PDN Impedance Measurements Using **Bode 500** and Picotest **PDN Probes**

13th Power Analysis & Design Symposium

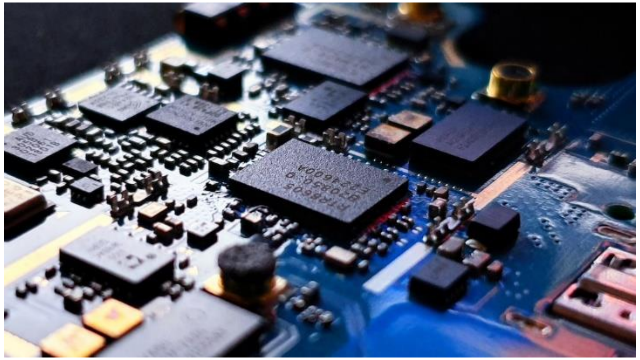
2023-04-17

OMICRON LAB

Agenda

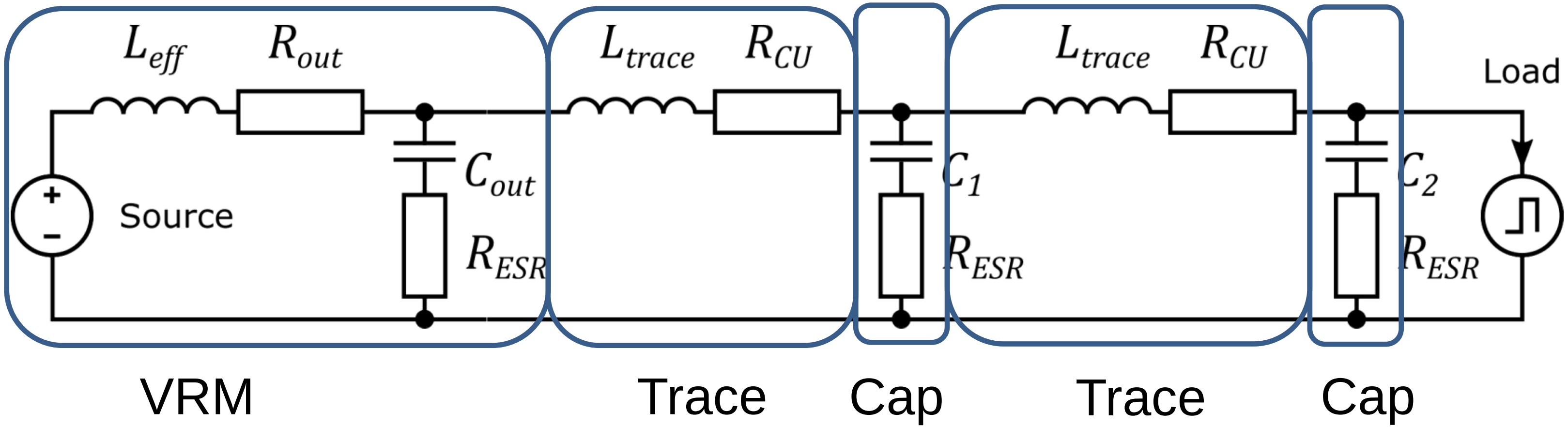
- PDN Impedance
- Shunt-Thru Measurement Method
- 2-Port Probe vs. 1-Port Probe
- Calibration & Correction
- Step-By-Step Procedure
- Measurement Example

Power Distribution Network (PDN)



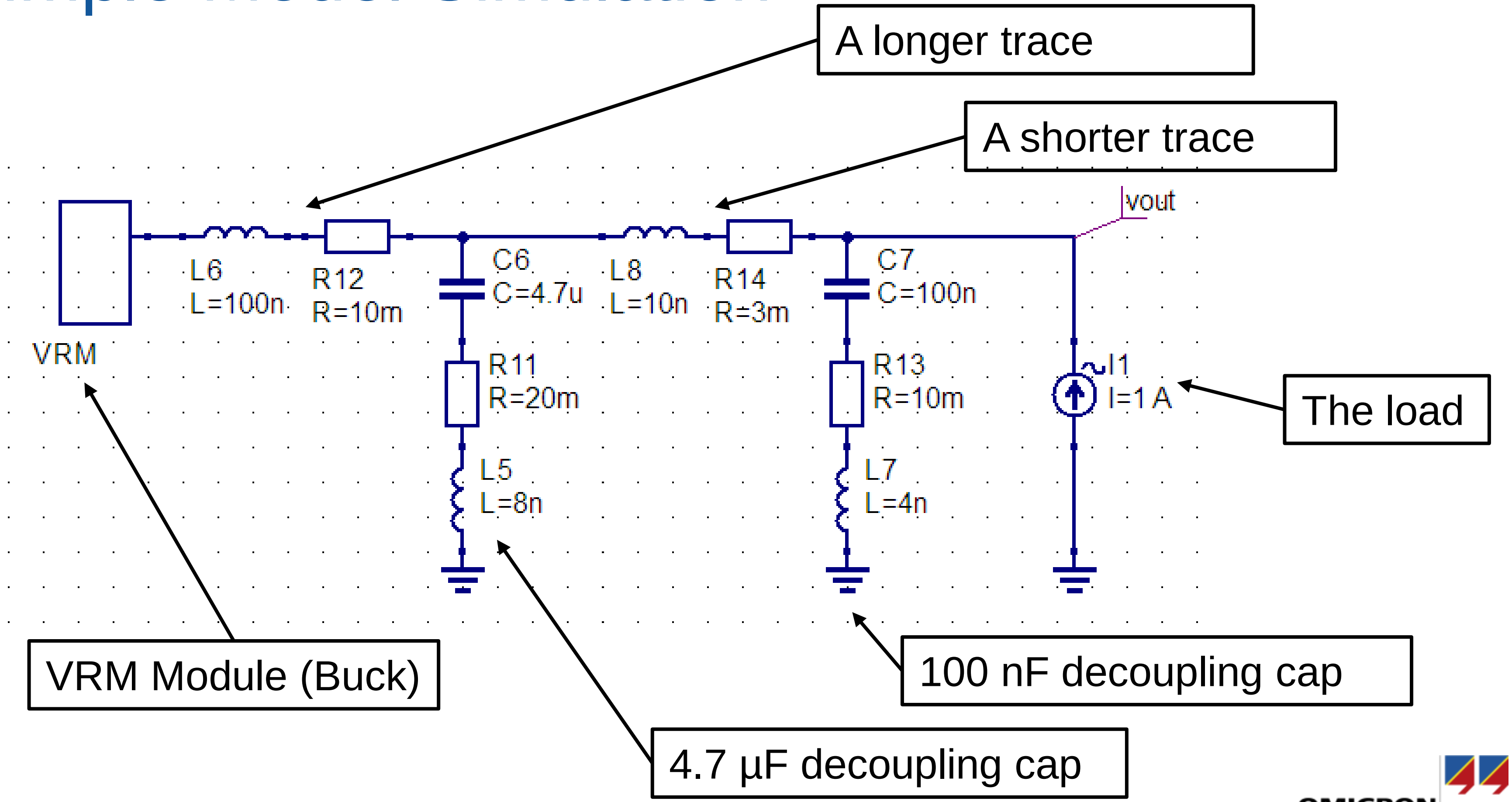
- Power source and input filters
- Voltage Regulator Module (VRM)
- Point of load regulator (POL)
- Output filtering (ferrites, capacitors)
- PCB lines, board planes, vias, capacitors
- Package leads, planes, bond-wire, on-die capacitance
- Return path (ground plane)

A Simple PDN Model

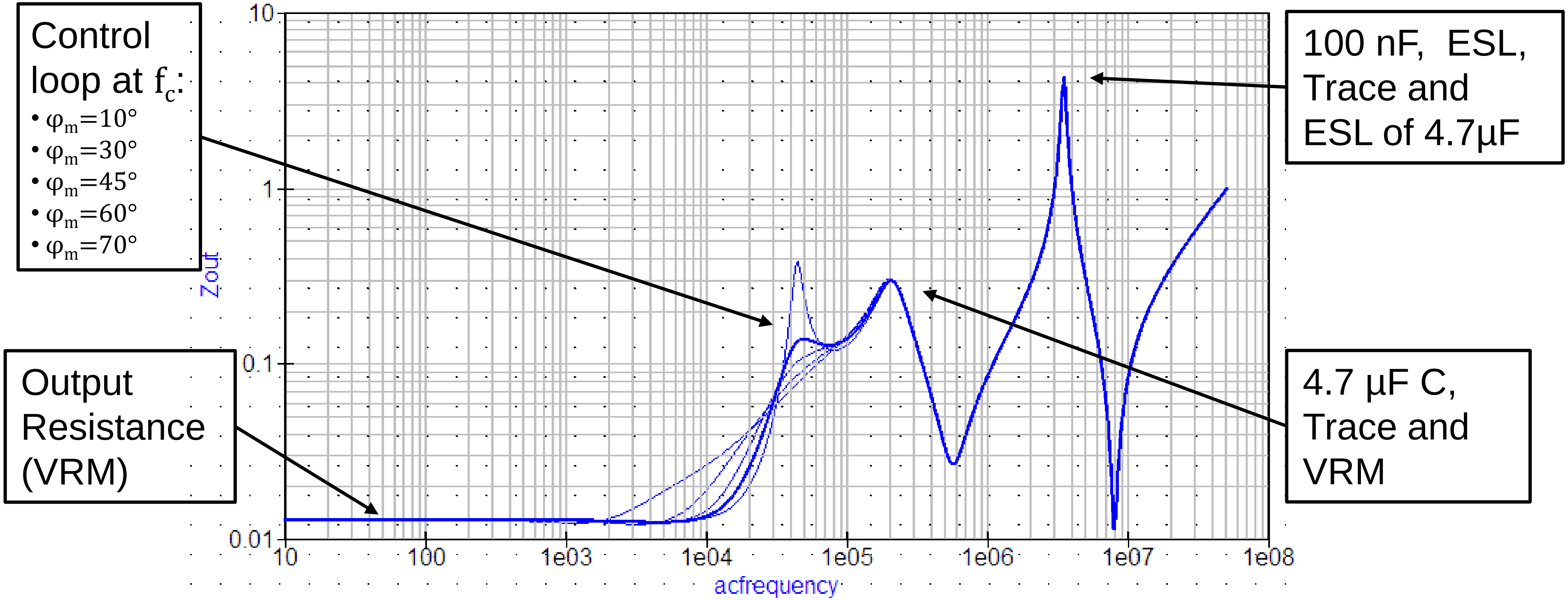


- Multiple L-C resonance circuits
  - Ceramic caps have generally very low ESR values.
  - Ferrites have generally low resistance.
  - The Q of the resonances can be high.

Simple Model Simulation



Impedance Profile at the Point of Load



- 200 kHz load current → 300 mΩ source impedance.
- 3 MHz load current → 3 Ω source impedance.

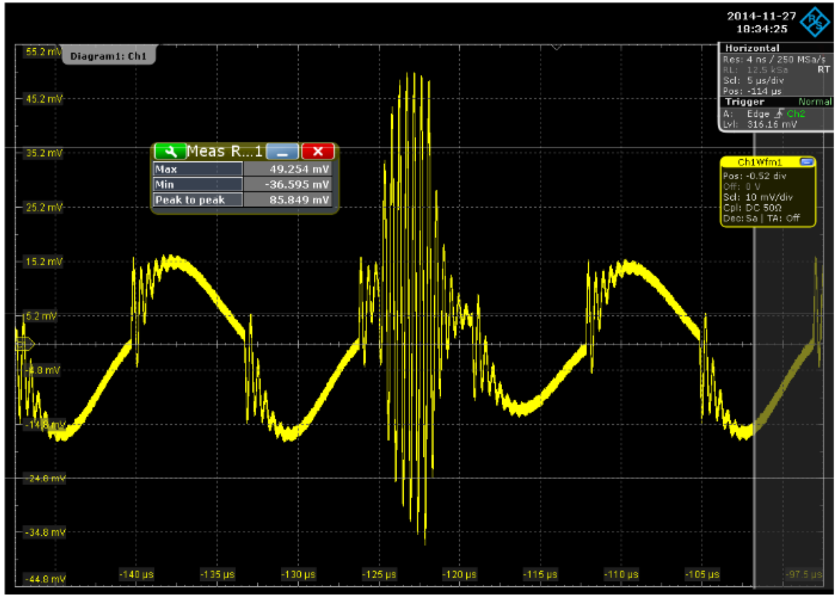
➢ 1 A load current causes 0.3V / 3 V drop.

Avoid Supply Impedance Peaks

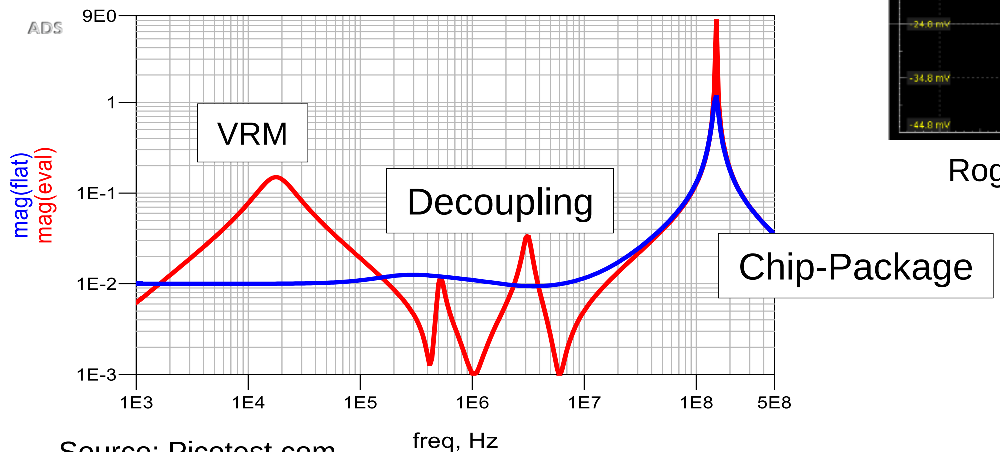
- Can violate the target impedance
- High impedance increases the risk of coupling noise to the supply voltage ($V = \sqrt{P \cdot R}$)
- Noise on the supply voltage can degrade performance of oscillators (Jitter), reference voltages, ADCs, low-noise amplifiers etc...
- And in worst case, they can stack...

Risk of Rogue Waves

- Dynamic load currents at multiple frequencies can superimpose.
- Worst case scenario is a "Rogue wave".
- "Flat Impedance Approach" can safely avoid this risk.



Rogue Wave captured by Steve Sandler (Picotest)



Source: Picotest.com

The PDN Impedance Plot

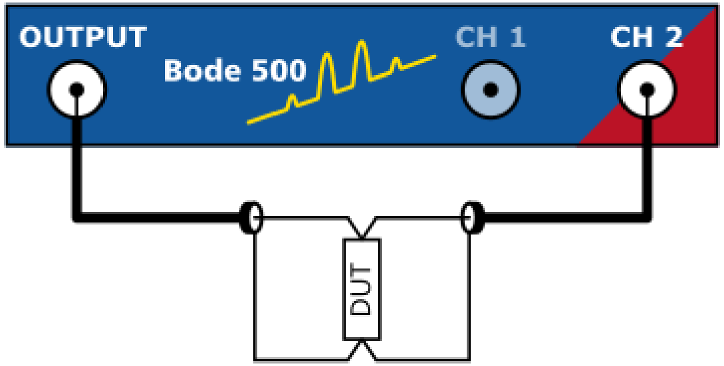
1. Can be a design goal in PDN design (target impedance).
2. Contains information about the stability (oscillation tendency) of the voltage regulator.
3. Reveals resonance frequencies of the decoupling network.

- Let’s measure it!
- Challenge: **Very low impedance**

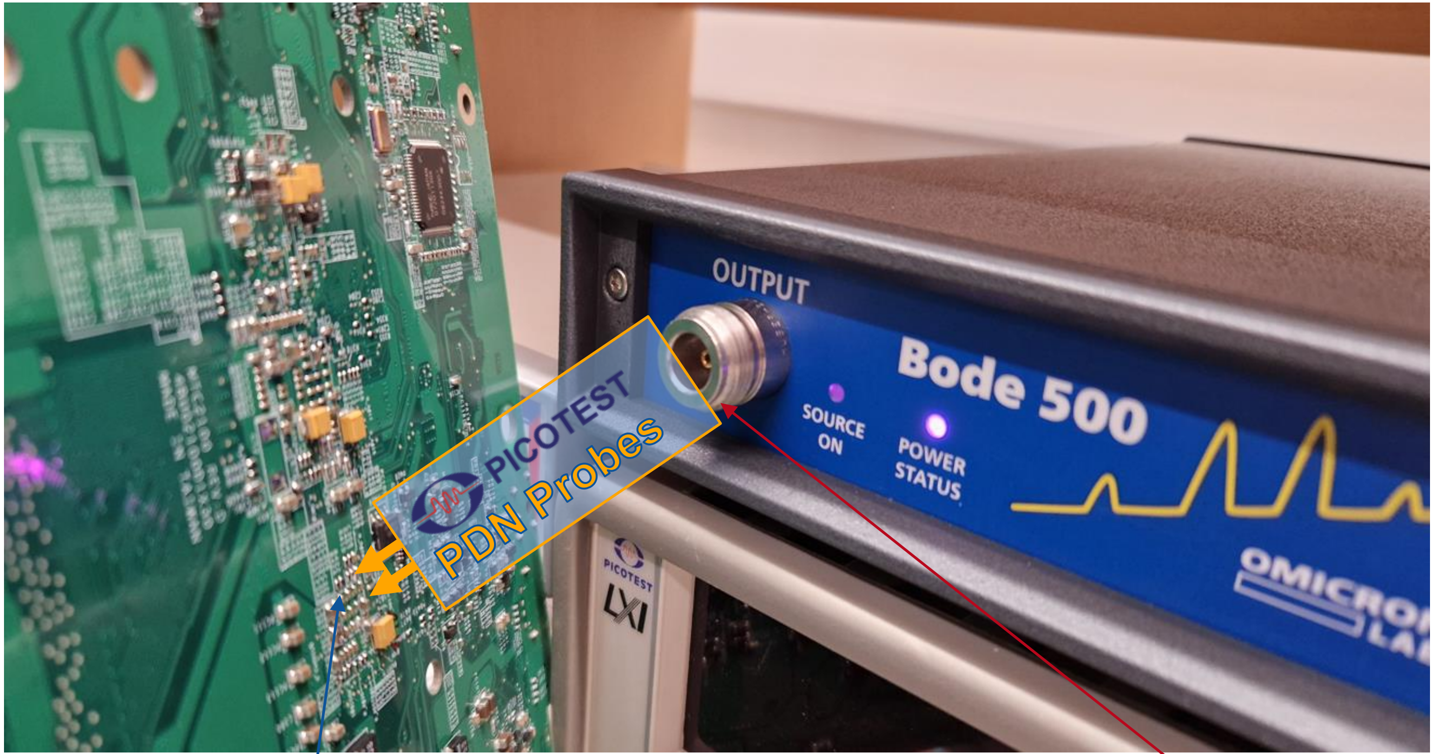
2-Port Shunt-Thru Measurement

- Provides high sensitivity for low impedance.
- Emulates a 4-wire kelvin connection.
- Can be used to measure into the µΩ range.
- Measures S21 and calculates Z via

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



Connecting Analyzer and DUT



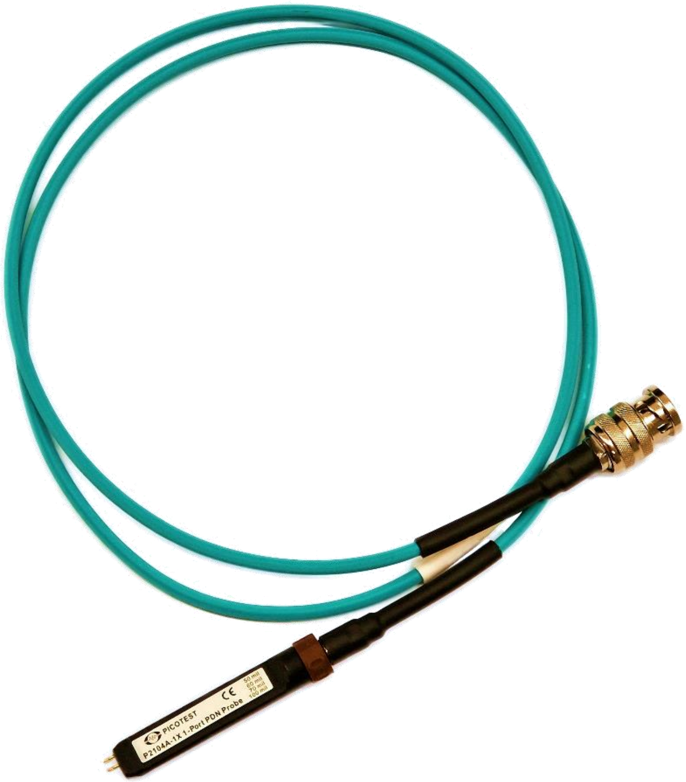
PCB with 0402, 0603, 0805, 1206 etc. SMD Pads

VNA with Type-N coaxial connectors

Picotest PDN Probes

PICOTEST

P2104A One-Port Probe

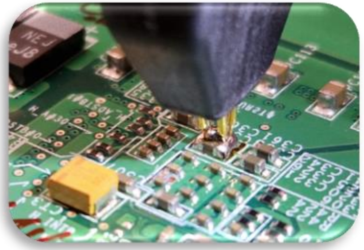
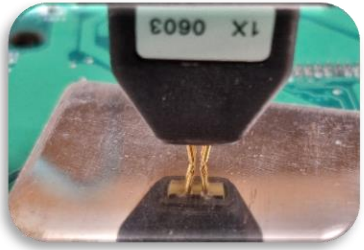
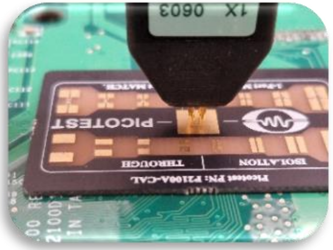


P2102A Two-Port Probe

OMICRON LAB

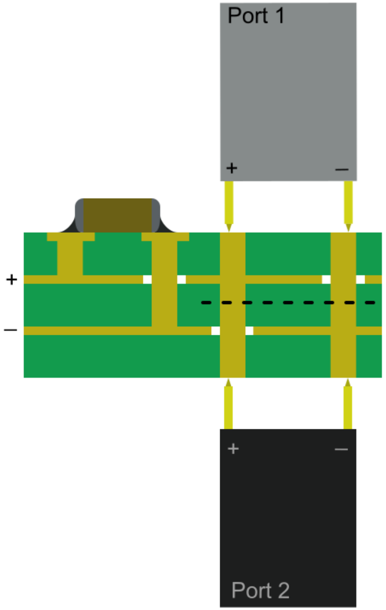
Picotest PDN Probes

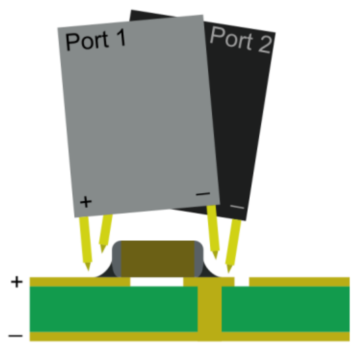
- High bandwidth & flat frequency response.
- Different coaxial connector styles (SMA, BNC, N).
- Picotest PDN Cable® (ultra high shield attenuation and ultra low shield resistance, highly flexible and thin).
- P2102A - four probe heads (0402, 0603, 0805, 1206).
- P2104A - different pitch sizes available (50mil-100mil).
- 1x, 2x, 5x or 10x attenuation options available.


1-Port Probe vs. 2-Port Probe

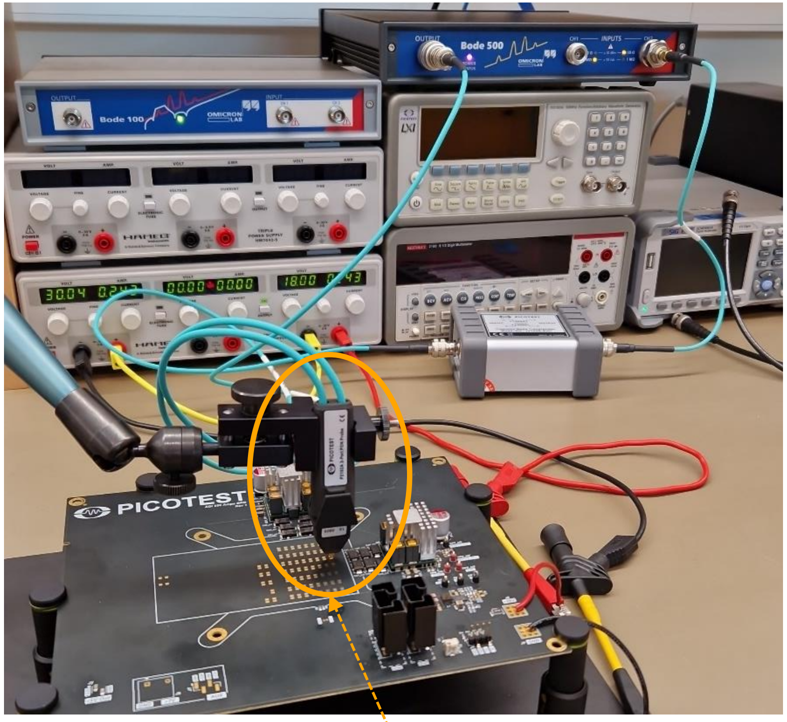
1. One-Port Probe (2 probes needed ☹)
   - 🙂 Flexible positioning
   - 🙂 Get into power planes by opposite placement
   - 😥 Difficult handling (probe holder)
   - 🧐 Allows measuring transfer impedance
2. Two-Port Probe (only **one** 😃)
   - 🙂 Can by used “by hand” (browser probe)
   - 🙂 Very easy & intuitive to handle
   - ☹ Less flexible, no opposite placement

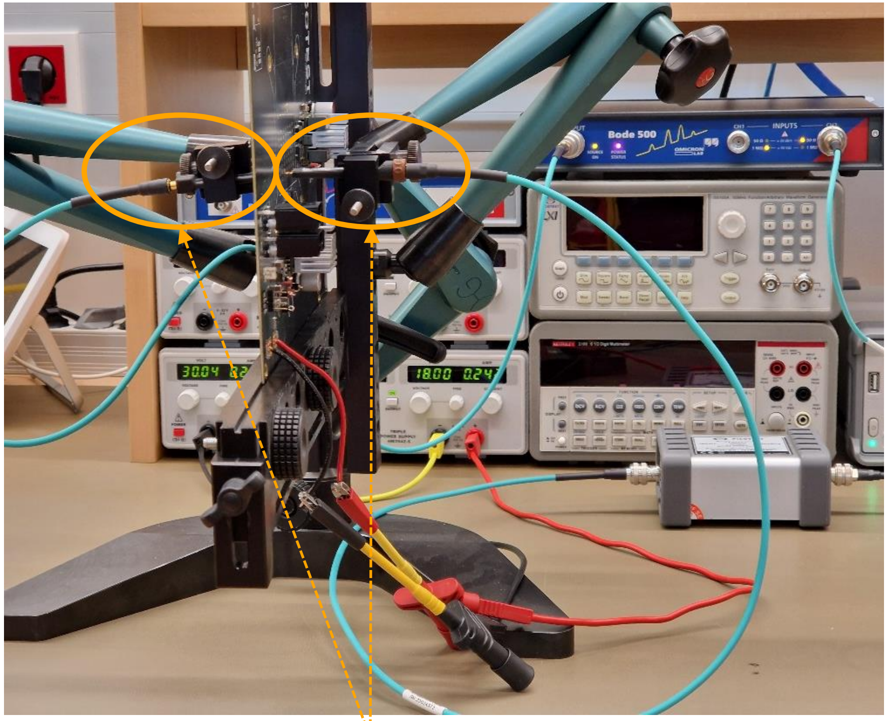




Measurement Setup Example

Probe & PCB clamping: http://www.clampman.info/





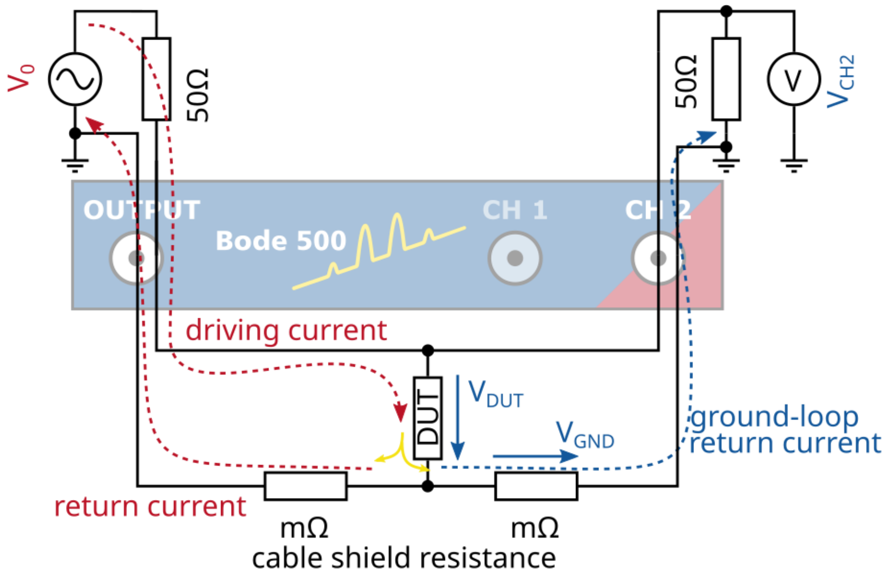
Setup with Bode 500 and Picotest **P2102A 2-Port Probe**

Setup with Bode 500 and **two** Picotest **P2104A 1-Port Probes**

Ground Loop Error in Shunt-Thru Setup

VNA has common ground on source and input port

- Return current splits between source and input ground
  → error voltage V_{GND}.
- Error depends on cable shield resistance, ground contact resistance, frequency (common mode inductance), DUT value [5]

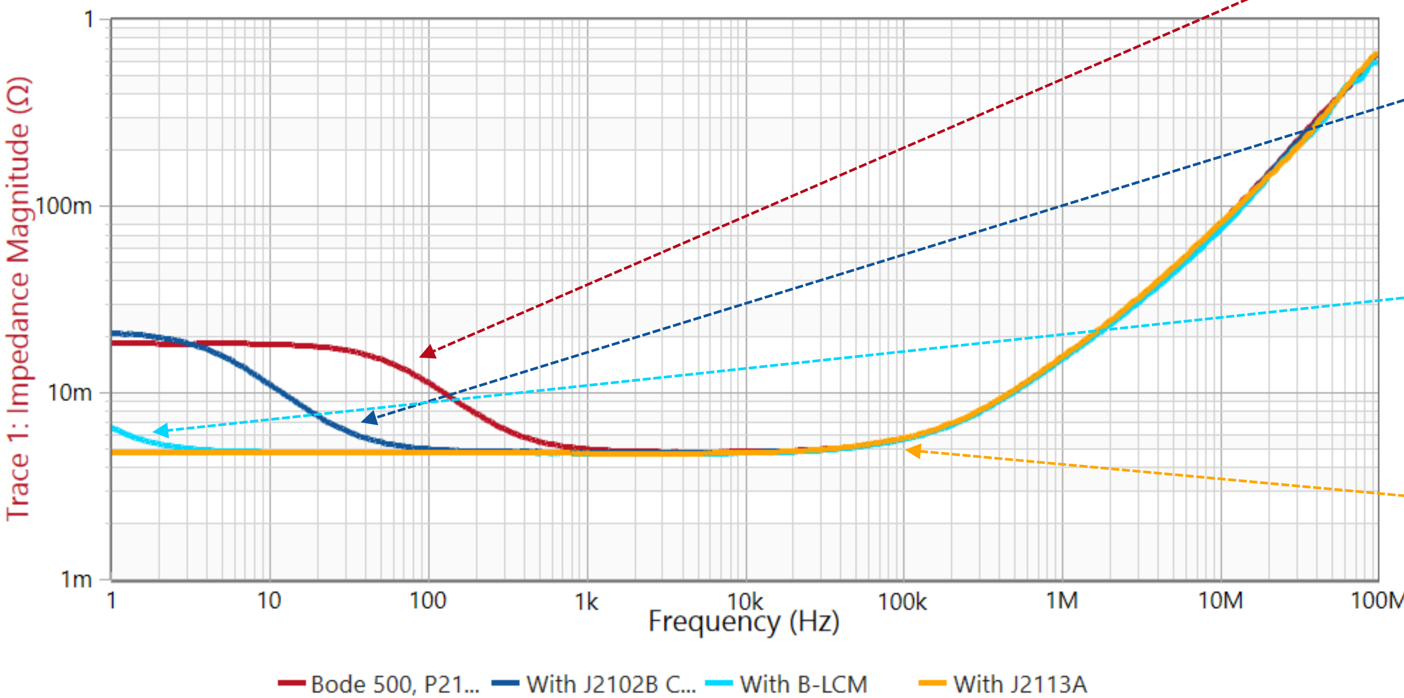


Methods to Reduce Ground Loop Error

- Use cables with low shield resistance and connectors with low ground contact resistance (PDN Cables)
- Use a Common Mode Choke (J2102A or B-LCM)
  - ☺ Easy to use, low impact at high frequency
  - ☹ Does not work at DC / low CMRR at low frequency
- Use a Differential Amplifier (J2113A)
  - ☺ Works down to DC
  - ☹ More impact at high frequency, limited CMRR, noisier
- Use a booster amplifier to reduce loading of VNA signal source (can reduce device internal crosstalk)

Identify the Ground Loop Error

Example: 5 mΩ on Bode 500 and P2102A:



Bode 500 with Picotest P2102A

Bode 500 with Picotest P2102A + **J2102A**

Bode 500 with Picotest P2102A + **B-LCM**

Bode 500 with Picotest P2102A + **J2113A**

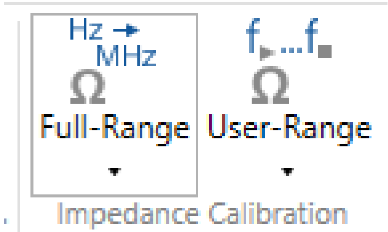
OMICRON LAB

Calibration / Correction

- Account for phase shift and attenuation of:
  - Common mode isolator
  - Cables & Probes
- Partially compensate for ground loop error *(depends on ground resistance – can be different from contact to contact!)*

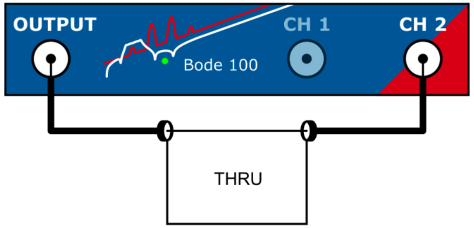
Bode Analyzer Suite offers:

- **Full-Range** Impedance Calibration
  Preferred if frequency range is unclear
  (uses interpolation)
- **User-Range** Impedance Calibration
  Preferred if frequencies are defined
  (no interpolation)

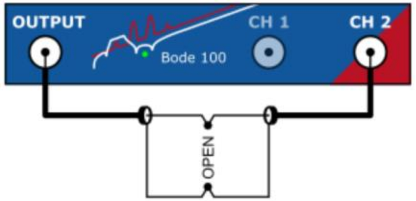


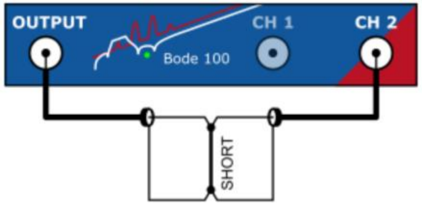
Thru or Open/Short/Load?

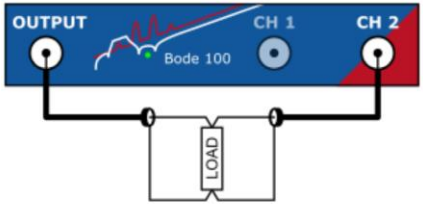
- **Thru** (Normalize S21 Measurement)
  - ☺ Only one calibration setup (thru).
  - ☺ Good signal / noise ratio during calibration.
  - ☹ Correction point at Z=∞ (far from Z<<).



- **Open/Short/Load** (Normalize directly to Z)
  - ☹ Requires three calibration setups (Open/Short/Load).
  - ☺ Calibration includes Short (close to Z<<).
  - ☹ A perfect Short cannot be constructed.
  - ☹ BAS does not yet account for Short resistance



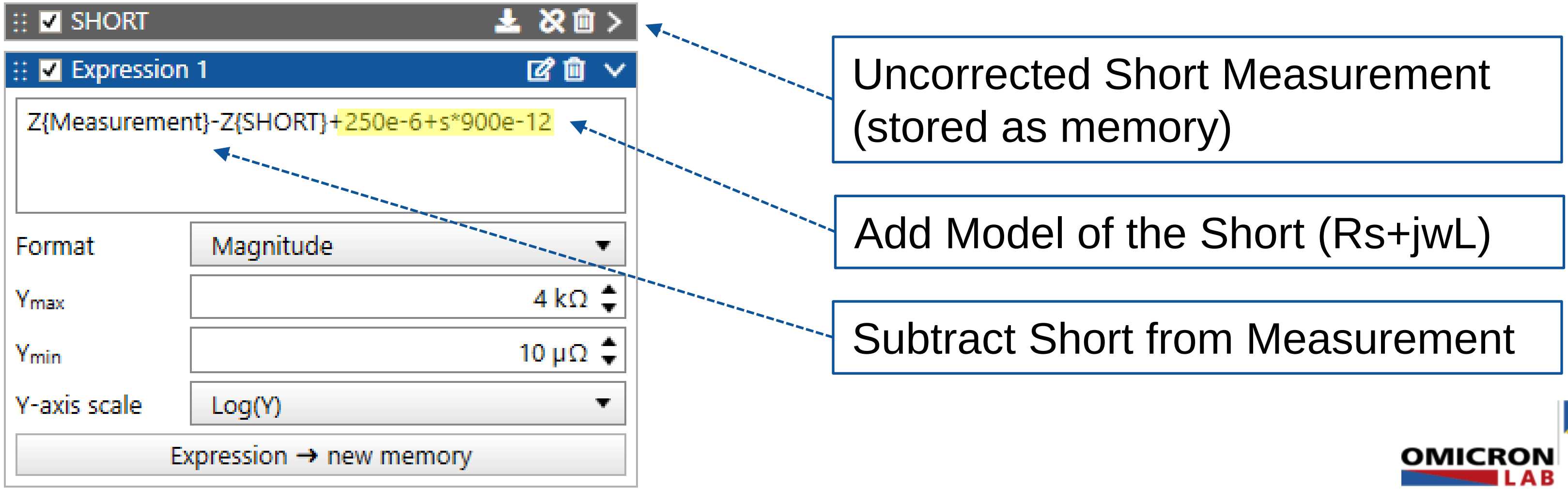




OMICRON LAB

Add Simple Short Correction

1. Characterize / Model a Short (Known Short)
   - Measure dc resistance (1 A & multimeter)
   - Determine effective Short inductance (simulation or measurement)
2. Measure the Short & store as Memory Trace
3. Use an Expression Trace to Correct measurement



Example (Bode 500 + P2102A + J2102A)

1.

Measure Short DC Resistance (P2100-CAL)

1 Adc → 0.250 mVdc
Short Resistance:
Rs = 250 µΩ

2.

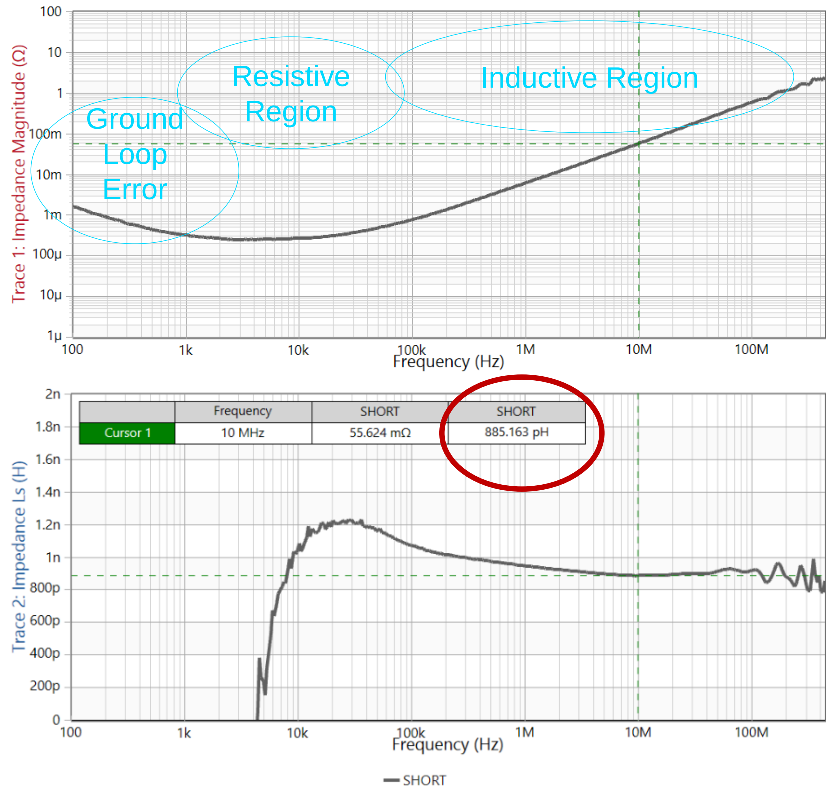
Perform Thru Calibration on P2100-CAL-Thru to correct for phase shift and attenuation of cables, probe & J2102A

Example (Bode 500 + P2102A + J2102A)

3.

Measure Short on P2100-CAL

Determine Short Inductance from high frequency measurement
Ls ≈ 900 pH



4.

Save Curve to Memory and name it “SHORT”

Example (Bode 500 + P2102A + J2102A)

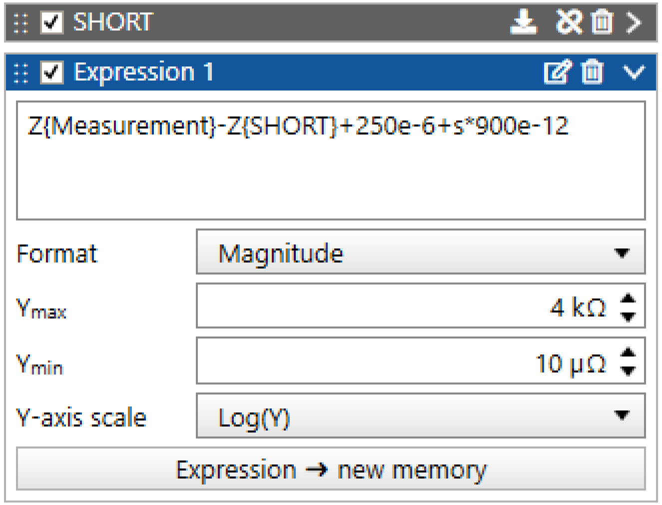
5.

Enter Expression to Correct for Short impedance

$$Z_{corrected} = Z_{measurement} - Z_{SHORT} + Z_{Shortmodel}$$

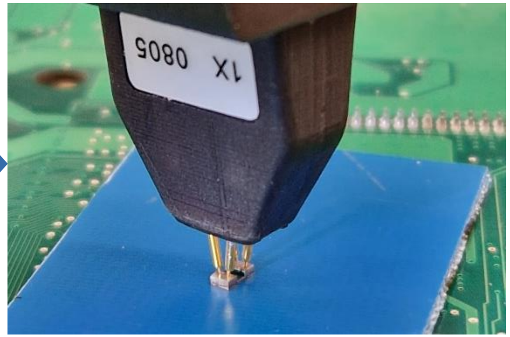
whereby a simple model of the short could be:

$$Z_{Shortmodel} = R_s + j\omega L_s = 250\ \mu\Omega + \mathrm{j} \cdot \omega \cdot 900\ \mathrm{pH}$$



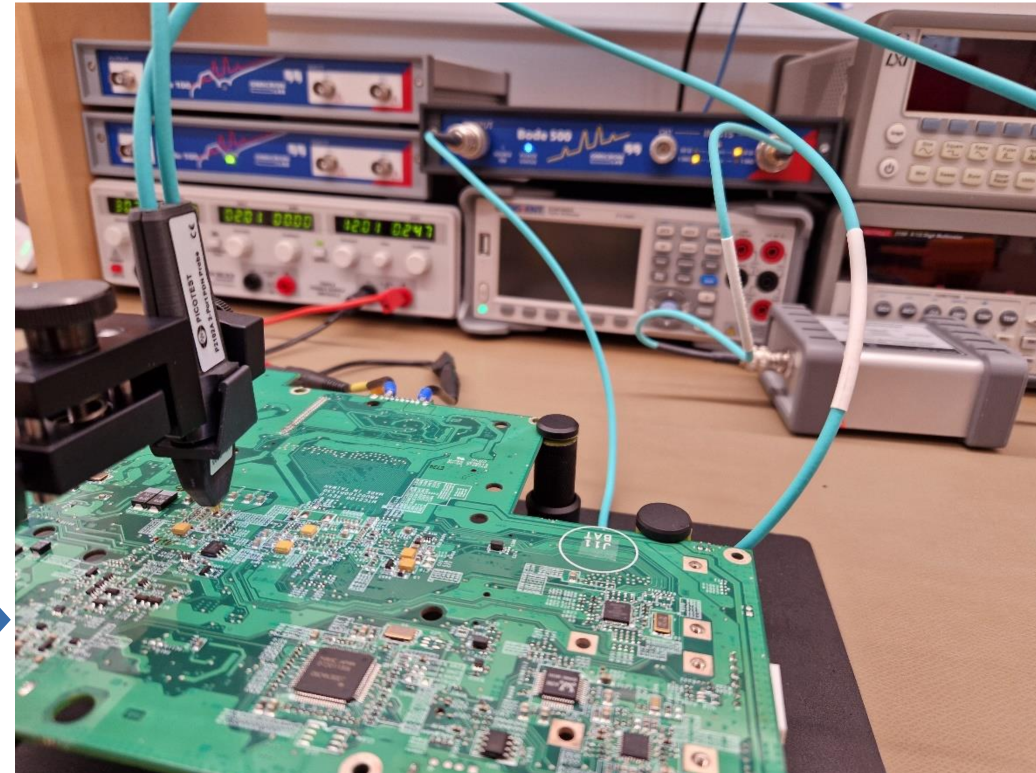
Example (Bode 500 + P2102A + J2102A)

6.



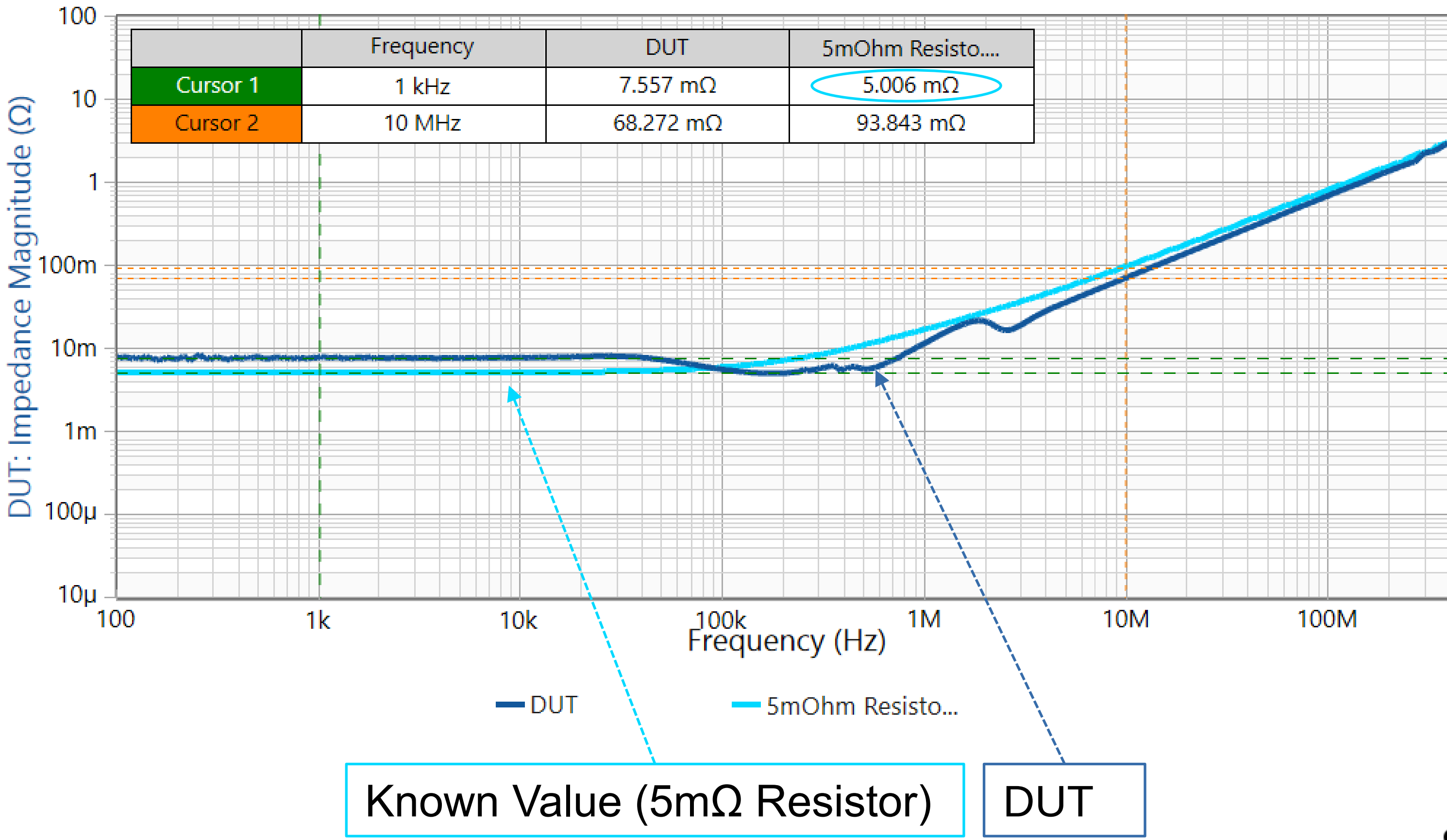
Known 5 mΩ Resistor

7.



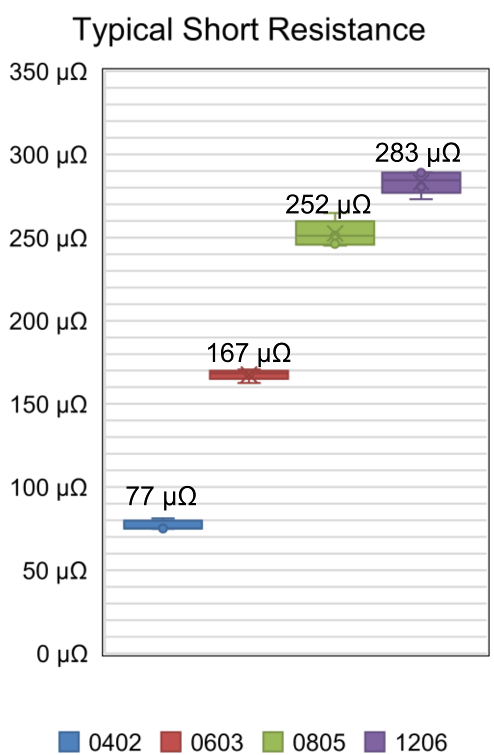
DUT Connection

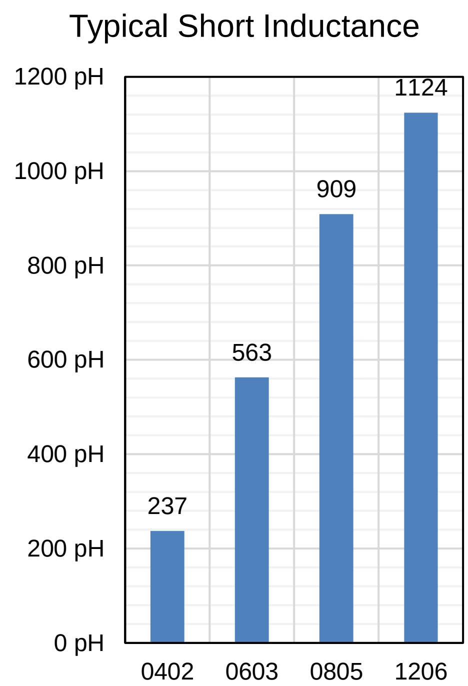
Example (Bode 500 + P2102A + J2102A)

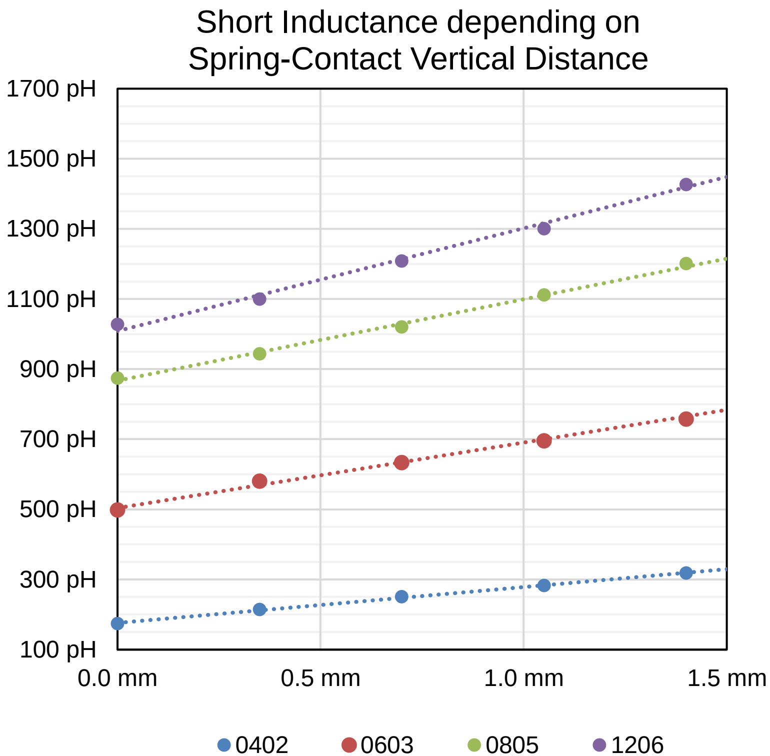


	Frequency	DUT	5mOhm Resisto....
Cursor 1	1 kHz	7.557 mΩ	5.006 mΩ
Cursor 2	10 MHz	68.272 mΩ	93.843 mΩ

P2102A + P2100-CAL Typical Values







Disclaimer: Due to my last-minute work, I was not able to confirm these values with Picotest! Values are subject to change without notice.

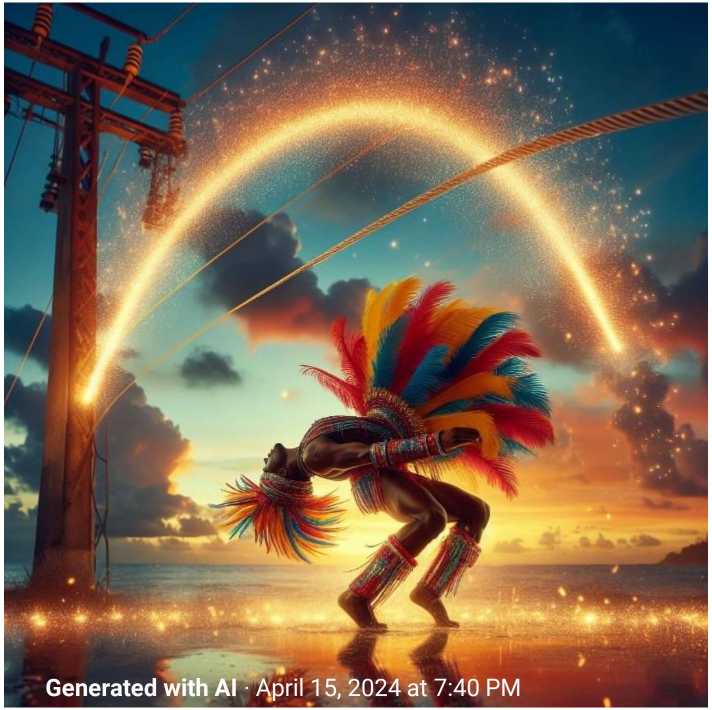
Ultra-Low Impedance (< 100µΩ)

- Use a Short with very low resistance (solid copper or silver)
- Suppress ground loop error as much as possible [4], [5]
- Use short cables whenever possible.
- Use cables with a low shield resistance (Picotest PDN cables).
- Measure something known of similar value. (1 Ω is not the same as 100 µΩ).
- Add calibration and reference elements to prototype layout. Thru-vias, short, etc.
- Use coaxial connectors.

How Low Can you Get?

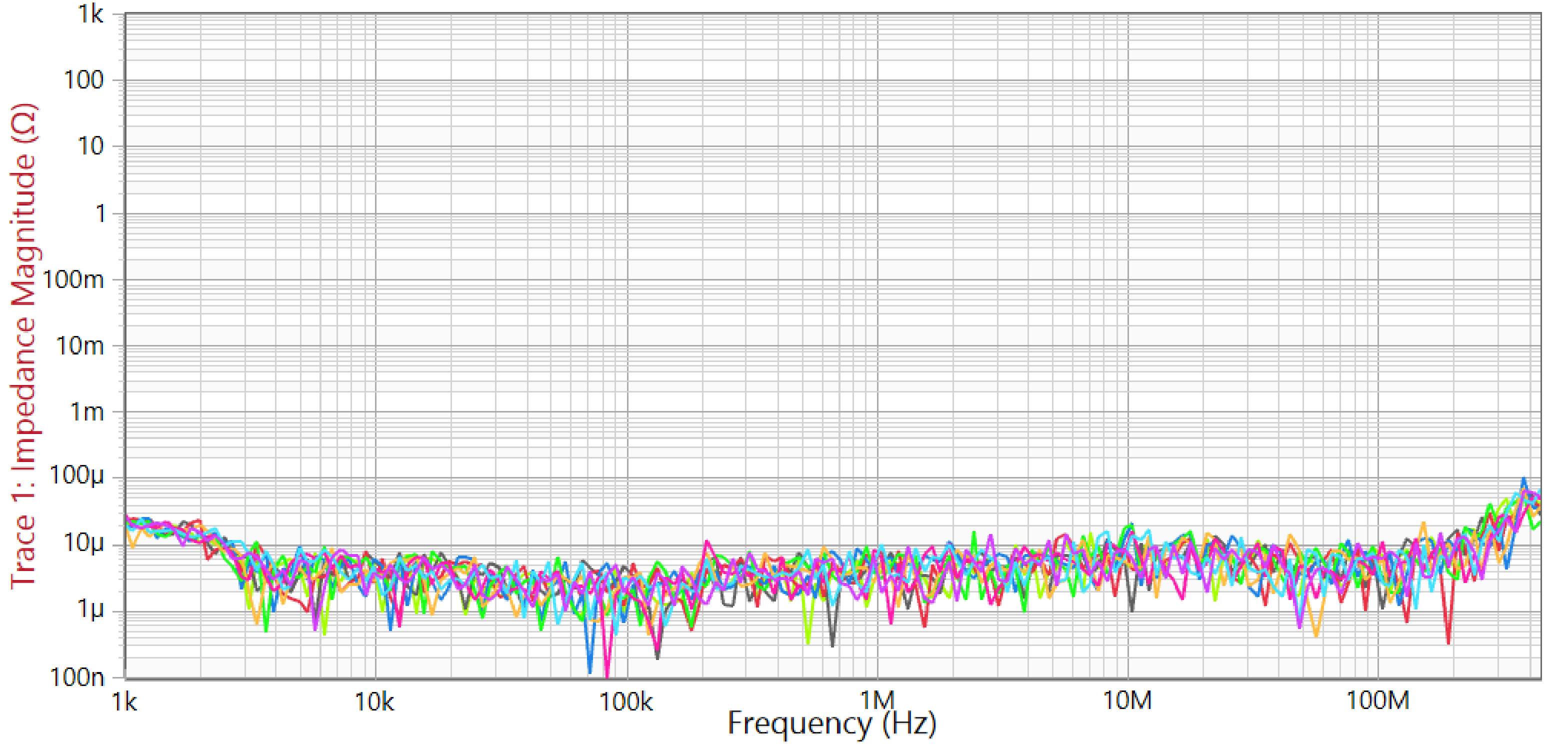
Impedance values get lower the higher the processing power gets. >100 A require < mΩ impedance.

- Limit is hard to tell.
- Increase dynamics using an amplifier.
- Non-Linear control algorithms like COT cause noisy measurement. This noise cannot be overcome due to the non-linearity of the DUT.
- Noise floor of Bode 500 is ≈ 10 µΩ

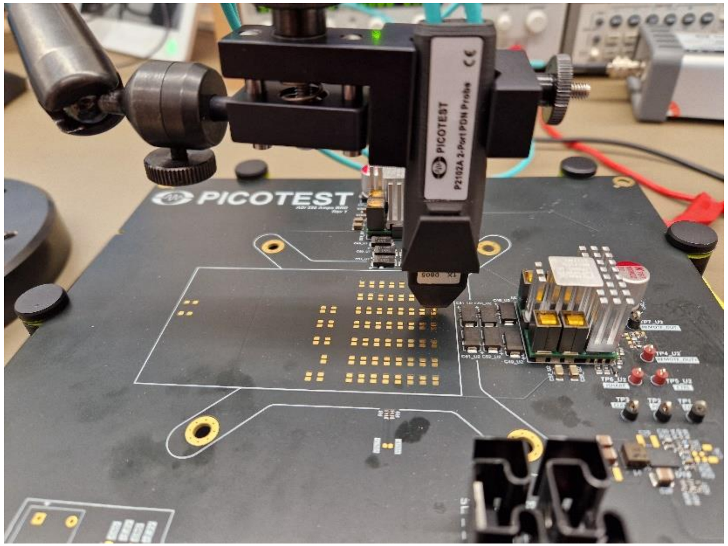


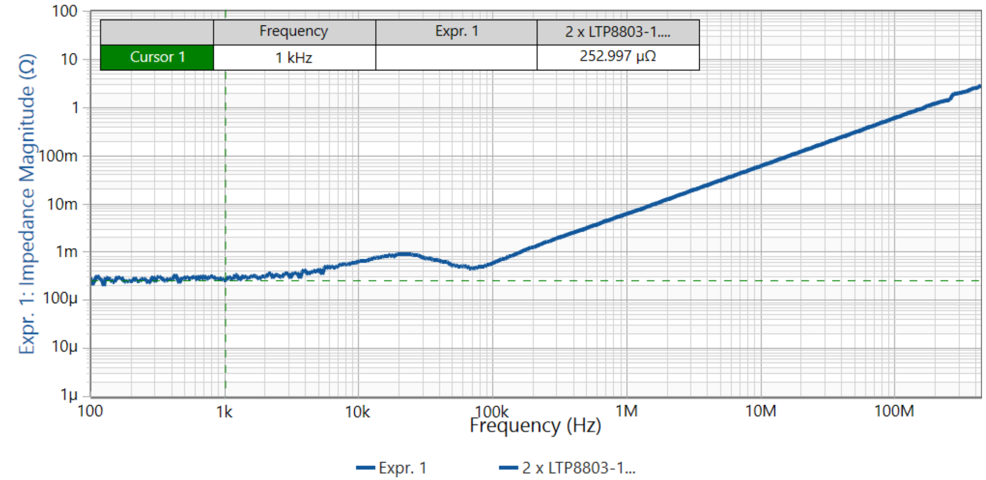
Bode 500 Noise Floor: 1 kHz – 450 MHz

Signal Source drives Short with 16dBm, 10Hz RBW, CH2 terminated.



Example of a Lower Impedance



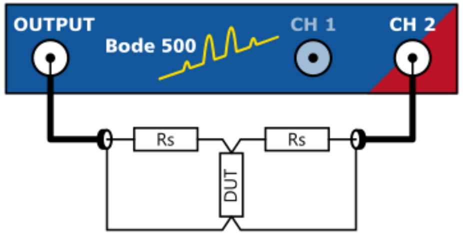


Picotest 256 A Demo-board with 2 x LTP8803-1A COT 48V to 1.1Vdc step down regulators.

250 µΩ at 1kHz. Noisy result at low frequency due to non-linear COT control mode.

Measuring PDN Impedance ≥ 3.3 Vdc

- Bode 500 Signal Source and 50 Ω input must be protected!
- Possible Measurement Methods:
  1. 3-Port measurement with Picotest J2111B current injector
  2. Shunt-Thru measurement with **2 dc-blocks**
     Note: Use calibration to remove the impedance of the dc-block
  3. Shunt-Thru measurement with **Series-Resistance**
     Note: Use thru-calibration to remove the resistor influence

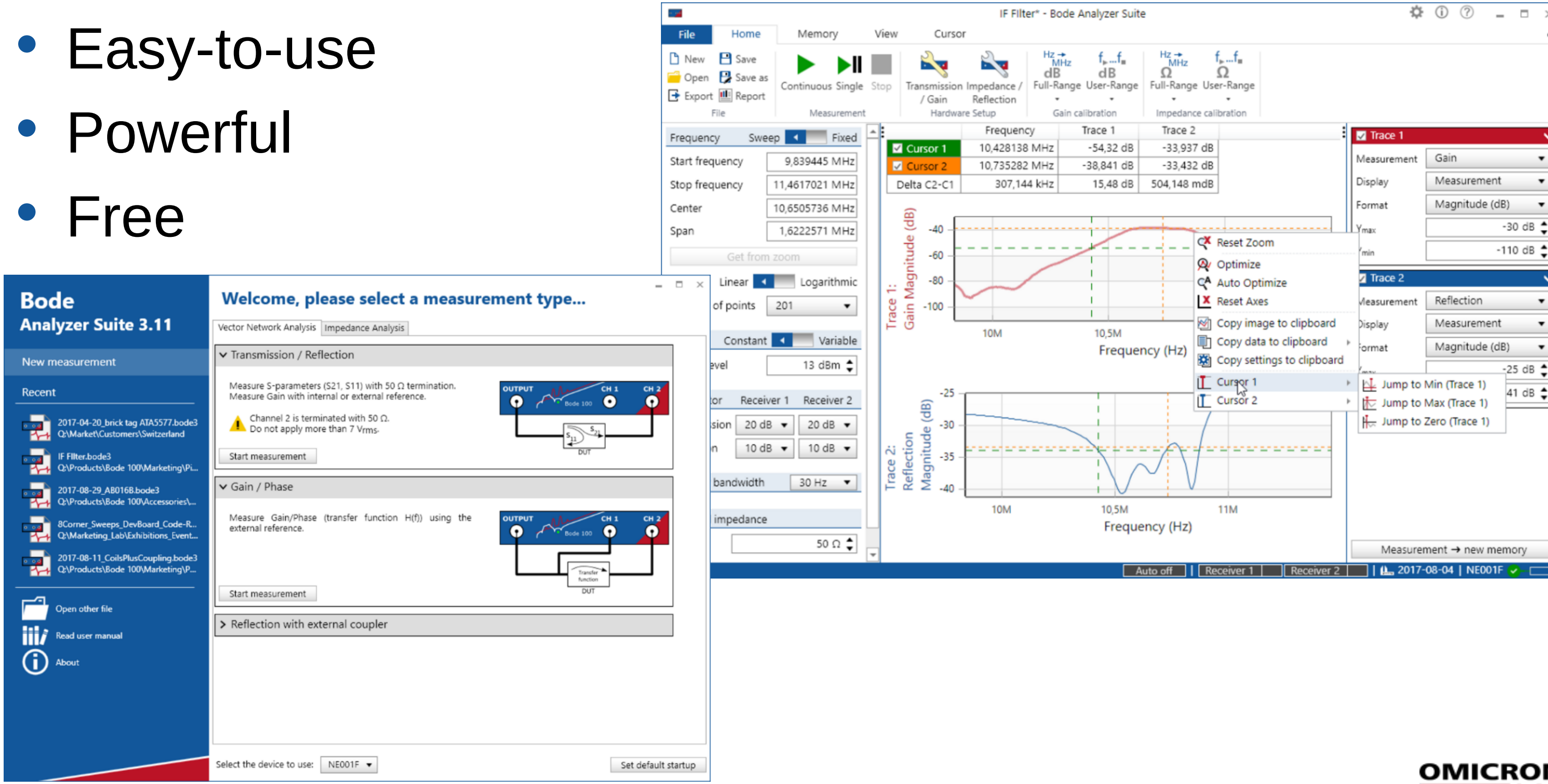


Key benefits of Bode 500

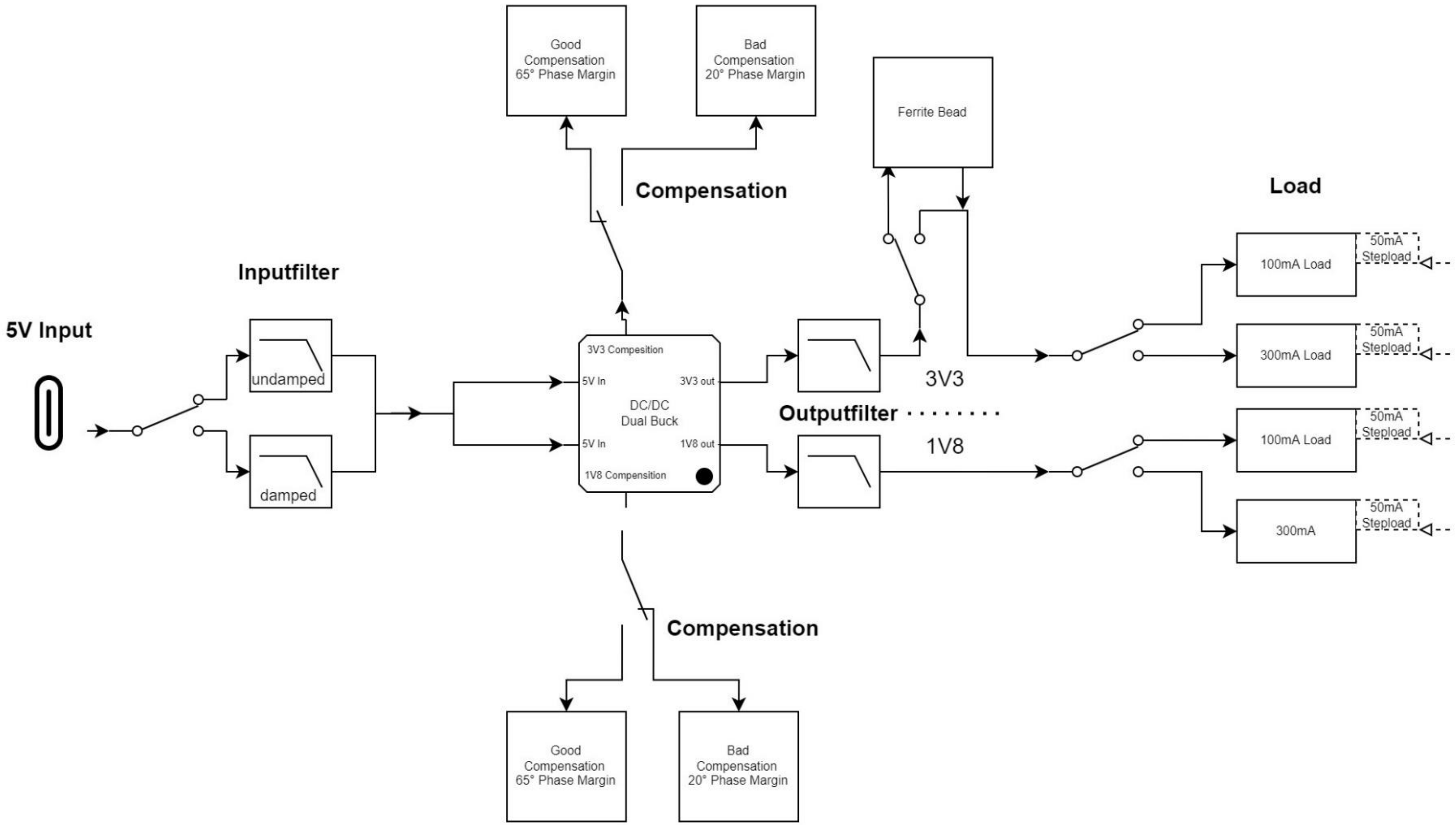
- Frequency Response Analyzer and Vector Network Analyzer in one device
- Reliable results – high accuracy, high dynamic range
- Easy to use – BAS controlled, USB-C, Ethernet
- Portable – compact lightweight design
- mHz to 450 MHz
- Silent

Bode Analyzer Suite

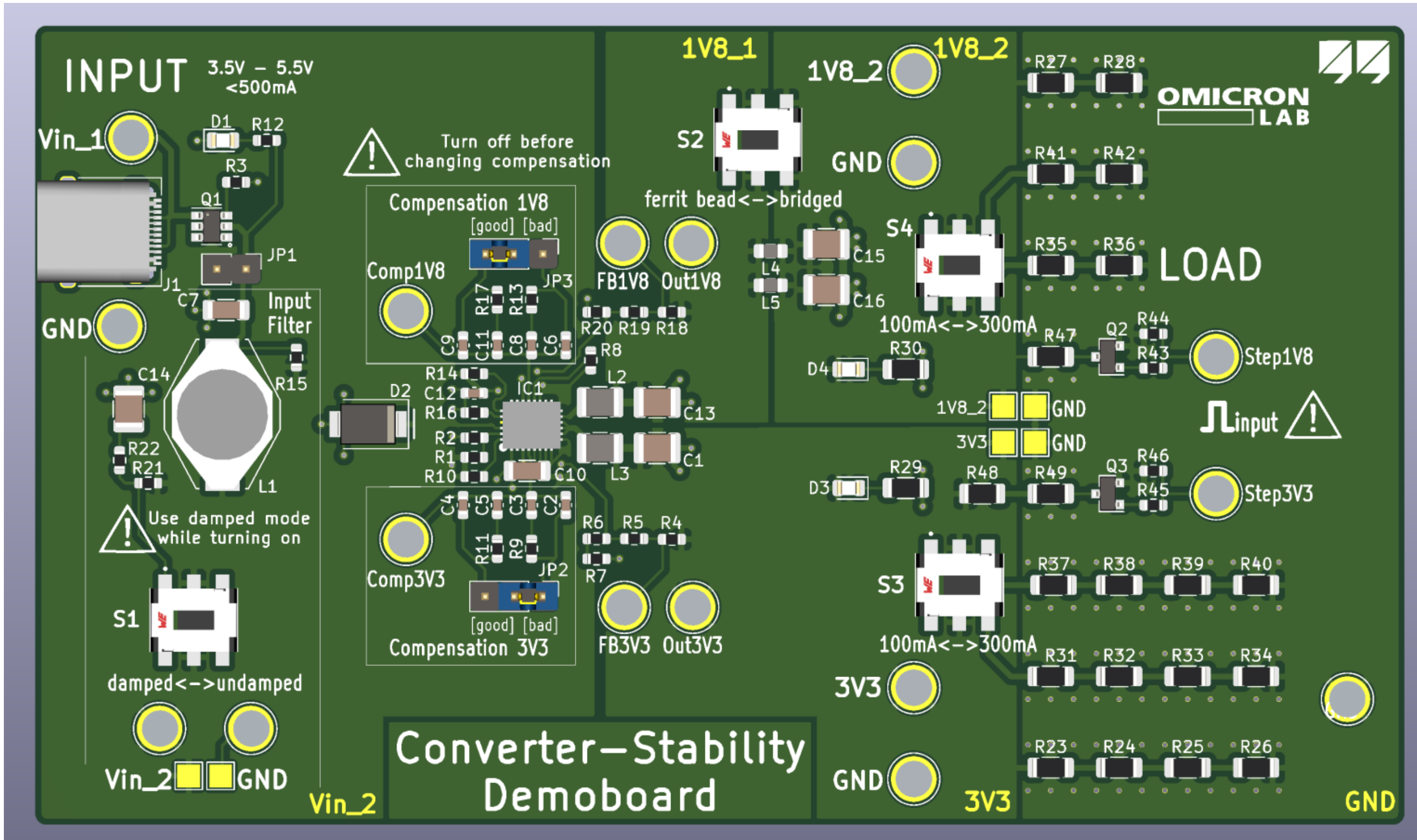
- Easy-to-use
- Powerful
- Free



Hands-On (Converter Stability Demoboard)

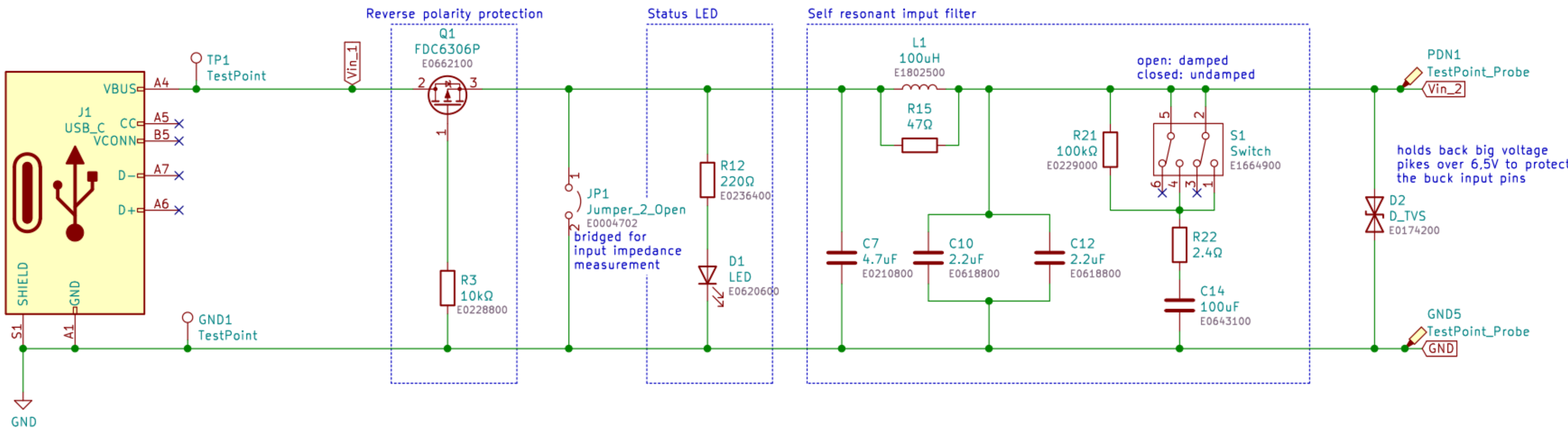


Hands-On (Converter Stability Demoboard)

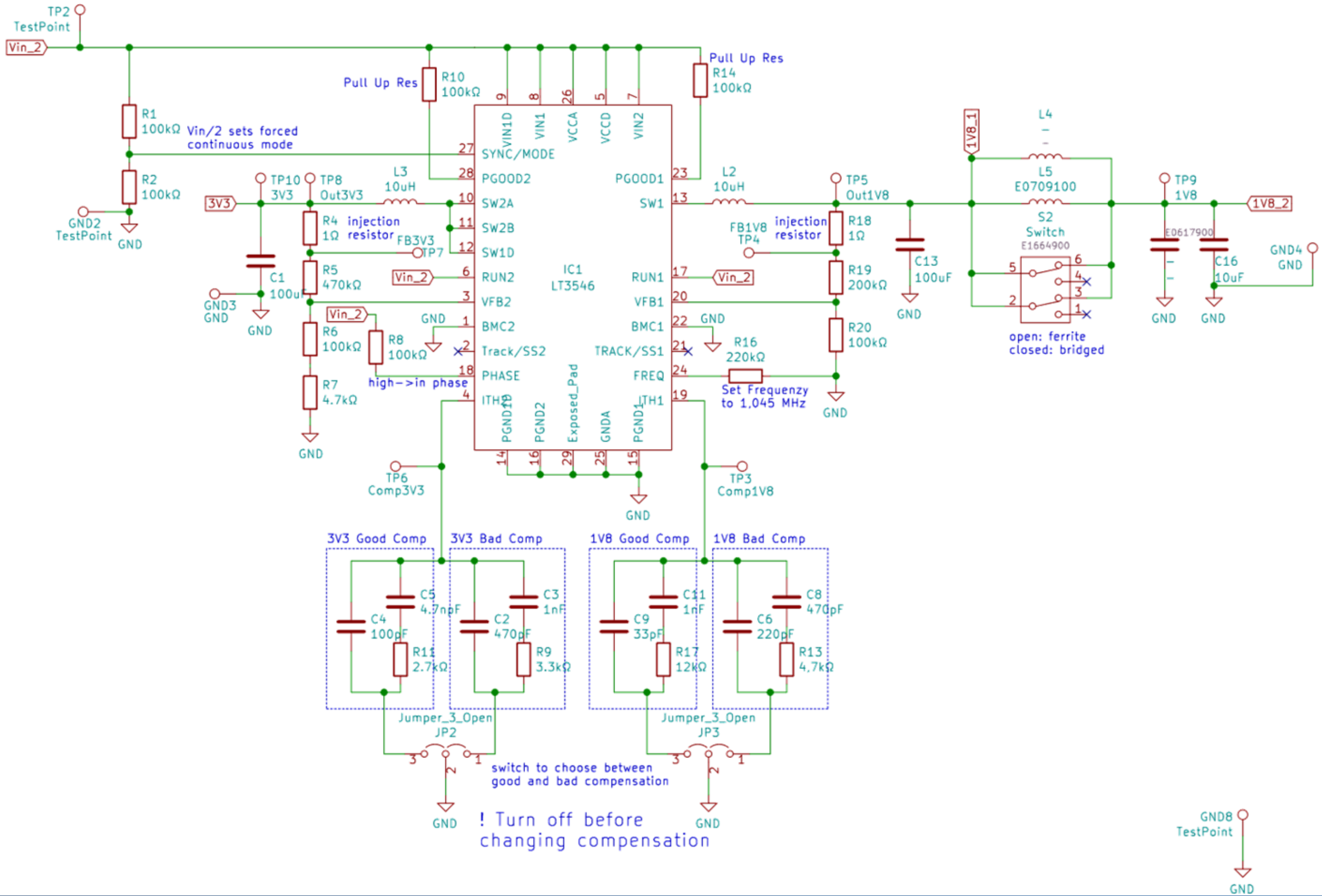


OMICRON LAB

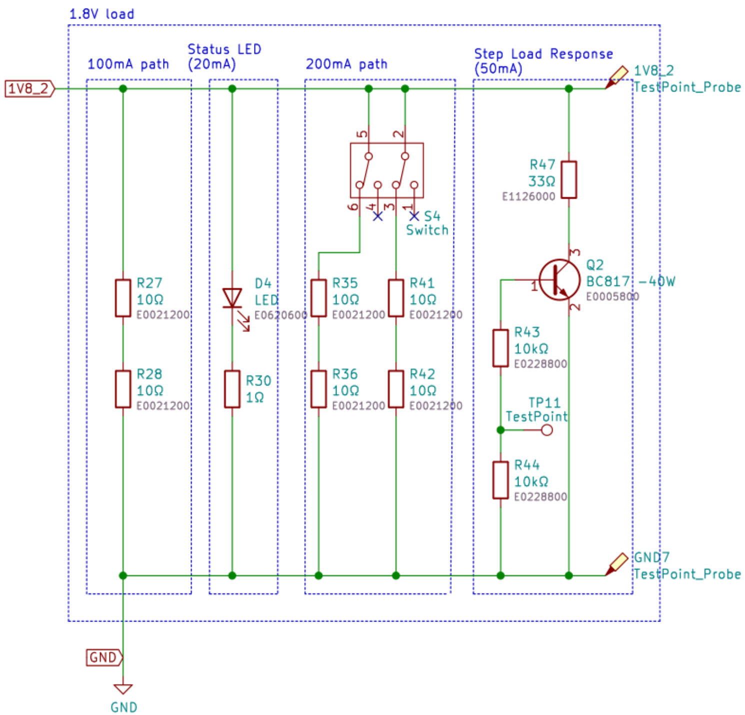
Input Filter Section

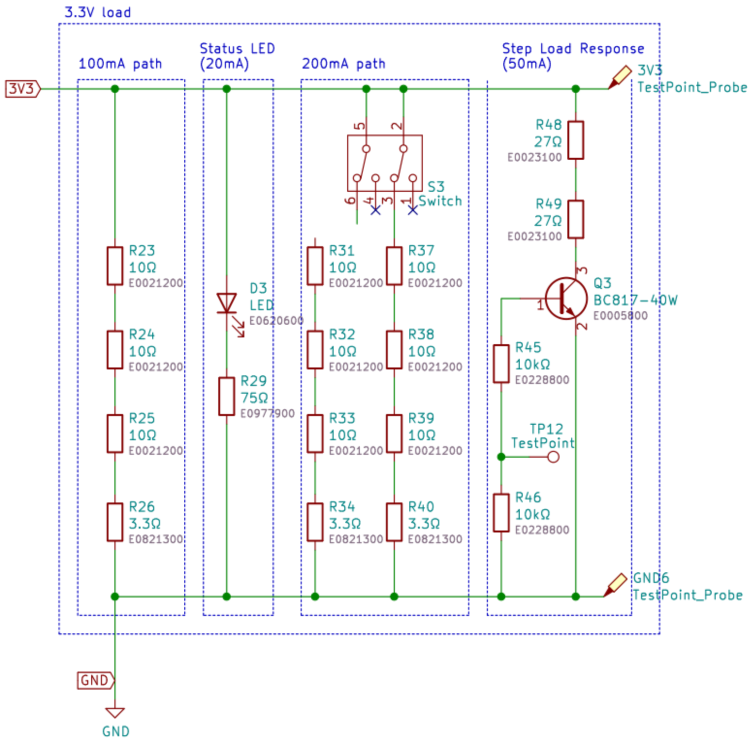


Dual DC/DC Section

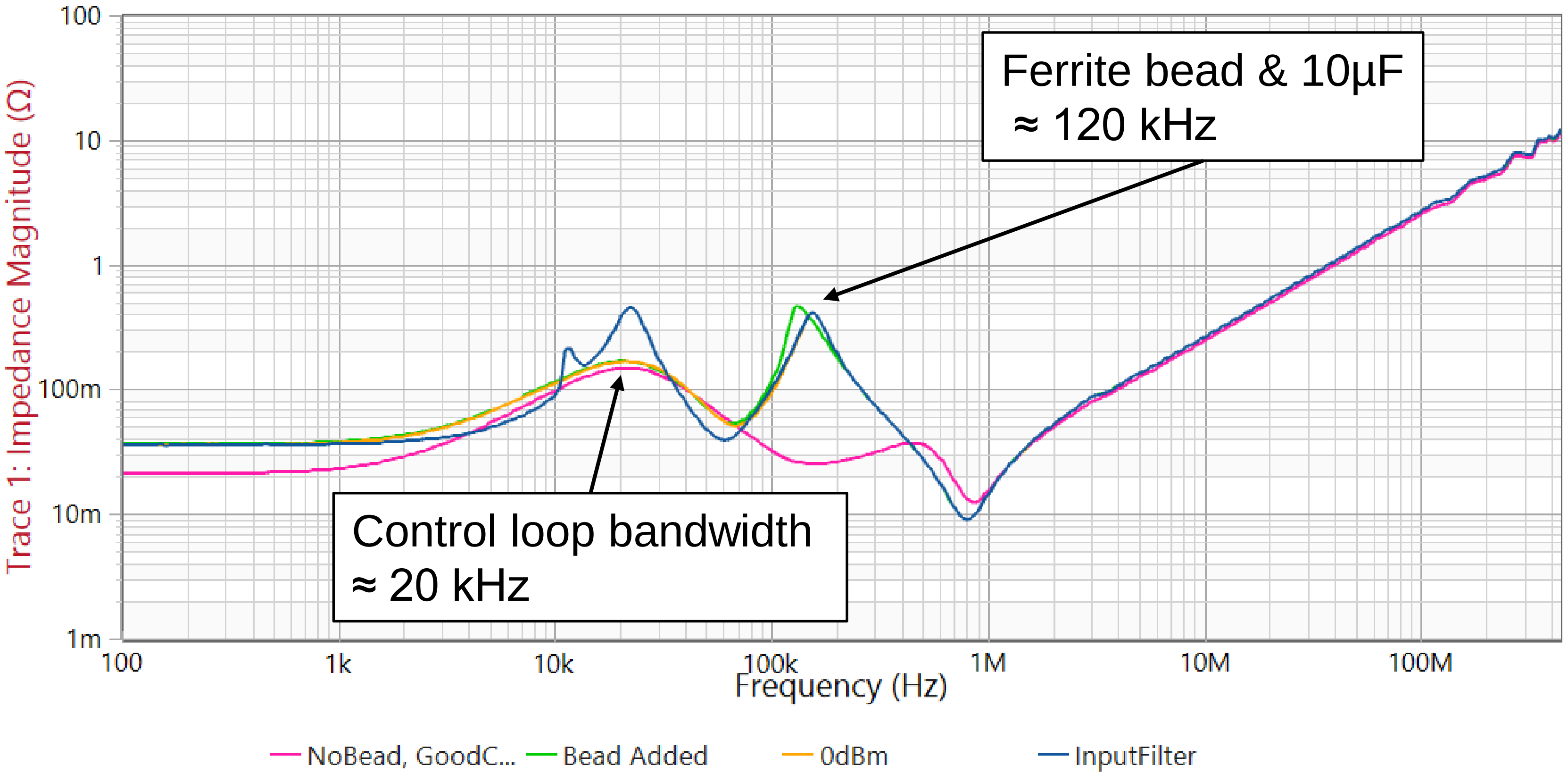


Load Section



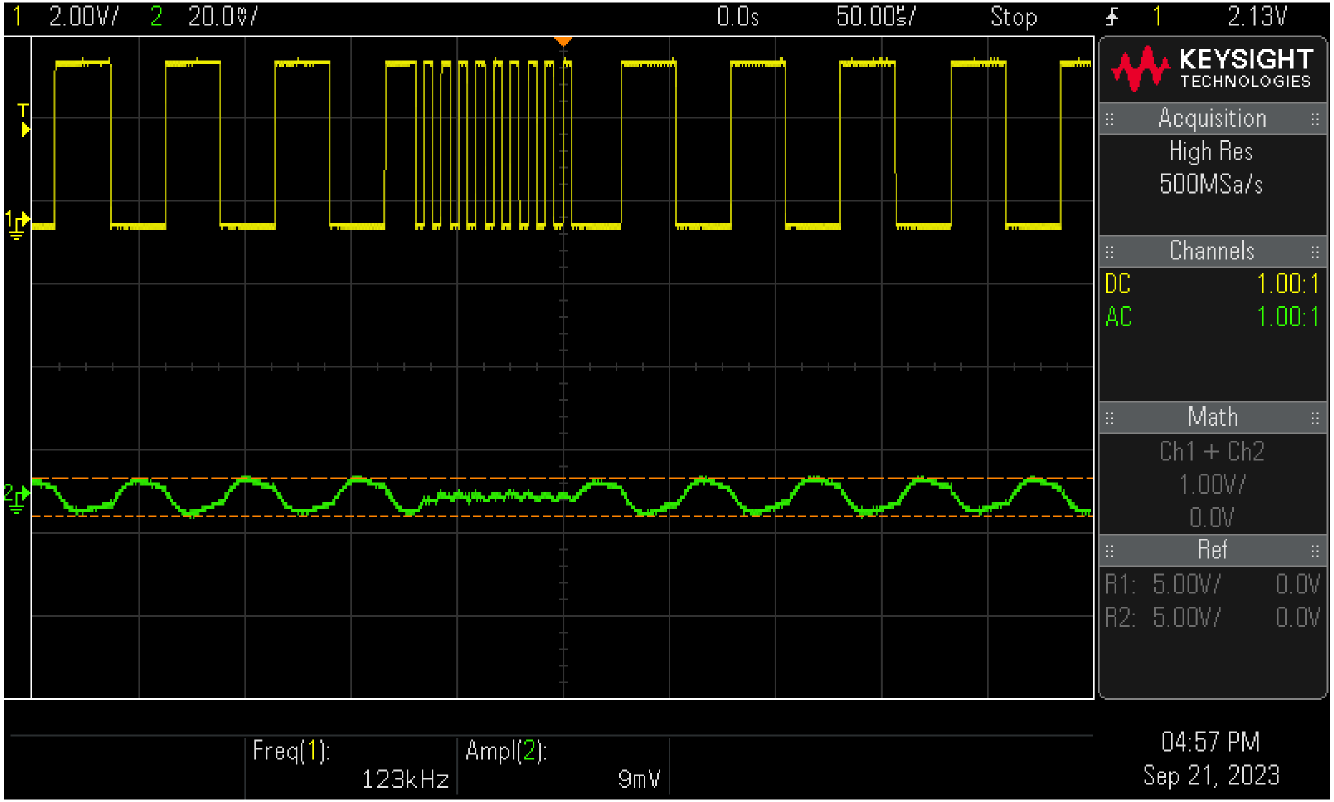


1V8 PDN Impedance



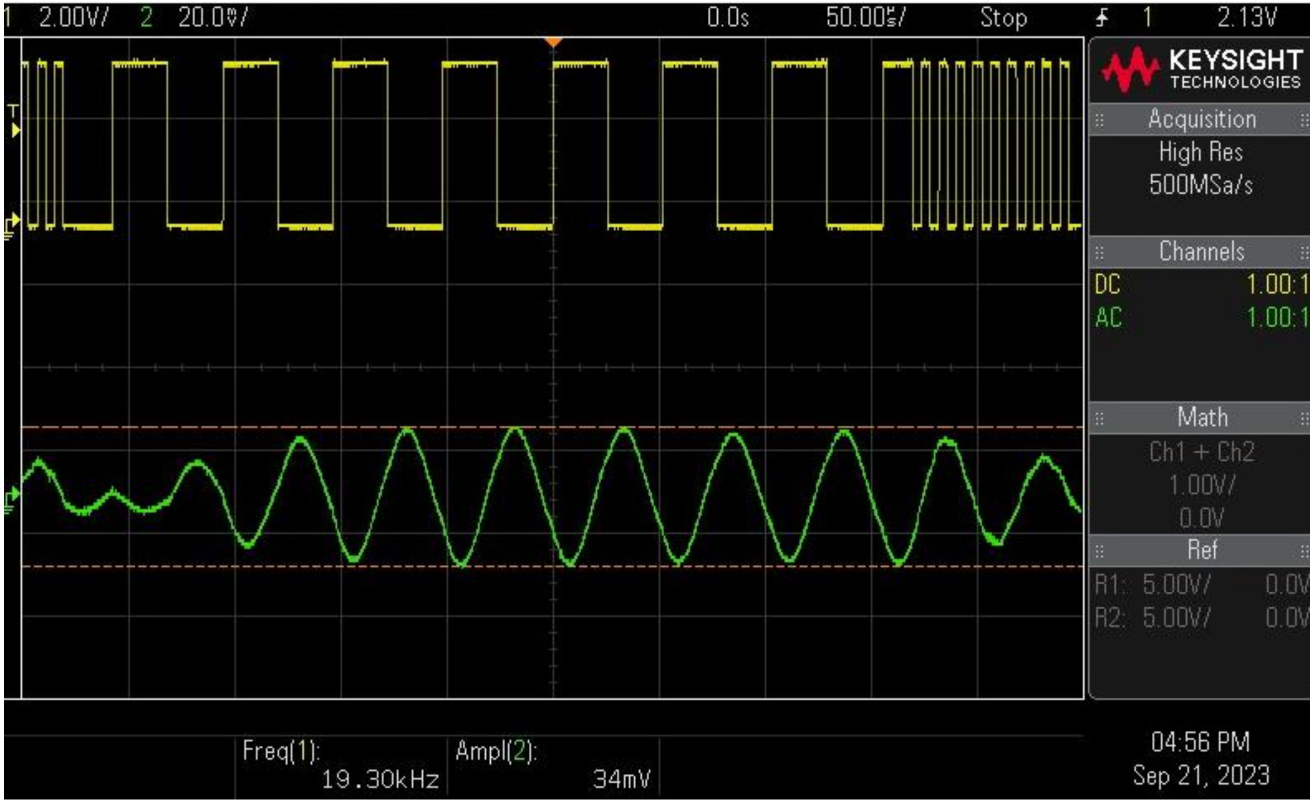
Load Stepping (20 kHz & 120 kHz)

50° Phase Margin, no 2^{nd} resonance ≈ 9 mVpp



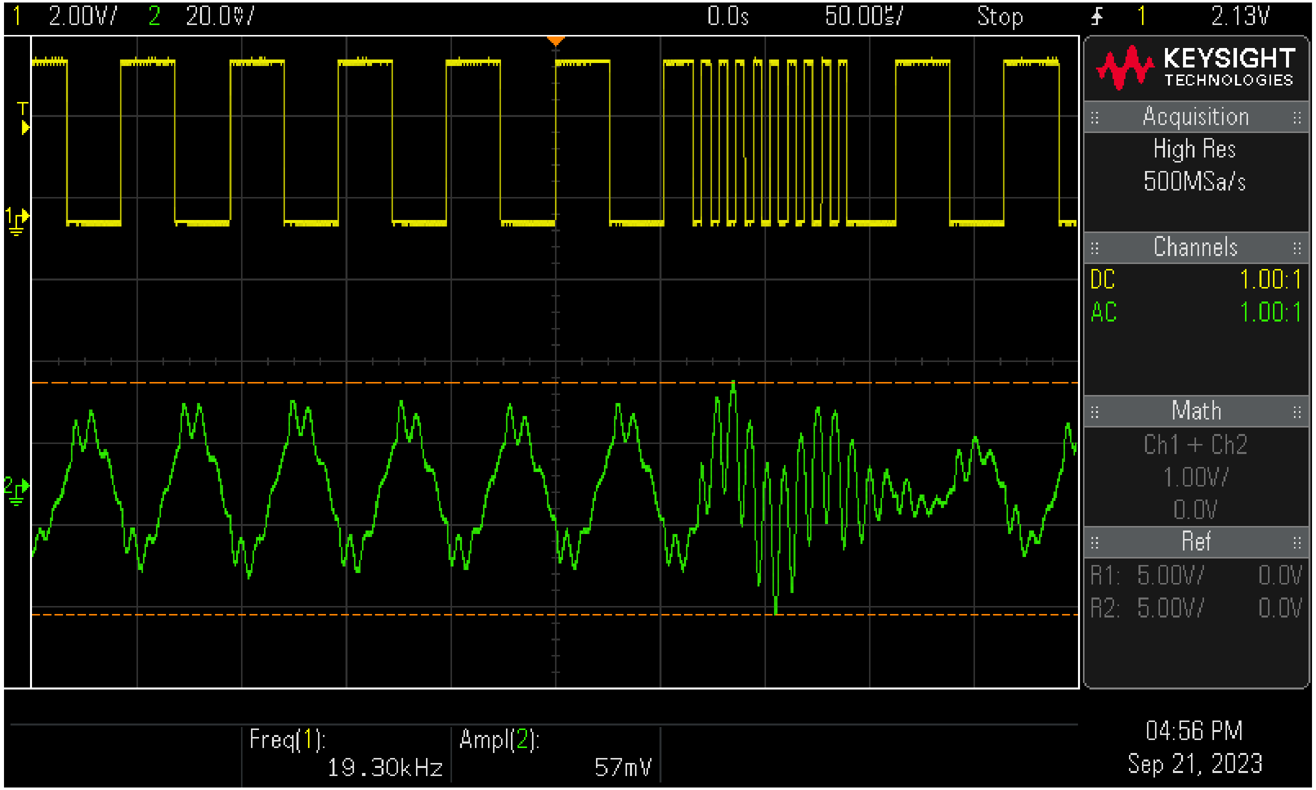
Load Stepping (20 kHz & 120 kHz)

15° Phase Margin, no 2nd resonance ≈ 34 mVpp



Load Stepping (20 kHz & 120 kHz)

15° Phase Margin + 2nd resonance ≈ 57 mVpp



Summary

- PDN impedance reveals information about
  - Control loop stability
  - Resonance frequencies in the PDN network
- Measuring PDN impedance is rather simple
  - The output capacitors are nearly always accessible
  - The control loop must not be broken
- A flat impedance approach guarantees optimum damping at all frequencies
- Lower output impedance results in less noise on power rail

References and further information:

[1] Sandler, S., *Designing Power for Sensitive Circuits, EDICon*, 2017

[2] Sandler, S., *Target Impedance and Rogue Waves, DesignCon*, 2016

[3] Sandler, S., *Power Integrity*, Mc Graw Hill Education Ltd, 2014

[4] Sandler, S., How to measure ultra-low impedance (100uOhm and lower) PDNs, EDI CON, 2018

[5] Dannan, B., Sandler, S., The Challenge of Measuring a 40 uOhm (2000 Amp) PDN with a 2-Port Probe – How Much CMRR is Needed?, www.signaledgesolutions.com, 2024

[6] Young, C., Novak, I., Simulating and Measuring Microohms in PDNs, DesignCon, 2015

[7] Novak, I., Miller, J., Frequency Domain Characterization of Power Distribution Networks, Artech House, 2007

Thank you for your attention!

If you have questions or proposals to the OMICRON Lab team, please contact us via info@omicron-lab.com.

My personal e-mail: florian.haemmerle@omicron-lab.com