Measuring Milliohms and PicoHenrys in Power Distribution Networks

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Requirements in Power Distribution

- $V_{dd}$ [V]
- Power [W]
- Current [A]
- Frequency [MHz]
- $Z_{target}$ [mohm]
- $L_{target}$ [nH]
What is a VNA

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

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

\[
S_{21} = \frac{b_2}{a_1} \Big|_{a_2=0}
\]
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 $Z_{DUT}$
Two-Port Self-Impedance Reading

First-order calculation:
Assume that

- \( L_p \approx 0 \)
- \( Z_{DUT} \ll Z_0 \)

Port 1 and Port 2 of VNA: 25 ohm

\[
Z_{DUT} = Z_{11} = S_{21} \times 25 \, [\text{ohm}]
\]
Transfer Impedance Measurement

Cable and Port1 of VNA: 50 ohm

Cable and Port2 of VNA: 50 ohm

$V_S \rightarrow V_1 \rightarrow V_2$
Transfer Impedance Reading

First-order calculation:
Assume that

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

$Z_{21} = Z_{12} = S_{21} \times 25 \text{ [ohm]}$
S21 Uncertainty

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

Self impedance:
- Coax and Port1 of VNA: 50 ohm
- $L_{p1}$
- $L_{p2}$
- $Z_{11} = Z_{DUT}$
- Coax and Port2 of VNA: 50 ohm

Transfer impedance:
- Cable and Port1 of VNA: 50 ohm
- $L_{p1}$
- $L_{p2}$
- $V_S$
- $V_1$
- $V_2$
- DUT
- Cable and Port2 of VNA: 50 ohm
$S_{21}$ Conversion to Self Impedance

$$Z_{ii} = S_{21} \left( \frac{Z_1}{2} - \frac{1}{1 - S_{21} \frac{Z_1 + Z_2}{2Z_2}} \right) \approx S_{21} \times 25 \times \frac{1 + j\omega \tau_p}{1 - S_{21}}$$

Where

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

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

$\tau_p = L_p/50$
S₂₁ Conversion to Transfer Impedance

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

\[ S_{21} \times 25 \times \frac{1 + j\omega \tau_p}{1 + 50 \times \left( \frac{S_{21}}{2} \right)^2} \times \left( 1 + \frac{Z_{11}}{Z_1} \right) \left( 1 + \frac{Z_{22}}{Z_2} \right) \]

Where

\[ Z_1 = 50 + j\omega L_{p1} \]
\[ Z_2 = 50 + j\omega L_{p2} \]
\[ \tau_p = L_p / 50 \]
Low-Frequency Ground Loop

VNA Port1: 50 ohm

VNA Port2: 50 ohm

L_{c1} \quad R_{c1} \quad R_{c2} \quad L_{c2} \quad Z_{DUT}=0

L_{b1} \quad R_{b1} \quad R_{b2} \quad L_{b2}

Imp. magnitude [ohm]

Frequency [Hz]

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Ground-Loop DC Error

\[ R_{DC\_error} = R_{b1} \parallel R_{b2} \]
Eliminating Ground Loop

Transformer
Differential amplifier

VNA Port1: 50 ohm

VNA Port2: 50 ohm

$V_S$
Transformer

Phillips core: TX51/32/19-3F3
- Diameter: 52mm
- 2x50 turns
- AWG 20
- bifilar
- SMA female
Transformer Impedance

- HP4395B
- HP87512A
- Open secondary
- $L_{\text{main}} = 9.5\text{mH}$
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
Calibration Setup

VNA Port1: 50 ohm

Isolation transformer

VNA Port2: 50 ohm

Calibration with

Z_{DUT} = 0.1-ohm reference
Isolation Amplifier

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Reduced Error Floor by Increased $P$

- Calibration at $-5\text{dBm}$
- HP4395B
- Power changed to $+15\text{dBm}$
Residual Noise

Impedance [ohm]

Frequency [Hz]


1.E-06 1.E-05 1.E-04 1.E-03

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Reading of Shorts

- Isolation transformer
- HP4395B
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
VRM Zout

- 1.5V VRM
- No external capacitor
Limitations at High Frequencies

Finite braid surface transfer impedance

Braid resonances

Plain coax

Coax, 2x4 ferrites

Solution:
Absorption ferrites

Residual impedance [ohm]

Frequency [Hz]
Ferrite-Covered Cable
Reference: Connection to Solid Plane

t=0.6-mil (half ounce) copper plane

da=70 mil center-to-center spacing

a=15-mil radius drilled vias
Probes and Vias

- Test board with via locations
- SMA-SSMB adaptors
- Probe: SSMB jack with two pins
Reading Across Solid Plane

- Half-ounce Cu
- 30-mil vias
- 70-mil via spacing
- 0.52 milliohms
- 5.5pH
DC Resistance Across Solid Plane

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

- \( d \): separation
- \( t \): thickness
- \( a \): radii

\[ A \rightarrow \text{separation} \rightarrow B \]

\[ a_{ \text{radii} } \]

\[ t_{ \text{thickness} } \]
Combined Impedance of PDN

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

Impedance of parallel capacitor banks

Frequency [MHz]

ZcSum
Z_corr
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