Measuring Milliohms and PicoHenrys in Power Distribution Networks

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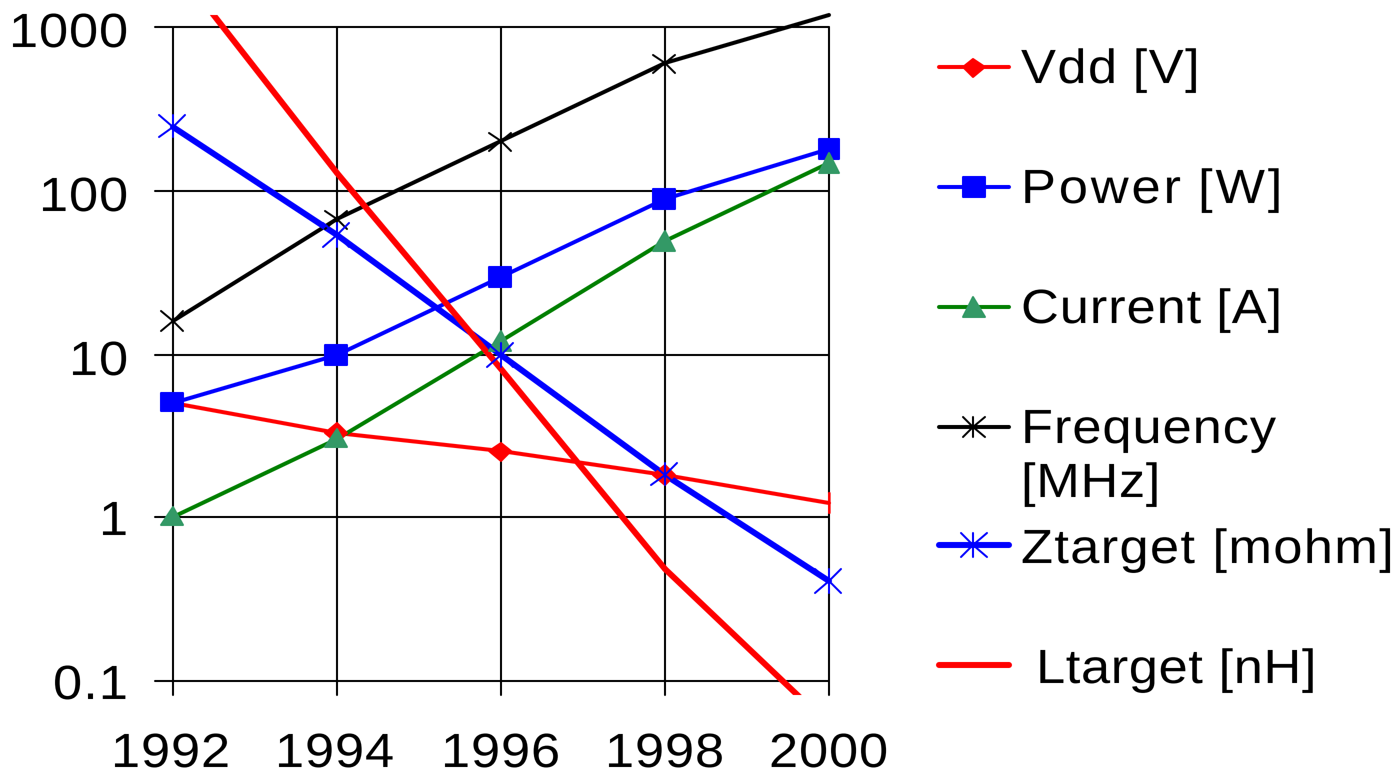
Outline

- Introduction
- Two-port VNA impedance measurements
- Low-frequency limitations
- Enhancement with transformer or amplifier
- High-frequency limitations
- Enhancement with ferrite-covered cable
- Measured power-distribution networks
- Resources
- References

Requirements in Power Distribution



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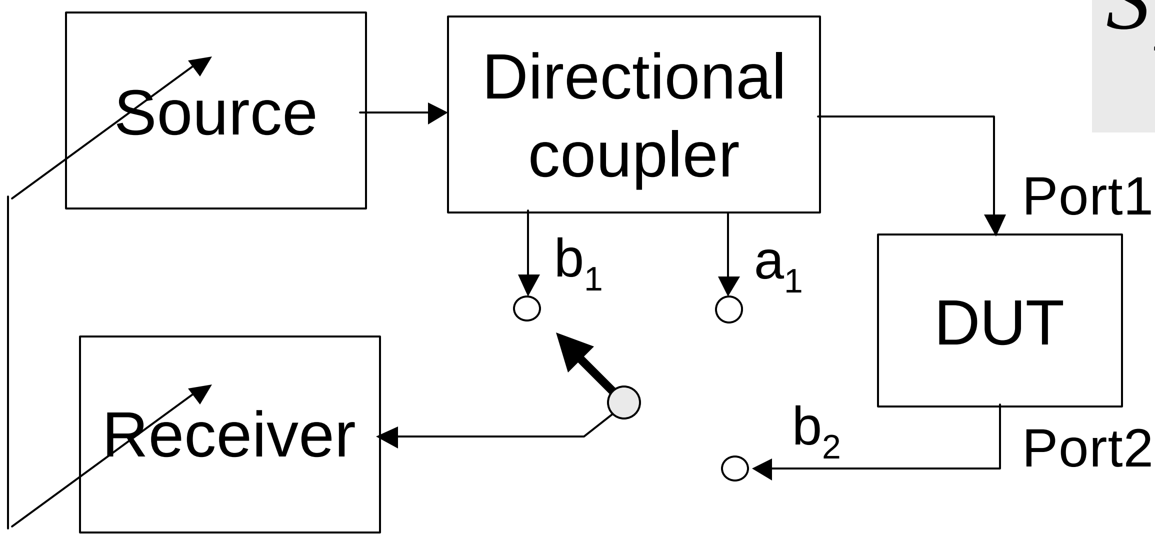
What is a VNA

- 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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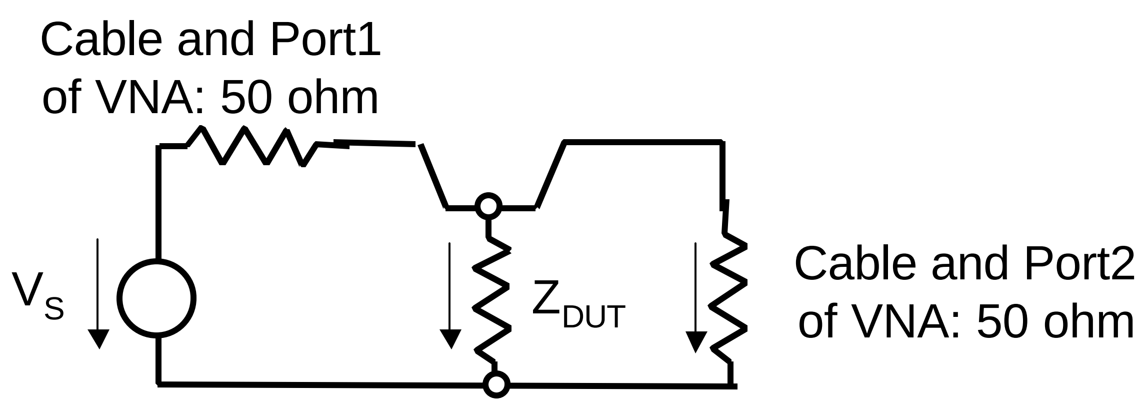
Two-Port Self-Impedance Measurement

- 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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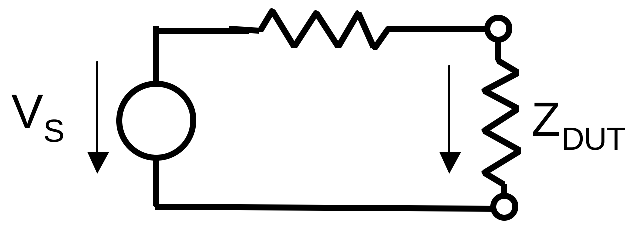
Two-Port Self-Impedance Reading

First-order calculation:

Assume that

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

Port1 and Port 2 of VNA: 25 ohm



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

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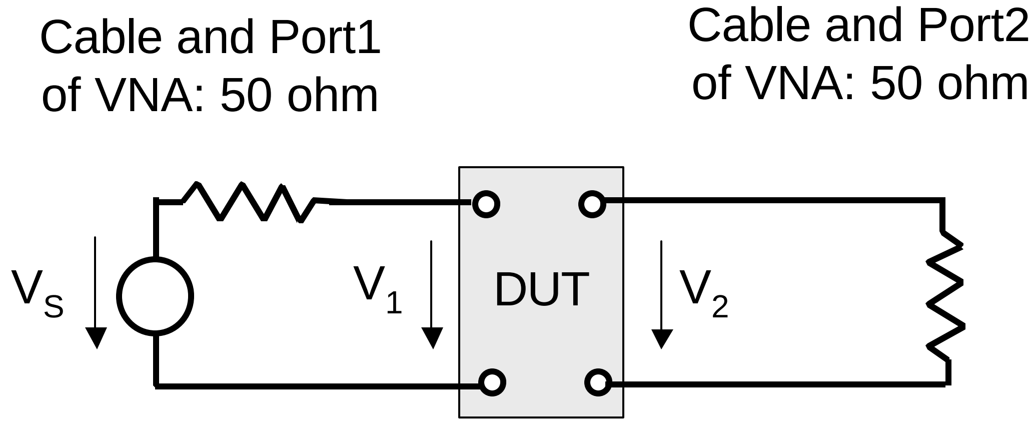
Transfer Impedance Measurement



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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 $|S_{21}|$ > -60dB range

  <3dB in the $|S_{21}|$ > -70dB range

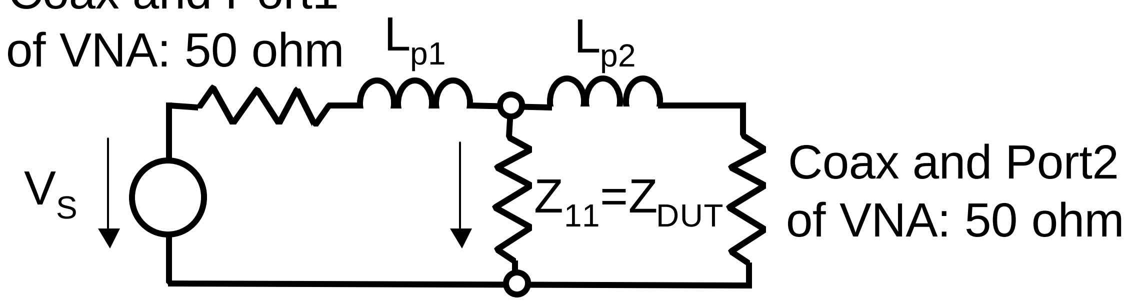
- Impedance uncertainty:

  1dB (10%) for Z_{DUT} > 25milliohms

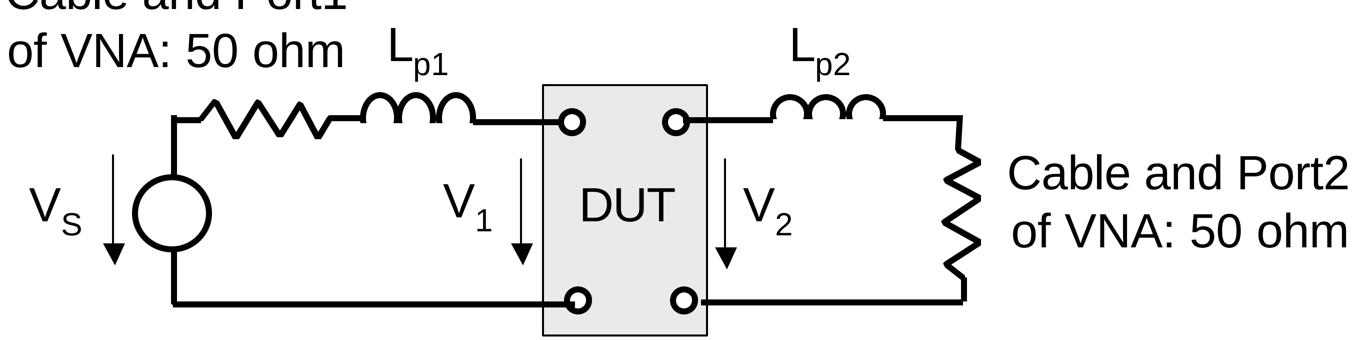
  3dB (40%) for Z_{DUT} > 8milliohms

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

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

$\tau_p = L_p/50$

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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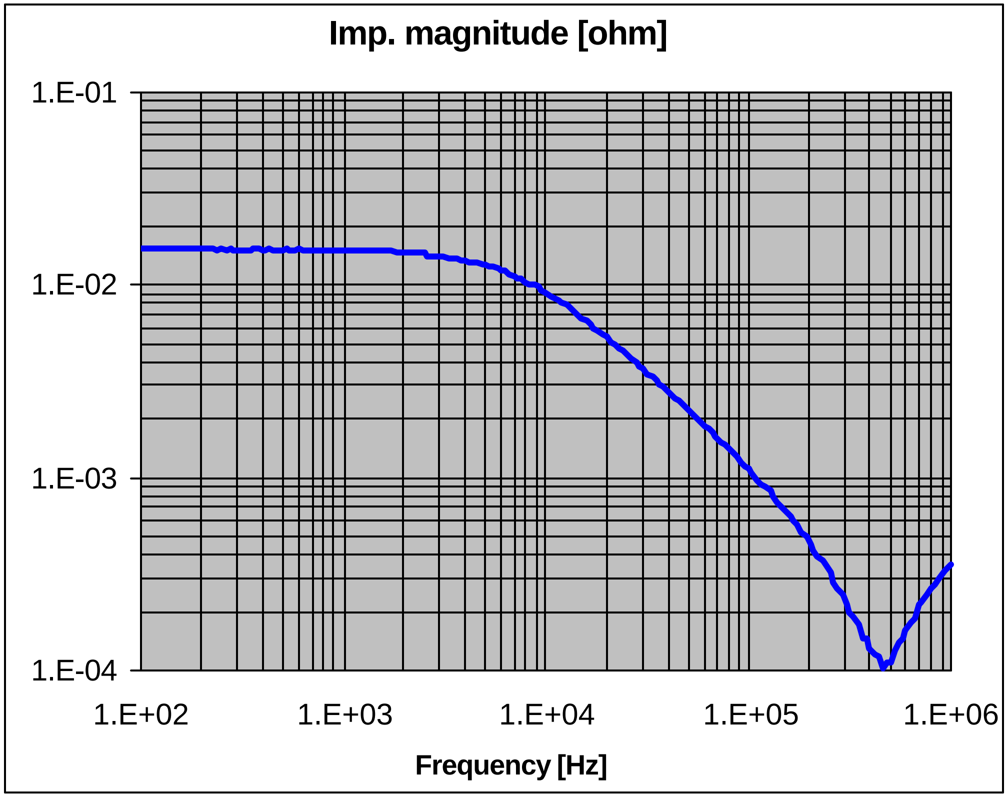
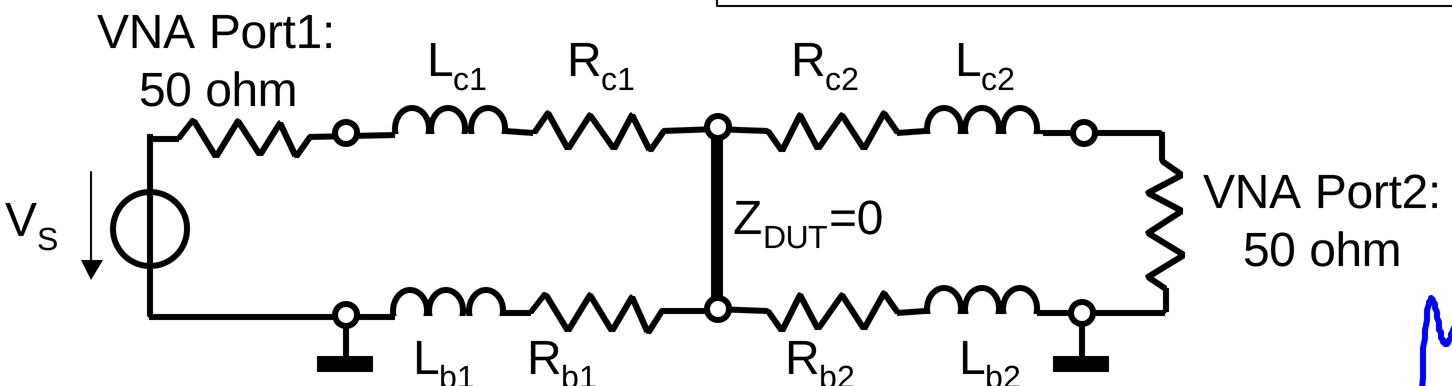
Low-Frequency Ground Loop





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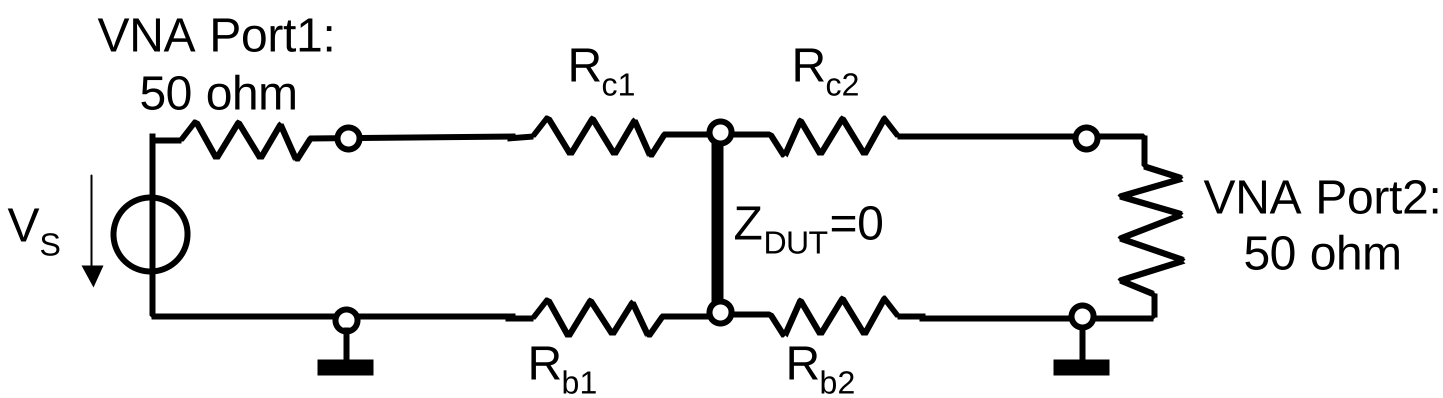
Ground-Loop DC Error

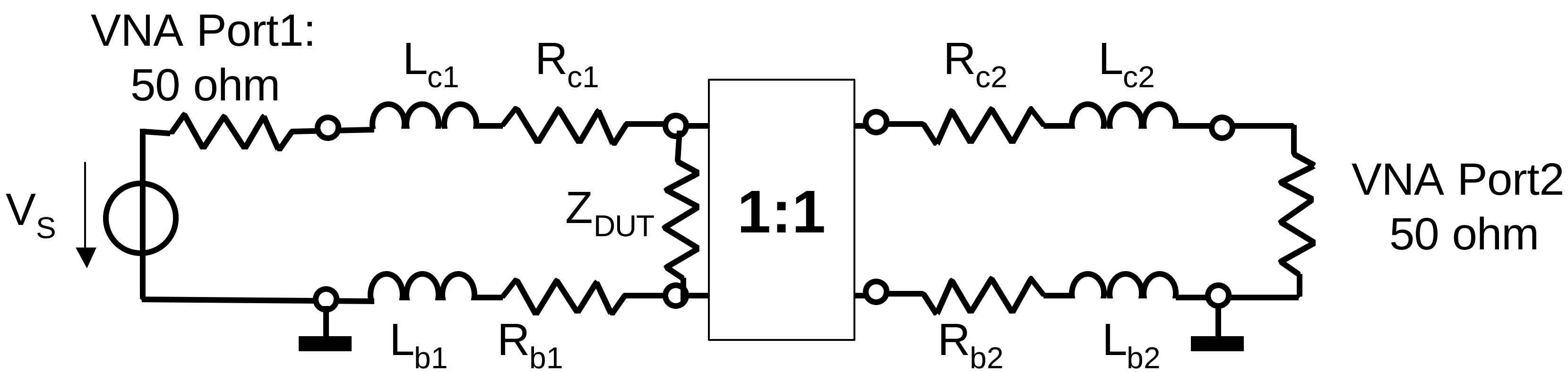
$$R_{DC\_error} = R_{b1} \parallel R_{b2}$$



Eliminating Ground Loop

Transformer

Differential amplifier



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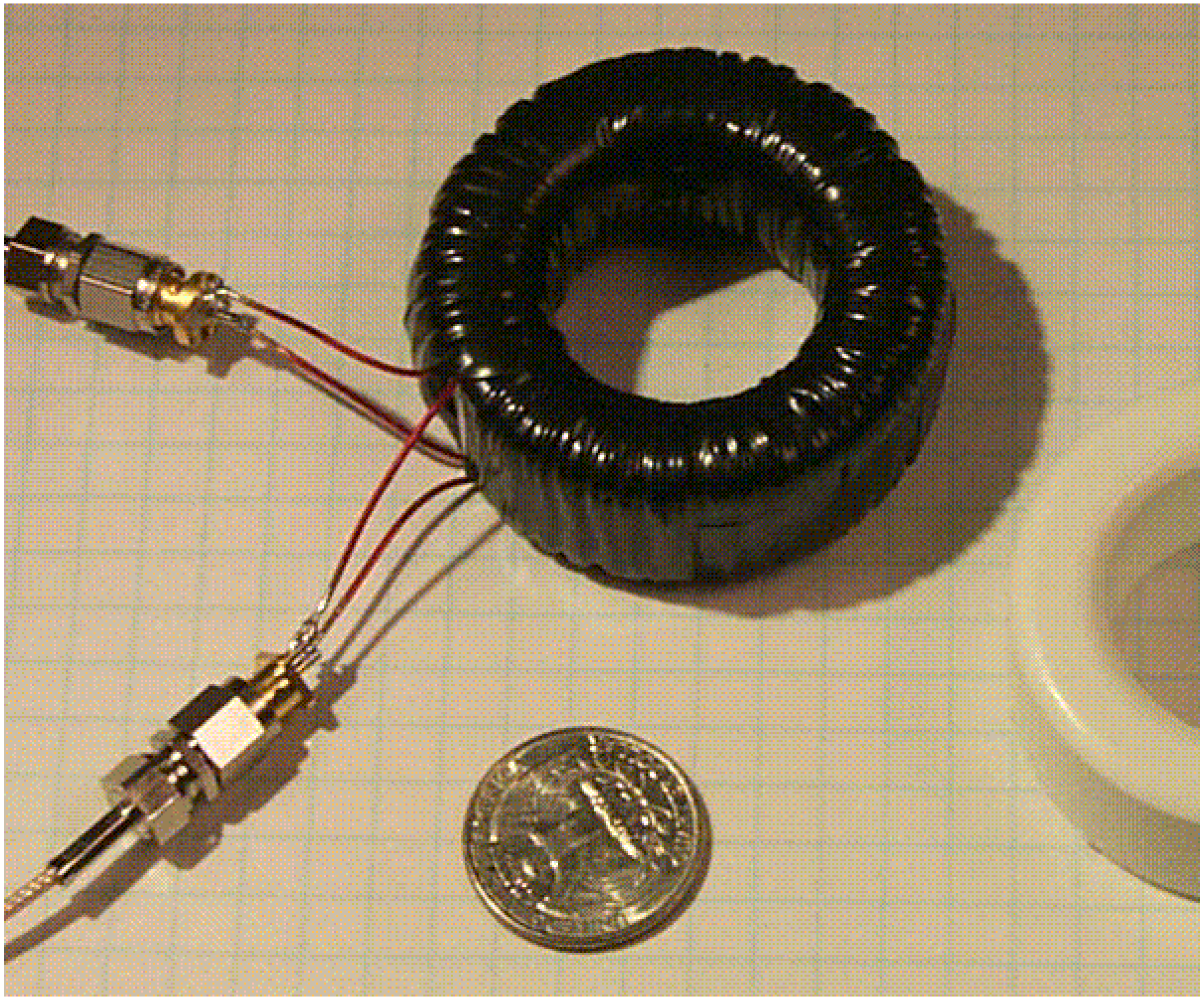
Transformer



Phillips core:
TX51/32/19-3F3

- Diameter: 52mm
- 2x50 turns
- AWG 20
- bifilar
- SMA female

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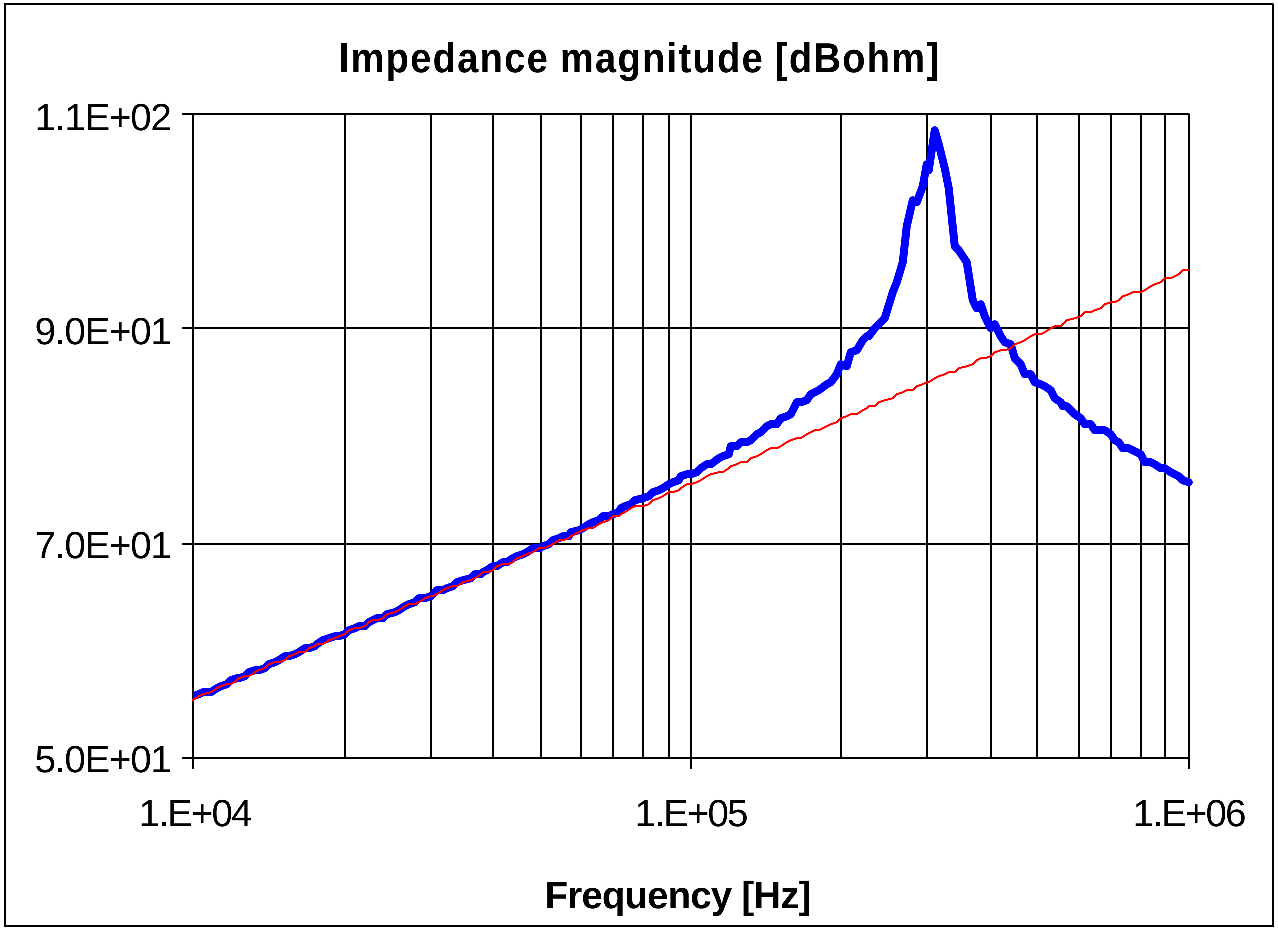
Transformer Impedance



- HP4395B
- HP87512A
- Open secondary
- L_{main}=9.5mH

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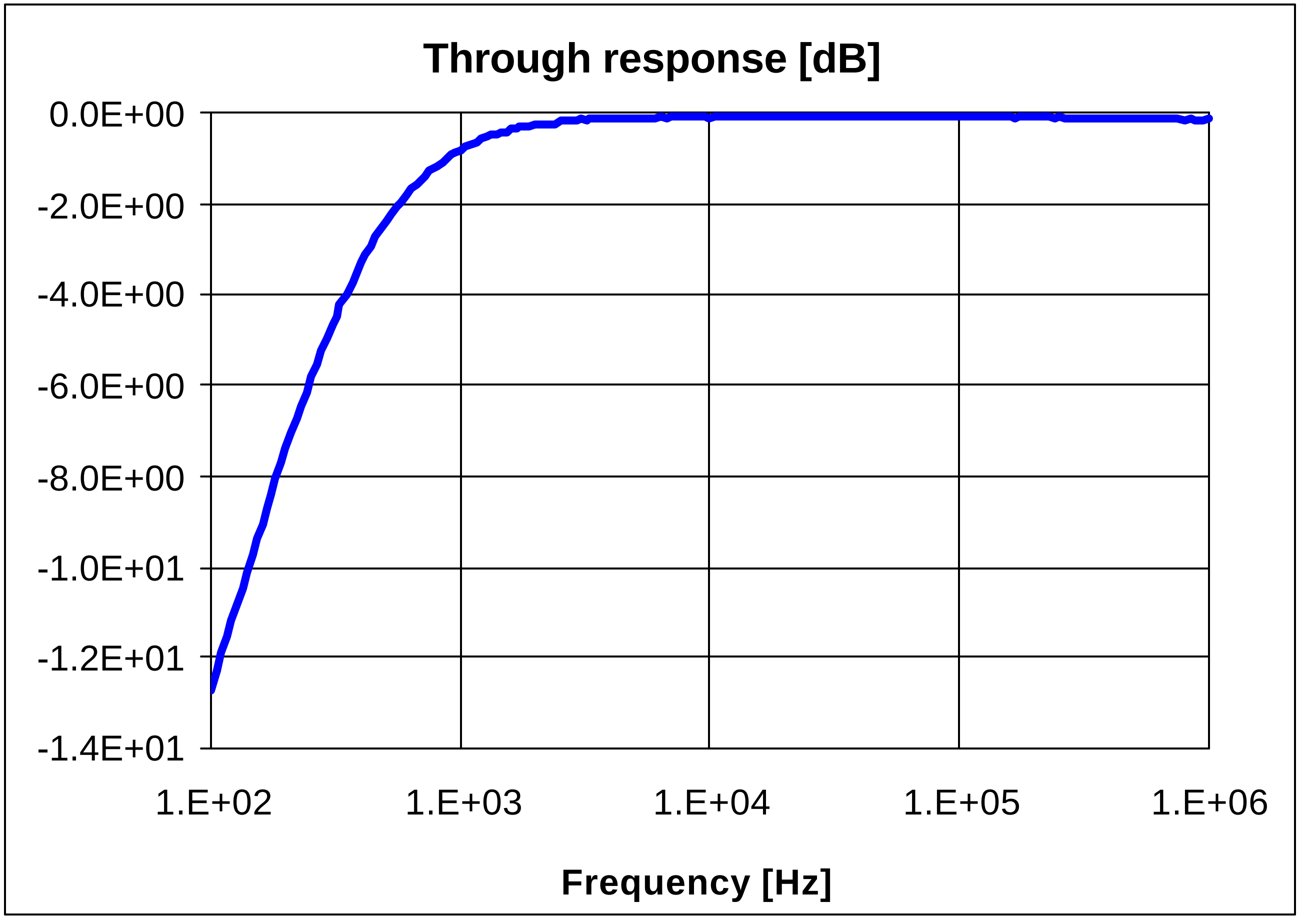
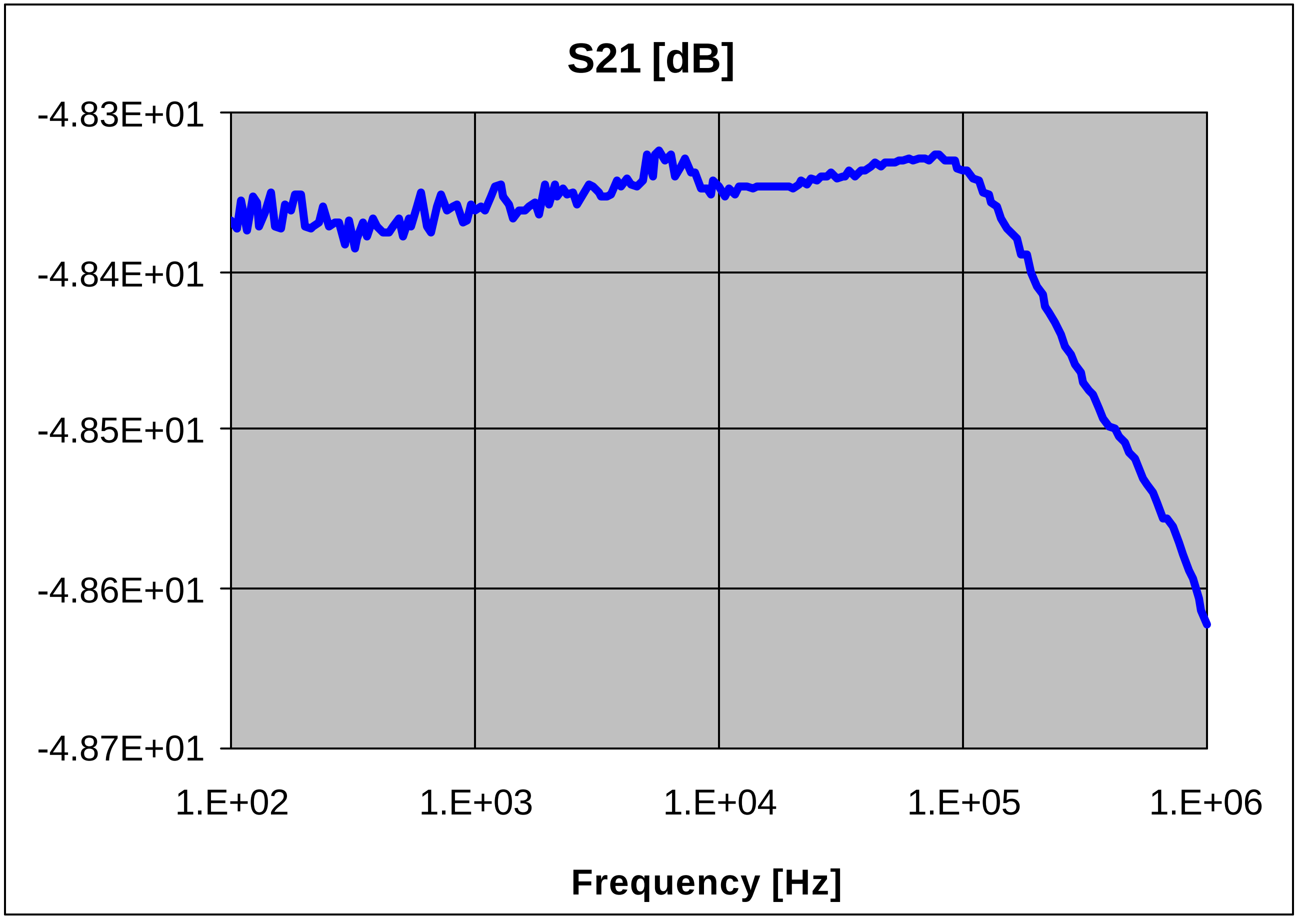
Transformer Response (1)



- 1:1 transformer
- HP4395B
- 50 ohms terminations

Transformer Response (2)



- 1:1 transformer
- HP4395B
- Calibrated with 50 ohms terminations
- 0.1 ohms shunt

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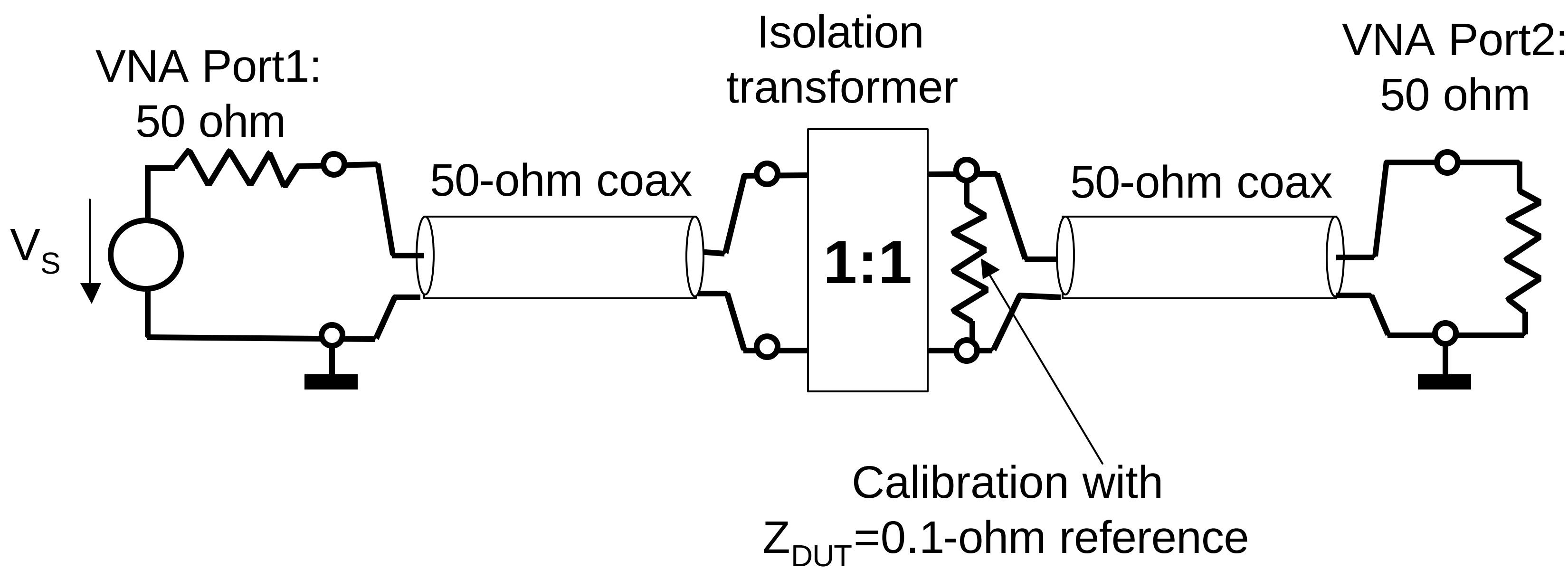
Calibration Setup



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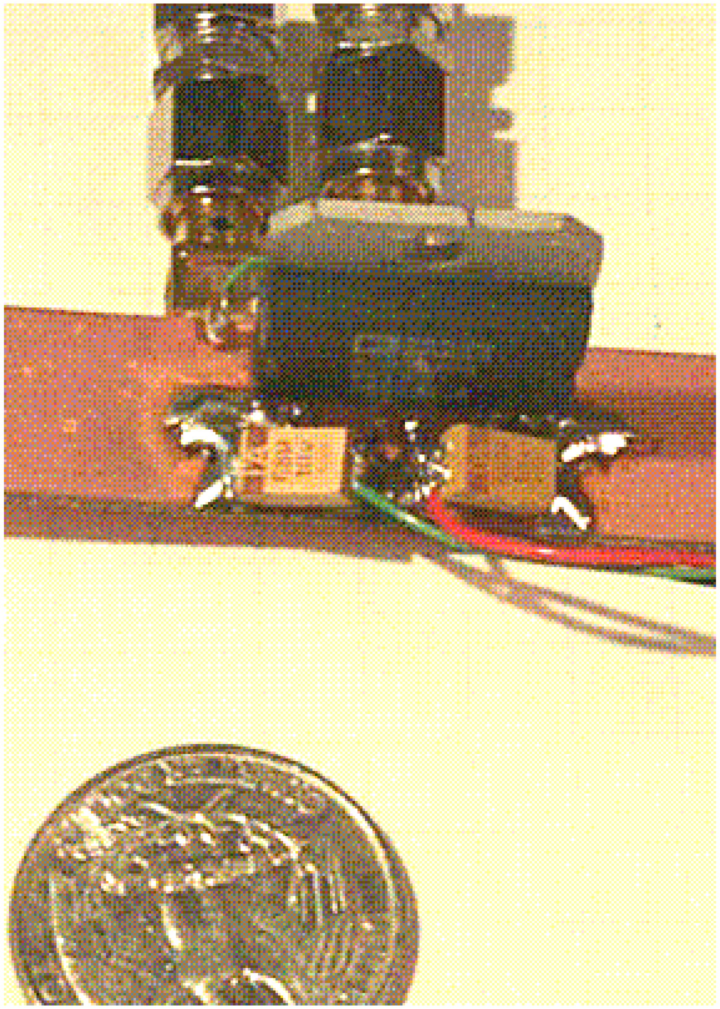
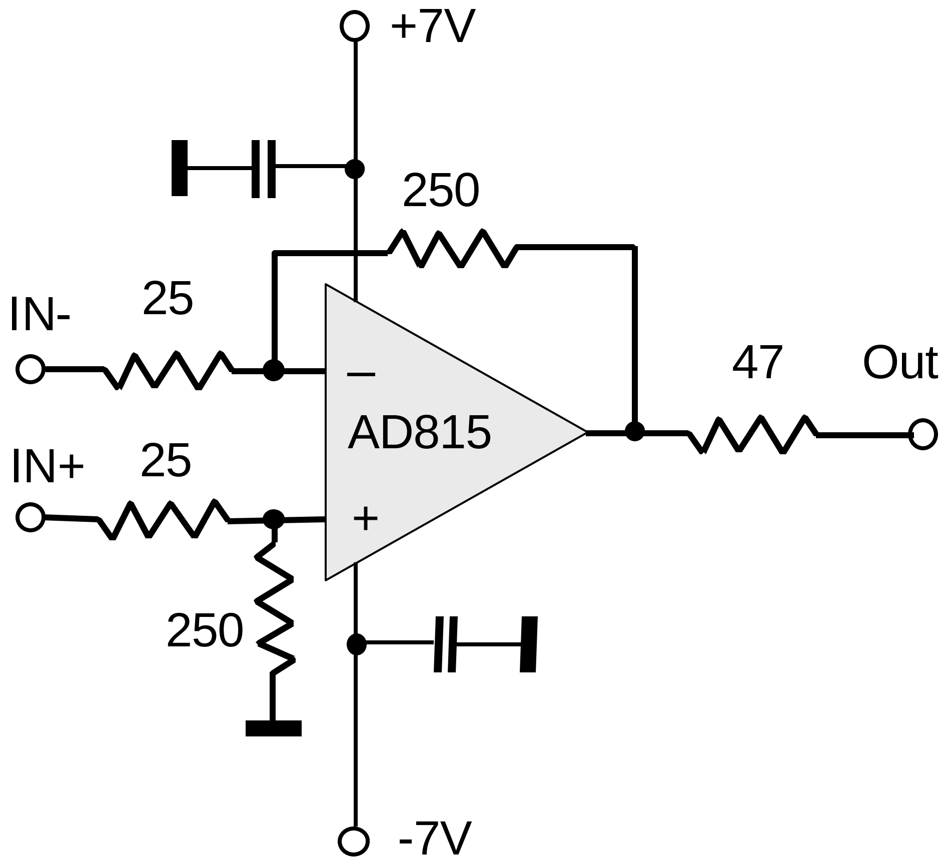
Isolation Amplifier





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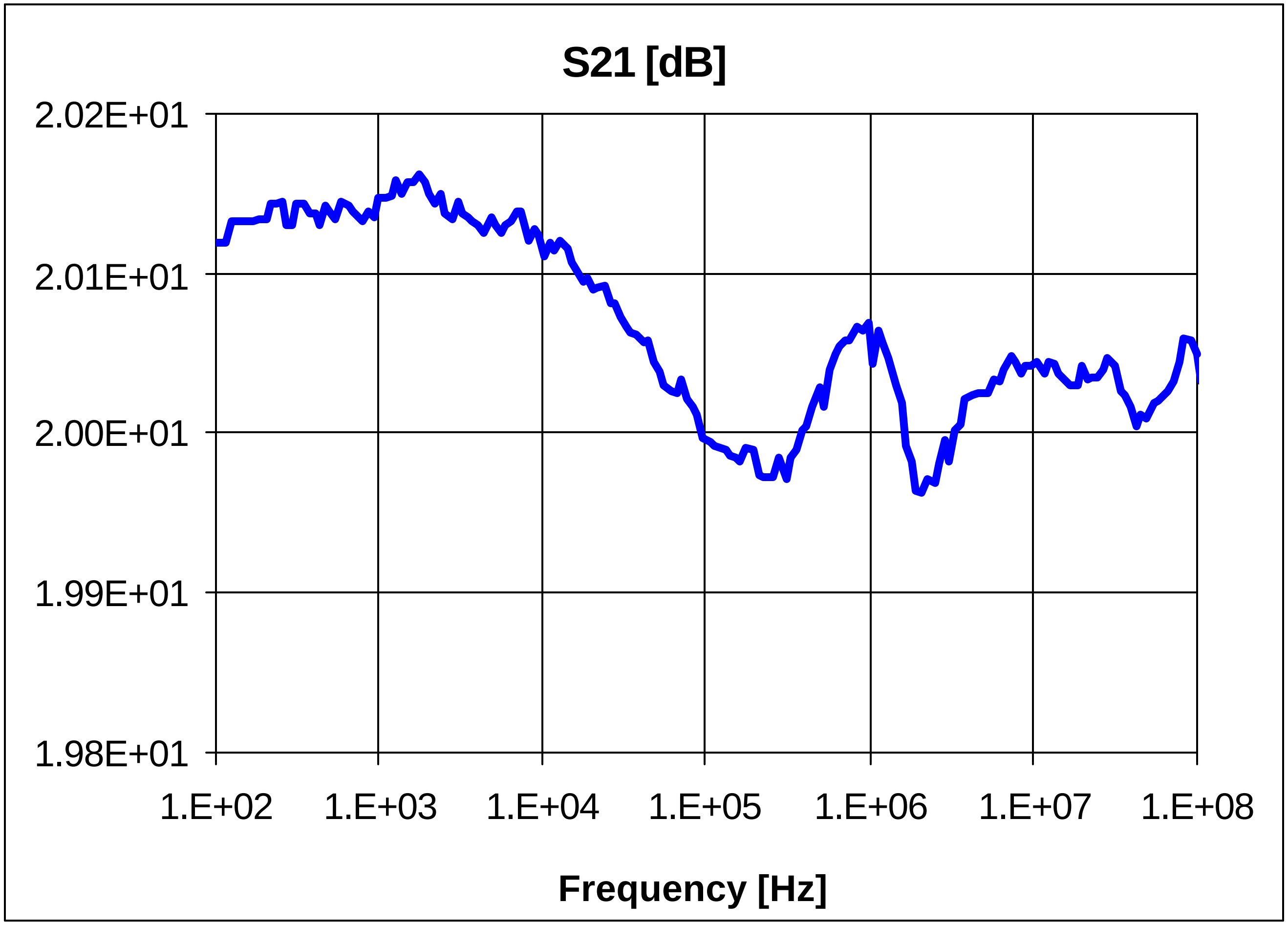
Reduced Error Floor by Increased P



- Calibration at –5dBm
- HP4395B
- Power changed to +15dBm

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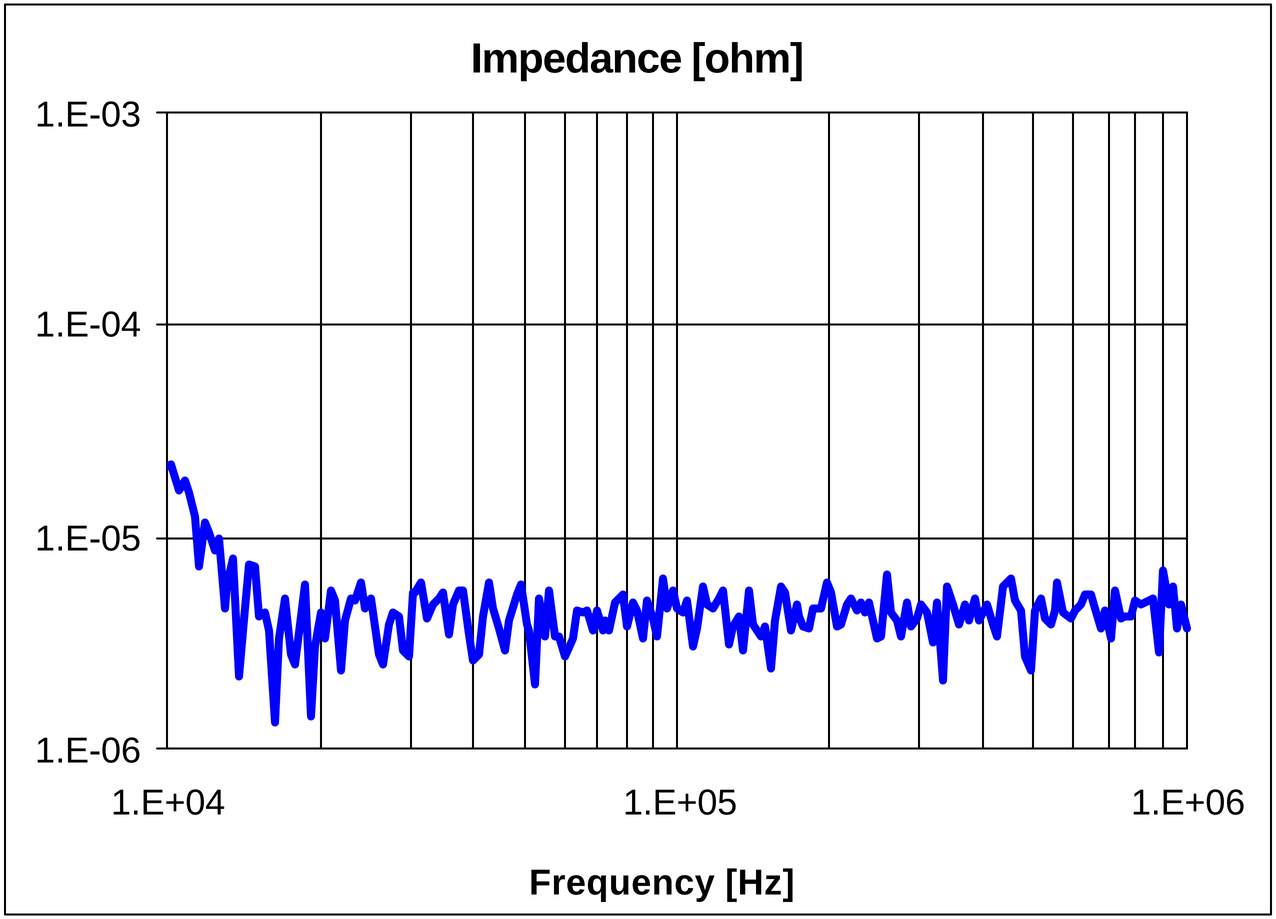
Residual Noise



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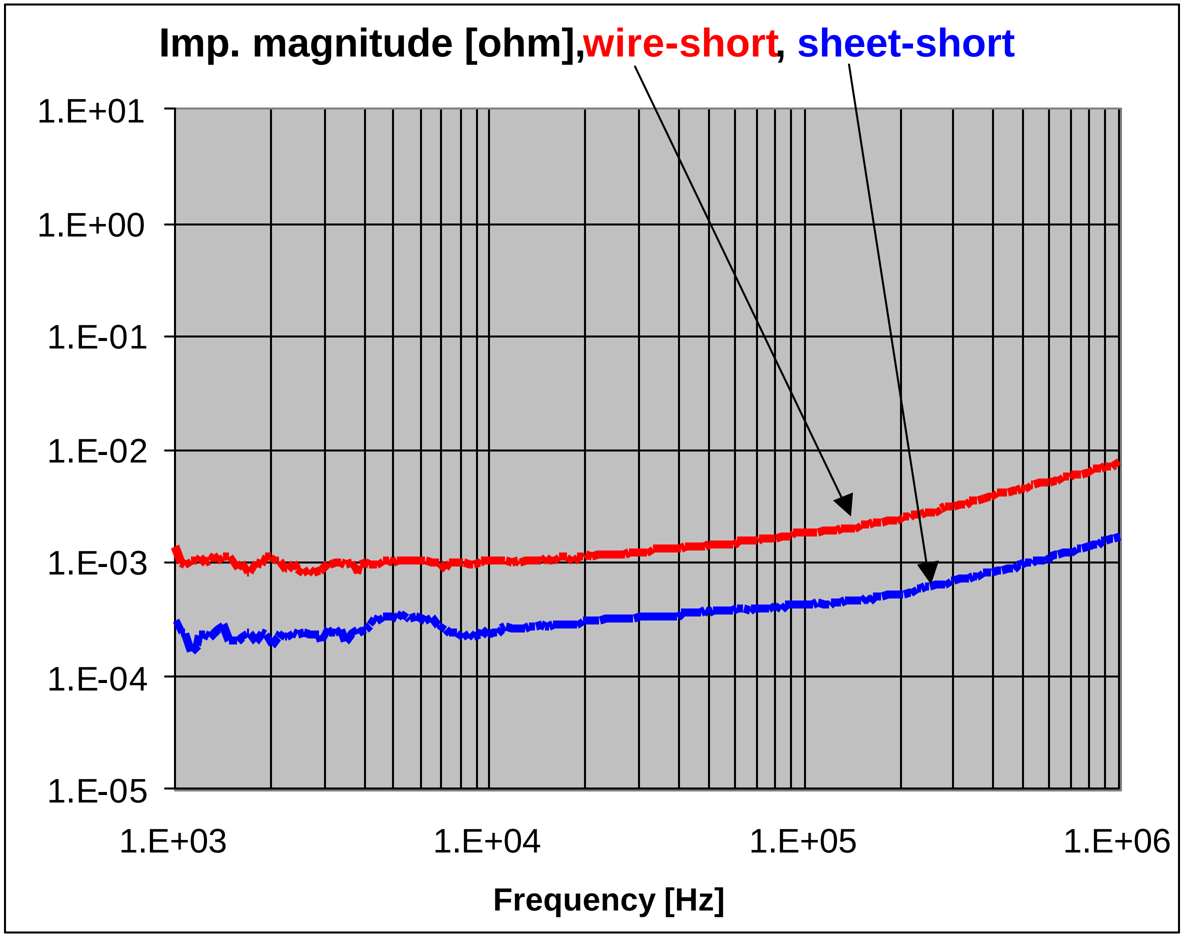
Reading of Shorts



- Isolation transformer
- HP4395B

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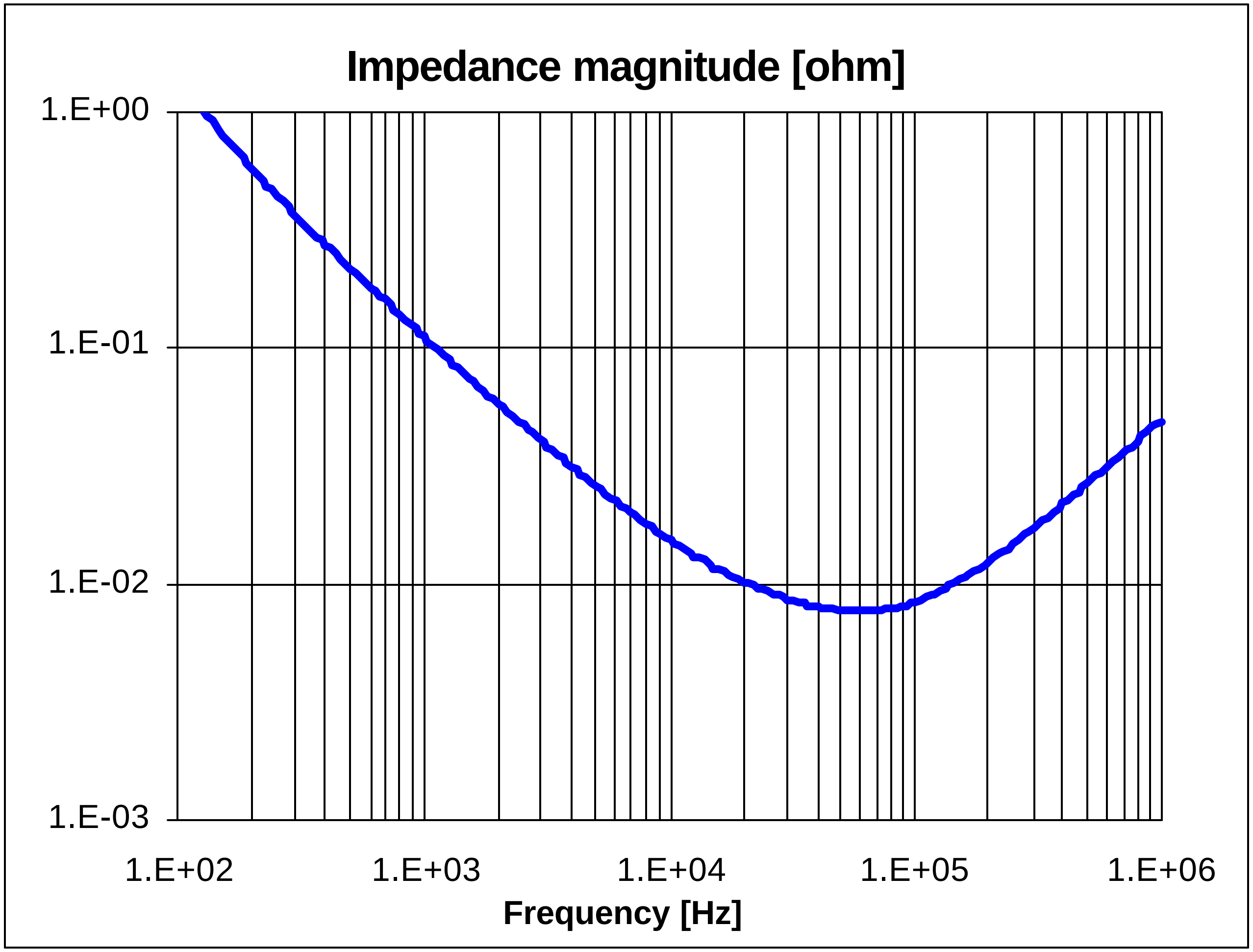
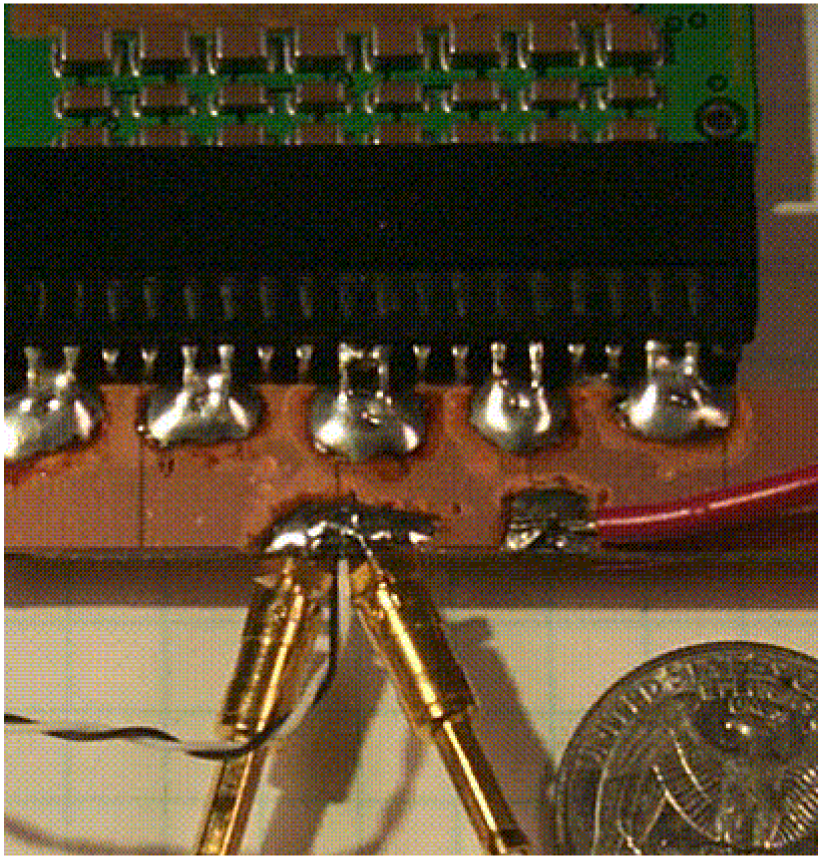
Measuring Low ESR



- 1:1 transformer
- HP4395B
- 0.1ohm calibration
- OSCON 1500uF 4V

Voltage Regulator Module



- 1.5V VRM
- Output pins connected by copper planes
- SSMB connectors

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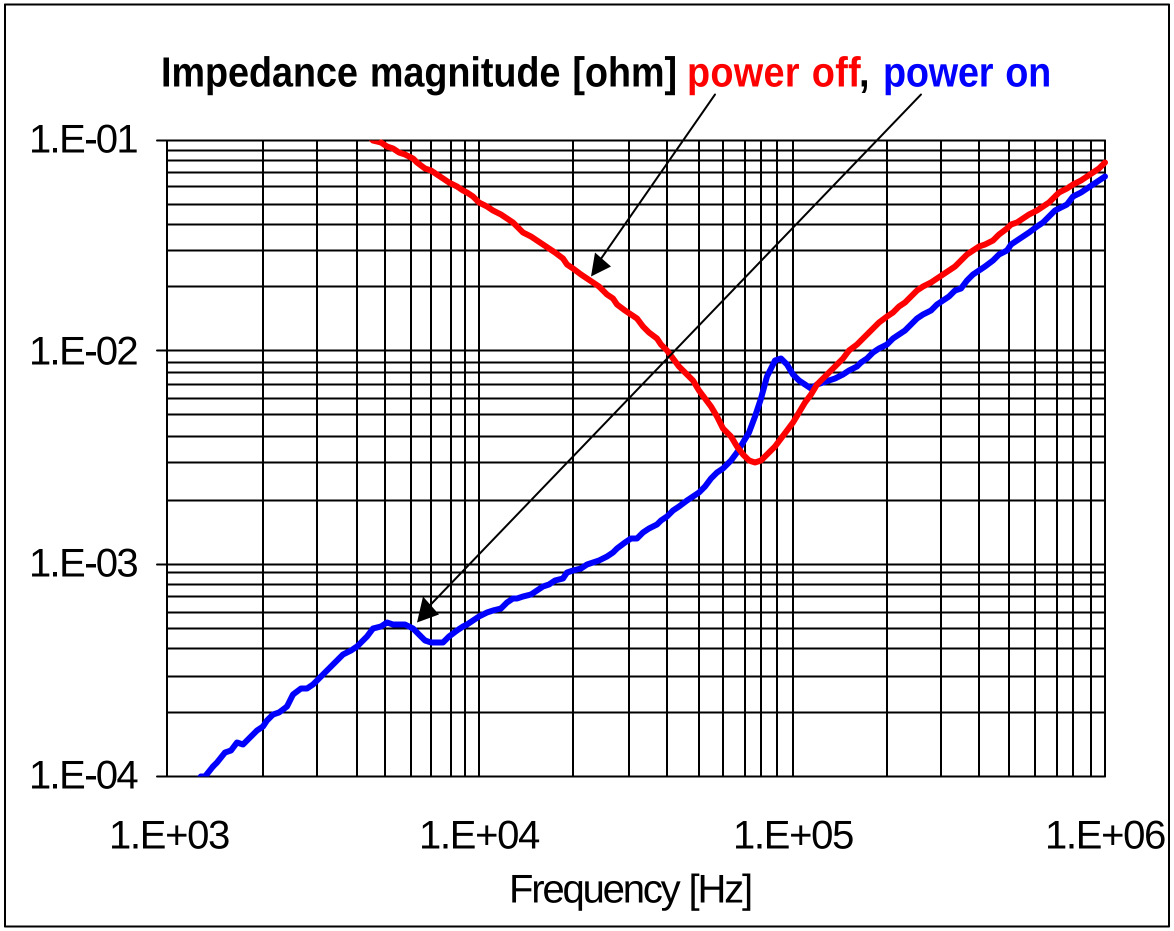
VRM Zout



- 1.5V VRM
- No external capacitor

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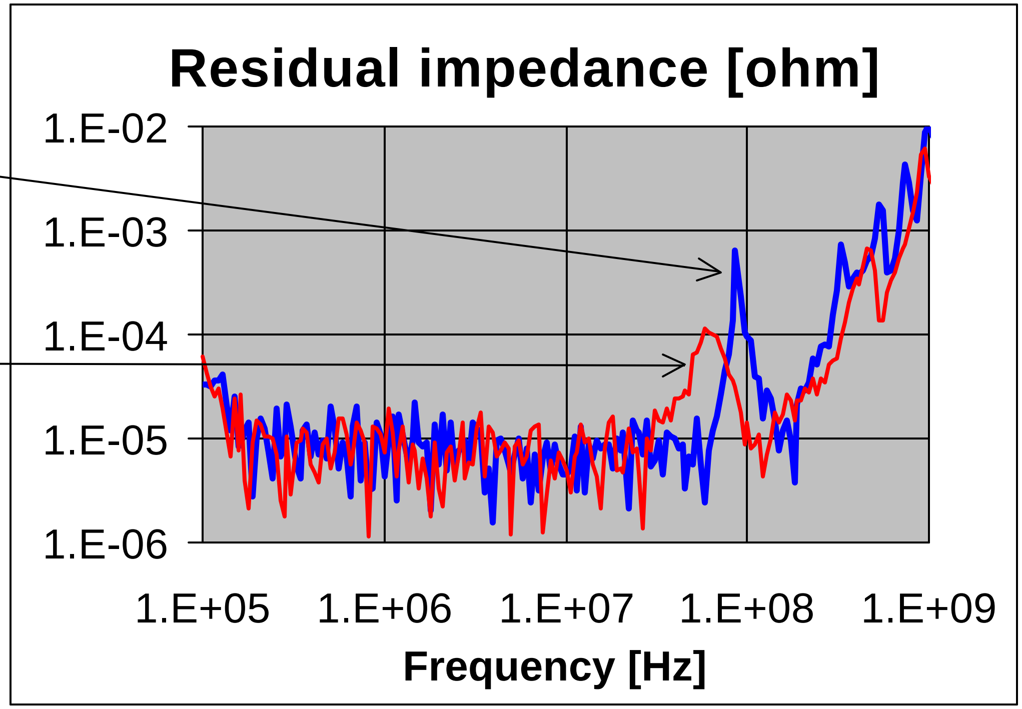
Limitations at High Frequencies

Finite braid surface transfer impedance

Braid resonances

Plain coax

Coax, 2x4 ferrites



Solution:

Absorption ferrites

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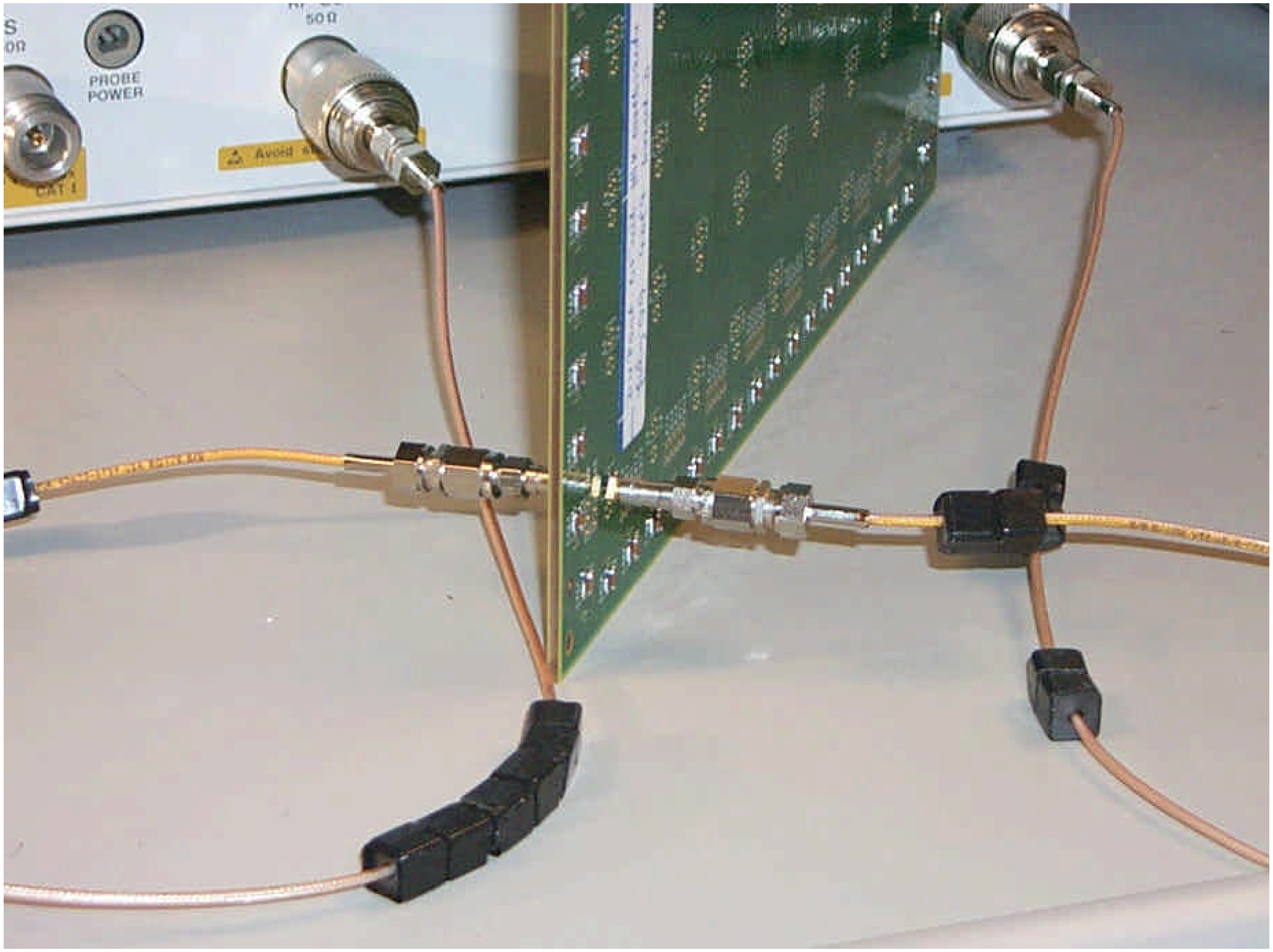
Ferrite-Covered Cable



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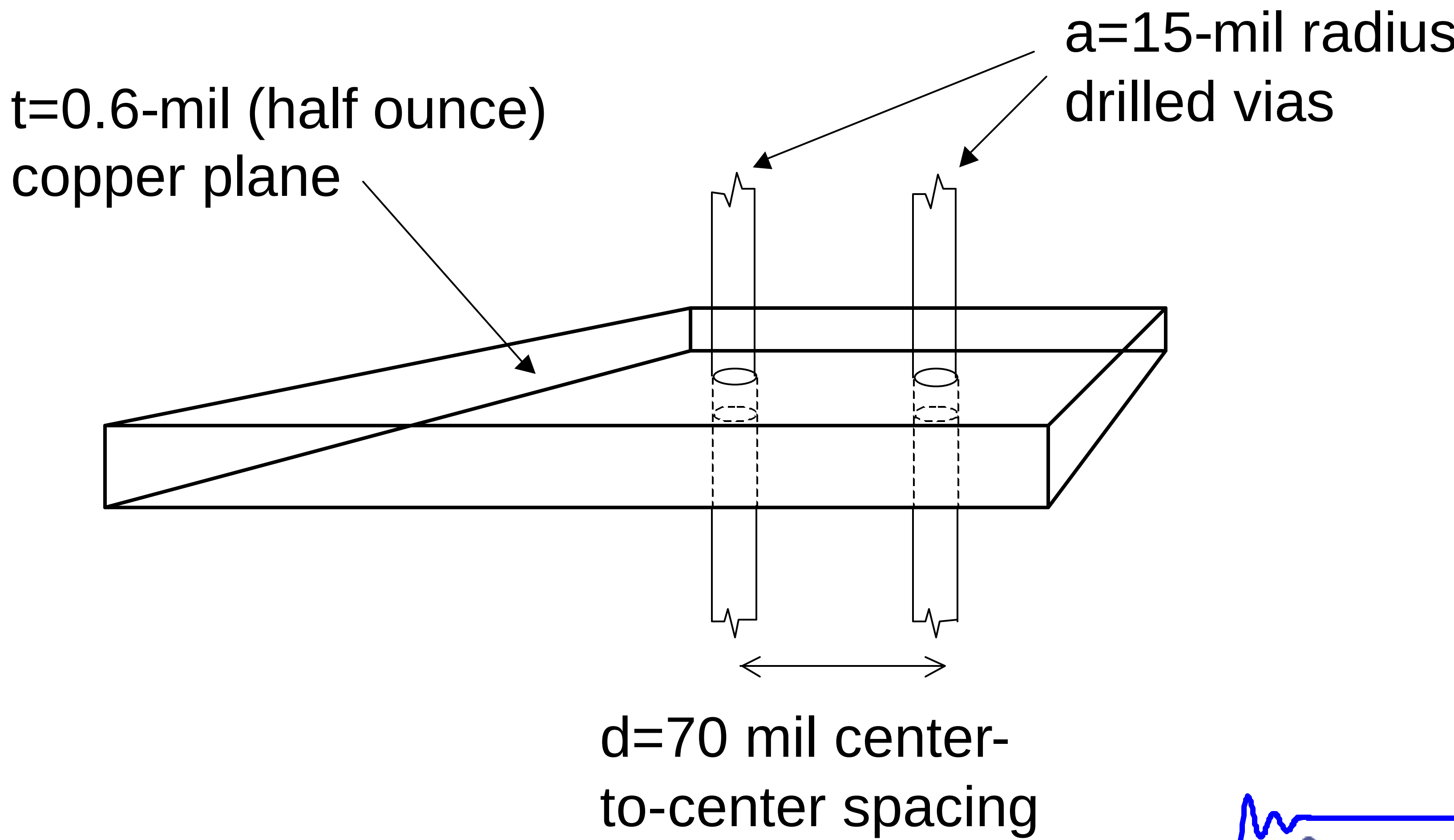
Reference: Connection to Solid Plane



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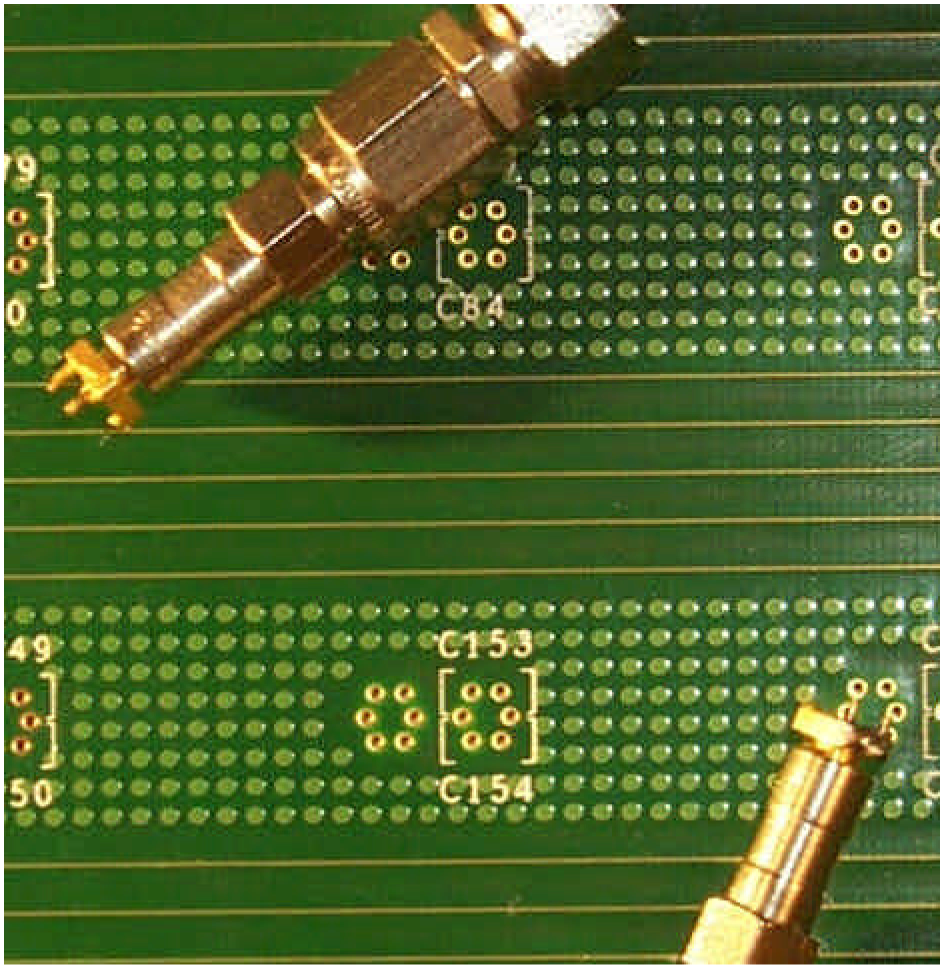
Probes and Vias



- Test board with via locations
- SMA-SSMB adaptors
- Probe: SSMB jack with two pins

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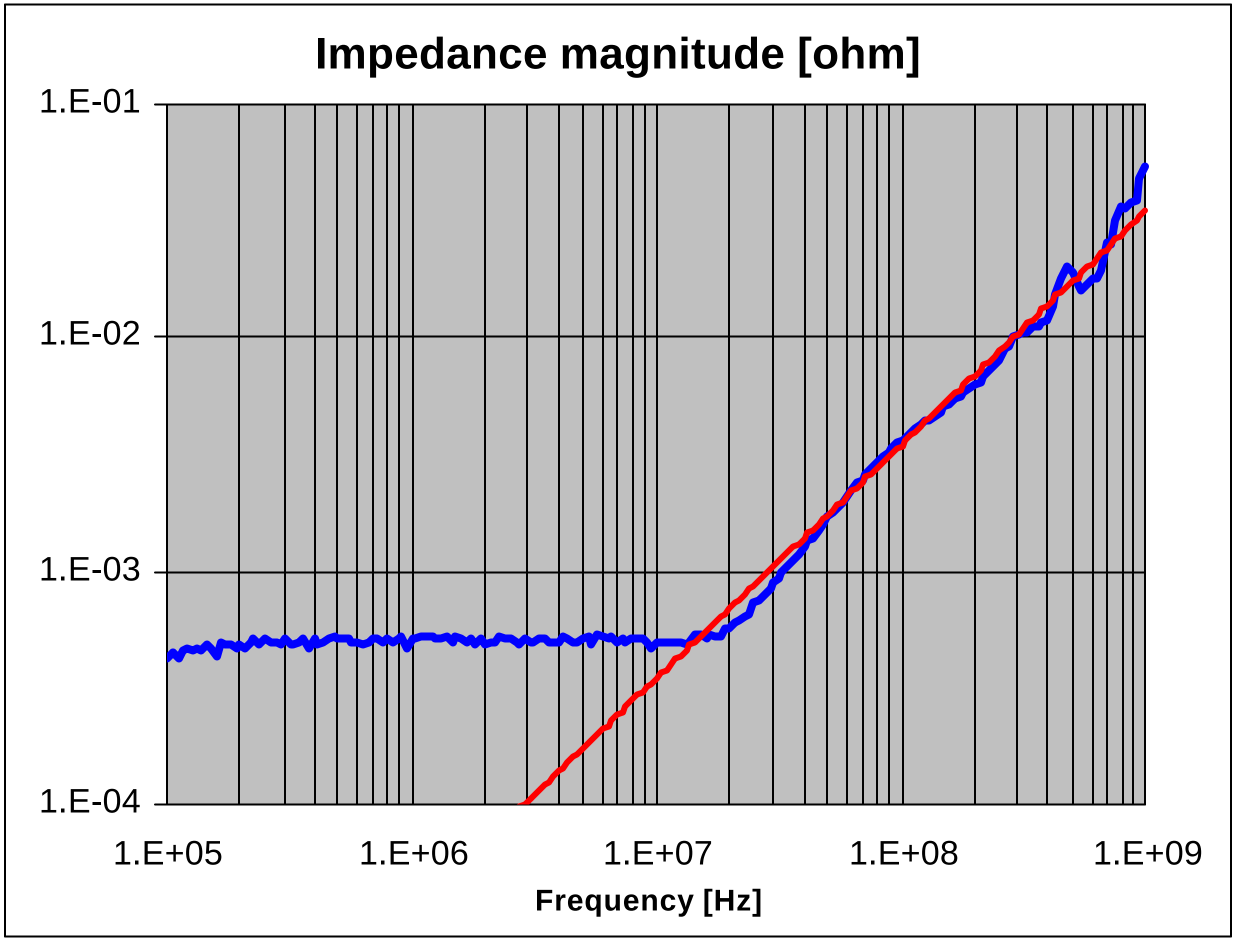
Reading Across Solid Plane



- Half-ounce Cu
- 30-mil vias
- 70-mil via spacing
- 0.52 milliohms
- 5.5pH

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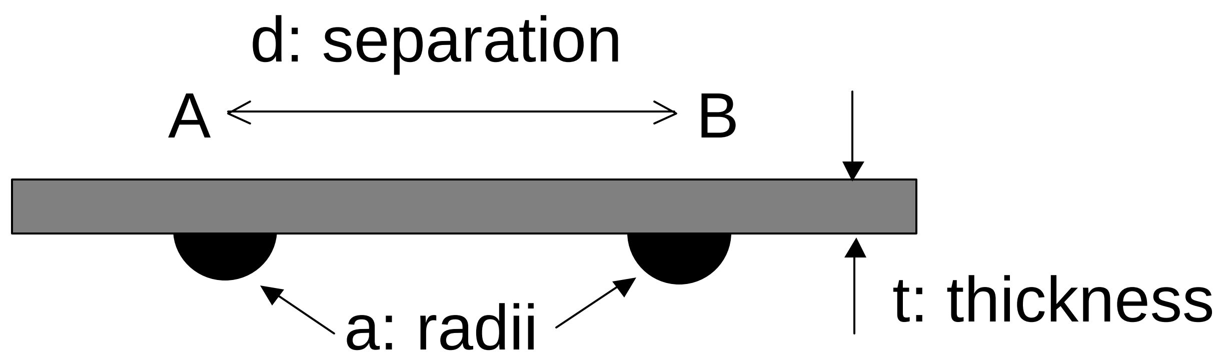
DC Resistance Across Solid Plane



$$R_{AB} \approx \frac{1}{p s a}\left[1+\frac{a}{t}\ln\left(\frac{\sqrt{1+\left(\frac{d}{2t}\right)^2}+1}{\sqrt{1+\left(\frac{a}{2t}\right)^2}+1}\right)\right]$$

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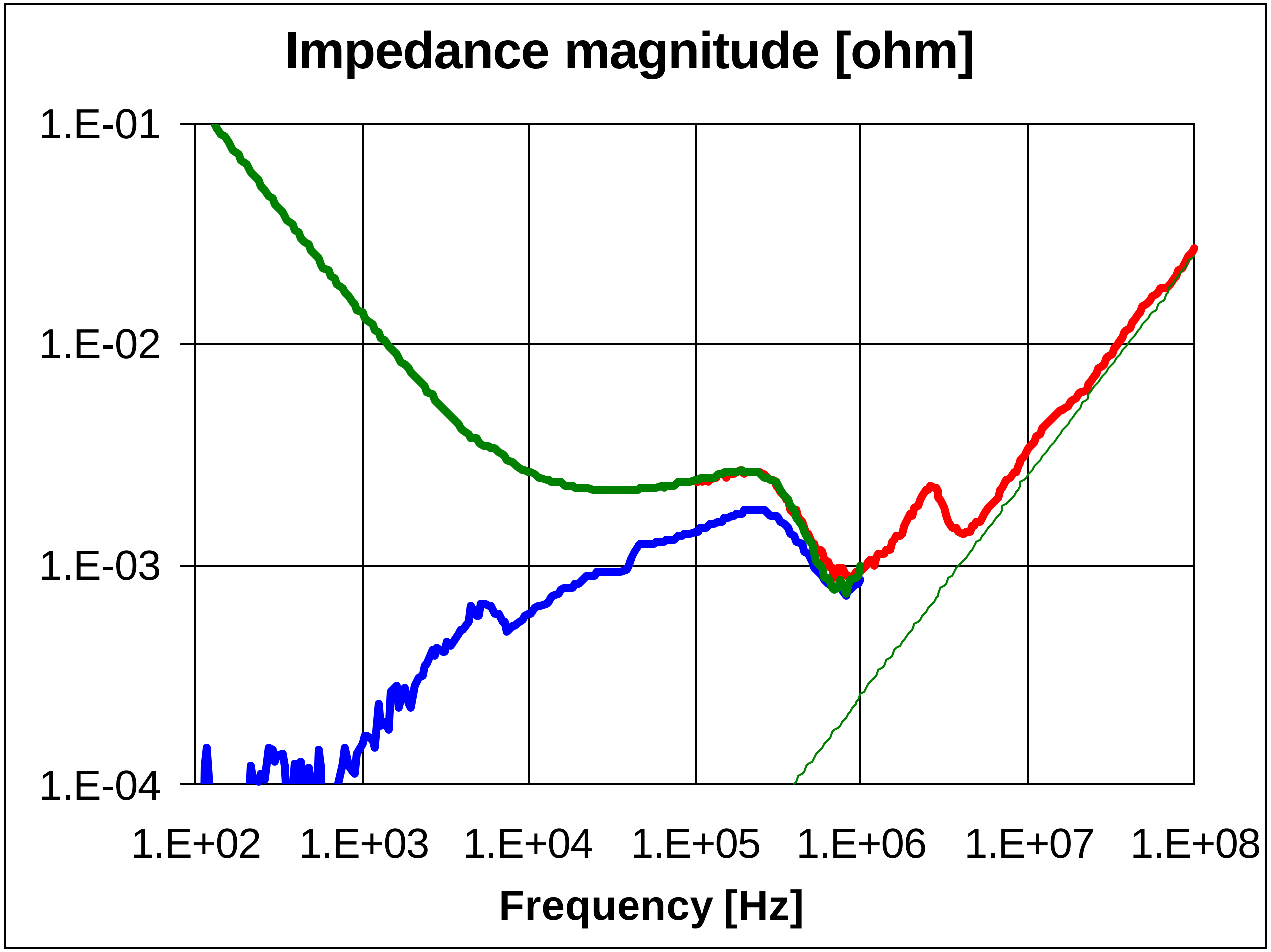
Combined Impedance of PDN



- VRM
- 2x3”x4” 2-mil planes
- Bulk capacitors
- 90 bypass capacitors

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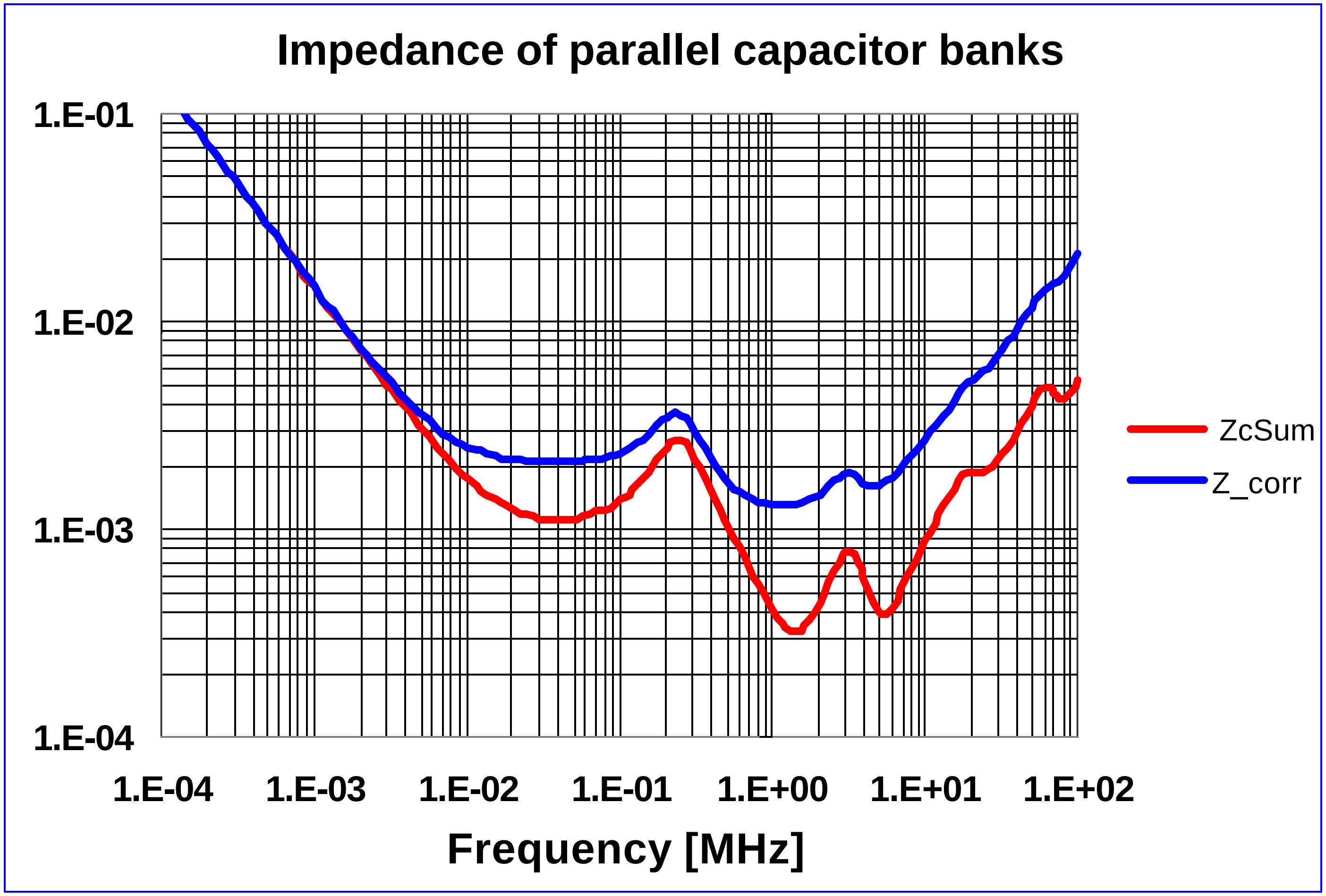
Simulated PDN Impedance



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Recommended Resources

Hewlett Packard Vector Network Analyzers:

- HP 4395 VNA 10Hz-500MHz
- HP 4396 VNA 100kHz-1.8GHz
- HP87512A DC-2GHz Transmission/Reflection Test Set
- HP 8720D VNA 50MHz-20GHz

Circuit simulator software:

- Avant! HSPICE

Conclusions

- Two-port measurements reduce effect of discontinuities
- Limitation at low frequencies: cable-braid ground loop
- Ground-loop is eliminated by transformer or amplifier
- Limitation at high frequencies: braid leakage and resonance
- Reliable reading and good correlation to simulations is achieved in the sub-milliohm range