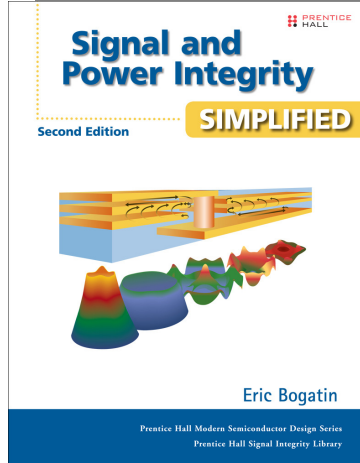
Schedule

- ✓ EMC 01: Measuring discrete components
- ✓ EMC 02: Building circuit models for discrete components
- ✓ **Lunch**
- ✓ EMC 03: Measuring and analyzing planes
- ✓ EMC 04: Measuring and analyzing planes with capacitors

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For More Information about Signal and Power Integrity Design



www.BeTheSignal.com

- Recent Publications
- Future class schedules
- EE Times Blog
- My Blog: What I learned this month
- www.PrintedCircuitUniversity.com for online training

Published by Prentice Hall, 2009



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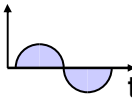
EMC 01 Measuring low Z Slide -5

Be The Signal 

S-Parameters: How “Precision” Reference Signals “Scatter” Off a DUT



VNA



Incident Wave



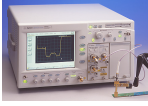
Reflected Wave

Transmitted Wave

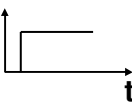
S21

S11

Frequency Domain $S_{11} = \frac{\text{sine wave out from port 1}}{\text{sine wave into port 1}}$ $S_{21} = \frac{\text{sine wave out from port 2}}{\text{sine wave into port 1}}$



TDR



Incident Wave



Reflected Wave

Transmitted wave

TDT

TDR

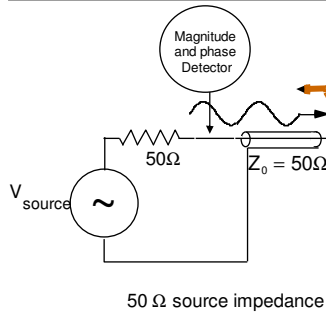
Time Domain

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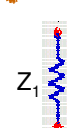
Be The Signal 

S11 is the Reflection From the **Input Impedance** of the DUT in the Frequency Domain



50 Ω source impedance

Reflection coefficient, rho



$S_{11} = \frac{Z_1 - 50}{Z_1 + 50}$

Z_1 = input impedance of the DUT

$$S_{11} = \frac{Z_1 - 50}{Z_1 + 50}$$

Analysis software:
QUCS, ADS, SPICE, Excel

$$Z_1 = 50\Omega \frac{1 + S_{11}}{1 - S_{11}}$$

(complex algebra)

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Bogatin's Ten Rules

- Goto www.PrintedCircuitUniversity.com
- Search on BTS218



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BTS218 Bogatin's 10 Rules



Dr. Eric Bogatin has been writing about, lecturing and teaching signal integrity topics for more than 25 years. He has taught more than 7,000 engineers and personally mentored more than 30. Along the way, he has developed some sayings that crystallize important rules to consider when working on signal integrity projects. Of course, these rules apply to more than just signal integrity. Here is the reprint of the column he wrote for PCDBF, Aug. 10, 2010, that summarizes these top 10 rules.

Currently no reviews.

[REVIEWS](#)
[VIEW DOCUMENT](#)

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Bogatin's 10 Rules

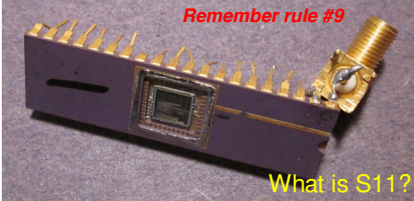
1. Answer "it depends" questions by "putting in the numbers"
2. Separate myth from reality by "putting in the numbers"
3. Watch out for the whac-a-mole effect
4. Most important step in solving a problem: find the root cause
5. Apply the Youngman Principle to optimize designs
6. Sometimes an OK answer now! is better than a good answer late
7. Evaluate "bang for the buck" with virtual prototypes
8. Watch out for mink holes
9. **Never perform a measurement or simulation without first anticipating what you expect to see**
10. There are two kinds of designers: those who have signal integrity problems and those who will

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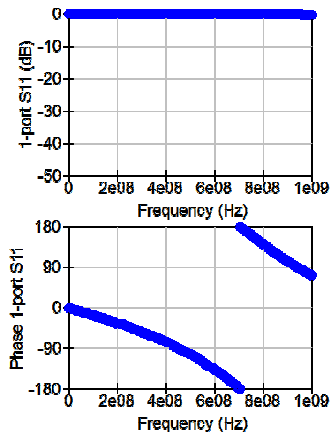
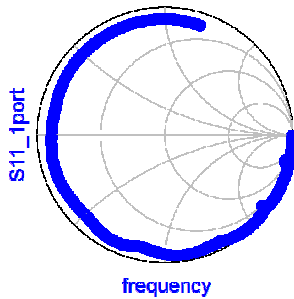


Pair of Leads in a DIP Package

Remember rule #9



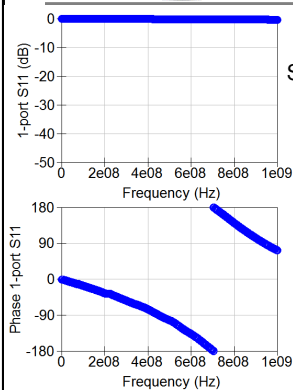
What is S11?



What do we do with this data?
What does it tell us about the component?



Pair of Leads in a DIP Package

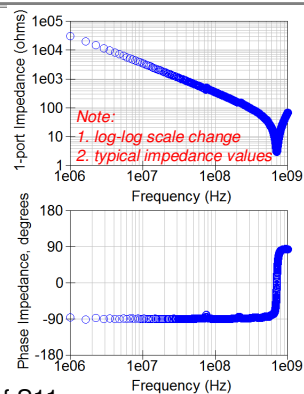


$$S_{11} = \frac{Z_1 - 50}{Z_1 + 50}$$

QUCS

$$Z_1 = 50 \Omega \frac{1 + S_{11}}{1 - S_{11}}$$

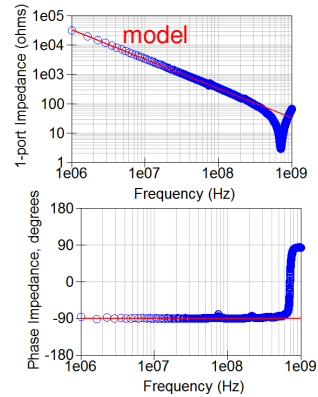
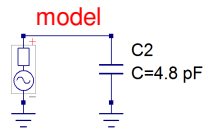
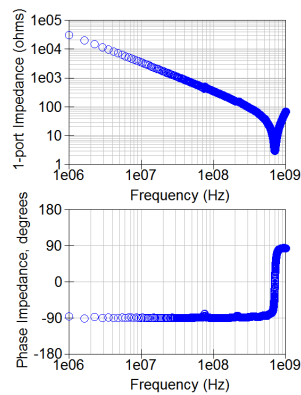
No assumptions
No model
No fitting
Based on definition of S11



What model does this impedance profile suggest?



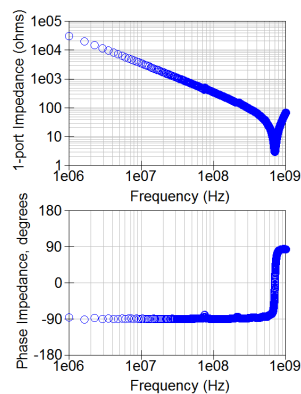
Modeling Package Leads



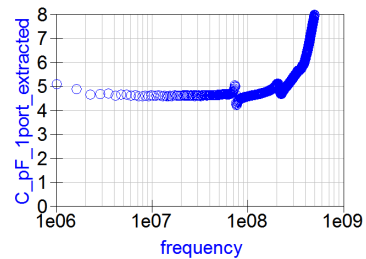
Simulated model of an ideal 4.8 pF capacitor
What is the bandwidth of the model?
What might be a higher bandwidth model?



Directly Extracting Package Lead Capacitance



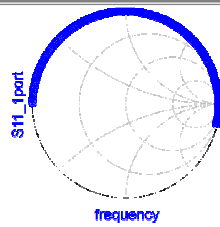
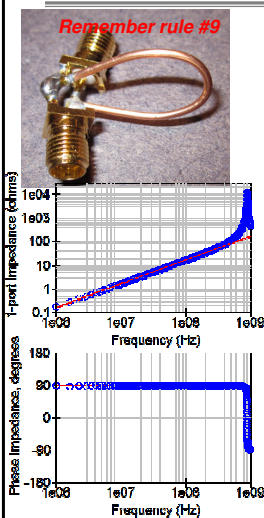
$$C = \frac{-1}{2\pi f \text{ imag}(Z)}$$



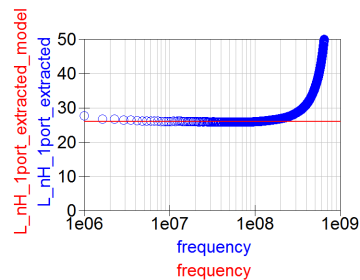
Why does the capacitance go up?



Impedance of a Wire Loop



$$L = \frac{\text{imag}(Z)}{2\pi f}$$



Cool! Any VNA is really an impedance analyzer!

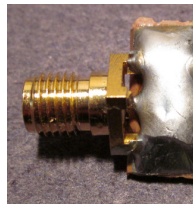


Impedance Measurements with a VNA

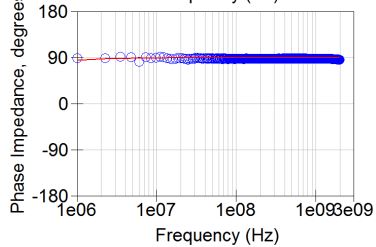
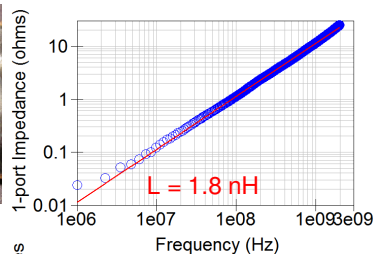
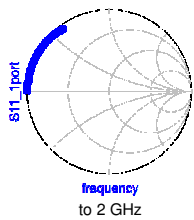
- A 1 port VNA can be used as an impedance analyzer
- Use algebra to display the "input" impedance of the DUT
- Based on simple L, C model interpret Z and extract the value of L, C
- Identify the bandwidth of the LC model



What about a “Dead Short”?

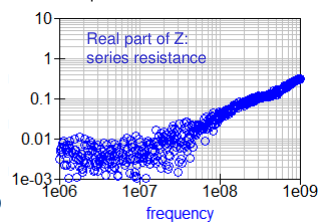


Remember rule #9

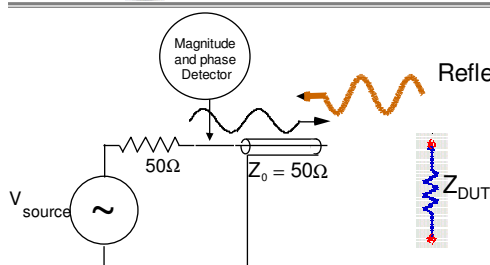


Why is a dead short so high an inductance?

1. Why is low resistance so noisy?
2. Why is low resistance frequency dependent?



Problem #1 with 1-Port Measurements of Low Impedance Structures



Reflection coefficient, S_{11}

$$S_{11} = \frac{Z_{DUT} - Z_1}{Z_{DUT} + Z_1} = \frac{Z_{DUT} - 50}{Z_{DUT} + 50}$$

When measuring a low impedance:

$$S_{11} = \frac{1 - 50}{1 + 50} = \frac{-49}{51} = -0.96$$

= -0.35 dB

$$S_{11} = \frac{0.1 - 50}{0.1 + 50} = \frac{-49.9}{50.1} = -0.996$$

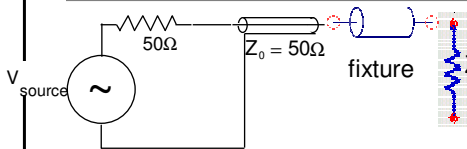
= -0.035 dB

Difficult to measure small changes from 1

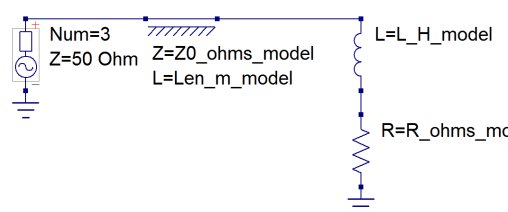
EMC 01 Measuring low Z Slide -17



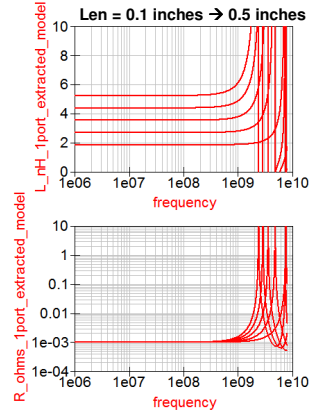
Problem #2 with 1-Port Measurements of Low Impedance Structures



$$S_{11} = \frac{(Z_{DUT} + Z_{fix}) - 50}{(Z_{DUT} + Z_{fix}) + 50}$$



Len = 0.1 inches → 0.5 inches



Fixture length can distort the measurements:
artificially high L, frequency dependent R

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Problem #3: “Contact Impedance” and Reproducibility

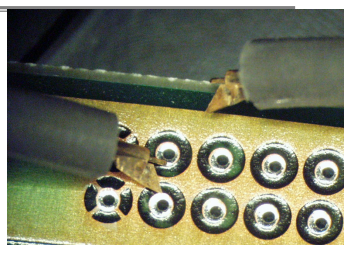


Probe model



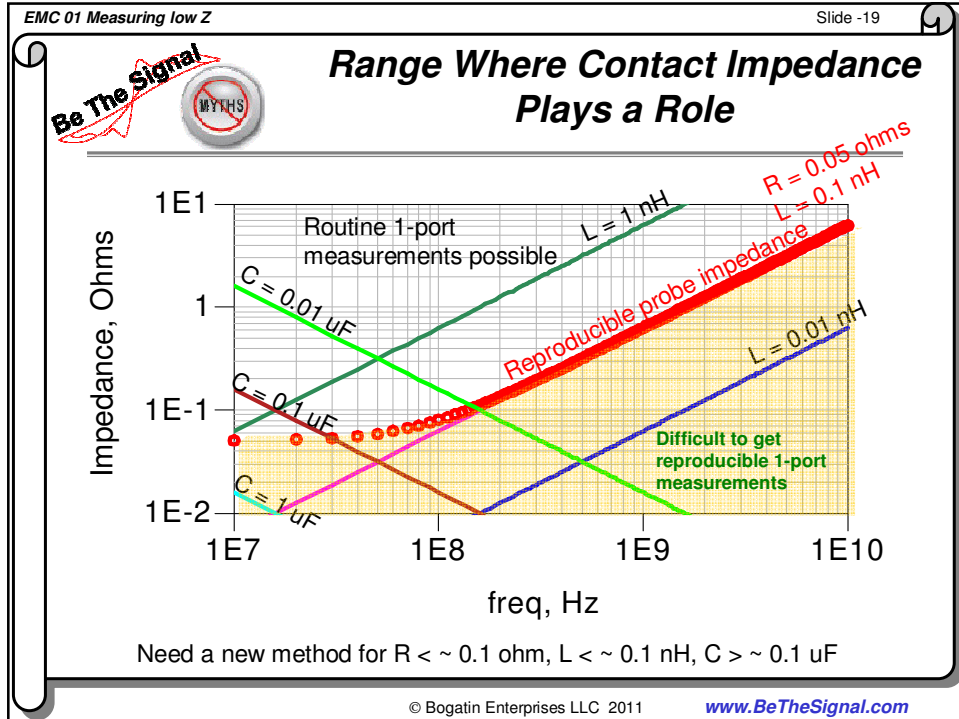
Residual R, L

- ✓ R ~ 0.01-0.1 ohms
- ✓ L ~ 0.05 – 0.1 nH (2-8 mils length changes)
- ✓ Variation from calibration to measurement



Photos Courtesy of GigaTest Labs 

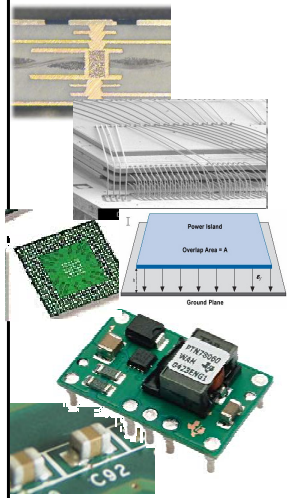
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Be The Signal 

Low Impedance Measurements with a 50 Ohm VNA Has Problems

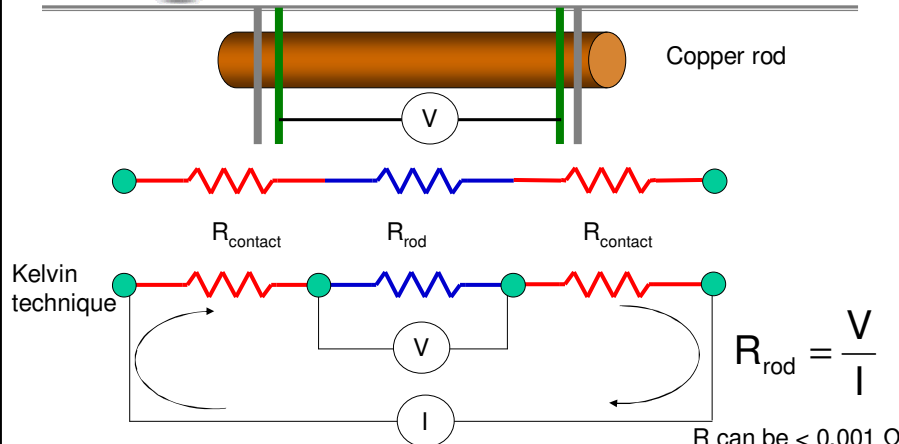


- There is a practical limit on how low an impedance can be measured with 1-port
 - ✓ Noise floor of instrument
 - ✓ Fixture length artifacts
 - ✓ Fixture contact impedance artifacts
- Why is low impedance important?
 - ✓ Vias
 - ✓ Package attach elements: wire bonds, solder balls
 - ✓ Ceramic capacitors
 - ✓ On chip capacitance
 - ✓ Planes
 - ✓ Power distribution networks
 - ✓ Voltage regulator modules (VRM)
- What to do?

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EMC 01 Measuring low Z Slide -21

Be The Signal  **An Alternative Approach, Based on Kelvin Technique for DC Resistance**



Copper rod

R_{contact} R_{rod} R_{contact}

Kelvin technique

$R_{\text{rod}} = \frac{V}{I}$

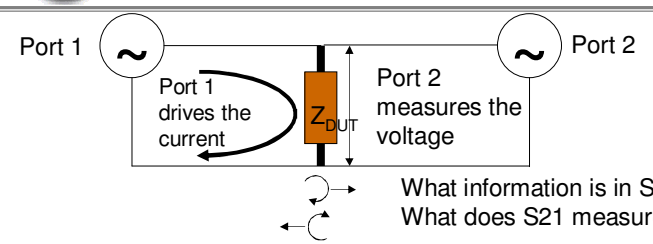
R can be < 0.001 Ω

Separate leads for current force and voltage sense eliminate contact resistance effects

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EMC 01 Measuring low Z Slide -22

Be The Signal  **2 Port Measurements to Reduce Fixturing Parasitics**



Port 1 $\sim$ Port 2

Port 1 drives the current

Port 2 measures the voltage

Z_{DUT}

What information is in S11, S22?
What does S21 measure?

- 1st order analysis, if $Z_{\text{DUT}} \ll 50$ ohms
 - ✓ Current out of port 1 = $V_{\text{port1}}/50$ ohms = 1 V/50 ohms ~ 20 mA
 - ✓ Voltage across DUT ~ 0
 - ✓ $\rho \sim -1$
 - ✓ Current through DUT = 2 x 20 mA
 - ✓ to **first order**, $V_{\text{DUT}} = V_{\text{port2}} = Z_{\text{DUT}} \times 2 \times V_{\text{port1}}/50$ Ohms = $Z_{\text{DUT}} \times V_{\text{port1}}/25$ ohms

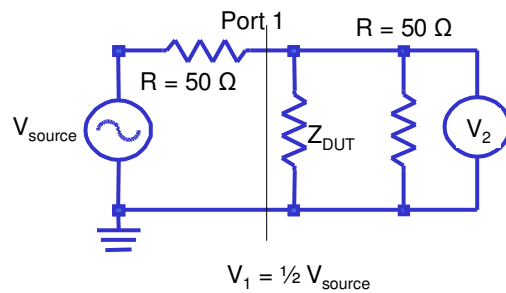
$$S_{21} = \frac{V_{\text{port2}}}{V_{\text{port1}}} = \frac{1}{25} Z_{\text{DUT}} \quad Z_{\text{DUT}} = 25\Omega \times S_{21}$$

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Second Order Analysis

Equivalent Circuit Model



$$V_2 = V_{\text{source}} \frac{50 \Omega Z_{\text{DUT}}}{50 \Omega + Z_{\text{DUT}}}$$

$$V_2 = V_{\text{source}} \frac{50 \Omega Z_{\text{DUT}}}{50 \Omega + \frac{50 \Omega Z_{\text{DUT}}}{50 \Omega + Z_{\text{DUT}}}}$$

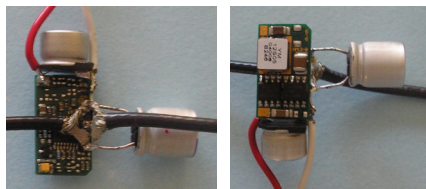
$$V_2 = V_{\text{source}} \frac{Z_{\text{DUT}}}{50 \Omega + 2Z_{\text{DUT}}}$$

$$S_{21} = \frac{V_2}{V_1} = \frac{2V_2}{V_{\text{source}}}$$

$$Z_{\text{DUT}} = 25 \Omega \frac{S_{21}}{1 - S_{21}} = Z_{21}$$

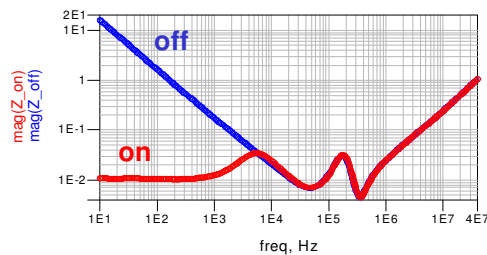


Measured Output Impedance of Voltage Regulating Module (VRM)



$$Z_{\text{DUT}} = 25 \Omega \frac{S_{21}}{1 - S_{21}} = Z_{21}$$

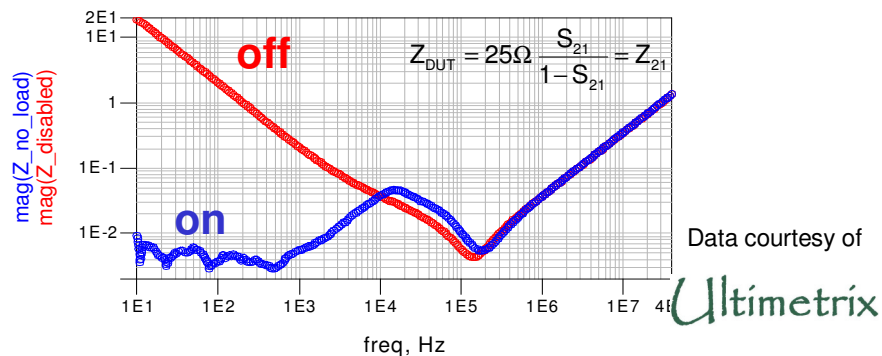
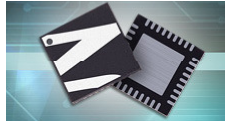
12v to 1.2v Supply from Power-One



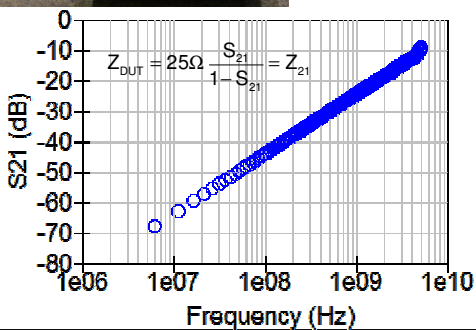
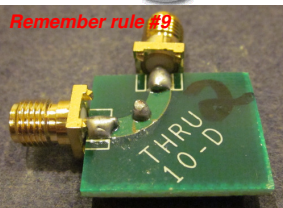
Courtesy of
Ultimetrix



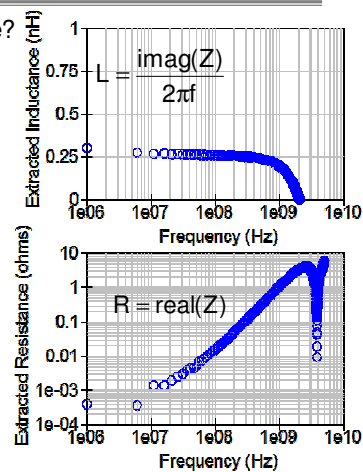
Measured Output Impedance of Voltage Regulating Module (VRM)



A Via

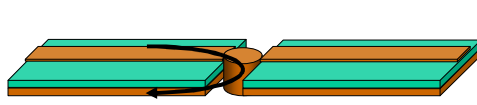


Is this reasonable?





Estimating the Total Inductance of THIS Via



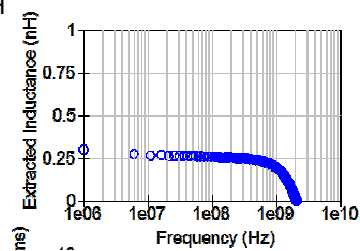
h = 64 mils
Diameter = 50 mils, r = 25 mils

$$L_{\text{total}} [\text{pH}] \sim 5 \times h [\text{mils}] \left\{ \ln \left(\frac{2d}{r} \right) - 0.75 \right\}$$

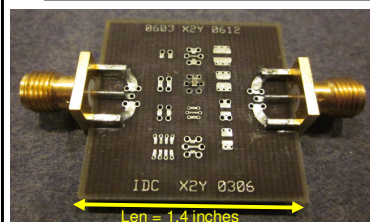
Partial self inductance
Neglecting mutual to the loop

$$L_{\text{total}} [\text{pH}] \sim 5 \times 64 \left\{ \ln \left(\frac{2 \times 64}{25} \right) - 0.75 \right\} = 0.28 \text{ pH}$$

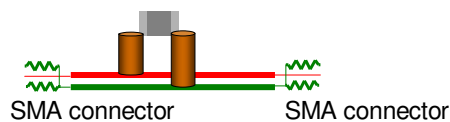
...but why does L drop off > 400 MHz?



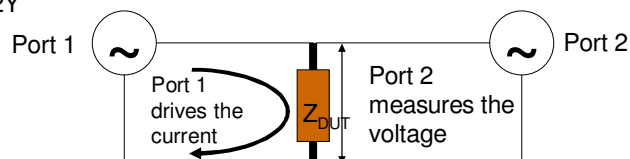
X2Y Capacitor Fixture Boards



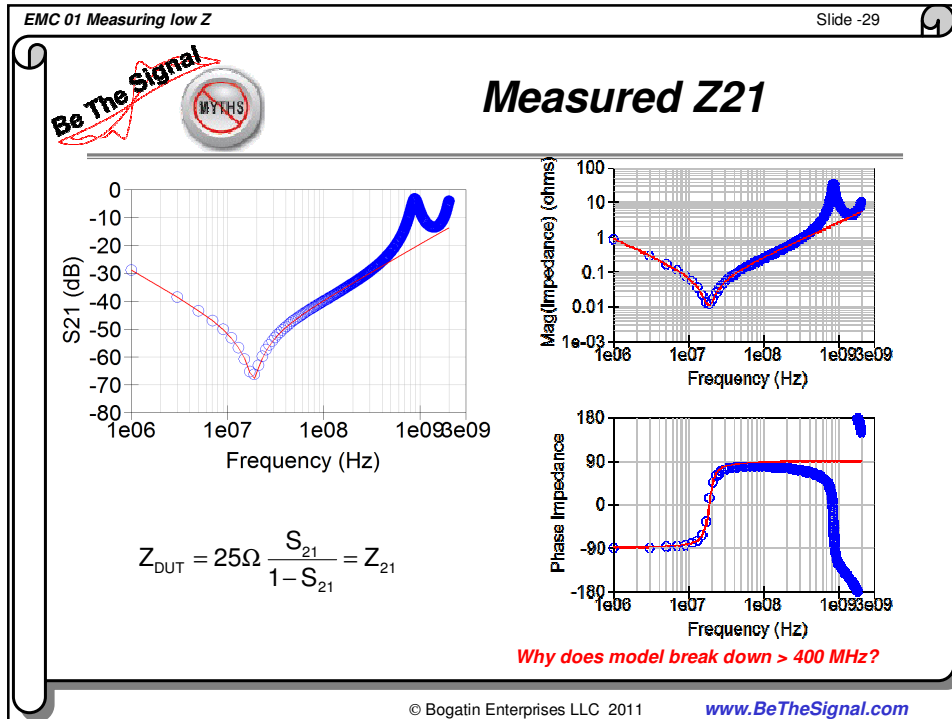
Len ~ 0.7 inches



Sample courtesy of X2Y



$$Z_{\text{DUT}} = 25 \Omega \frac{S_{21}}{1 - S_{21}} = Z_{21}$$



EMC 01 Measuring low Z Slide -30

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Conclusions

- Don't rely on 1-port VNA for low Z measurements
 - ✓ Too much opportunity for artifacts
- Use 2-port VNA measurements for low impedance
- Impedance ~ S₂₁
- Hard to read R, L, C values directly from VNA
- Still some artifacts to evaluate
- Measurements requires some analysis

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EMC 02 Analyzing Discrete PDN ComponentsSlide -1



Schedule

- ✓ EMC 01: Measuring discrete components
- ✓ **EMC 02: Building circuit models for discrete components**
- ✓ Lunch
- ✓ EMC 03: Measuring and analyzing planes
- ✓ EMC 04: Measuring and analyzing planes with capacitors

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EMC 02 Analyzing Discrete PDN ComponentsSlide -2



Analysis Tools

- To analyze the measured 2-port S-parameters, you must bring the measurements into an analysis tool environment
- Example: QUCS (can also use: HyperLynx, ADS, SPICE, ...)
 - ✓ <http://qucs.sourceforge.net/download.html>




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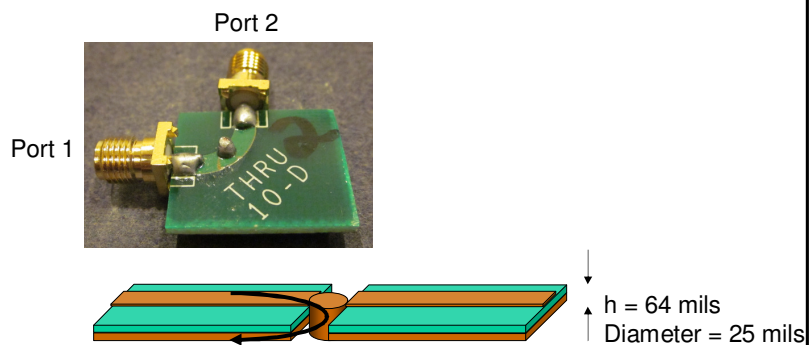


Examples

- Vias
- Dead short (ultimate limits)
- Capacitors
- VRMs

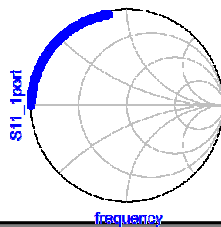
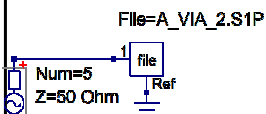
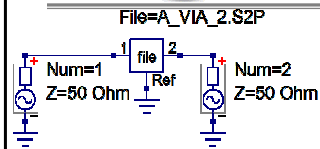


Example: 1 Shorting Via

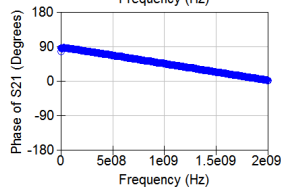
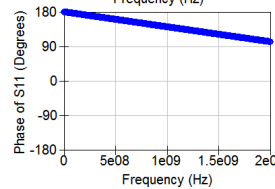
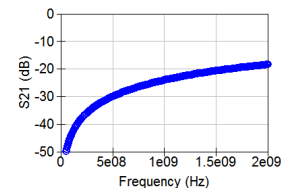
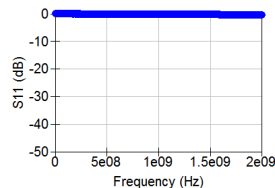




Read Touchstone File

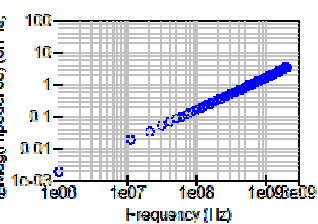
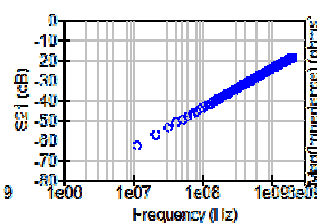


1. Bring them into the simulation environment
2. Read touchstone files
3. Plot the S-Parameters



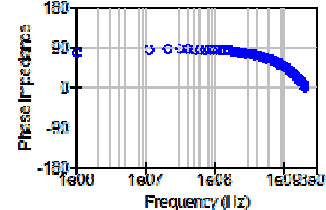
**“You can observe a lot by looking”
- Yogi Berra**

- Plot dBS21 vs log freq
- Convert to Z
- Extract L, R



Equation

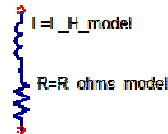
```
Z_1port=50*(1+S[5,5])/(1-S[5,5])
Z_1port_model=50*(1+S[3,3])/(1-S[3,3])
Z_2port=25*S[2,1]/(1-S[2,1])
phZ_2port=phase(Z_2port)
phZ_1port=phase(Z_1port)
Z_model=25*S[4,3]/(1-S[4,3])
phZ_model=phase(Z_model)
phZ_1port_model=phase(Z_1port_model)
```





Extracting Simple R, L Values

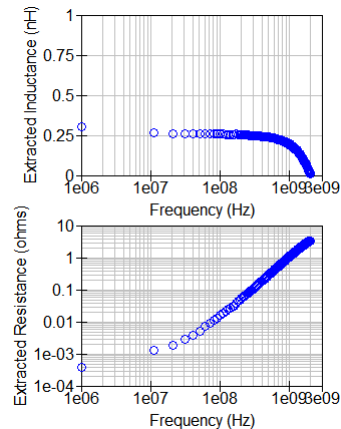
- Based on assuming the model is:



Equation

$$L_{nH_extracted} = \text{imag}(Z_{2port}) / (2 * \pi * \text{frequency}) * 1e9$$

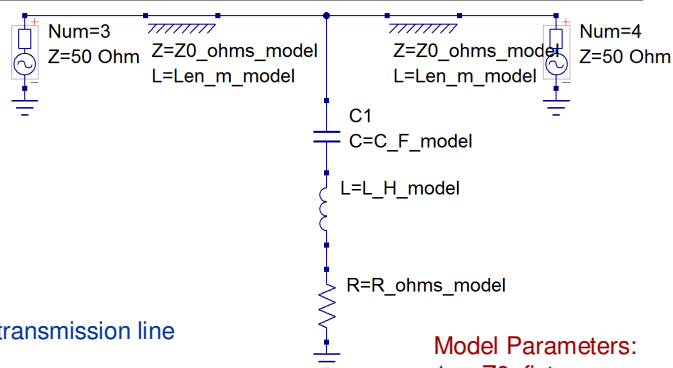
$$R_{ohms_extracted} = \text{real}(Z_{2port})$$



But why does L drop off and R increase?



Analysis: Build a Simple Model of the Structure



Simple fixture:

1. Symmetrical
2. Ideal lossless transmission line

Device Under Test (DUT):

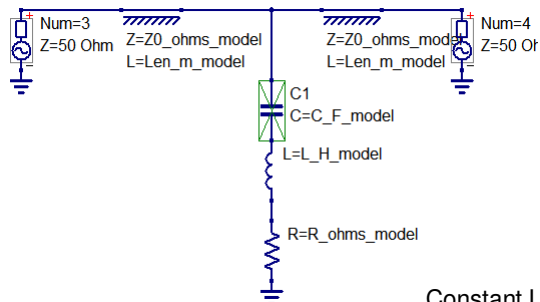
1. Ideal C
2. Ideal L
3. Ideal R

Model Parameters:

1. Z0_fixture
2. Len_fixture
3. C
4. L
5. R



Parameter Values



Equation

$Z0_ohms_model=50$
 $L_nH_model=0.25$
 $C_nF_model=175$
 $R_ohms_model=0.001$
 $Dk_model=4$

Equation

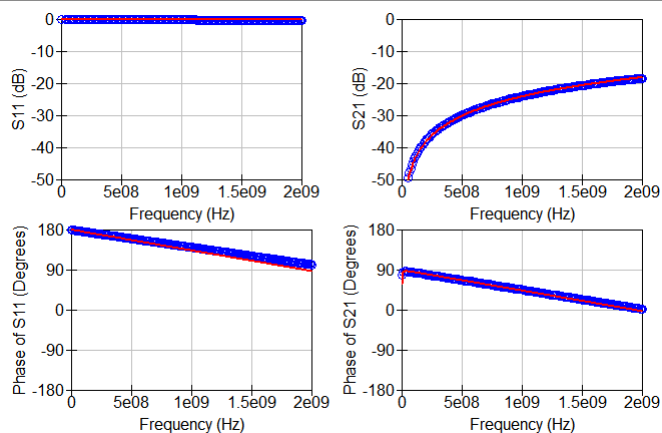
$Len_inches_model=0.35$

(Dk = 4)

Constant L, R with frequency



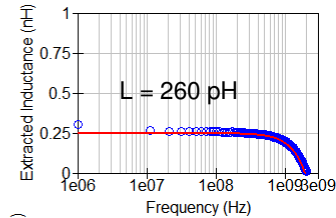
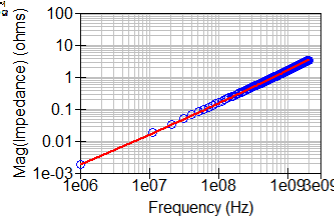
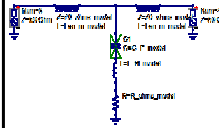
Measured and Simulated



How do you find the optimum values for each parameter?



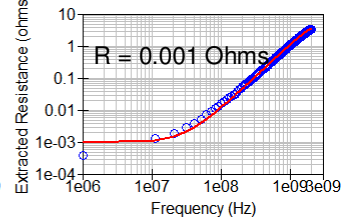
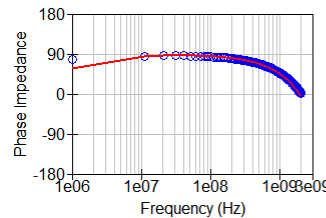
Extracted R, L Values



Why does L drop off?
It doesn't!

Why does R
increase?
It doesn't!

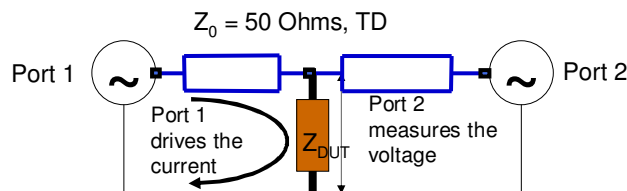
The fixture is causing
the frequency
dependence to R, L



Model simulated with constant L, R with frequency



Effect of the Fixture on Z₂₁



S₂₁ will have a phase shift of $(2 \times TD) \times f$

Z_{DUT} measured will have an anomalous phase shift

To keep Z phase shift $\ll 90$ degrees, keep $TD \ll 1/(2 \times 4 \times f)$

At 1 GHz, keep $TD \ll 1/8 \text{ nsec}$ or $\ll 1 \text{ inch}$, like $\sim 0.3 \text{ inches}$

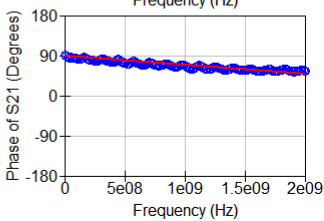
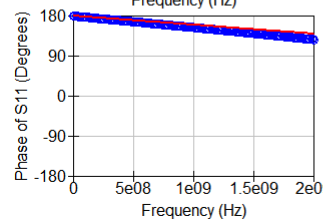
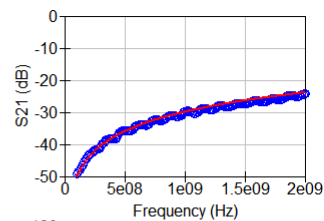
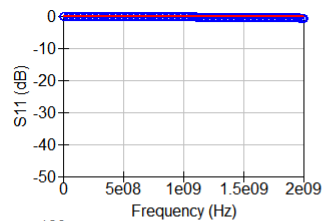
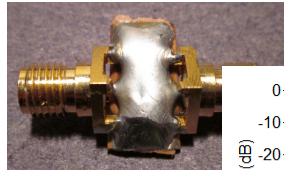


$F_{\max} < 0.3/\text{Len}$ or $\text{Len} < 0.3/F_{\max}$ with $F_{\max}$ in GHz, Len in inches

Always ok to use circuit topology de-embedding of the fixturing
from S-Parameter measurements directly



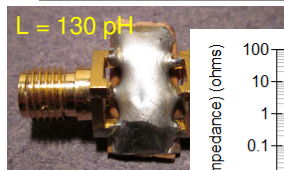
A Dead Short: Limits to this Method



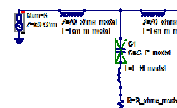
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How Low an Inductance is this?



L = 130 pH

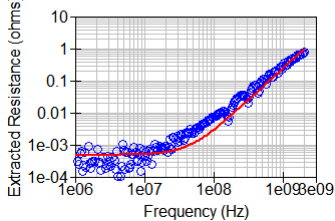
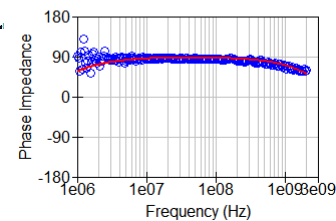
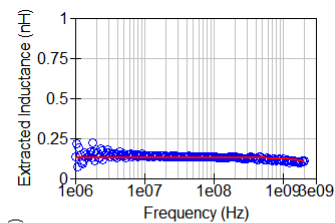
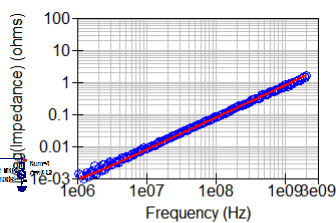


Equation

Z0_ohms_model=50
 L_nH_model=0.13
 C_nF_model=175
 R_ohms_model=0.0005
 Dk_model=4

Equation

Len_inches_model=0.15



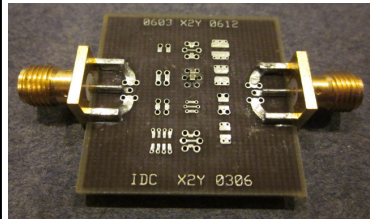
Smallest short that can be fabricated with SMA is ~ 100 pH

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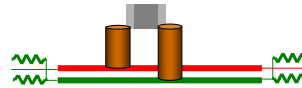
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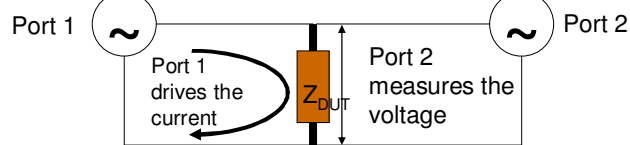
X2Y Capacitor



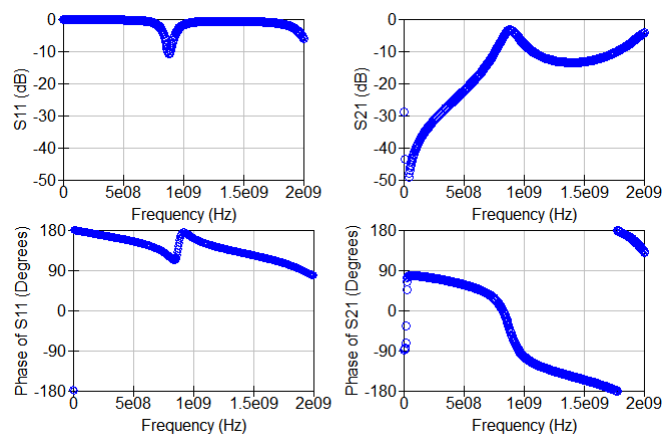
Len ~ 0.7 inches, $F_{max} \sim 0.3/0.7 = 420 \text{ MHz}$



Sample courtesy of X2Y

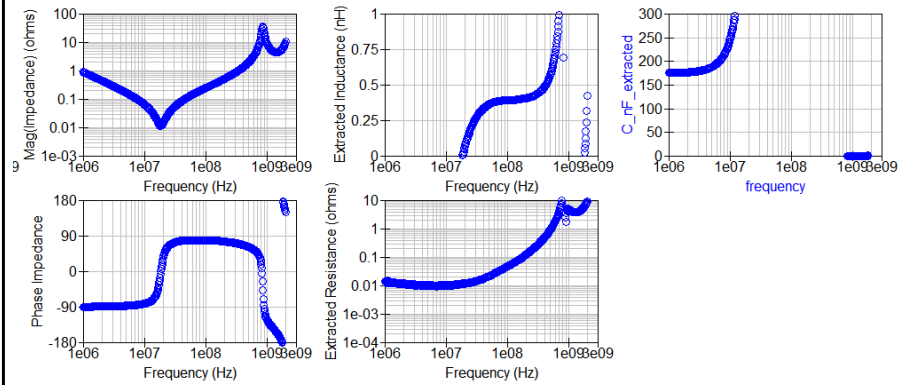


Raw Measurements

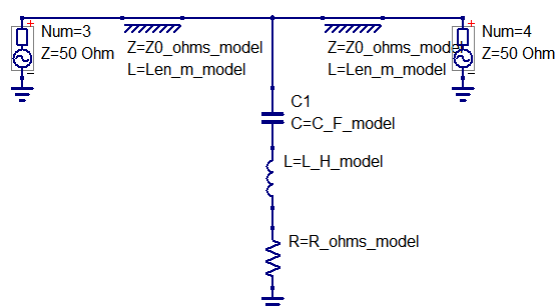




Extracted Values What does this mean?



The Model



Equation

$Z0_{\text{ohms_model}}=3.1$
 $L_{\text{nH_model}}=0.40$
 $C_{\text{nF_model}}=175$
 $R_{\text{ohms_model}}=0.01$
 $Dk_{\text{model}}=4$

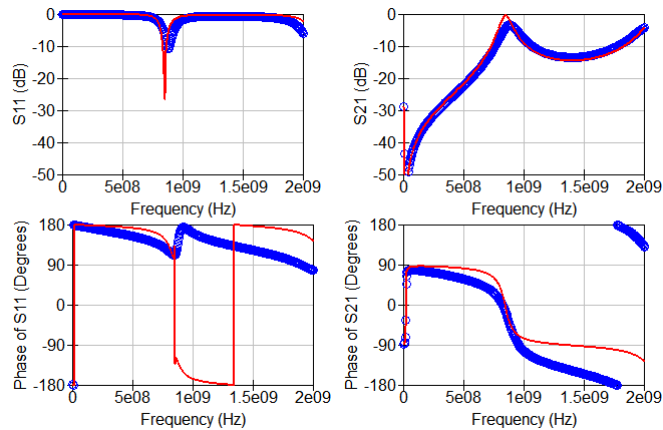
Equation

$\text{Len_inches_model}=0.7$

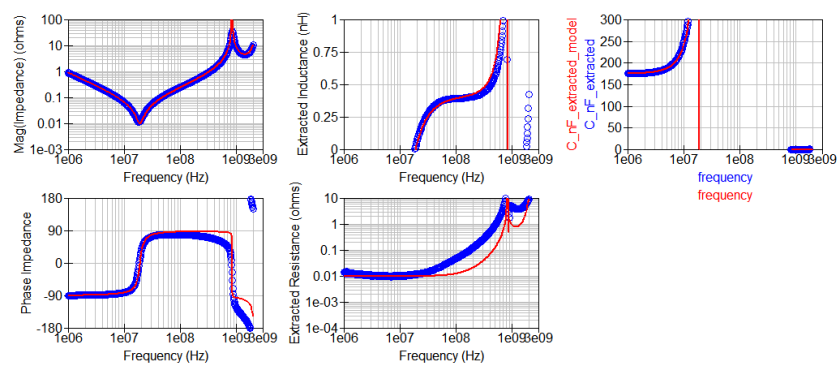
How do you find the parameter values?



S-parameters



Extracted terms

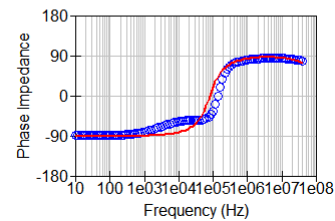
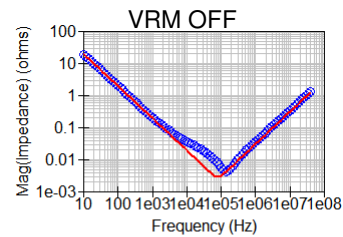


How to improve the fit:

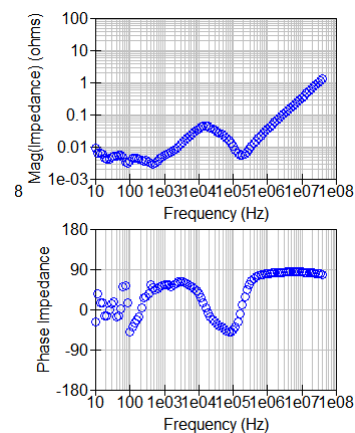
1. Change model to include SMA path and circuit board fixture
2. Maybe R is frequency dependent



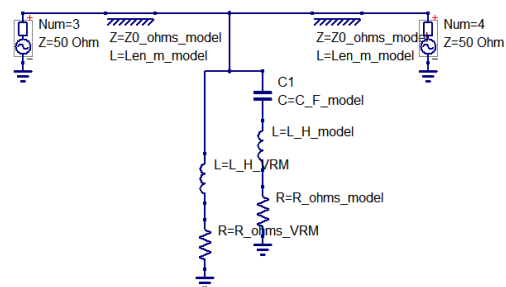
VRM- Zilker Labs



VRM: On



What is the model?





Simulated and Measured

Equation

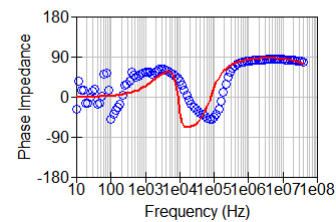
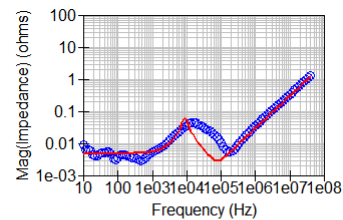
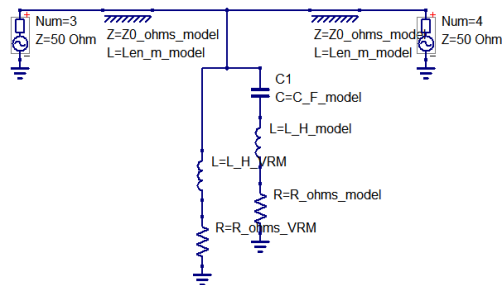
Z0_ohms_model=50
L_nH_model=5
C_nF_model=8e5
R_ohms_model=0.003
Dk_model=4

Equation

Eqn34
L_nH_VRM=400
R_ohms_VRM=0.005

Equation

Len_inches_model=3



Power One VRM

Equation

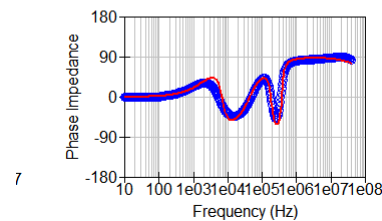
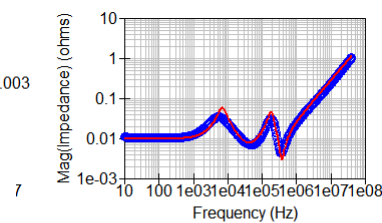
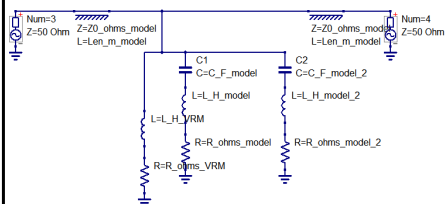
Z0_ohms_model=50
L_nH_model=20
C_nF_model=7e5
R_ohms_model=0.008
Dk_model=4

Equation

Eqn34
L_nH_VRM=700
R_ohms_VRM=0.01

Equation

L_nH_model_2=6
C_nF_model_2=3e4
R_ohms_model_2=0.003





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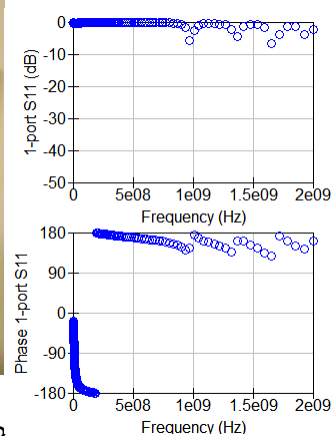
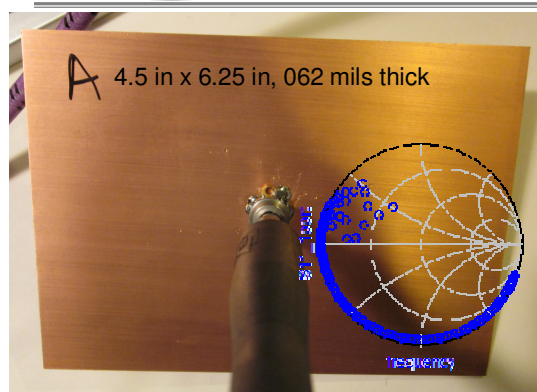


Schedule

- ✓ EMC 01: Measuring discrete components
- ✓ EMC 02: Building circuit models for discrete components
- ✓ Lunch
- ✓ **EMC 03: Measuring and analyzing plane cavities**
- ✓ EMC 04: Measuring and analyzing planes with capacitors



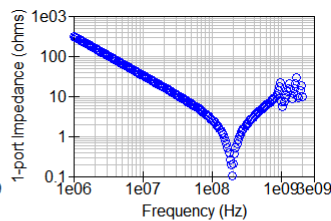
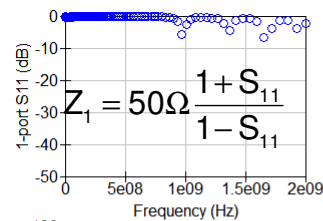
Measured 1-port Impedance of a Simple Bare Board



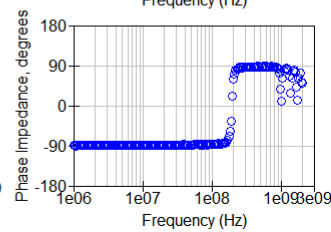
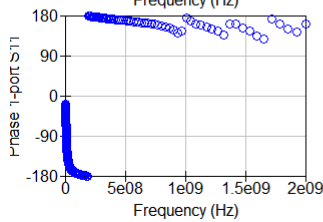
- How do we interpret these results?



1-port Impedance Analysis



What is the root cause of the 200 MHz resonance?



What circuit model does this match?

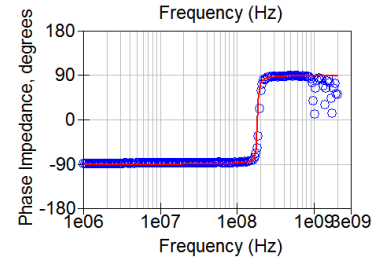
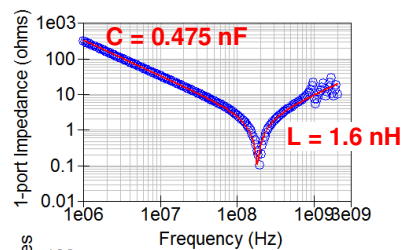
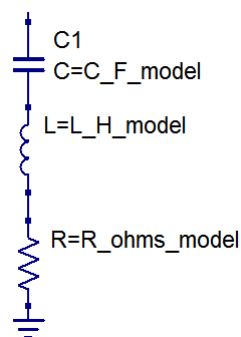


Matches an RLC Model

$L_nH_model = 1.6$

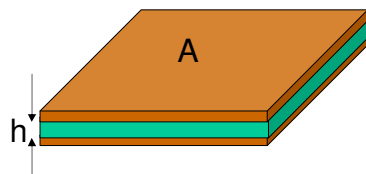
$C_nF_model = 0.475$

$R_ohms_model = 0.1$





Capacitance in Plane Cavity



$$C = \epsilon_0 Dk \frac{A}{h}$$

$\epsilon_0 = 0.225 \text{ pF/in}$
 $Dk = 4$
 $A = \text{area in in}^2$
 $h = \text{dielectric thickness, inches}$

$$C = \epsilon_0 Dk \frac{A}{h} = \frac{A}{h}$$

$Dk = 4$
 $A = \text{area in in}^2$
 $h = \text{dielectric thickness, mils}$

Estimate for this example:

If $Dk = 4$ $C = \epsilon_0 \times 4 \frac{4.5 \times 6.25}{62} = 0.41 \text{ nF}$

If $Dk = 4.6$ $C = \epsilon_0 \times 4.6 \frac{4.5 \times 6.25}{62} = 0.47 \text{ nF}$

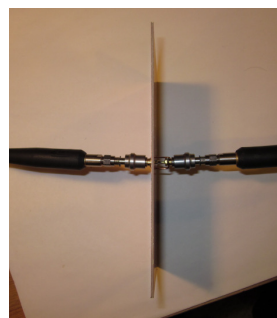


What is the Inductance?

- What does the 1.6 nH correspond to?
 - ✓ The fixture!

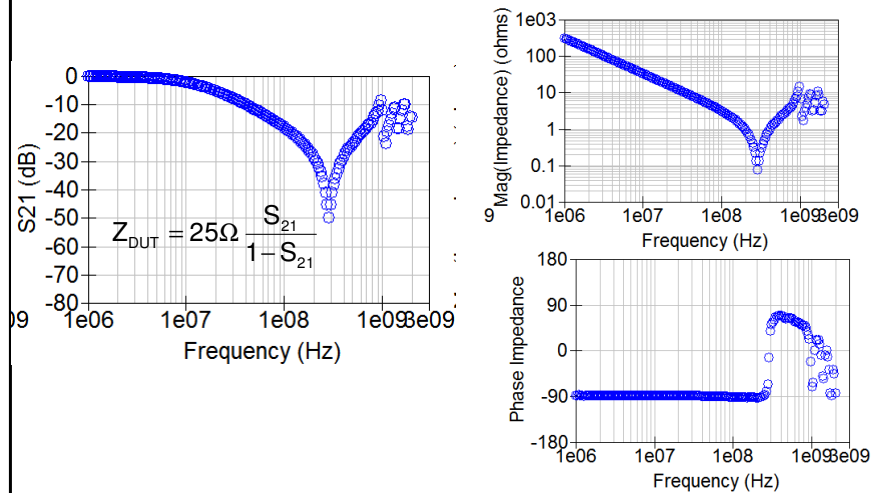


Need to use 2-port technique

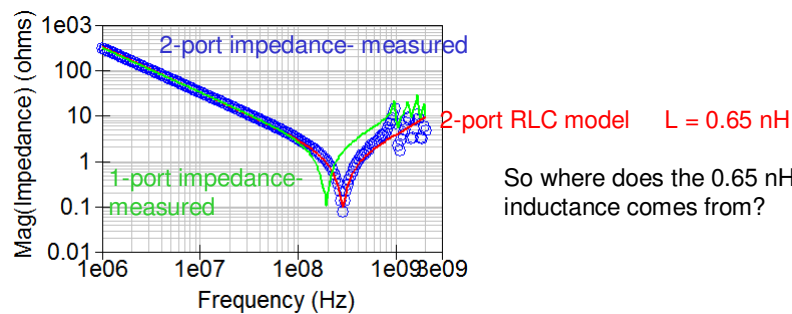




Measured 2-port Impedance



2-Port Impedance Model



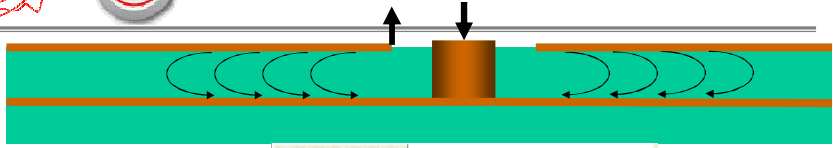
So where does the 0.65 nH inductance comes from?

Ans: Spreading inductance

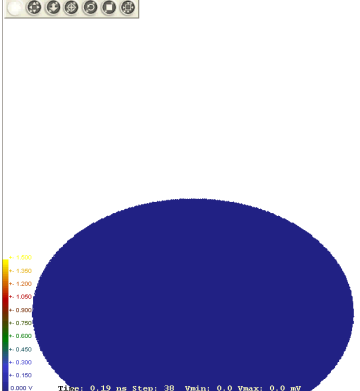
EMC 03 Analyzing the plane cavities Slide -9

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Most Important Property of Cavities



- Features
 - ✓ Wave propagates outward at speed of light in material
 - ✓ Current spreads out
 - ✓ Impedance drops off
 - ✓ Voltage wave drops off radially
 - ✓ Wave reflects at boundaries
 - ✓ Resonances show up



Voltage distribution between the planes

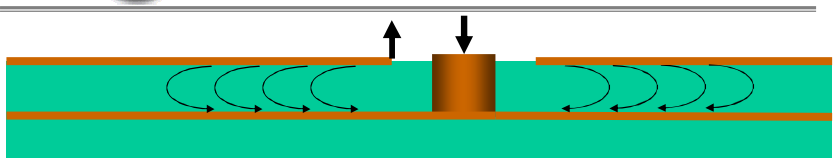
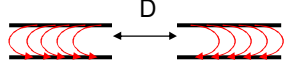
Simulated with HyperLynx 8.0

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EMC 03 Analyzing the plane cavities Slide -10

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Radial Wave Current Loop Between the Planes

$$Z_{\text{instantaneous}} = \frac{60\Omega}{\sqrt{Dk}} \frac{h}{R} = 30\Omega \frac{h}{R}$$

$$L[pH] = 5.1 \times h[\text{mils}] \times \left(\ln\left(\frac{2R}{D}\right) - \frac{3}{4} \right)$$

Instantaneous Impedance

Related to the open at the boundaries

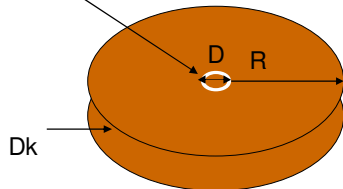
h = dielectric thickness between the planes
 Dk = dielectric constant between the planes
 R = distance from via center to observation point
 D = diameter of contact point

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Spreading Inductance Estimate

Contact

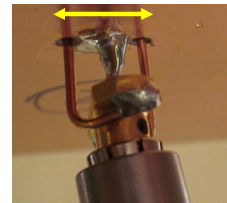


$$L[\text{pH}] = 5.1 \times h[\text{mils}] \times \left(\ln\left(\frac{2R}{D}\right) - \frac{3}{4} \right)$$

$$L[\text{pH}] = 5.1 \times 062 \times \left(\ln\left(\frac{5}{0.4}\right) - \frac{3}{4} \right) = 0.56 \text{ nH}$$

R = radius to edge of plane ~ 2.5 inches
 D = diameter of contact ~ 0.4 inches
 h = spacing between the planes ~ 062 mils

~ 0.4 inches

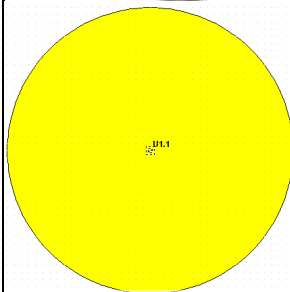


Spreading Inductance Analytical Analysis

$$L = \frac{\mu_0}{2\pi} h \times \left[\ln\left(\frac{B}{r}\right) - \frac{3}{4} \right]$$

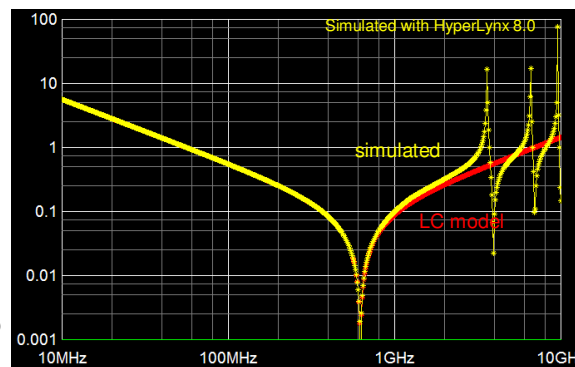
$$f_{\text{res}} = \frac{1}{2\pi \sqrt{LC}}$$

$$C = \epsilon_0 \times Dk \frac{\pi B^2}{h}$$



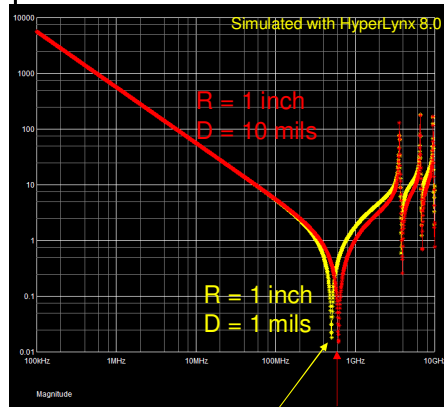
Simple disc example

- ✓ h = 1 mil = 0.001 inches
- ✓ B = 1 inch radius of the plate, 2 inch diameter
- ✓ r = 5 mil radius of the via, 10 mil diameter
- ✓ Dk = 4, emulating FR4
- ✓ ϵ_0 = permittivity of free space = 0.225 pF/inch
- ✓ μ_0 = permeability of free space = 4 p x 100 nH/m = 32 nH/inch





Self Resonance Frequency (SRF) for Circular Plane Cavities:



$f = 0.51 \text{ GHz}$ $f = 0.62 \text{ GHz}$

$$C = \epsilon_0 \times Dk \frac{\pi R^2}{h} \quad L = \frac{\mu_0}{2\pi} h \times \left(\ln \left(\frac{2R}{D} \right) - 0.75 \right)$$

$$f_{\text{res}} = \frac{1}{2\pi \sqrt{LC}}$$

$$f_{\text{res}} = \frac{1}{2\pi \sqrt{\epsilon_0 Dk \frac{\pi R^2}{h} \times \frac{\mu_0}{2\pi} h \left(\ln \left(\frac{2R}{D} \right) - 0.75 \right)}}$$

$$f_{\text{res}} = \frac{1}{\pi \sqrt{2} R \sqrt{Dk \mu_0 \epsilon_0} \sqrt{\left(\ln \left(\frac{2R}{D} \right) - 0.75 \right)}} \quad \text{h drops out!}$$

$$f_{\text{res}} = \frac{11.8}{\pi \sqrt{2} \sqrt{Dk} R \sqrt{\left(\ln \left(\frac{2R}{D} \right) - 0.75 \right)}} = \frac{1.33}{R \sqrt{\left(\ln \left(\frac{2R}{D} \right) - 0.75 \right)}} \quad \text{f in GHz, R in inches}$$

$Dk = 4$

$R = 1 \text{ inch}$

$D = 10 \text{ mils}$

$f_{\text{res}} = 0.62 \text{ GHz}$

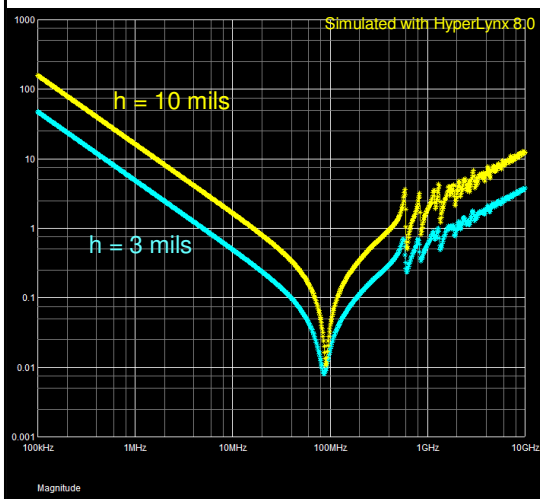
$R = 1 \text{ inch}$

$D = 1 \text{ mils}$

$f_{\text{res}} = 0.51 \text{ GHz}$



Plane Cavity Properties with Decreasing h



Decreasing h

- ✓ Increases C , decreases low freq Z
- ✓ Spreading inductance decreases

$$L[pH] = 5.1 \times h[\text{mils}] \times \left(\ln \left(\frac{2R}{D} \right) - \frac{3}{4} \right)$$

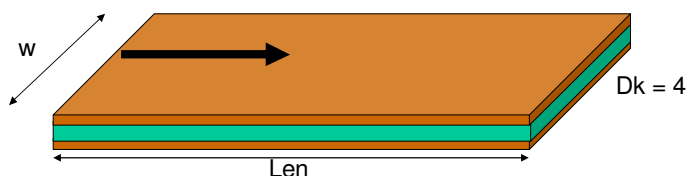
- ✓ No change in SRF

$$f_{\text{res}} = \frac{1.33}{R \sqrt{\left(\ln \left(\frac{2R}{D} \right) - 0.75 \right)}}$$

- ✓ Note: more dampening of "resonances"



Damping for Long Rectangular Sheet of Planes



$$S_{21-Len} = 4.34 \left(\frac{R_L}{Z_0} + G_L Z_0 \right) \text{ dB/in}$$

$$Z_0 = \frac{377 \Omega}{\sqrt{Dk}} \frac{h}{w} = 188 \Omega \frac{h}{w}$$

$$S_{21-Len} = 4.34 \left(0.043 \frac{\sqrt{Dk} \sqrt{f}}{h} + 0.53 Df \sqrt{Dk} f \right)$$

$$R_L = 2 \times \frac{8.14}{w} \sqrt{f} \text{ Ohms/in}$$

w, h in mils, f in GHz

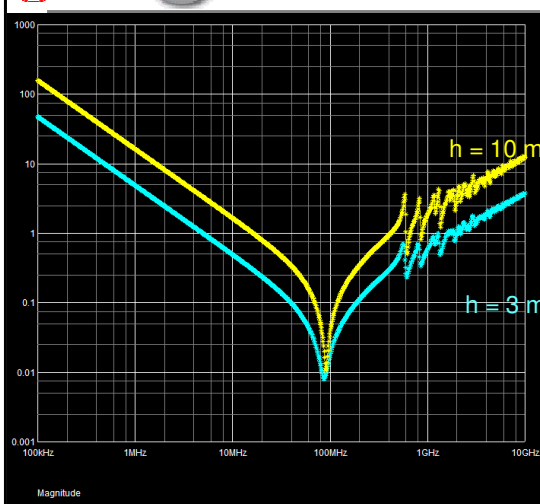
$$S_{21-Len} = \sqrt{Dk} \left(0.187 \frac{\sqrt{f}}{h} + 2.3 Df f \right)$$

Dk = 4:

$$S_{21-Len} = 0.374 \frac{\sqrt{f}}{h} + 4.6 Df f \text{ dB/in}$$



Dampening of Resonances



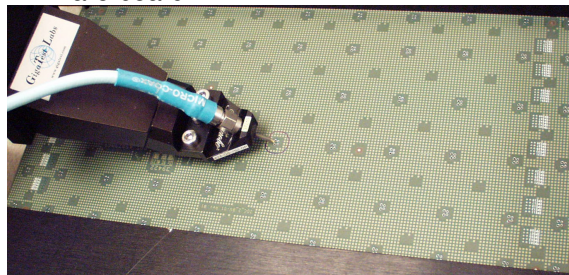
$$S_{21-Len} = 0.374 \frac{\sqrt{f}}{h} + 4.6 Df f \text{ dB/in}$$

- Dampening of resonances
 - ✓ Increase with sqrt(f)
 - ✓ Increase with thinner h
- Consequences
 - ✓ Higher frequency, more dampening
 - ✓ Thinner dielectric, more conductor loss, lower amplitude of resonances

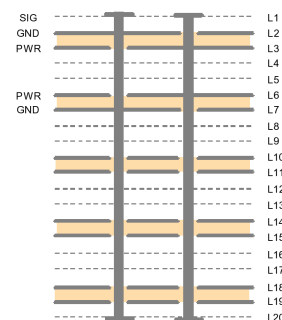


Multilayer Board Example: 5 in x 10 in, 5, 2 mil thick dielectric layers

- Courtesy of
 - ✓ Istvan Novak, Sun Microsystems, for providing sample boards and measurements
 - ✓ GigaTest Labs for providing the photos
- Bare board

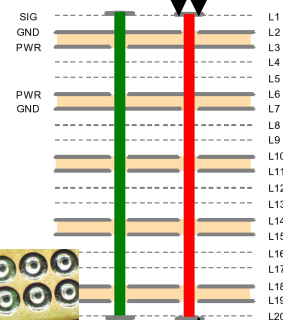
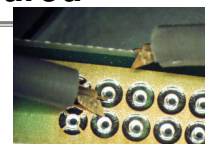


Only 2 plane pairs connected to the vias



How a Board is Probed Influences What is Measured

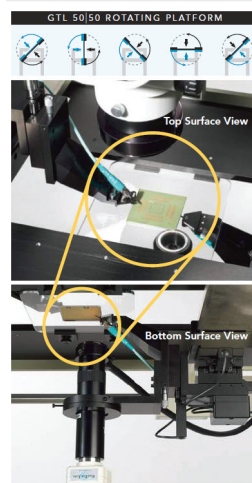
- Both ports on same pads
 - ✓ Via loop inductance
 - ✓ + spreading inductance
- Each port on same via, opposite sides of the board
 - ✓ Spreading inductance





The GigaTest Labs GTL5050 Rotating Platform Probe Station

Photos Courtesy
of GigaTest Labs

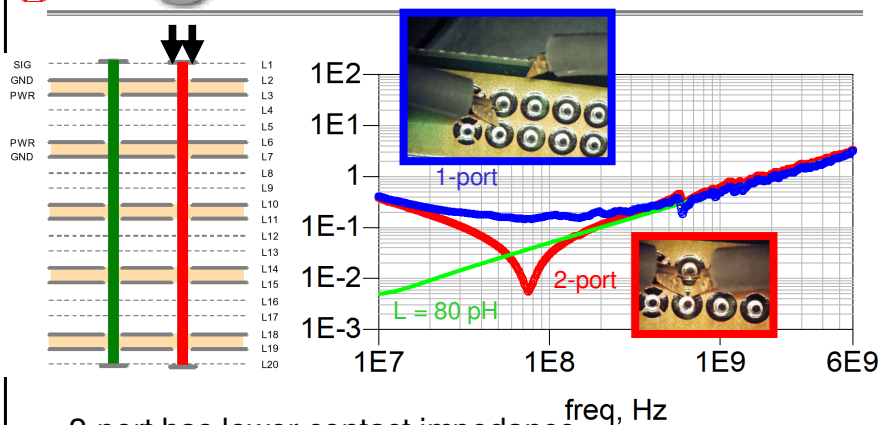


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Measurements from the Top



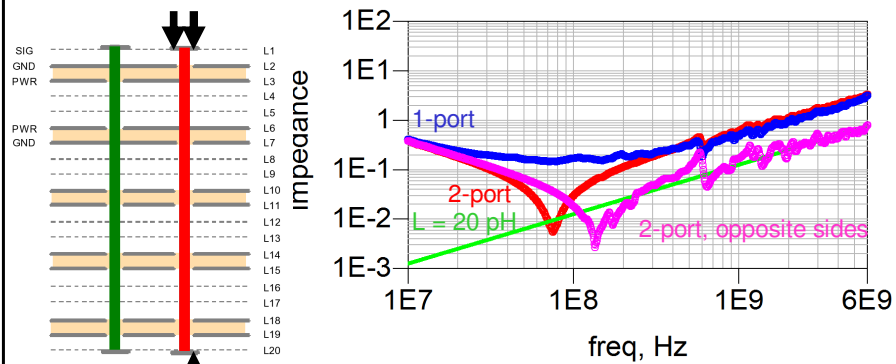
- 2-port has lower contact impedance
- What is the inductance being measured?
 - ✓ Via loop inductance + spreading inductance = 80 pH

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Probing from Opposite Sides

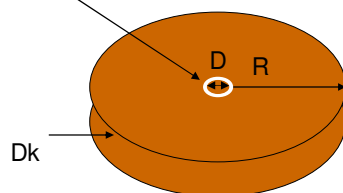


Cavity spreading inductance = 20 pH
Via loop inductance = 80 pH – 20 pH = 60 pH



Estimate Spreading Inductance

Contact



$$L[\text{pH}] = 5.1 \times h[\text{mils}] \times \left(\ln\left(\frac{2R}{D}\right) - \frac{3}{4} \right)$$

R = radius to edge of plane ~ 2.5 inches
D = diameter of contact on bottom plane ~ 0.1 inches
h = spacing between the planes ~ 002 mils

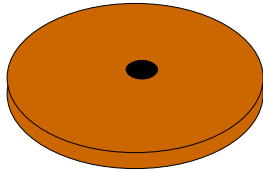
$$L[\text{pH}] = 5.1 \times 002 \times \left(\ln\left(\frac{5}{0.1}\right) - \frac{3}{4} \right) = 32 \text{ pH}$$



"if all you have is a hammer, everything looks like a nail"



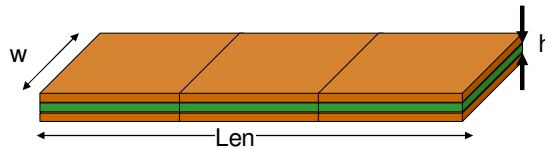
Spreading Inductance is the Limit to ANY Cavity Impedance Measurement



$$L[\text{pH}] = 5.1 \times h[\text{mils}] \times \left(\ln\left(\frac{2R}{D}\right) - \frac{3}{4} \right)$$

If $2R \sim 5$ inches
 $D \sim 0.05$ inches

$$L[\text{pH}] = 5.1 \times h[\text{mils}] \times \left(\ln(100) - \frac{3}{4} \right) \sim 20 \times h[\text{mils}]$$



$$L = \left(32^{\text{pH/mil}} \times h \right) \times \frac{\text{Len}}{w}$$

Sheet
inductance # of
squares

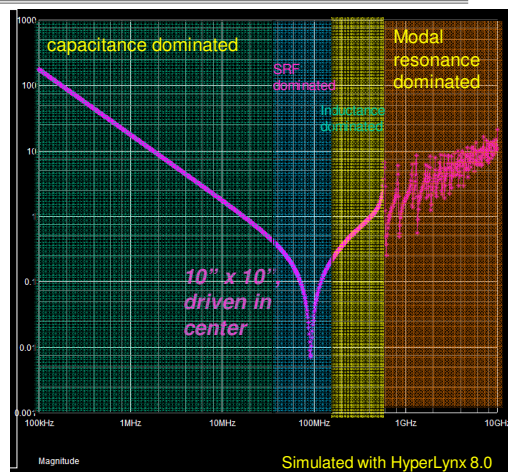


Spreading inductance $\sim 2/3 \times$ Sheet Inductance



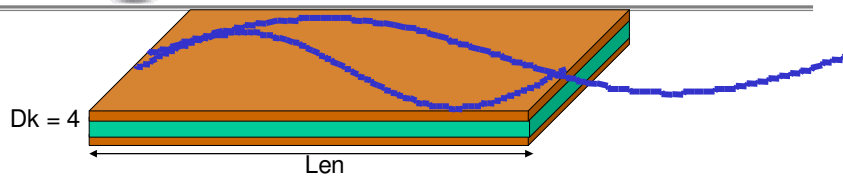
Four Regimes of Cavity Behavior

- Low frequency: capacitance dominated
 - ✓ plane capacitance
 - ✓ $C \sim$ board capacitance
- Self Resonant Frequency
 - ✓ All about the RLC
 - ✓ $C \sim$ board capacitance
 - ✓ $L \sim$ spreading inductance
 - ✓ $R \sim$ spreading resistance
- Inductance dominated
 - ✓ All about the cavity spreading inductance
 - ✓ $L \sim$ spreading inductance
- High frequency, modal resonances





Rectangular Board Resonance Frequency



resonance is when $Len = n \times \frac{1}{2} \lambda$

$$f_{res} = n \times \frac{v}{2 \times Len} = n \times \frac{12 \text{ in/nsec}}{\sqrt{Dk} \times 2 \times Len} \sim n \frac{3}{Len} \text{ GHz}$$

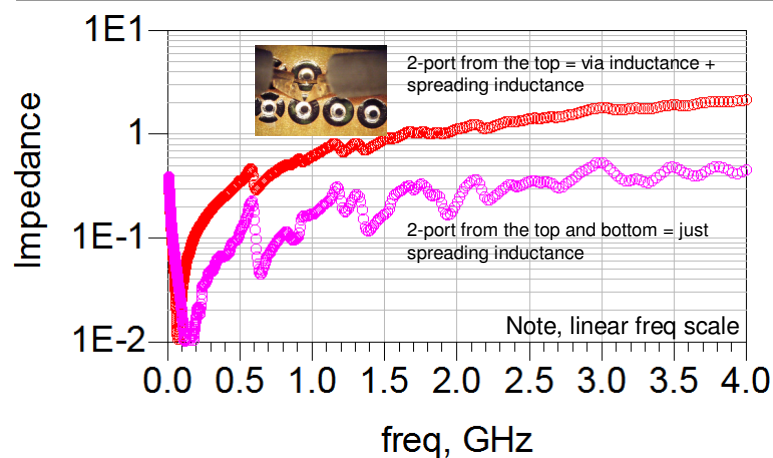
n = 1 mode: Len = w

Len	f _{res}
2 in	1.5 GHz
4	0.75
5	0.6
6	0.5
10	0.3

Cavity modes are an intrinsic property of the cavity
Independent of 1 or 2 port impedance



Board Driven w, wo Via Inductance

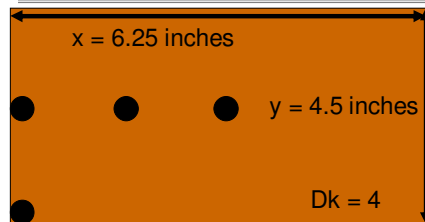


Board Len = 10 x 5 inches

f_{res} for 5 inches = 0.6 GHz, 1.2 GHz, 1.8 GHz, ...



Where Board is Probed Influences Which Modes are Excited



$$f_{res} = n \times \frac{v}{2 \times Len} = n \times \frac{12 \text{ in/nsec}}{\sqrt{Dk} \times 2 \times Len} = n \times \frac{3}{Len}$$

(Dk = 4, at higher freq)

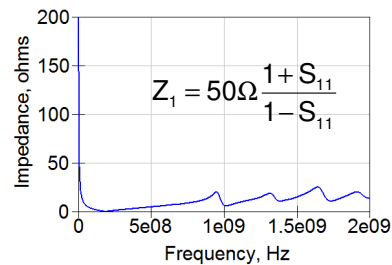
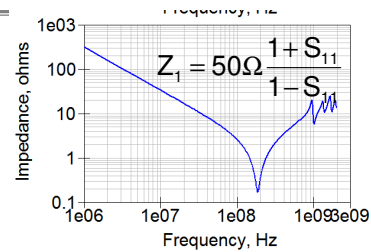
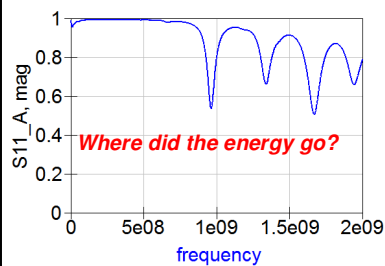
$$f_{res} = n \times \frac{3}{6.25} = 0.48 \text{ GHz}$$

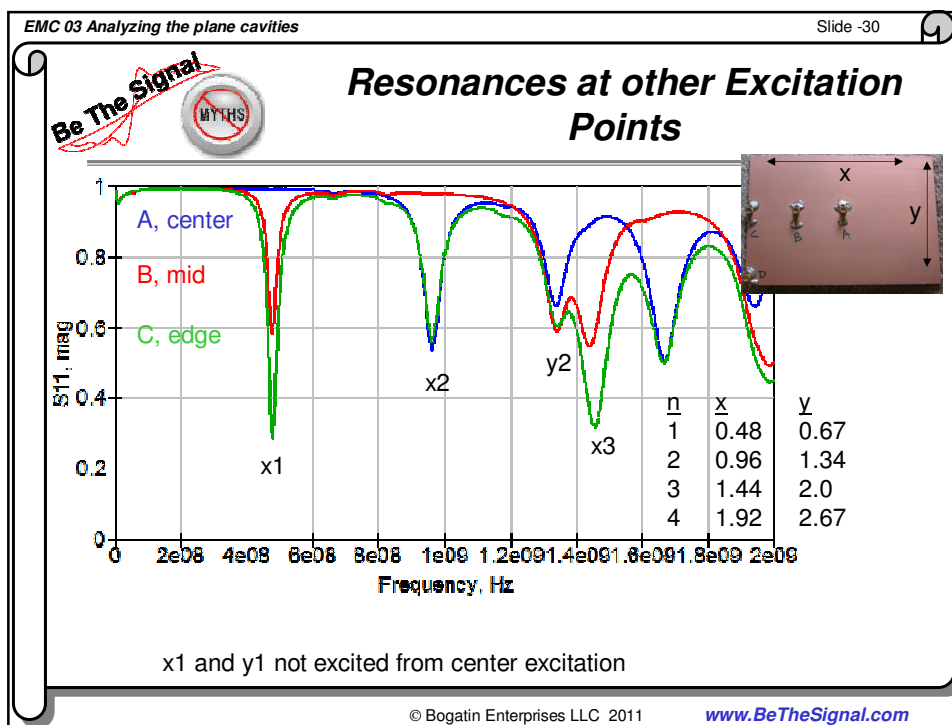
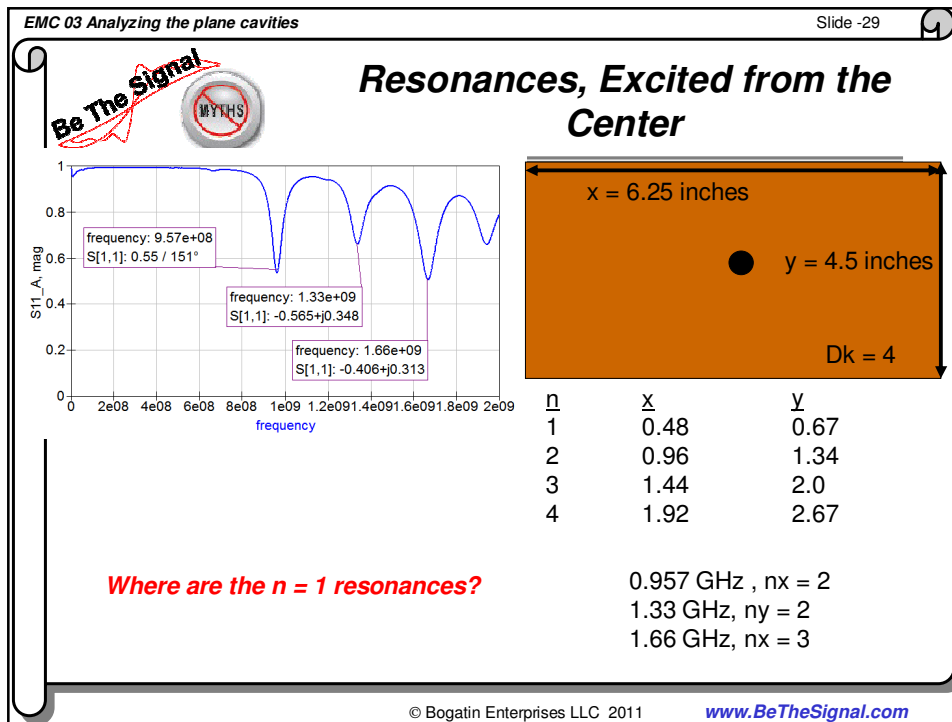
$$f_{res} = n \times \frac{3}{4.5} = 0.67 \text{ GHz}$$

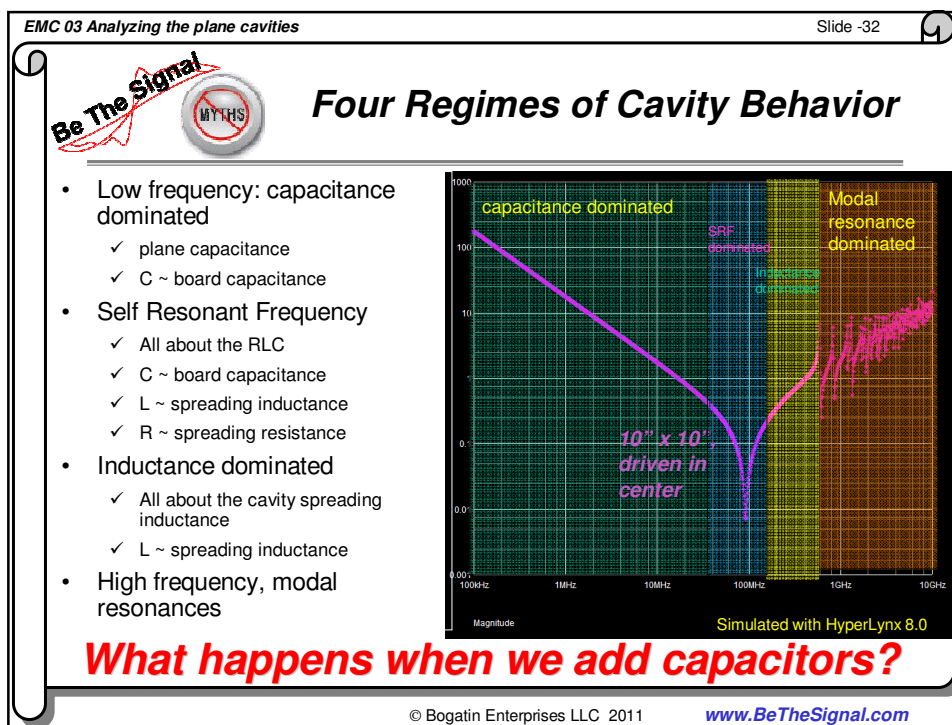
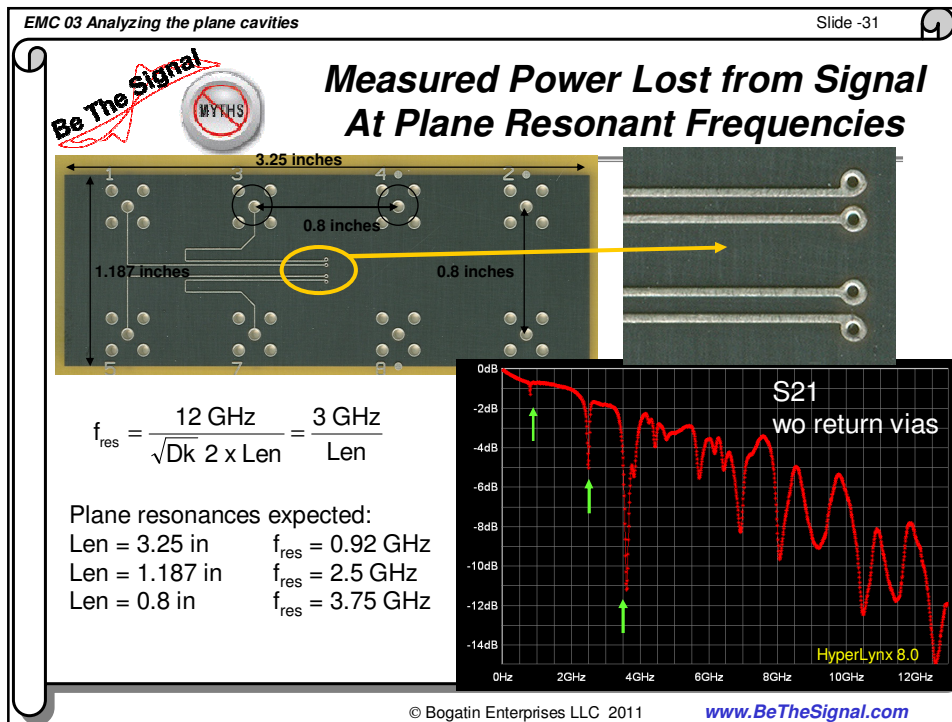
n	x	y
1	0.48	0.67
2	0.96	1.34
3	1.44	2.0
4	1.92	2.67



Impedance Profiles from 1-port Measurements









EMC 04 Planes with Capacitors

Slide -1

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MYTHS

Schedule

- ✓ EMC 01: Measuring discrete components
- ✓ EMC 02: Building circuit models for discrete components
- ✓ Lunch
- ✓ EMC 03: Measuring and analyzing plane cavities
- ✓ EMC 04: Measuring and analyzing planes with capacitors

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EMC 04 Planes with Capacitors

Slide -2

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MYTHS

Measuring the Impedance of the Plane Cavity at One Point Means Going Through the Cavity Spreading Inductance

$$L = 5.1 \times h \times \ln\left(\frac{2R}{d}\right)$$

Mag(Impedance) (ohms)

Frequency (Hz)

Dominated by spreading inductance

$$Z_{\text{instantaneous}} = \frac{60\Omega}{\sqrt{Dk}} \frac{h}{R} = 30\Omega \frac{h}{R}$$

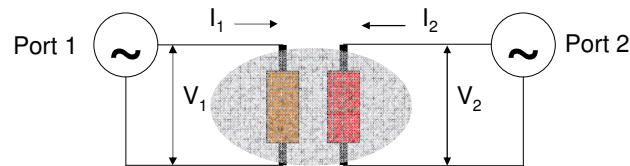
$V_2(R)$

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Using Z-Parameters to Explore Spreading Inductance



$$V_1 = Z_{11}I_1 + Z_{12}I_2$$

Self impedance:

$$Z_{11} = \left. \frac{V_1}{I_1} \right|_{I_2=0}$$

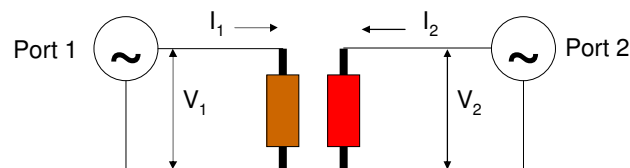
$$V_2 = Z_{21}I_1 + Z_{22}I_2$$

Transfer impedance:

$$Z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2=0}$$



Self Impedance When $I_2 = 0$



$$V_1 = Z_{11}I_1 + \cancel{Z_{12}I_2}^0$$

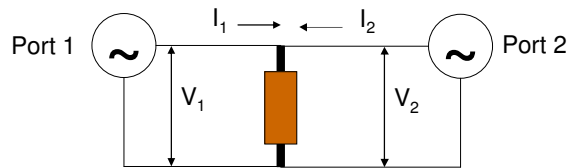
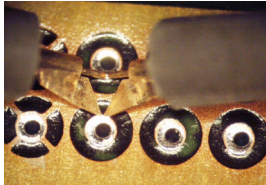
Self impedance:

$$Z_{11} = \left. \frac{V_1}{I_1} \right|_{I_2=0}$$

When no current flows through port 2,
self impedance is the impedance of the DUT,
with all the artifacts of a 1 port measurement



Transfer Impedance: Z_{21} Special Case- probing same point



$$V_2 = Z_{21}I_1 + Z_{22}I_2 \quad \text{Transfer impedance: } Z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2=0}$$

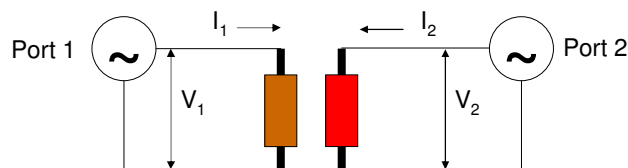
Related to the voltage generated at port 2 for a current from port 1

Transfer impedance is counter intuitive

With a large Z_{21} , a small current produces large voltage (lots of coupling)



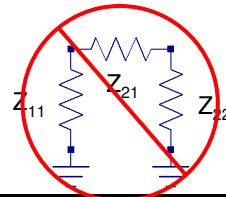
Transfer Impedance: Z_{21}



$$V_2 = Z_{21}I_1 + Z_{22}I_2 \quad \text{Transfer impedance: } Z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2=0}$$

Transfer impedance is a measure of the voltage generated across port 2 due to a current from port 1

Do not think of Z_{21} as an impedance "between" two ports

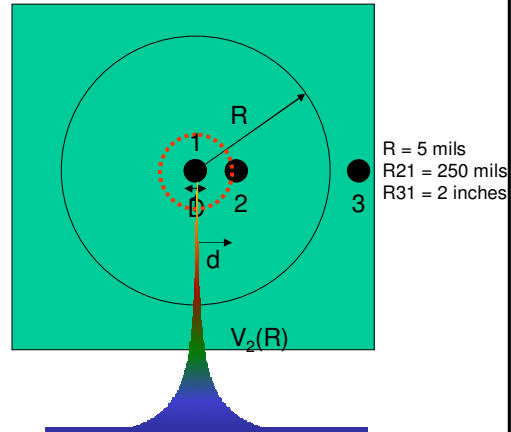




Transfer Impedance in a Cavity

- Exciting cavity from the middle
- Observing voltage farther away
- Transfer impedance, Z_{21} :

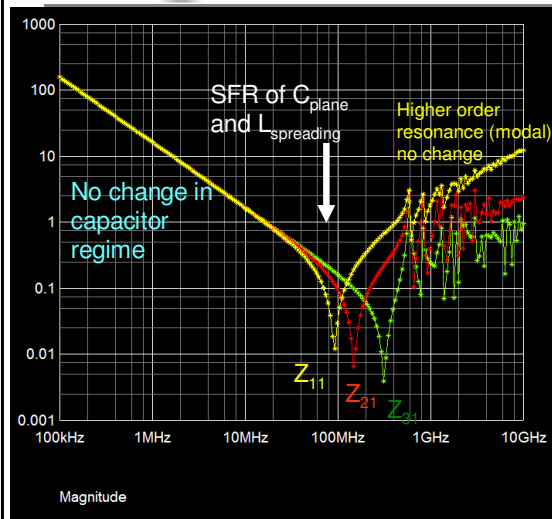
$$Z_{21} = \frac{V_2}{I_1} \Big|_{I_2=0}$$



What will $V(2)$ look like?
 What will Z_{11} , Z_{21} , Z_{31} look like?



Impedance for 10" x 10" Planes, $h = 10$ mils



Spreading L decreases

It is as though you see the spreading inductance of a larger contact point

$$\text{SRF of cavity} \sim \frac{1}{\sqrt{L}} = \frac{1}{\sqrt{\ln\left(\frac{1}{R}\right)}}$$

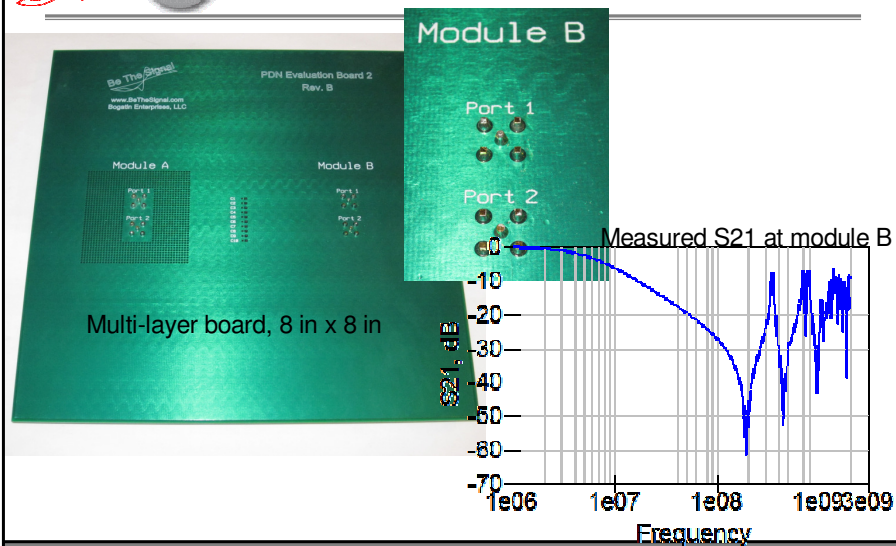
SRF is not intrinsic to the planes
 $D = 10$ mils, SRF ~ 95 MHz

$R_{21} = 250$ mils,
 Expected SRF $\sim 1.8 \times 95 = 170$ MHz
 Sim SRF = 150 MHz

$R_{31} = 2$ inches
 Expected SRF $\sim 2.3 \times 95 = 220$ MHz
 Sim SRF = 300 MHz



2-Port Impedance Measurements of Planes

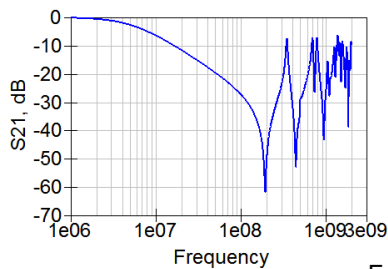


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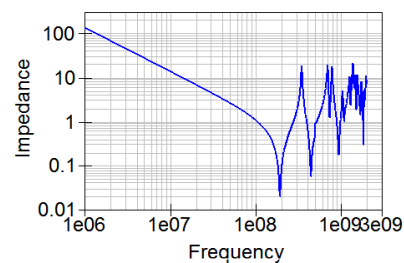
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Features of the Measured Impedance of Board with No Caps

Note flattening of S21 at low freq- why?



$$Z_{DUT} = 25\Omega \frac{S_{21}}{1 - S_{21}}$$



• Features

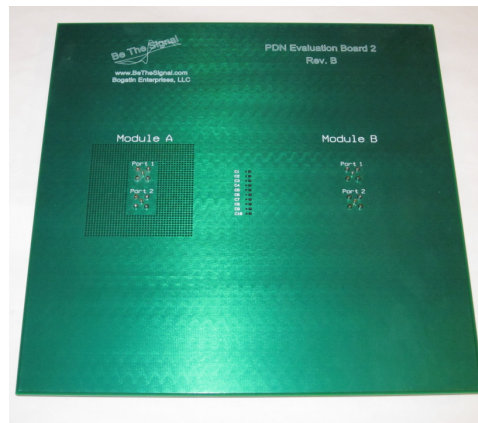
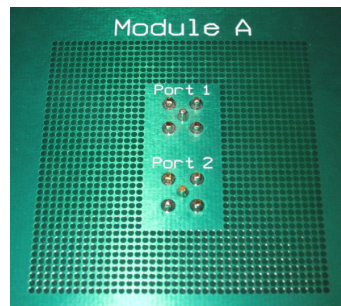
- ✓ Capacitance at low freq
- ✓ SRF due to spreading inductance, with ports separated ~ 0.75 inches
- ✓ Spreading inductance increasing impedance
- ✓ On-set of cavity resonances

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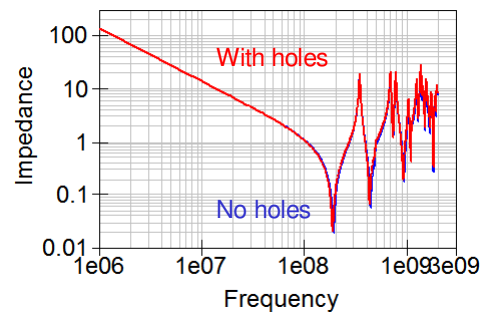
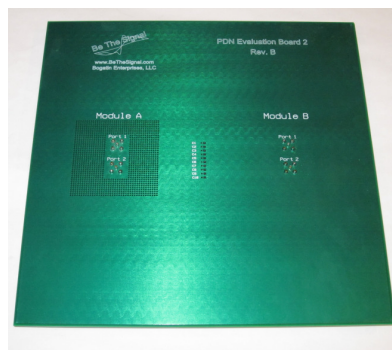
What Will be the Impact of Looking Through a Large Clearance Hole Field?



Measured from module A, and B, looking at entire board



What Will be the Impact of Looking Through a Large Clearance Hole Field?

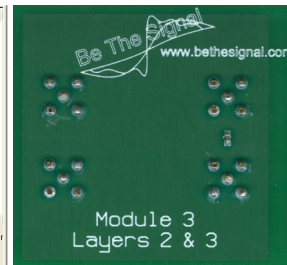
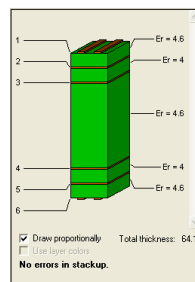
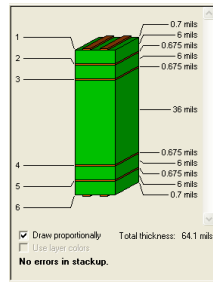


Very slightly higher inductance looking through the hole field



What Happens to Cavity Impedance When a Capacitor is Added?

6 mil core
6 mil pre-preg
36 mil core
6 mil pre-preg
6 mil core



Cavity: layers 2-3: 6 mils below the surface, 6 mils thick

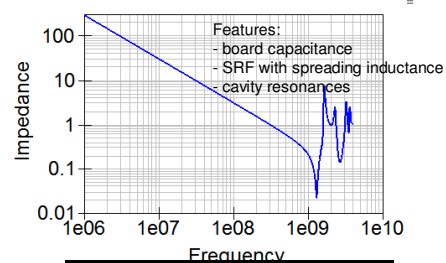


2-Port Cavity Impedance, no Cap



0603, via in pad

What will be the impact of adding a cap?

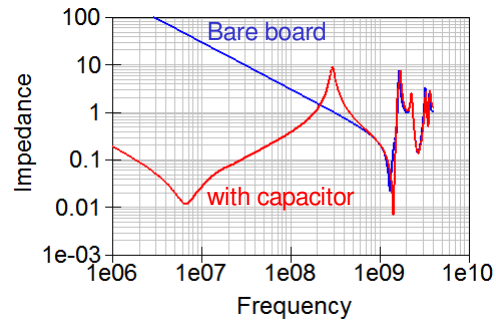




Adding a Capacitor

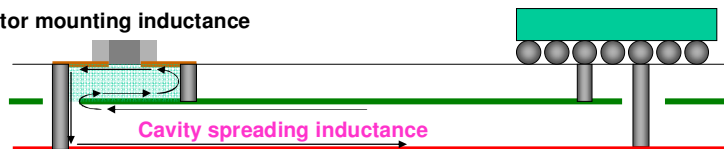
Features:

- ✓ Capacitor's C
- ✓ Capacitor's R
- ✓ Capacitor's L
- ✓ SRF of capacitor RLC
- ✓ Parallel resonance between capacitor L and cavity C
- ✓ Cavity SRF
- ✓ Cavity resonances

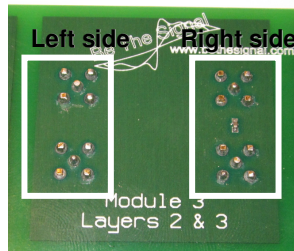


What is the Capacitor's L?

Capacitor mounting inductance



$$\text{Capacitor's } L = \text{mounting } L + \text{cavity spreading } L$$



$$L_{\text{spreading}} \sim 32 \text{ pH/mil} \times h$$

What happens to spreading inductance contribution when measured on left or right side?

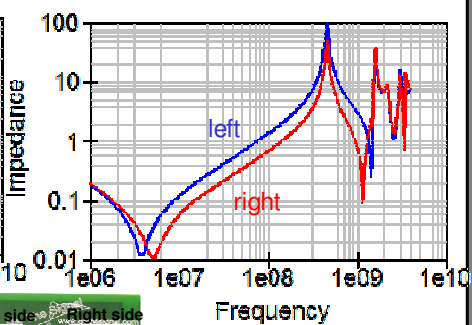
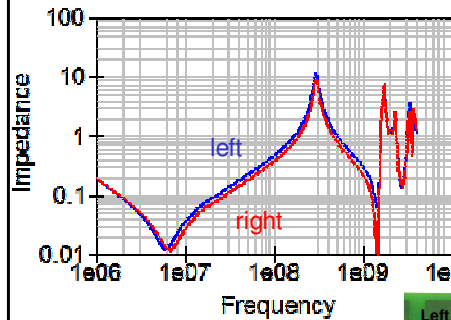
Right side: minimum spreading inductance
Left side, max spreading inductance



Impact of Spreading Inductance

2,3 Cavity = 6 mils thick, $L_{\text{spread}} \sim 32 \times 6 = 0.2 \text{ nH}$

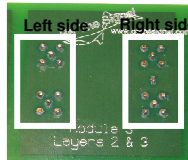
2,4 Cavity = 42 mils thick, $L_{\text{spread}} \sim 32 \times 42 = 1.3 \text{ nH}$



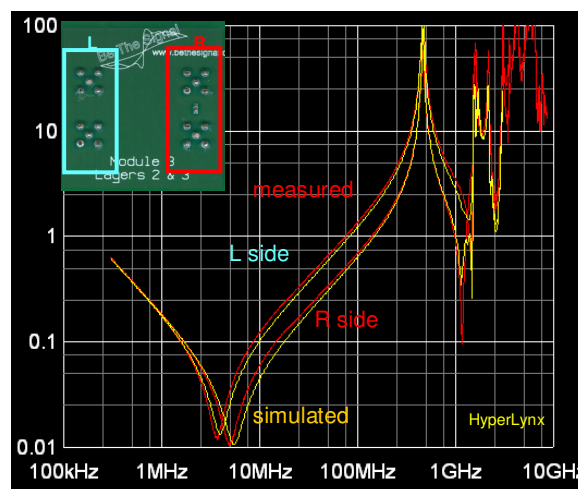
Does position matter?

If spreading $L \gg$ mounting L , yes

If spreading $L \ll$ mounting L , no

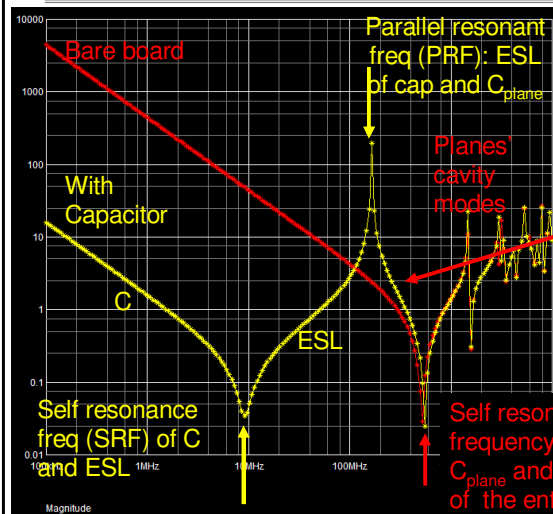


Accurately Modeling Spreading Inductance





Features of the Impedance Profile w, wo Capacitor

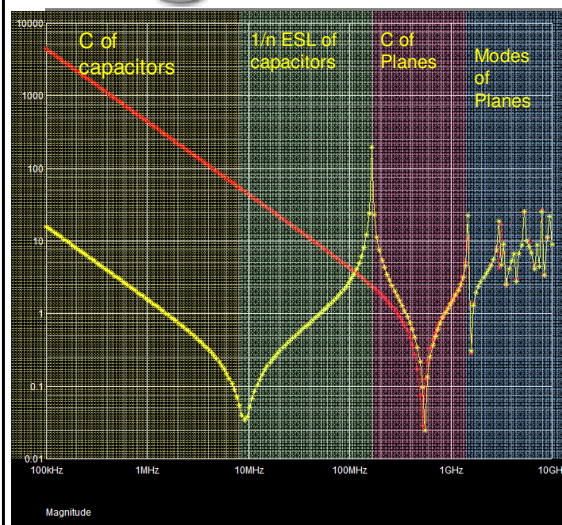


Note: above modal resonance of the planes, high ESL capacitor plays no role in board level impedance

Capacitance of the planes dominates over capacitance of capacitors



Impedance Profile of Cavities with Capacitors



Transition frequency of pin impedance dominated by cavity capacitance over capacitor capacitance is PRF

$$PRF \sim \frac{160 \text{ MHz}}{\sqrt{\frac{1}{n} ESL C_{planes}}} = \sqrt{\frac{n \times h}{ESL A}} 160 \text{ MHz}$$

$$C_{planes} = \frac{A}{h} \text{ nF} \quad \begin{matrix} A \text{ in sq inches} \\ h \text{ in mils} \end{matrix}$$

Example:

ESL = 2 nH, n = 10

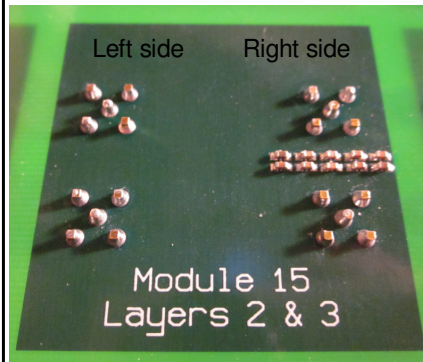
A = 10" x 10" = 100 sq inch

h = 5 mils

$$PRF = \frac{\sqrt{10 \times 5}}{\sqrt{2 \times 100}} = 80 \text{ MHz}$$



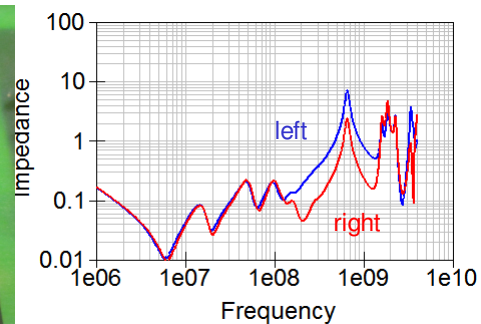
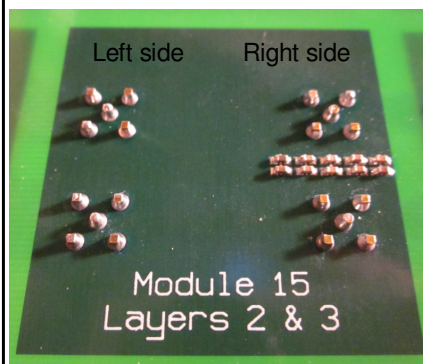
Multiple Different Value Capacitors



10 capacitors
What should right and left sides look like?



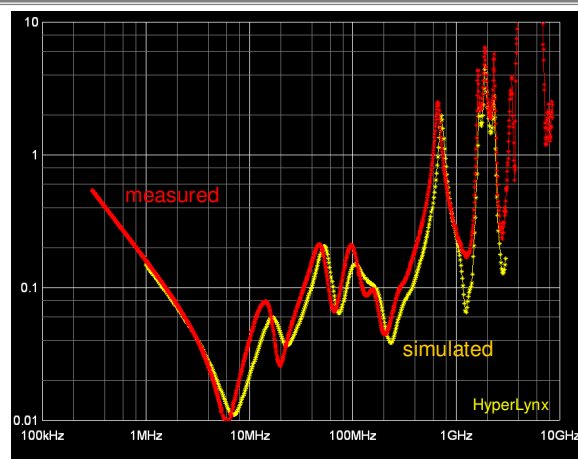
Measured Response



With 10 caps, $1/n$ ESL is very small
Spreading inductance can dominate at high freq



Simulated

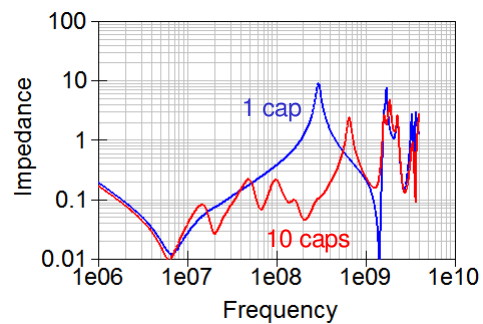


Using spec'd values of capacitor C, ESR



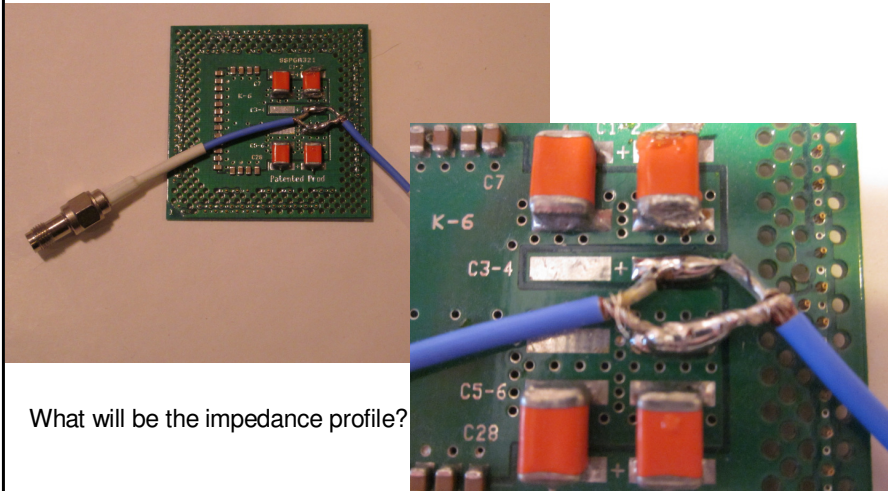
1 cap and 10 caps

- Multiple caps, if the values are chosen correctly, can dramatically reduce impedance at high frequency





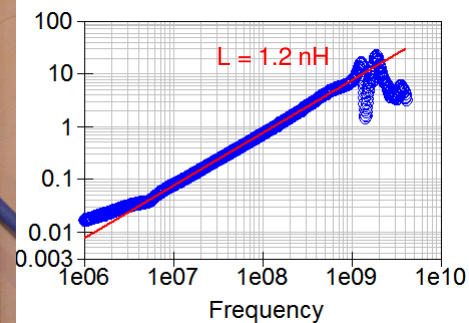
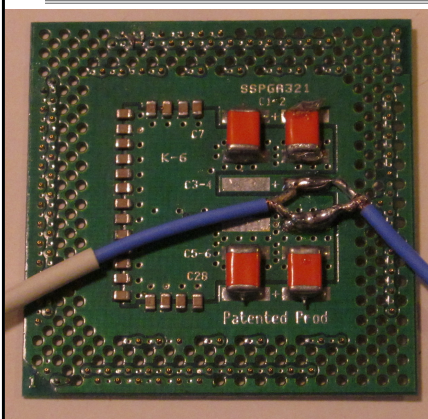
Instrumenting Any Board for 2-port Measurement



What will be the impedance profile?



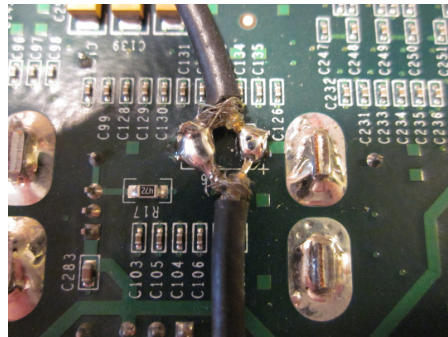
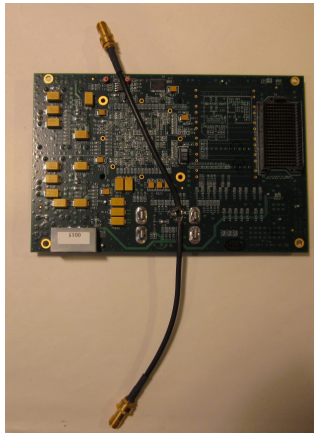
Measured Impedance Profile



Very poor use of planes
Makes all the caps at high freq worthless



Populated Circuit Board

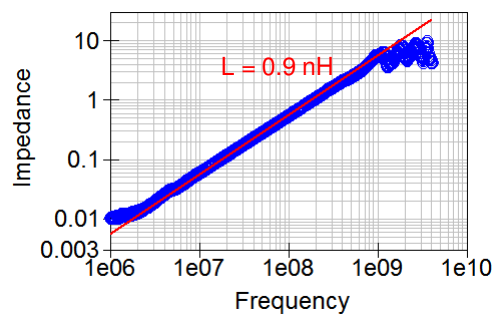


Remove a capacitor
Probe capacitor pads

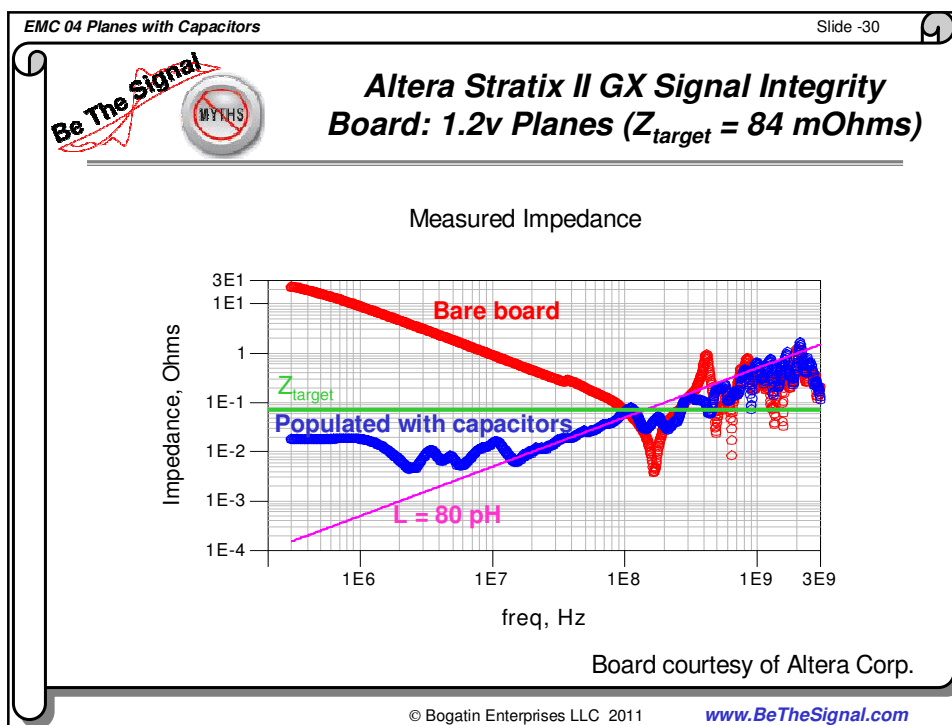
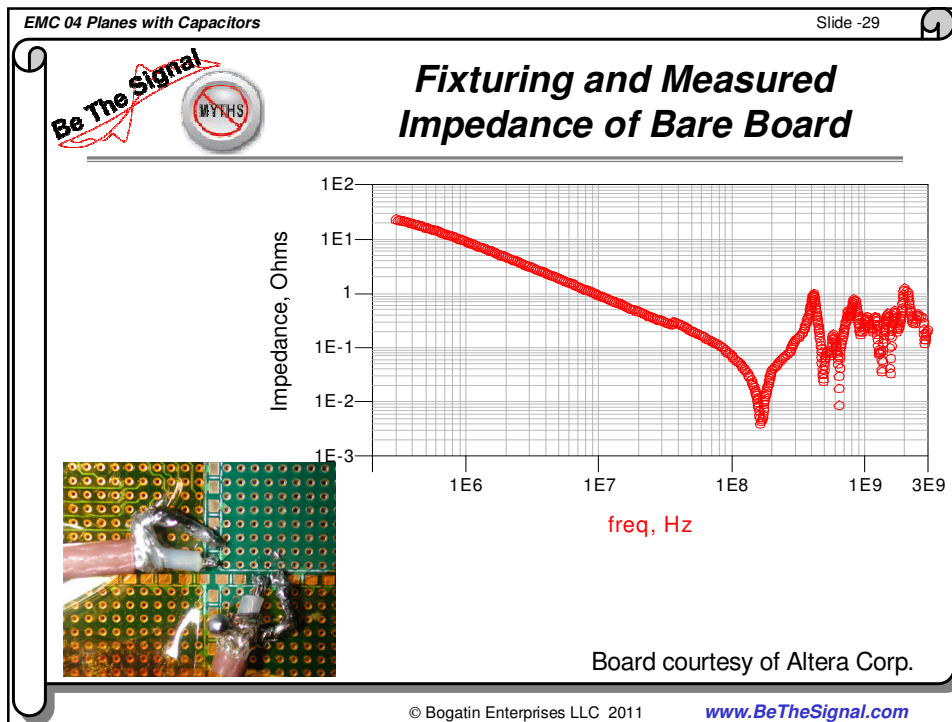
Looking at a specific power rail



Measured Impedance Profile



Any power rail on any board can be measured in this way



EMC 04 Planes with Capacitors Slide -31

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EMC 04 Planes with Capacitors Slide -32

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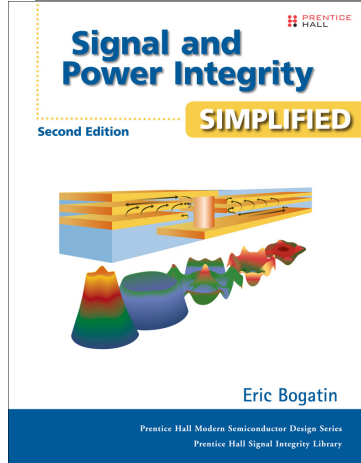
Schedule

- ✓ EMC 01: Measuring discrete components
- ✓ EMC 02: Building circuit models for discrete components
- ✓ Lunch
- ✓ EMC 03: Measuring and analyzing plane cavities
- ✓ EMC 04: Measuring and analyzing planes with capacitors

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Brightking Electronics Inc.	Manufacturer specializing in production of surge protection devices such as TVS diodes and ESD protectors. Provides total solution and technical service for surge protection.	Amy	Zhou	Santa Clara	CA	95054	408-844-8830	usasales@brightking.com.tw
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EMSCAN	World leading developer of magnetic near-field measurement tools. EMScan is dedicated to providing real-time lab-bench systems which are efficient and cost-effective. They offer dramatic project cost containment and accelerated time-to-market.	Ruska	Patton		Canada		403-291-0313 x292	ruska.patton@emscan.com
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Gigatest Labs	Gigatest Labs specializes in measurement and behavioral models of high-speed digital-interconnects to 50 GHz; modeling/simulation for 2D /3D structures. Gigatest also manufactures precision probing systems.	Harry	Christie	Sunnyvale	CA	94085	408-524-2700	harry@gigatest.com
Giga-Tronics	ISO 9001 and AS 9100 certified. Manufacturer of best-in-class RF and microwave signal generators, microwave power amplifiers, USB power sensors, microwave power meters and broadband switching matrices.	Leonard	Dickstein	San Ramon	CA	94583	925-328-4650	ldickstein@gigatronics.com

Haefely EMC	Precision EMC transient immunity test equipment for surge, ESD, EFT and power quality testing to IEC/EN, ANSI/IEEE, UL, Bellcore, FCC, ITU standards and more.	Jerry	Ramie	San Jose	CA	95132	408-263-6486	jramie@arctechnical.com
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IN Compliance Magazine	In depth coverage of worldwide regulatory compliance issues every month. IN Compliance covers EMC, Product Safety, Telecommunications, ESD, and Environmental topics. F	Sharon	Smith	Hopedale	MA	1747	978-760-0093	sharon.smith@incompliancemag.com
Interference Technology	The only media to focus exclusively on the EMC industry, publishes in print and online in North America, China, Japan and Europe.	Bob	Poust	Plymouth Meeting	PA	19462	484-688-0300 x15	bpoust@interferencetechnology.com
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MC Microwave	Full service EMC sales representative in Northern California with suppliers such as Teseq Inc. and Panashield.	Brian	Guthrie	San Jose	CA	95129	408-446-4100	brian@mcmicrowave.com
Teseq Inc.	Teseq Inc., Formerly Schaffner EMC Systems, is a leading international company for EMC test systems. We develop and manufacture test instruments, software and accessories for EMC emissions and immunity testing.	Randy	Johnson	Rolling Meadows	IL	60008	847-612-8358	randy.johnson@teseq.com
Vanguard	High Performance Elastomeric gaskets, seals, tubing, moldings, and EMI/RFI shielding gaskets	Ken	Swick	Sherman	TX	75090	214-923-9210	ken@emisystems.net
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