Probes and Setup for Measuring Power-Plane Impedances with Vector Network Analyzer

Istvan Novak

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Outline

- Introduction
- Z, Y, and S parameters
- Self and transfer impedances
- VNA
- One-port impedance measurement
- Two-port impedance measurement
- DUTs
- Measured self and transfer impedances
- Correlation to simulations
- Resources
- References

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Requirements in Power Distribution

In digital and mixed analog/digital systems:

- Core and signaling voltages drop
- Noise margin goes down
- Core and total I/O current go up
- Bandwidth goes up

Requirement:

Few milliohms over hundreds of MHz bandwidth.

Solution:

In multilayer boards, power and ground are distributed over (solid) planes.

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Z, Y, and S Parameters

$$\mathbf{v} = \mathbf{Z}\,\mathbf{i}$$

$$v_1 = Z_{11}i_1 + Z_{12}i_2$$

$$v_2 = Z_{21}i_1 + Z_{22}i_2$$

$$\mathbf{i} = \mathbf{Y}\,\mathbf{v}$$

$$i_1 = Y_{11}v_1 + Y_{12}v_2$$

$$v_2 = Y_{21}v_1 + Y_{22}v_2$$

- Zero volt/current is hard to set
- Calibration plane is critical

$$\mathbf{b} = \mathbf{S}\,\mathbf{a}$$

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

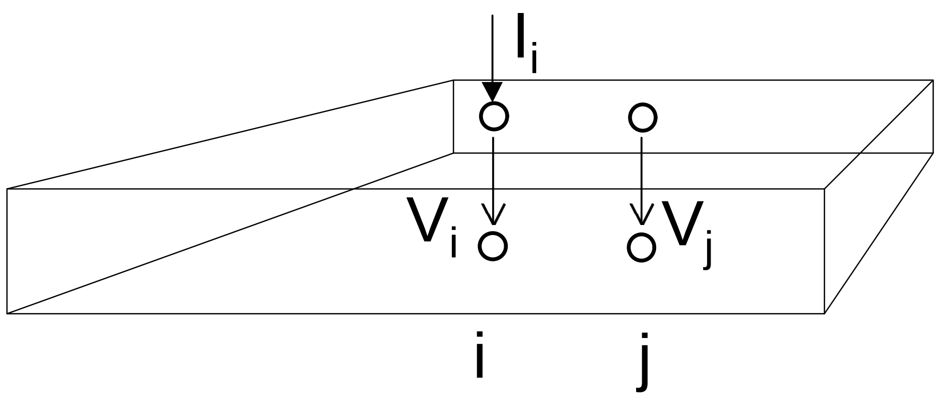
$$b_2 = S_{21}a_1 + S_{22}a_2$$

- Zero wave is easier to set
- Calibration plane is not critical

Which Parameters Do We Need

At high frequencies, S parameters are easier to measure, but

- Digital designers deal with voltages and currents
- Good power-distribution network is a voltage source >>> Z parameters needed



$$Z_{ii} = \frac{v_i}{i_i}\Big|_{i_j=0}$$

$$Z_{ji} = \frac{v_j}{i_i}\Big|_{i_j=0}$$

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Measuring Power-Distribution Network

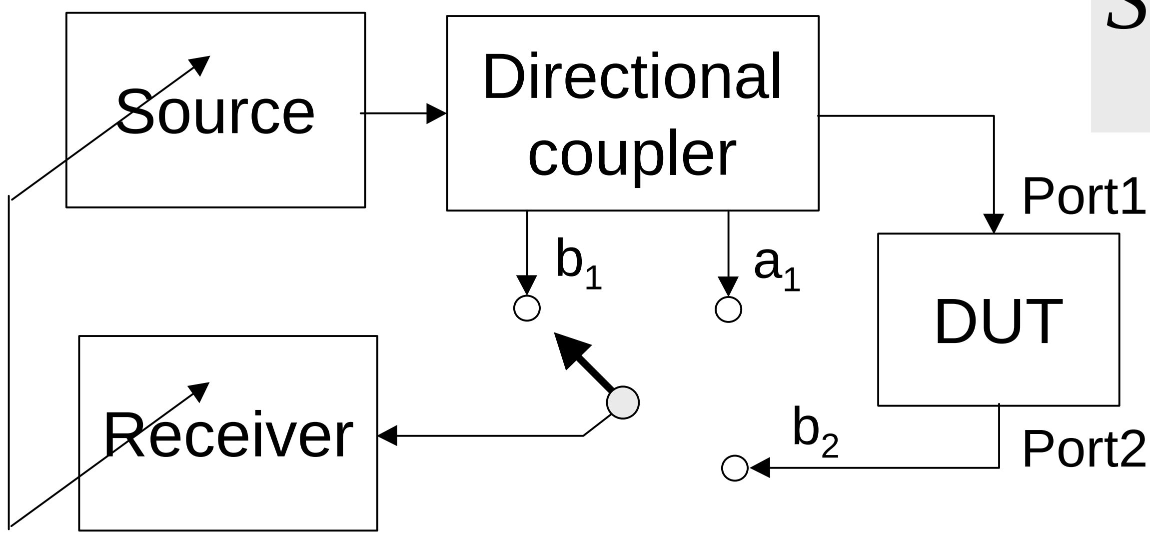
- TDR
- LCR Bridge
- VNA Γ or S11, and S21

What is a VNA

- Tuned sinewave generator
- Directional couplers
- Tracking receiver(s)

$$S_{11} = \frac{b_1}{a_1}\Big|_{a_2=0}$$

$$S_{21} = \frac{b_2}{a_1}\Big|_{a_2=0}$$



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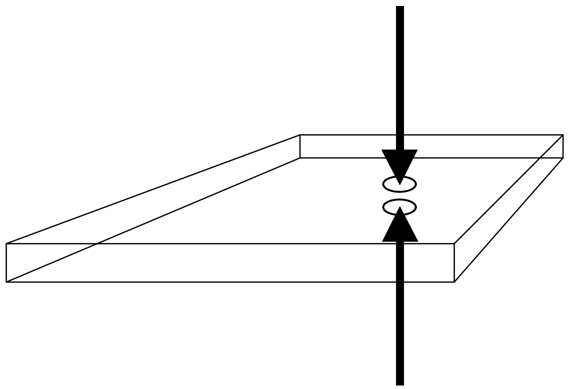
One-Port Self-Impedance Measurement



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

$$Z_{11} = Z_{in} = 50\frac{1 + S_{11}}{1 - S_{11}}$$

The impedance is measured between the ground and power planes at the selected point

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Errors of One-Port Self-Impedance Measurement

- VNA accuracy is lower at high reflections
- Connecting discontinuity is in series of low-Z DUT

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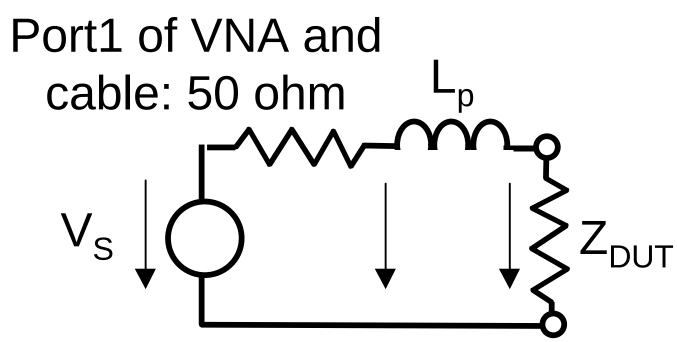
VNA Error in S11 Measurement

- |S11| uncertainty of HP8720D is 1.5% at $|\Gamma|\sim1$ in the 50-2000MHz range
- Impedance uncertainty is 0.375 ohms
- For low measurement errors, Z_{DUT} must be in the ohms range

But we want to measure fractions of an ohm

Errors Due to Discontinuities

- 50 mils of pigtail connector/cable discontinuity is L_p ~0.4nH
- 0.4 nH is Z_p ~ 2.4 ohms at 1GHz
- Problem: Z_p is in series to Z_{DUT}



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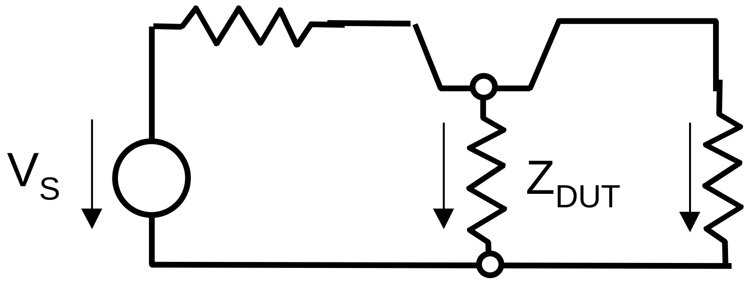
Two-Port Self-Impedance Measurement

- S_{21} instead of S_{11} is measured
- S_{21} uncertainty is less
- Z_p is in series to 50 ohms instead of Z_{DUT}



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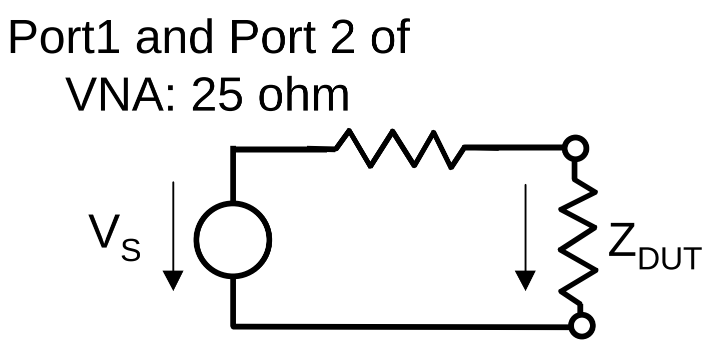
Two-Port Self-Impedance Reading

First-order calculation:

Assume that

- $L_p \sim 0$
- $Z_{DUT} << Z_0$



$$Z_{DUT} = Z_{11} = S_{21} * 25 \text{ [ohm]}$$

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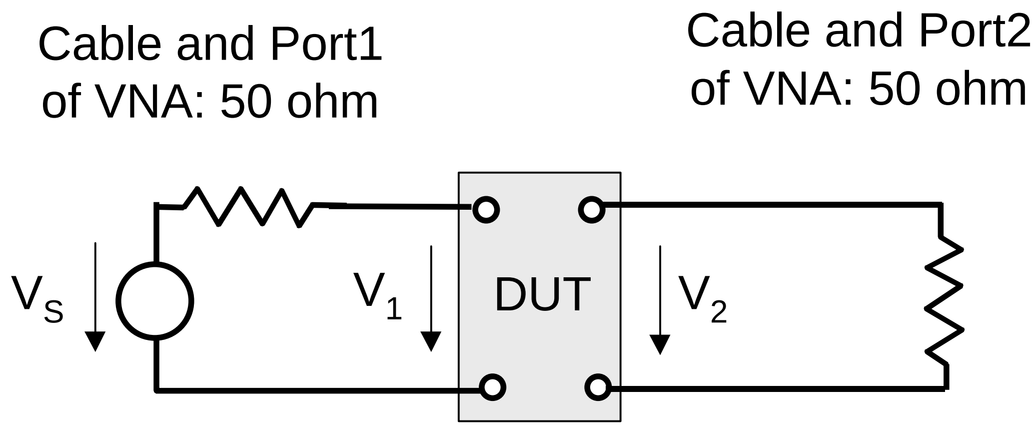
Transfer Impedance Measurement



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Transfer Impedance Reading

First-order calculation:

Assume that

- $L_p \sim 0$
- $Z_{11} << Z_0$
- $Z_{22} << Z_0$
- $Z_{21} << Z_0$

$$Z_{21} = Z_{12} = S_{21} * 25 \text{ [ohm]}$$

S21 Uncertainty

- $|S_{21}|$ uncertainty of HP8720D:
  <1dB in the $|S_{21}| > -60$dB range
  <3dB in the $|S_{21}| > -70$dB range
- Impedance uncertainty:
  1dB (10%) for $Z_{DUT} > 25$milliohms
  3dB (40%) for $Z_{DUT} > 8$milliohms

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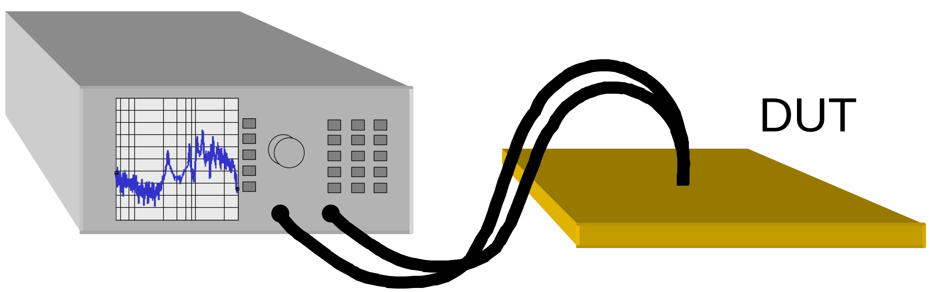
Measurement Setup

Vector Network Analyzer: HP 4396 or HP 8720C VNA

Probe: 2 pieces of 12-inch long semirigid coax



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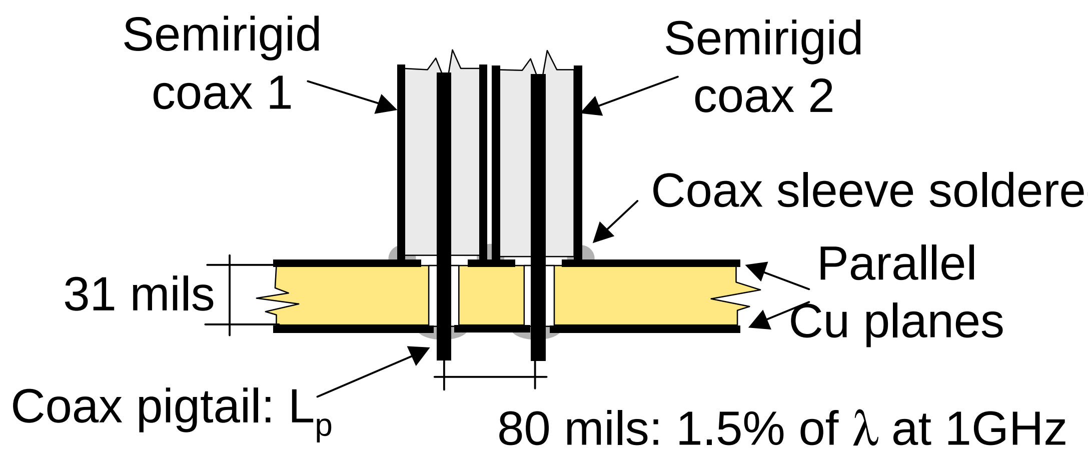
Dual Semirigid Probe

Cross-sectional view of the
Dual Semirigid Probe
NOT TO SCALE



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Device Under Test (1)

31 mil plane separation

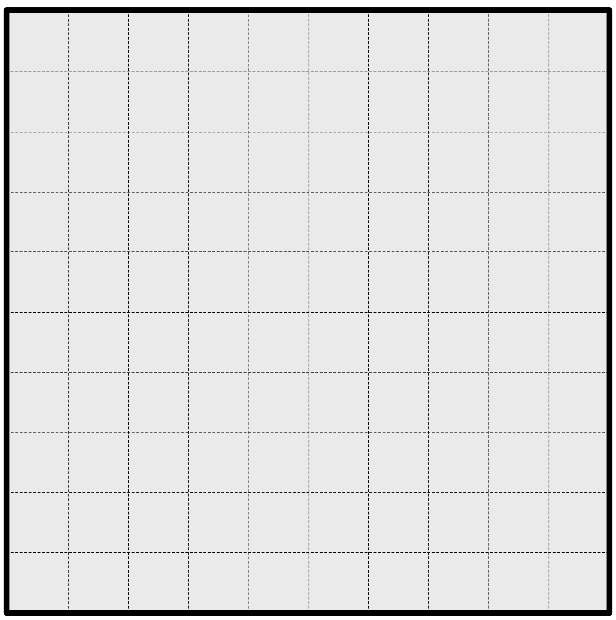
10-inch by 10-inch FR4 two-sided PCB

Bare PCB or 5.1 ohm/inch DET

Signal input and output: 12” Dual Semirigid Probe

Test points: on a 1-inch by 1-inch grid

Top view:



Side view without and with DET:

805 SMD
5.1 ohm per inch

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Device Under Test (2)

2 mil plane separation

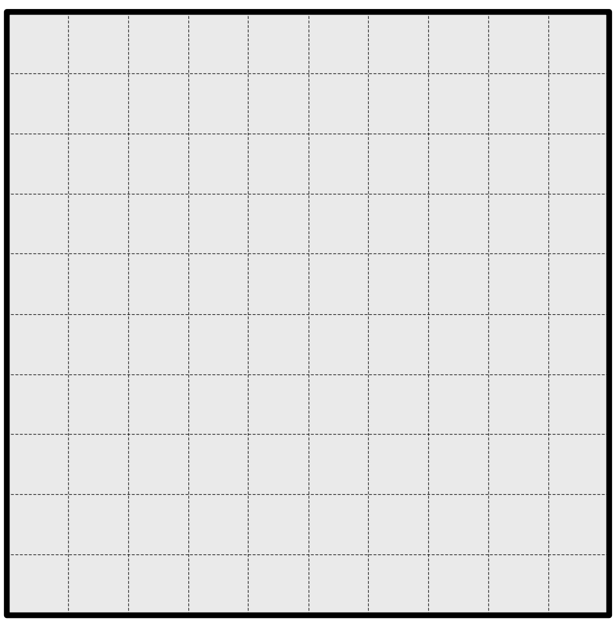
10-inch by 10-inch FR4 PCB

Bare PCB or 1 ohm/half-inch DET

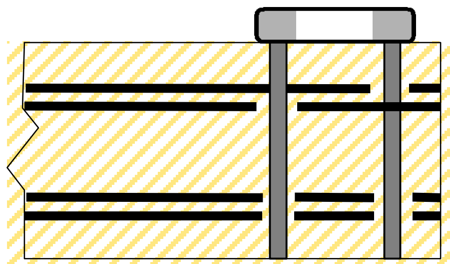
Probes: 12” Dual Semirigid Probe

Test points: on a 1-inch by 1-inch grid

Top view:



Side view with DET:



805 SMD
1 ohm / half inches

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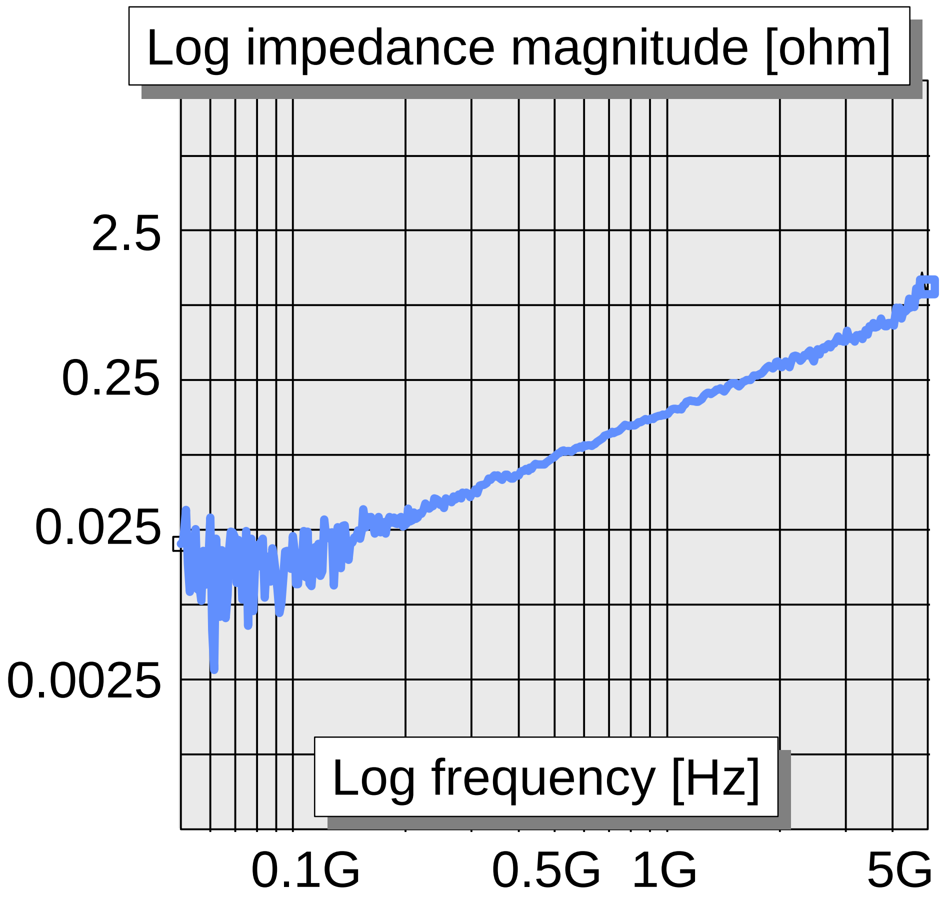
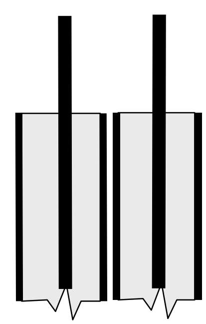
Residual Probe Response (1)



- DUT is not in place
- Dual Semirigid Probe, 50-mil pigtails, disconnected



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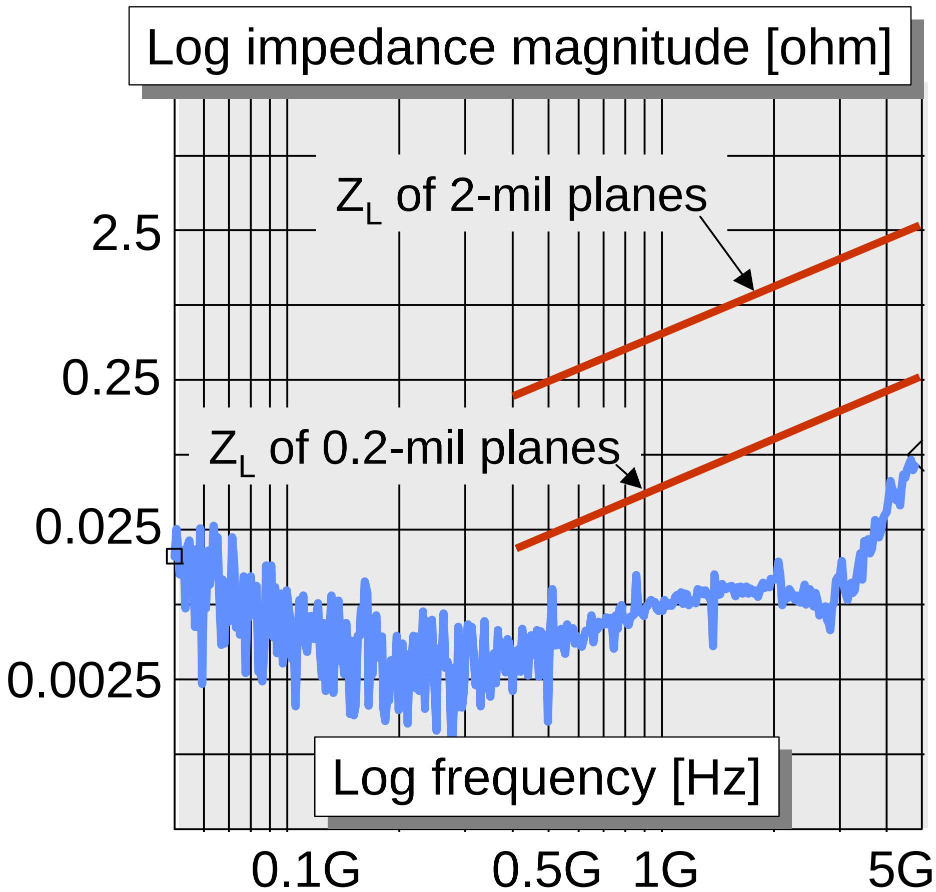
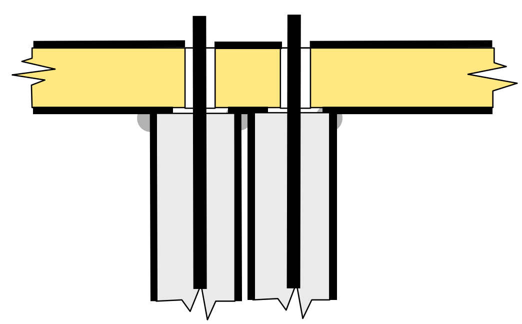
Residual Probe Response (2)



- Probe sleeves are soldered to 31-mil DUT
- 50-mil probe tails in place, but not connected



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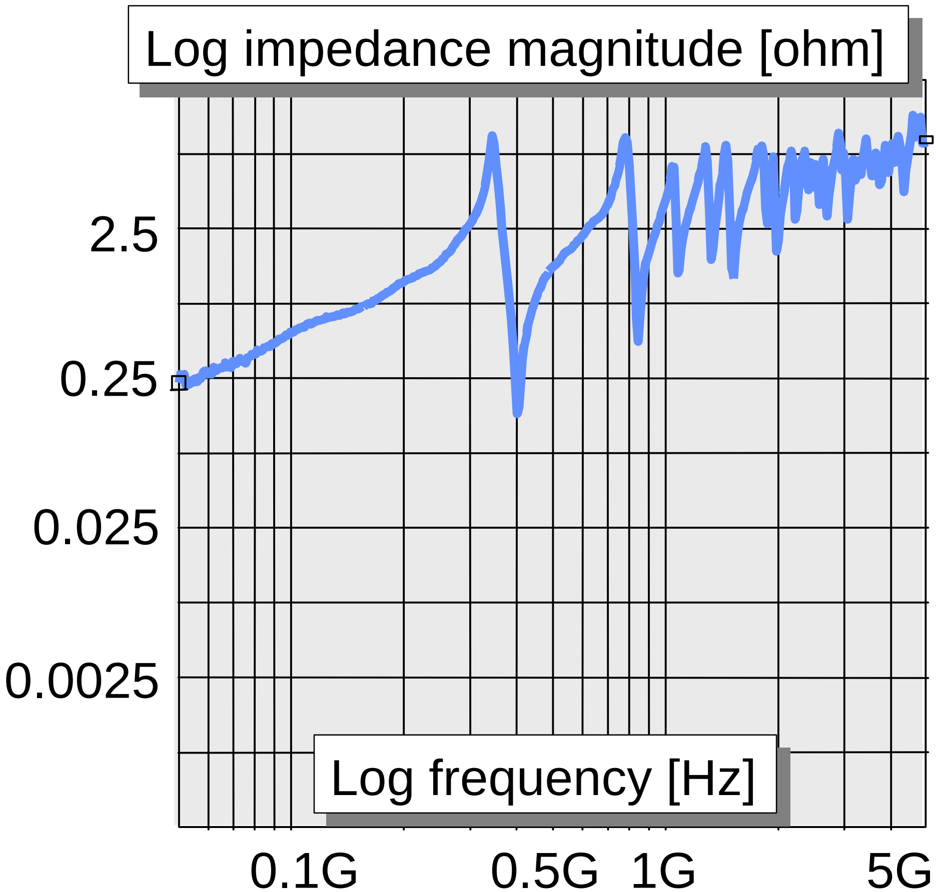
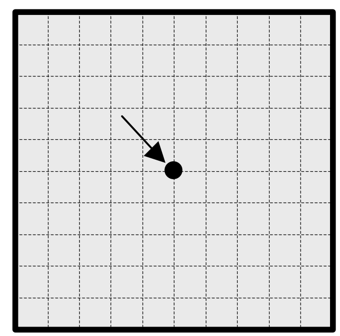
Measured Self Impedance of Bare Board at Center



- 31-mil DUT, edge open
- Dual Semirigid Probe at center of planes



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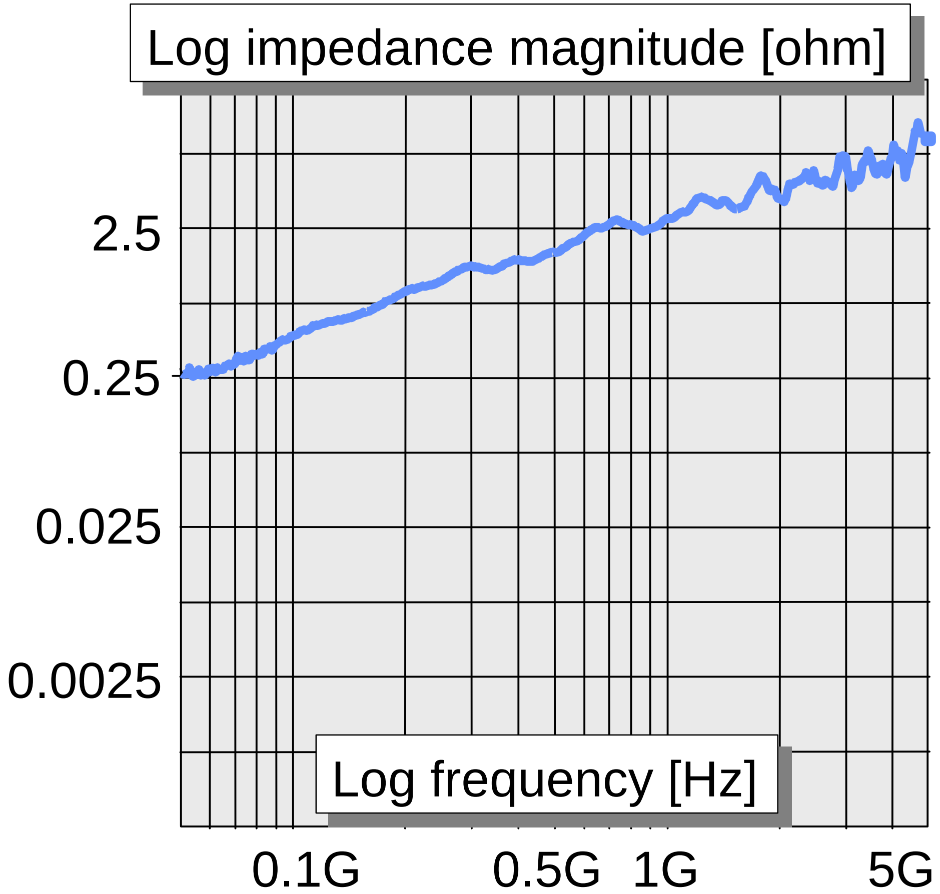
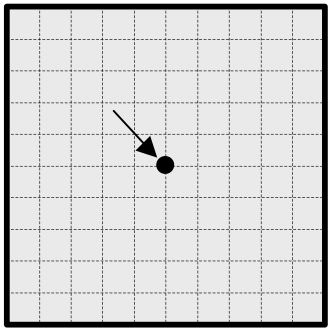
Measured Self Impedance of Board with DET at Center



- 31-mil DUT, edge terminated with 40x5.1 ohms
- Dual Semirigid Probe, at center of planes



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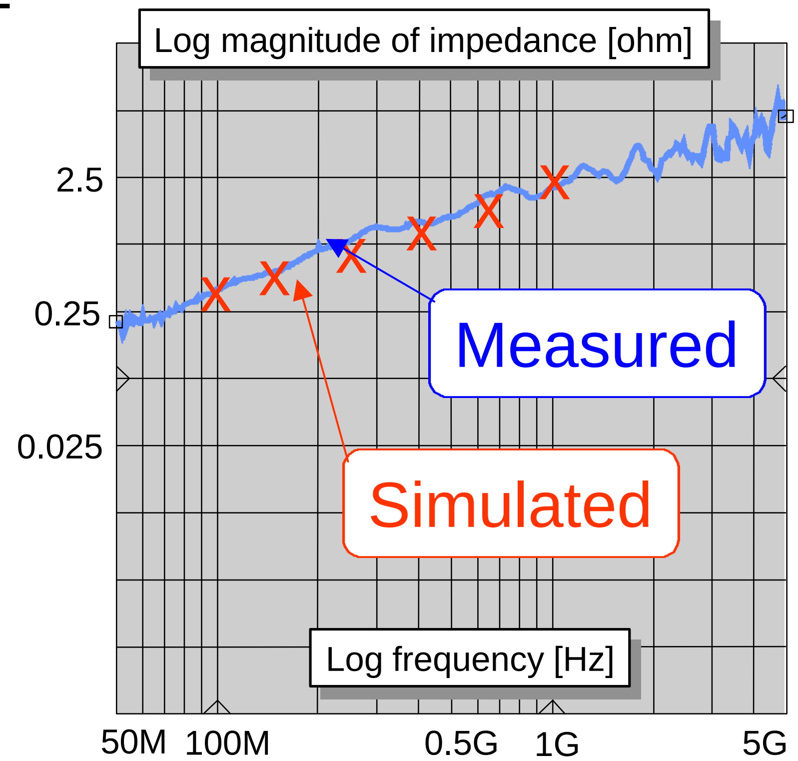
Measured vs. Simulated Self-Impedance of DUT

- 10” x 10” x 31mil FR4 with DET
- Measured with HP8720C VNA
- Simulated with 1-inch grid at center node:

Freq [Hz]	Zmagn[ohm]
1.00E+08	0.3143
1.58E+08	0.4413
2.51E+08	0.6574
3.98E+08	1.233
6.31E+08	1.744
1.00E+09	2.645

Measured at center node



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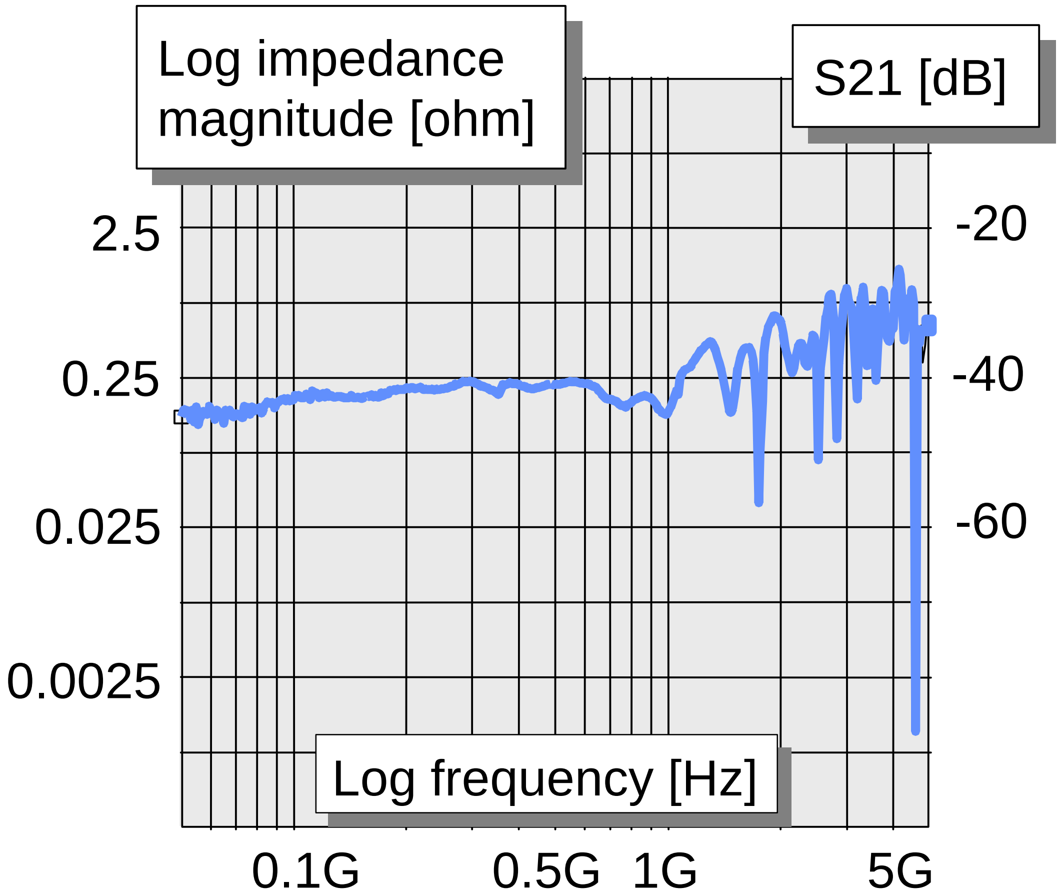
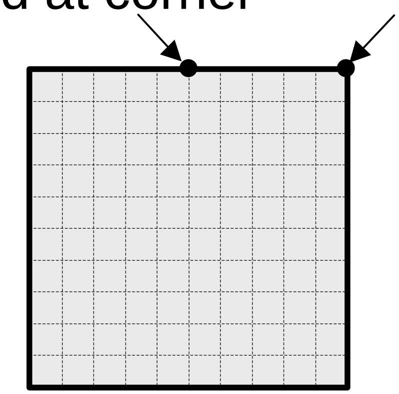
Measured Transfer Impedance



- 31-mil DUT, edge terminated with 40x5.1 ohms
- Two separate semirigid probes, at middle of side and at corner



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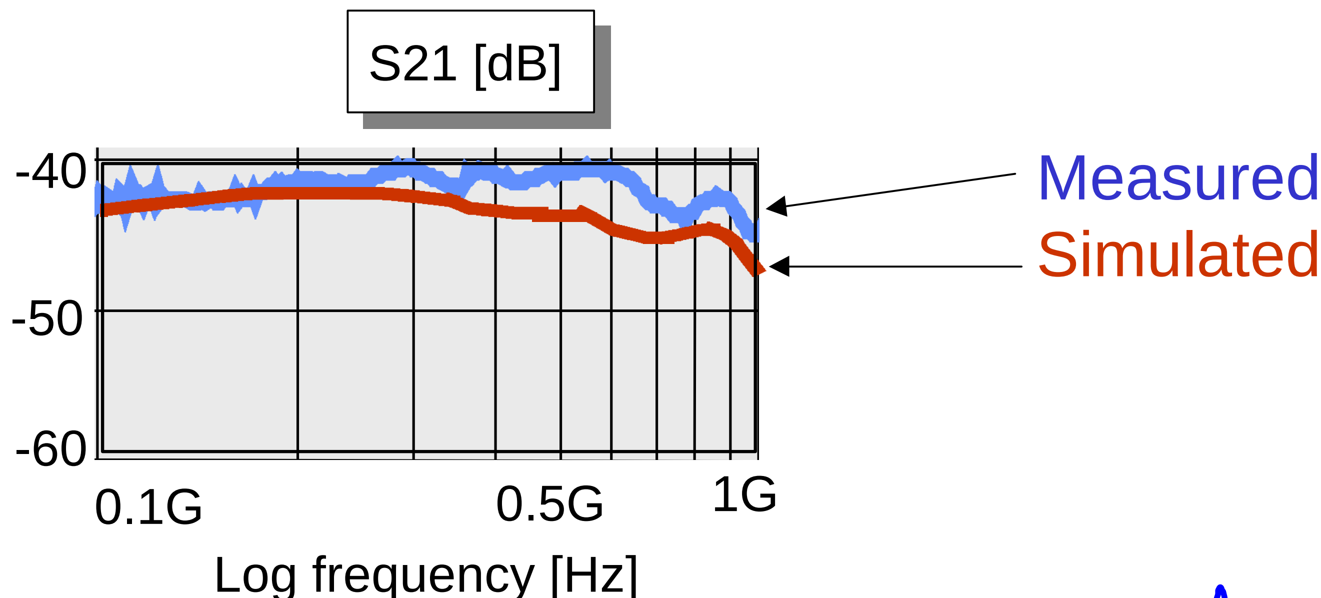
Measured vs. Simulated Transfer Impedance of DUT

Zoomed responses:



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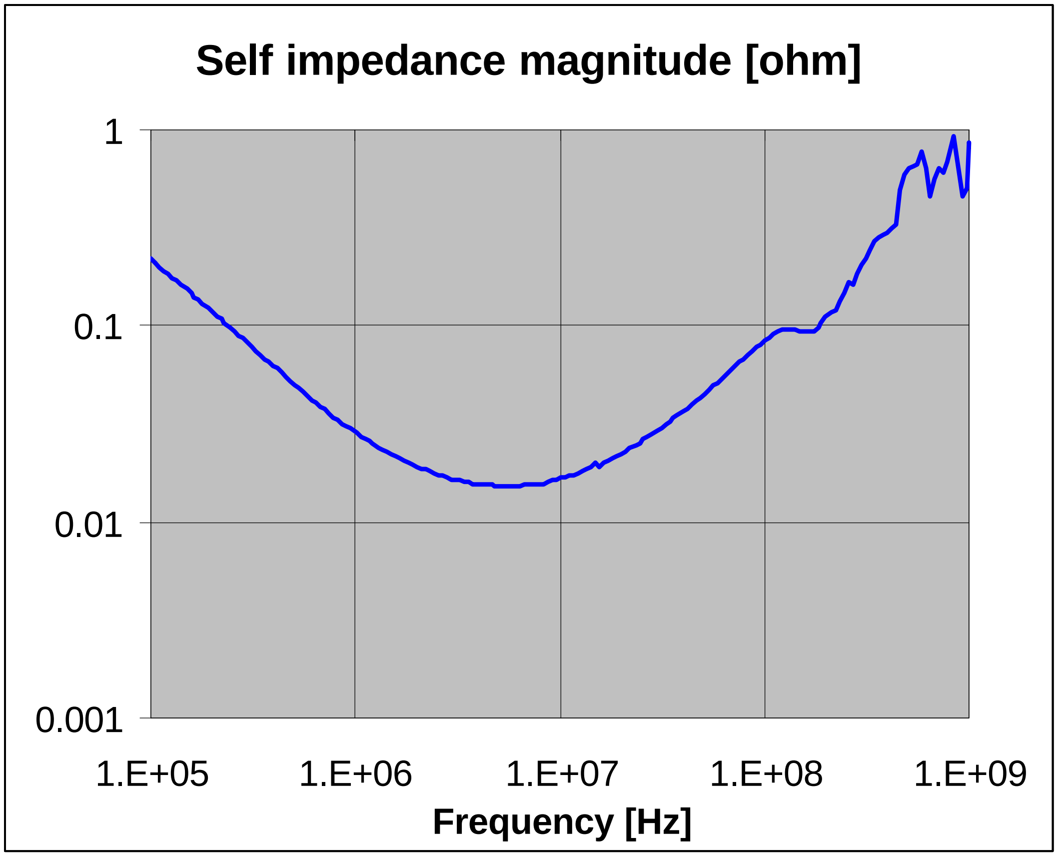
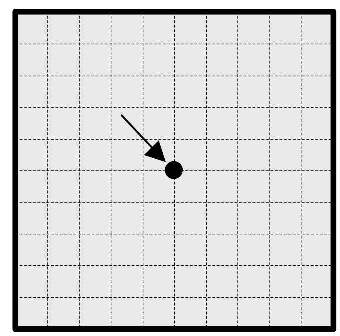
Self Impedance, 2-mil DUT



- 2-mil DUT, edge terminated with 80x(1ohm + 100nF)
- Dual Semirigid Probe, at center of planes



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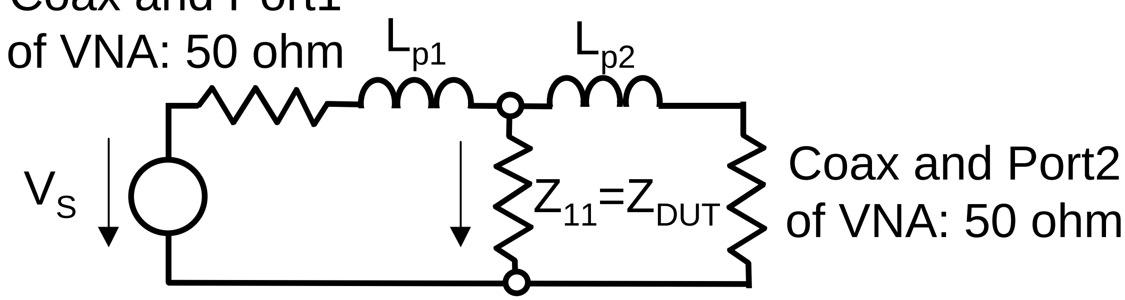
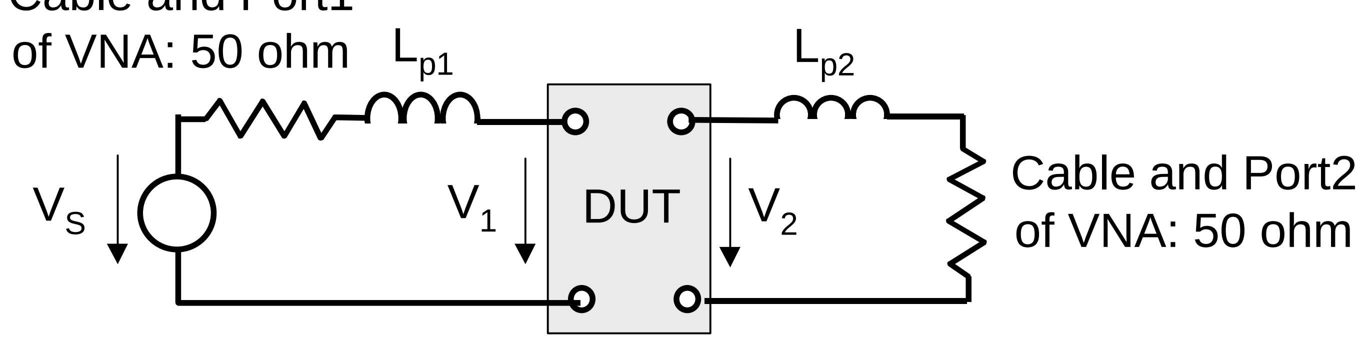
Equivalent Circuit of Probes Connection

Self impedance:



Transfer impedance:



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S_{21} Conversion to Self Impedance

$$Z_{ii} = S_{21}\frac{Z_1}{2}\frac{1}{1-S_{21}\frac{Z_1+Z_2}{2Z_2}} \approx S_{21} * 25 * \frac{1+jwt_p}{1-S_{21}}$$

Where $Z_1 = 50+j\omega L_{p1}$

$Z_2 = 50+j\omega L_{p2}$

$\tau_p = L_p/50$

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S_{21} Conversion to Transfer Impedance

$$Z_{ji} = S_{21}\frac{Z_1}{2}\frac{\left(1+\frac{Z_{11}}{Z_1}\right)\left(1+\frac{Z_{22}}{Z_2}\right)}{1+\frac{S_{21}Z_{21}}{2}\frac{Z_1}{Z_2}} \approx$$

$$S_{21} * 25 * \frac{1+jwt_p}{1+50*\left(\frac{S_{21}}{2}\right)^2} * \left(1+\frac{Z_{11}}{Z_1}\right)\left(1+\frac{Z_{22}}{Z_2}\right)$$

Where $Z_1 = 50+j\omega L_{p1}$

$Z_2 = 50+j\omega L_{p2}$

$\tau_p = L_p/50$

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Recommended Resources

Hewlett Packard Vector Network Analyzers:

- HP 8720 VNA
- HP4396 VNA

Circuit simulator software:

- Avant! HSPICE

Conclusions

- Power-distribution network is characterized by self and transfer impedances
- One-port measurements cannot handle low impedances
- 2-port VNA measurement introduced
- Probes: Dual semirigid coax with soldered pigtail
- Transmission-line grid is used to simulate parallel planes
- Good agreement between measured and simulated self and transfer impedances was found

References

[1] Dale Becker, Larry Smith, "Power Distribution Design for High Performance Systems," Short course at the 1998 Topical Meeting on Electrical Performance of Electronic Packaging, October 26-28, 1998, West Point, NY

[2] Understanding the Fundamental Principles of Vector Network Analysis, Hewlett Packard Application Note 1287-1.

[3] I. Novak, "Reducing Simultaneous Switching Noise and EMI on Ground/Power Planes by Dissipative Edge Termination," Proceedings of the 1998 Topical Meeting on Electrical Performance of Electronic Packaging, October 26-28, 1998, West Point, NY, pp.181-184.

[4] E. Leroux, Peter Bajor, "Modeling of Power Planes for Electrical Simulations," Proceedings of the 1996 Wroclaw EMC Symposium, June 25-28, 1996.

[5] Henry Wu, Jeffrey Meyer, Ken Lee, Alan Barber, "Accurate Power Supply and Ground Plane Pair Models," Proceedings of the 1998 Topical Meeting on Electrical Performance of Electronic Packaging, October 26-28, 1998, West Point, NY, pp.163-166.

[6] Personal communications with Rich Hoft, Hewlett Packard, Burlington, MA.