DC Biased Impedance Measurements

OMICRON Lab Webinar Series 2020

2020-05-06

Webinar Hints

Open the Q&A function

Send questions to the presenters

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- Founder of AEI Systems in 1995 and Picotest in 2010
- Author of several Books and dozens of articles
- Specializing in Power Integrity, Simulation and Measurement since 1990
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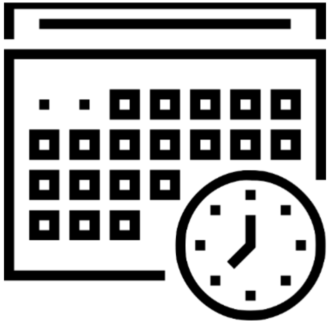
Agenda

- DC Bias Inductor Measurements (Steve Sandler)
  - Live Hands-On Measurements

- DC Bias Capacitor Measurements (OMICRON Lab)
  - Why DC Biasing?
  - Bode 100 Maximum Ratings
  - DC Voltage Biasing and DC Blocking
  - Measuring Capacitors
  - Live Hands-On Measurements



DC Biased Inductor Measurements

Steve Sandler, Managing Director, Picotest

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LinkedIn: Power Integrity for Distributed Systems

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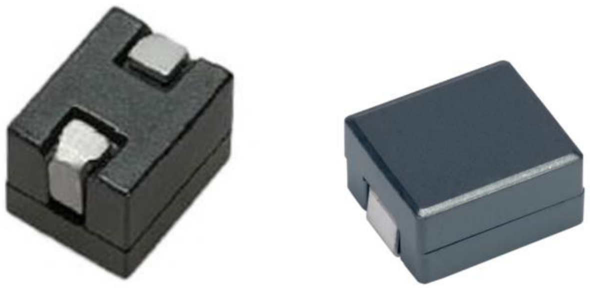
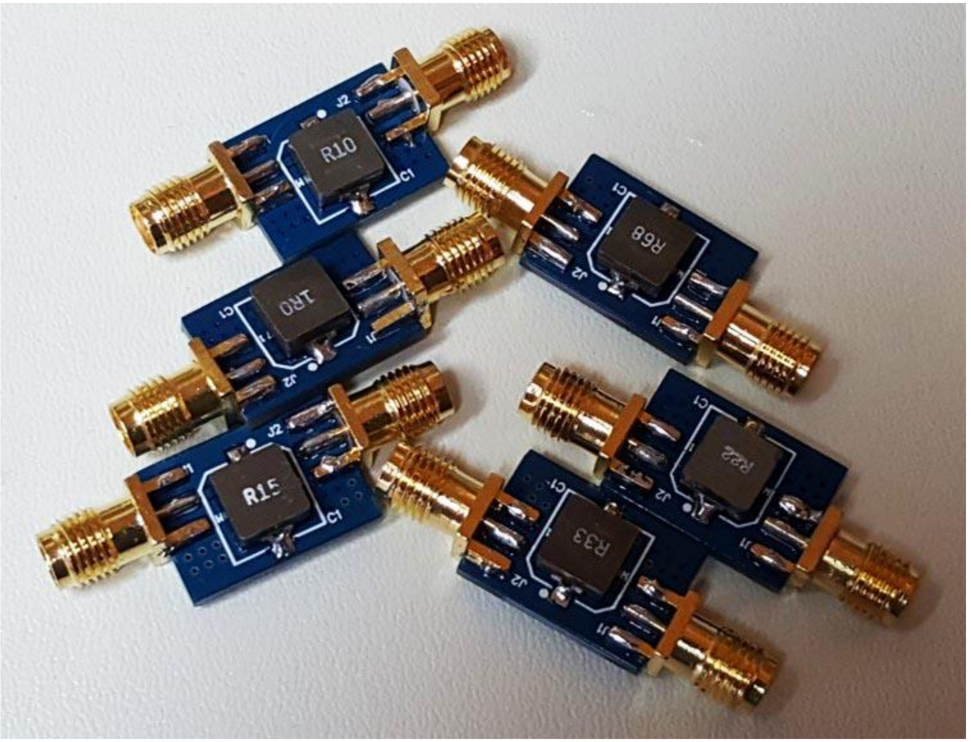
Why Measure Inductors at All?



- As efficiencies increase, the inductor losses have more impact
- Major influence on voltage ripple
- Counterfeit materials abound
- To Obtain, L, R, C model for simulation



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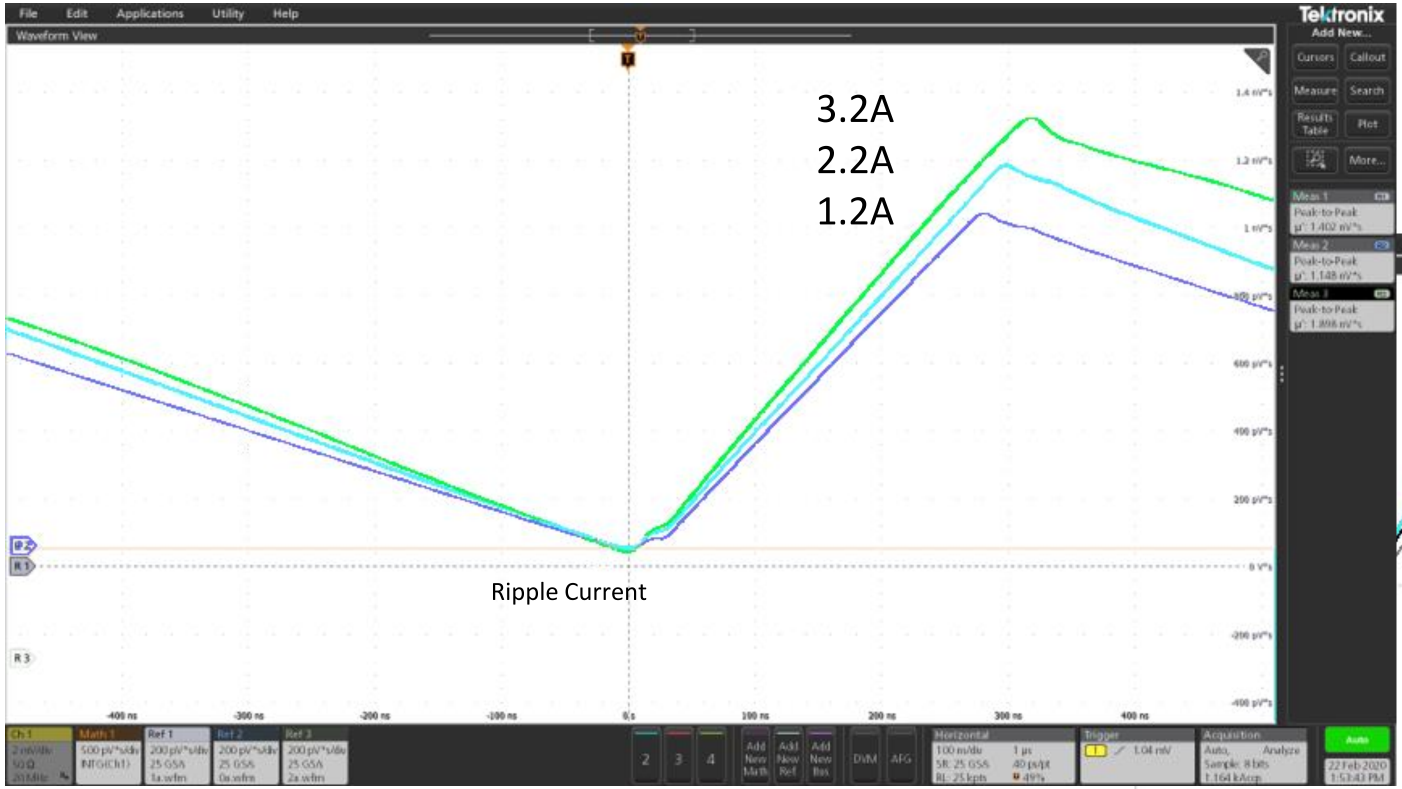
Why With DC Bias

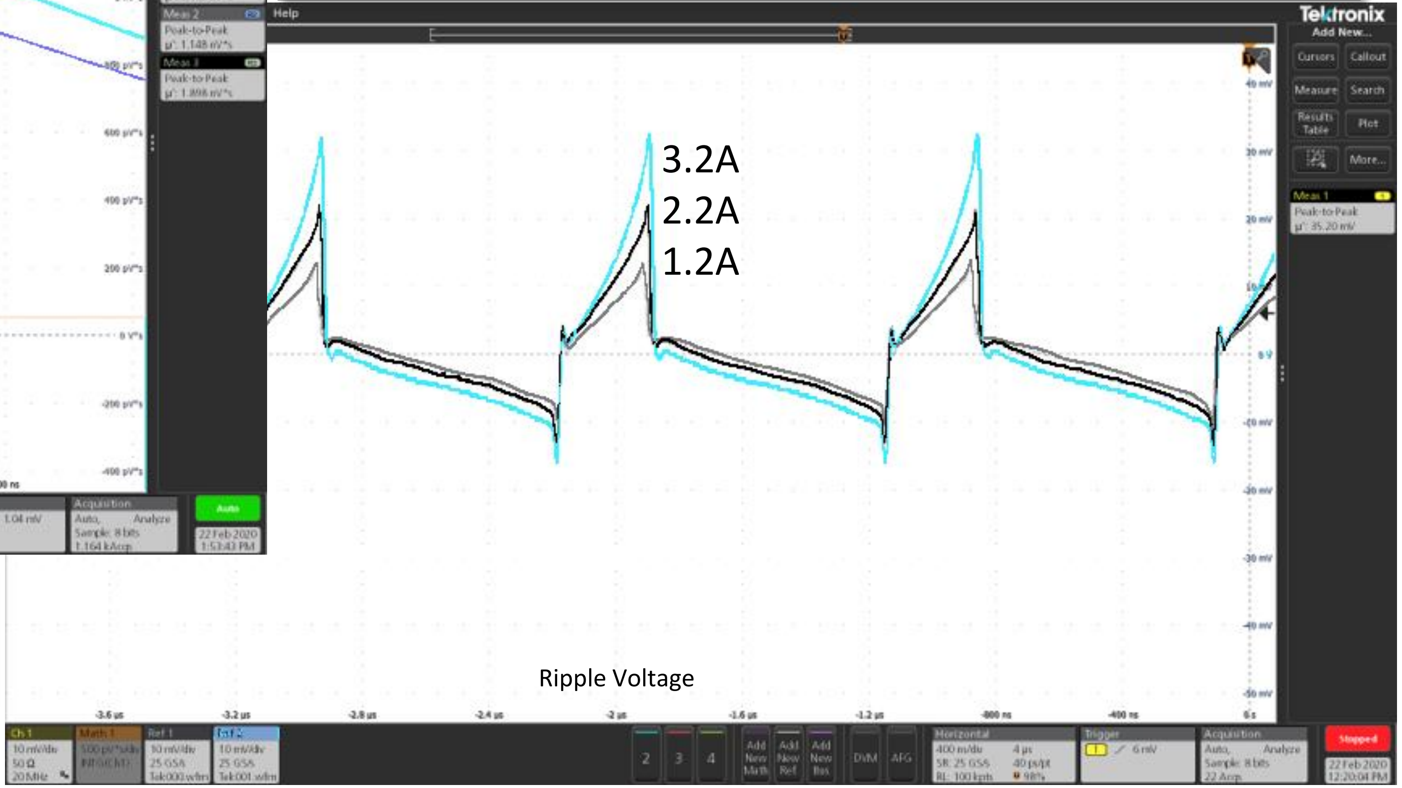
DC-DC Converters are shrinking, we need smaller components

Optimizing is important



Saturated inductors result in higher ripple current, degrading efficiency

Saturated inductors results in higher ripple voltage



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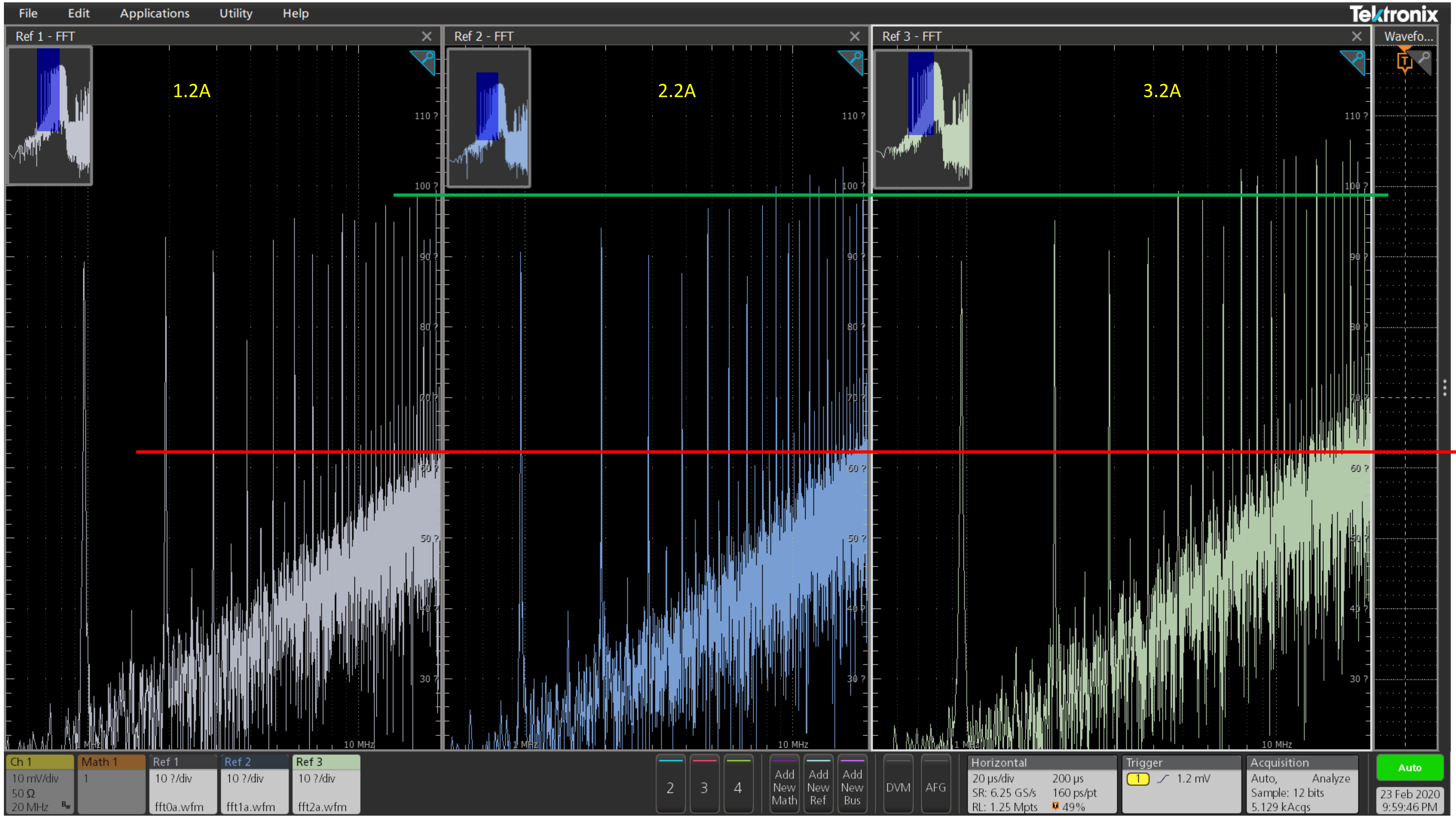
Inductor Current Spectral Content

Saturated inductors results in increased high frequency content causing increased core loss, increased skin effect loss, and increased EMI



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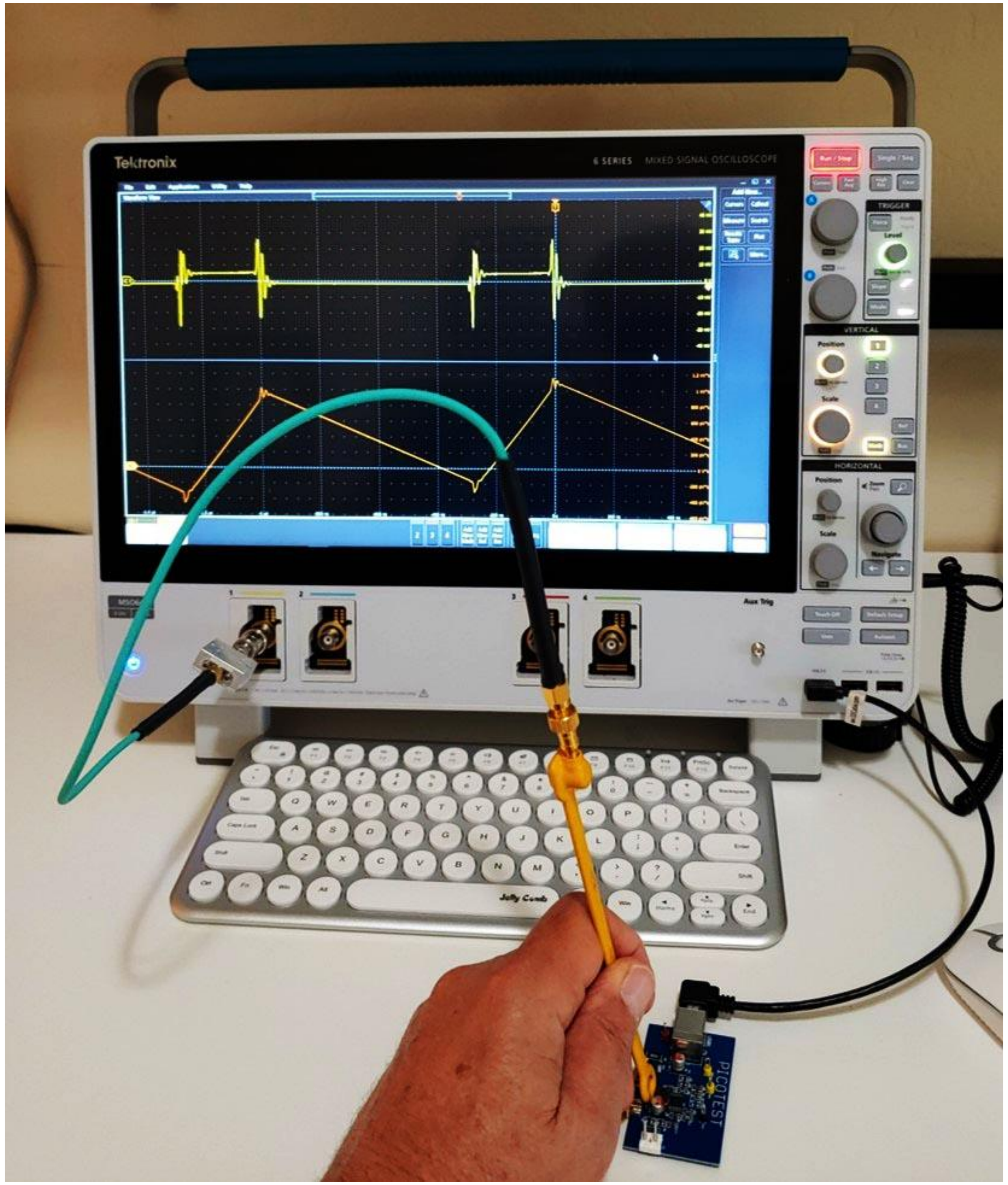
Measuring in Circuit

- Measure ripple current using a near field probe
- Integrate measurement using math function
- Scale using probe calibration curve or based on known current

$$L = \frac{V_{ind}}{di/dt}$$

$$V_{ind} \approx V_{out}\ during\ current\ fall\ time$$

$$V_{ind} \approx V_{in} - V_{out}\ during\ current\ rise\ time$$



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Advantages and Disadvantages

Advantages

- Little equipment is needed other than scope
- Existing load is used to adjust inductor current

Disadvantages

- Measurement is after design is completed
- Little comparative information is obtained
- Some inductors are well shielded, which can degrade accuracy

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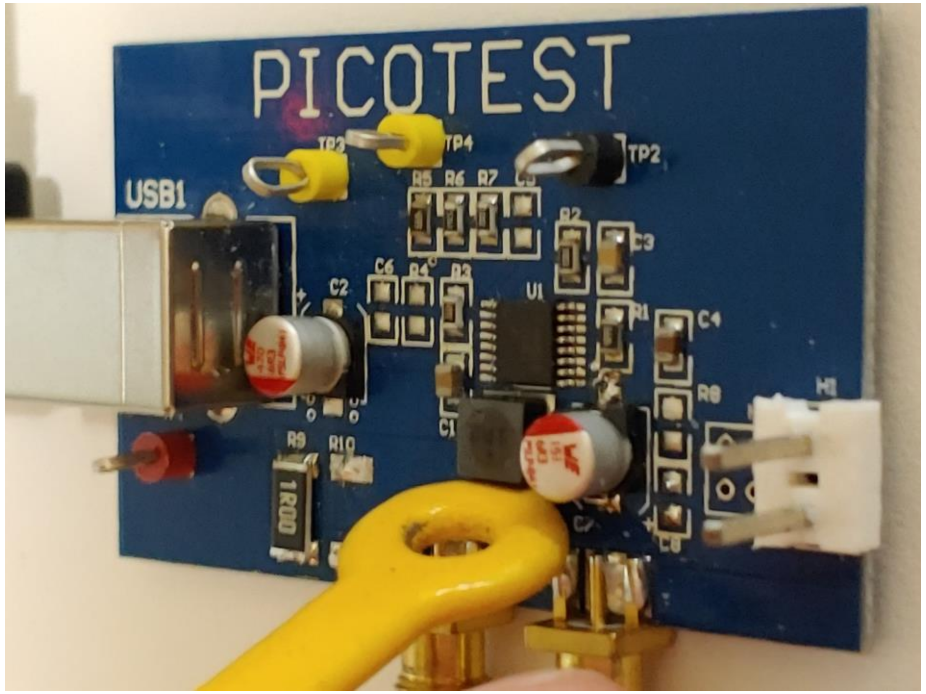
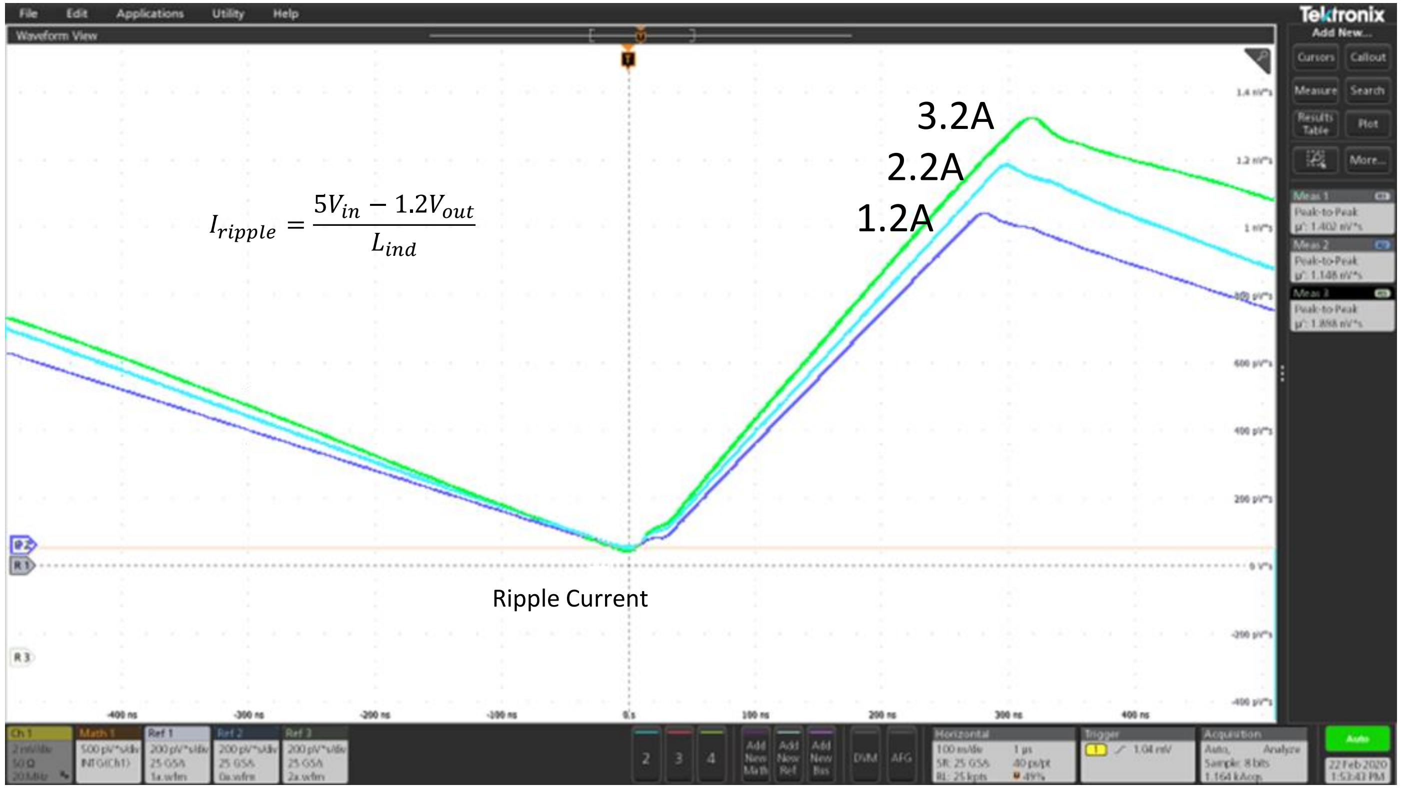
Picotest LM20143 Demo Board

Beehive H field probe properly oriented



Measured using on-board 1.2A load; also 1A and 2A additional load from electronic load



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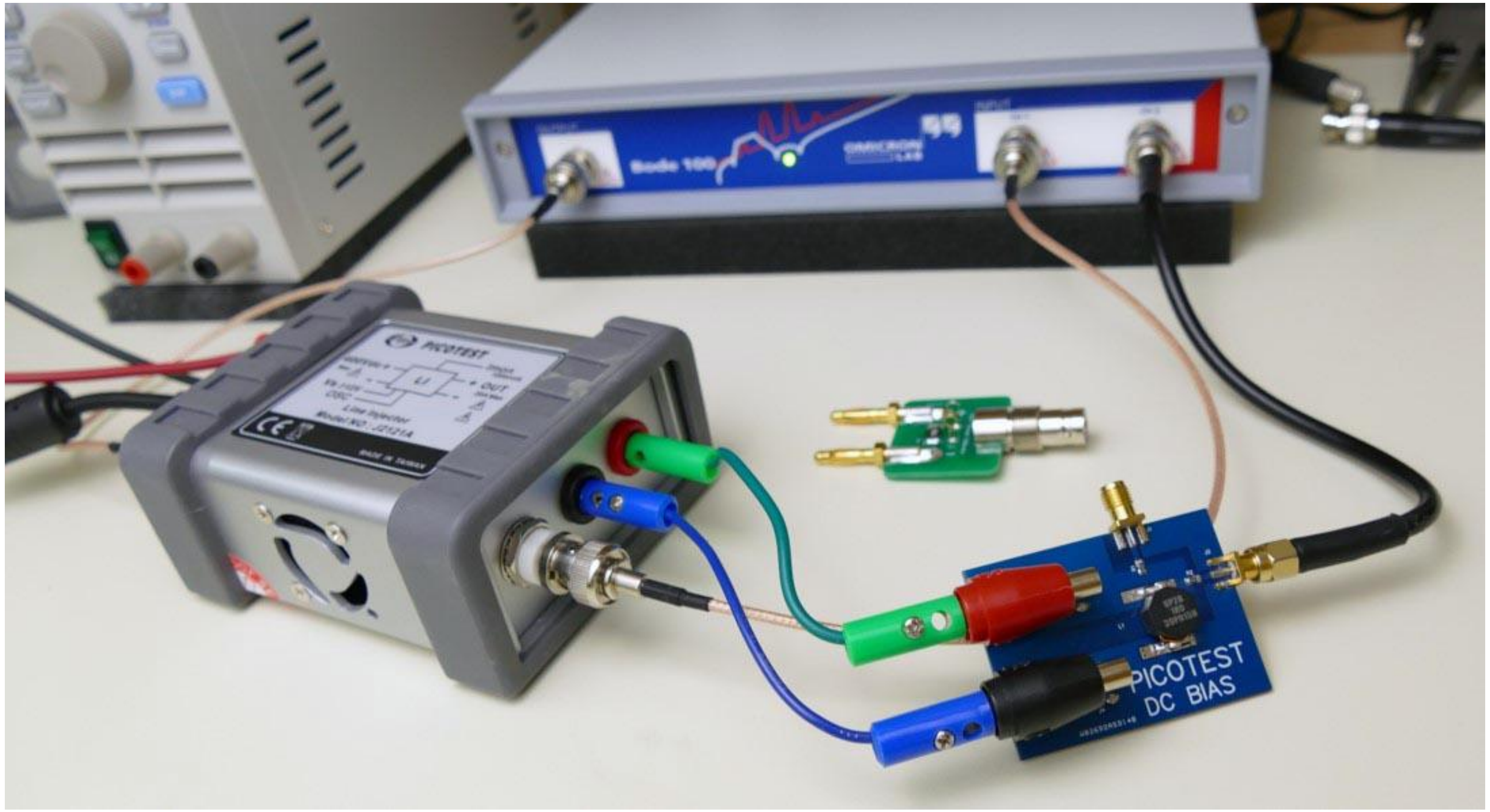
Three Port FRA Measurement



- **Set bias current using constant current mode on bench power supply (<0.7A for cal)**
- **Perform THROUGH calibration with 1Ω resistor**
- **Modulate inductor voltage using J2121A Line Injector**
- **Measure inductor voltage**
- **Measure inductor current using monitor or external current probe**

$$Z = \frac{V_{ind}}{I_{ind}}$$

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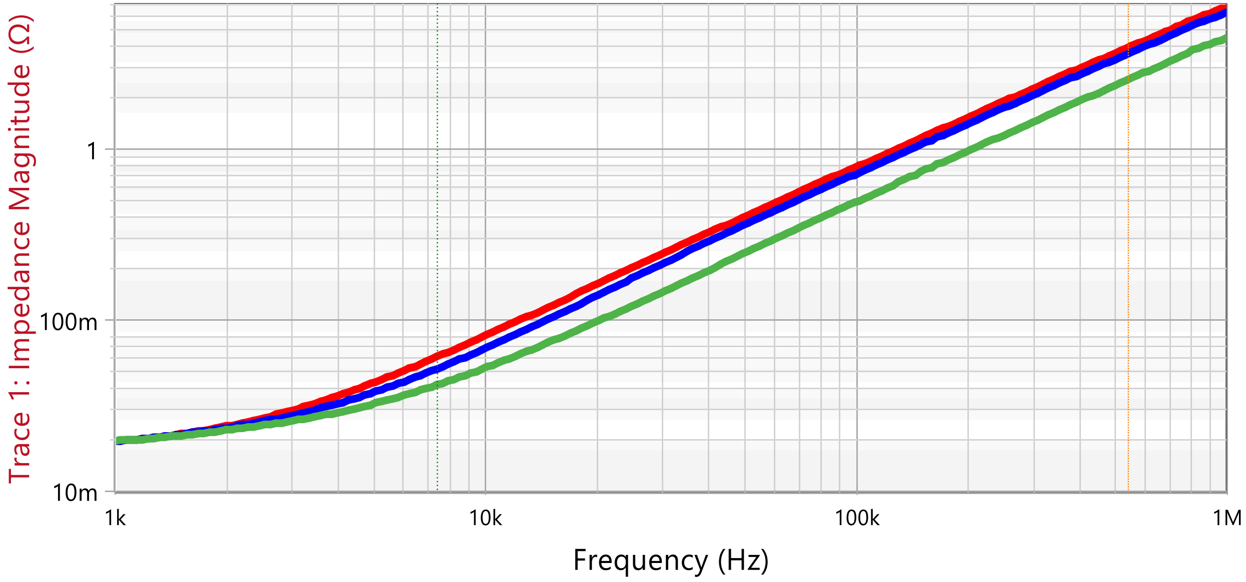
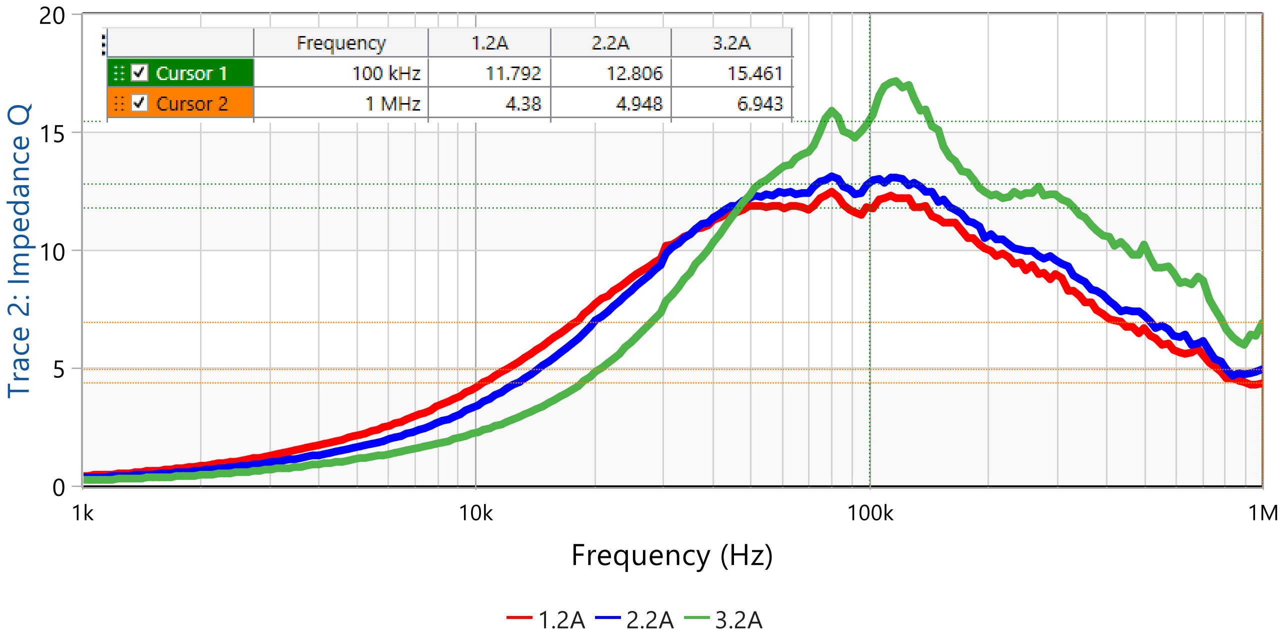
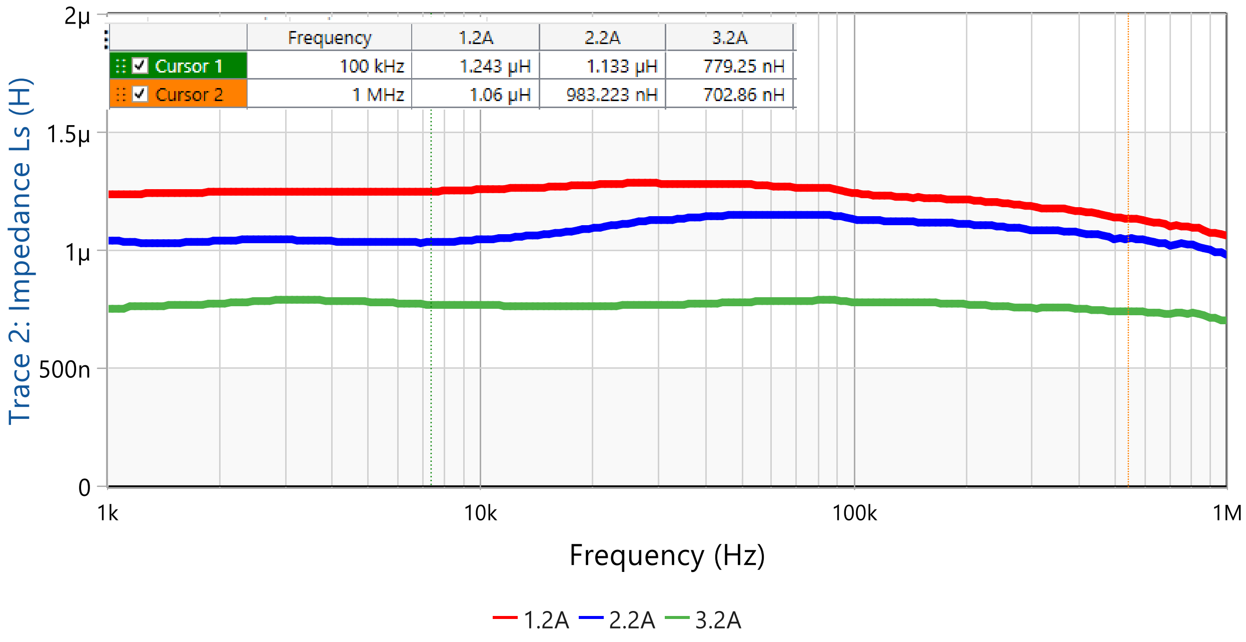
Frequency Domain

Frequency domain offers much higher resolution data, in a variety of formats that are easier to assess and compare







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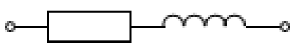
1MHz Single Frequency Equivalent Circuits

Format	Value
Real	1.383 Ω
Imaginary	6.609 Ω
Magnitude	6.752 Ω
Magnitude (dB)	16.589 dB Ω
Phase (°)	78.183 °
Phase (rad)	1.365 rad

Series equivalent circuit

Rs = 1.383 Ω



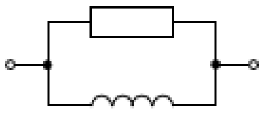
Ls = 1.052 μH

Q = 4.78

tan(δ) = 209.214 m

Parallel equivalent circuit

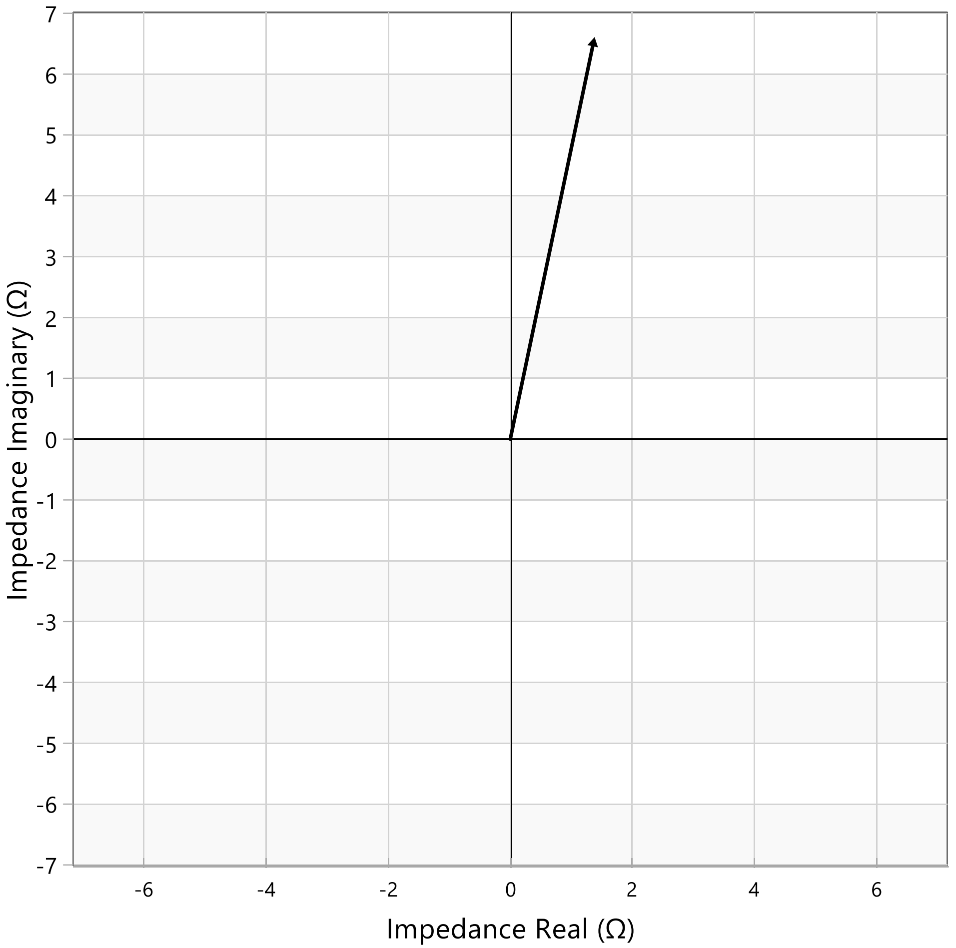
Rp = 32.974 Ω



Lp = 1.098 μH

Q = 4.78

tan(δ) = 209.214 m



The best comparative figure of merit for the inductor performance is Q

At a single frequency, the inductor model can be directly displayed

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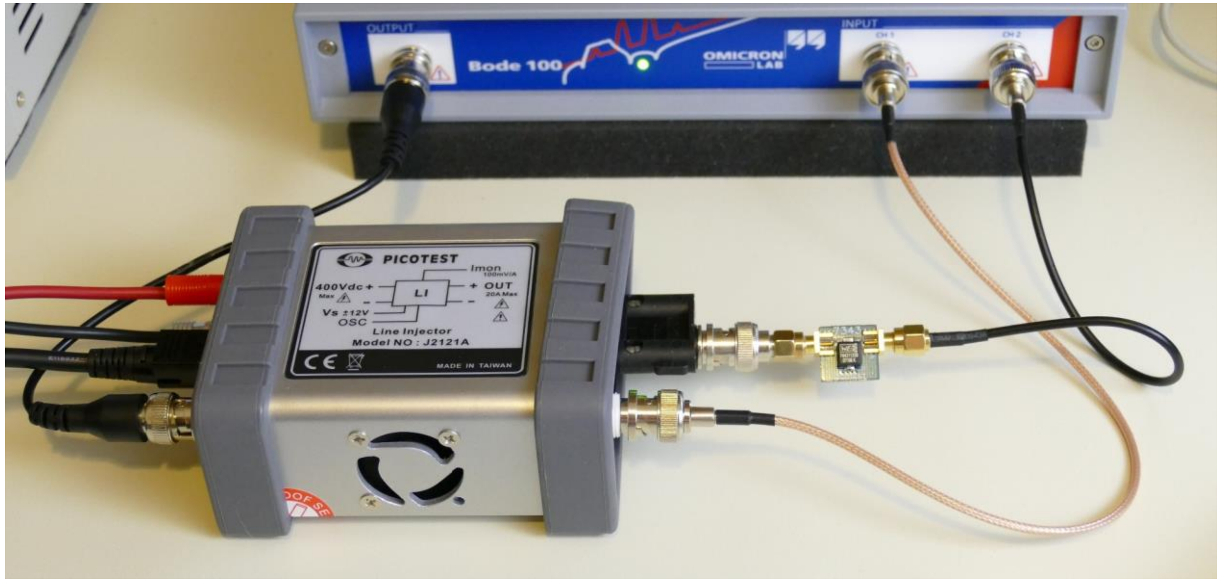
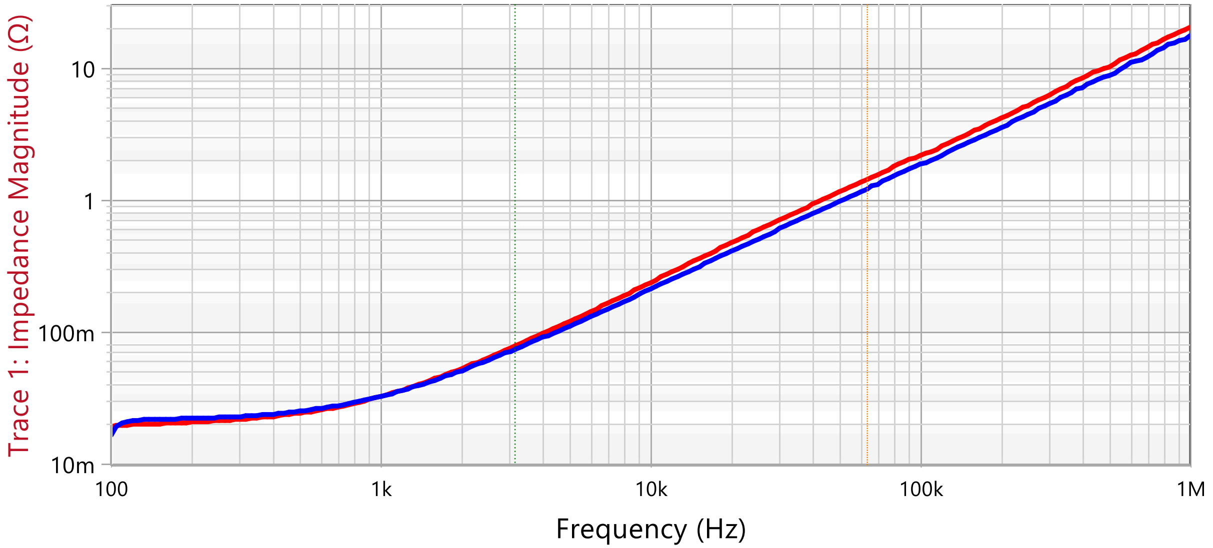
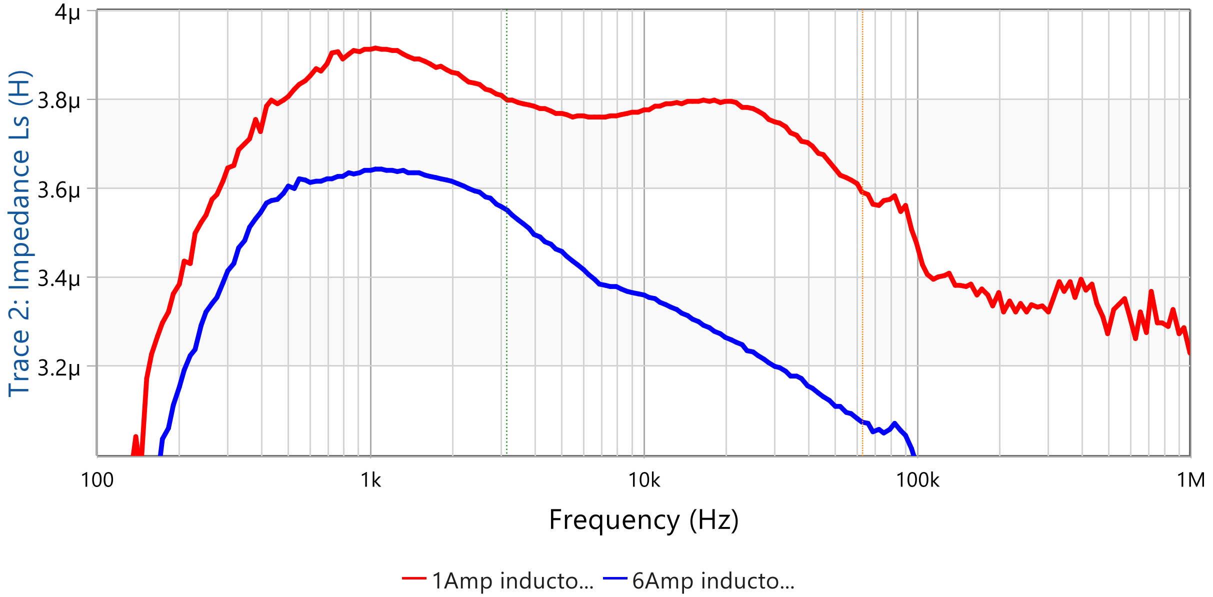
Example







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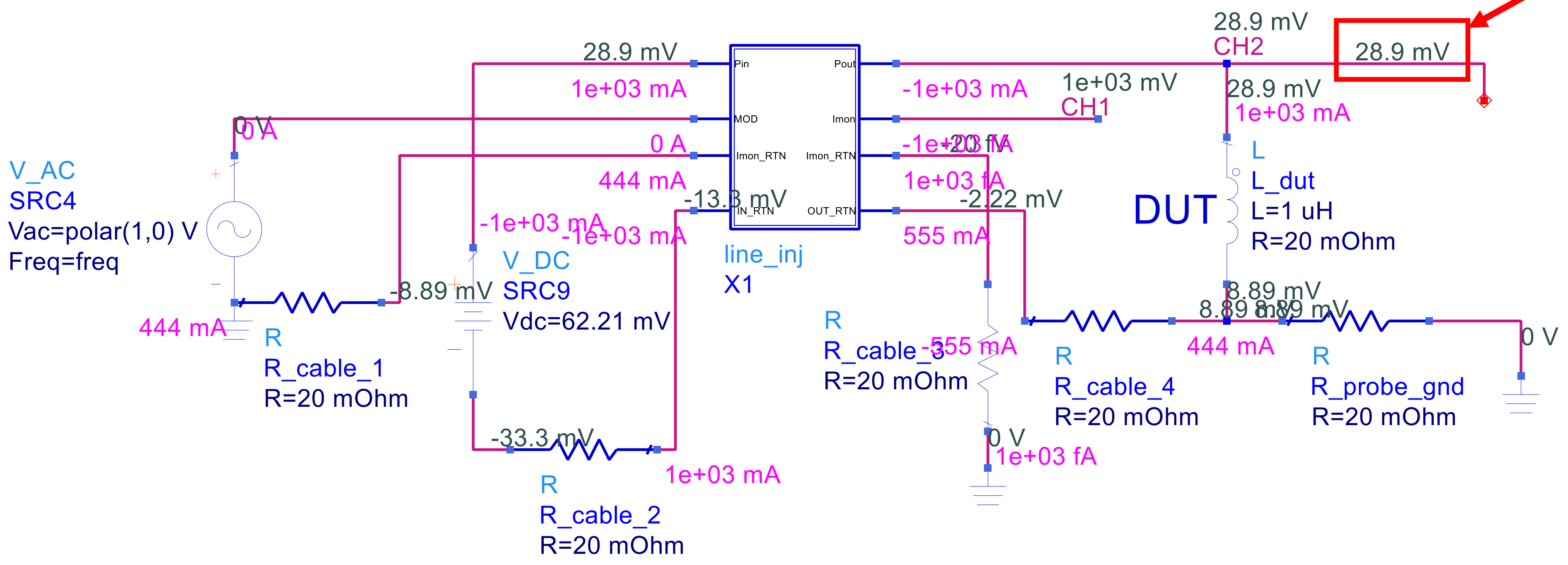
3-Port Ground Loop

Note that at 1A 20mΩ DUT should read 20mV



While the DUT is biased at 1 Amp, note that current flows through some of the cables, generating offset voltages that degrade accuracy

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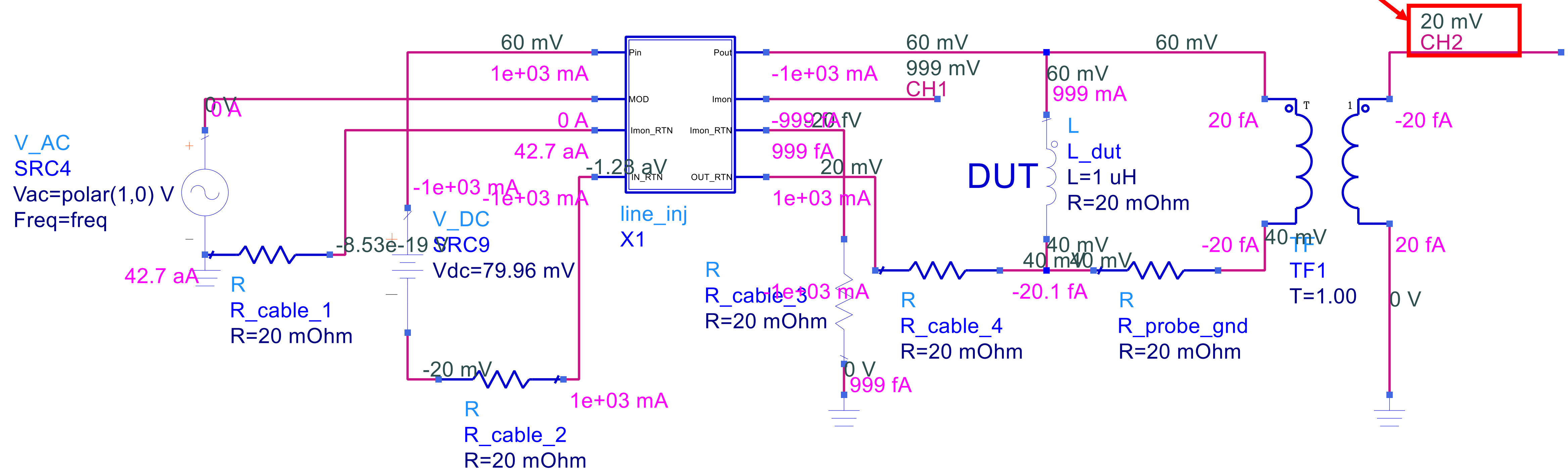
3-Port Ground Loop

Differential probe eliminates the ground loop



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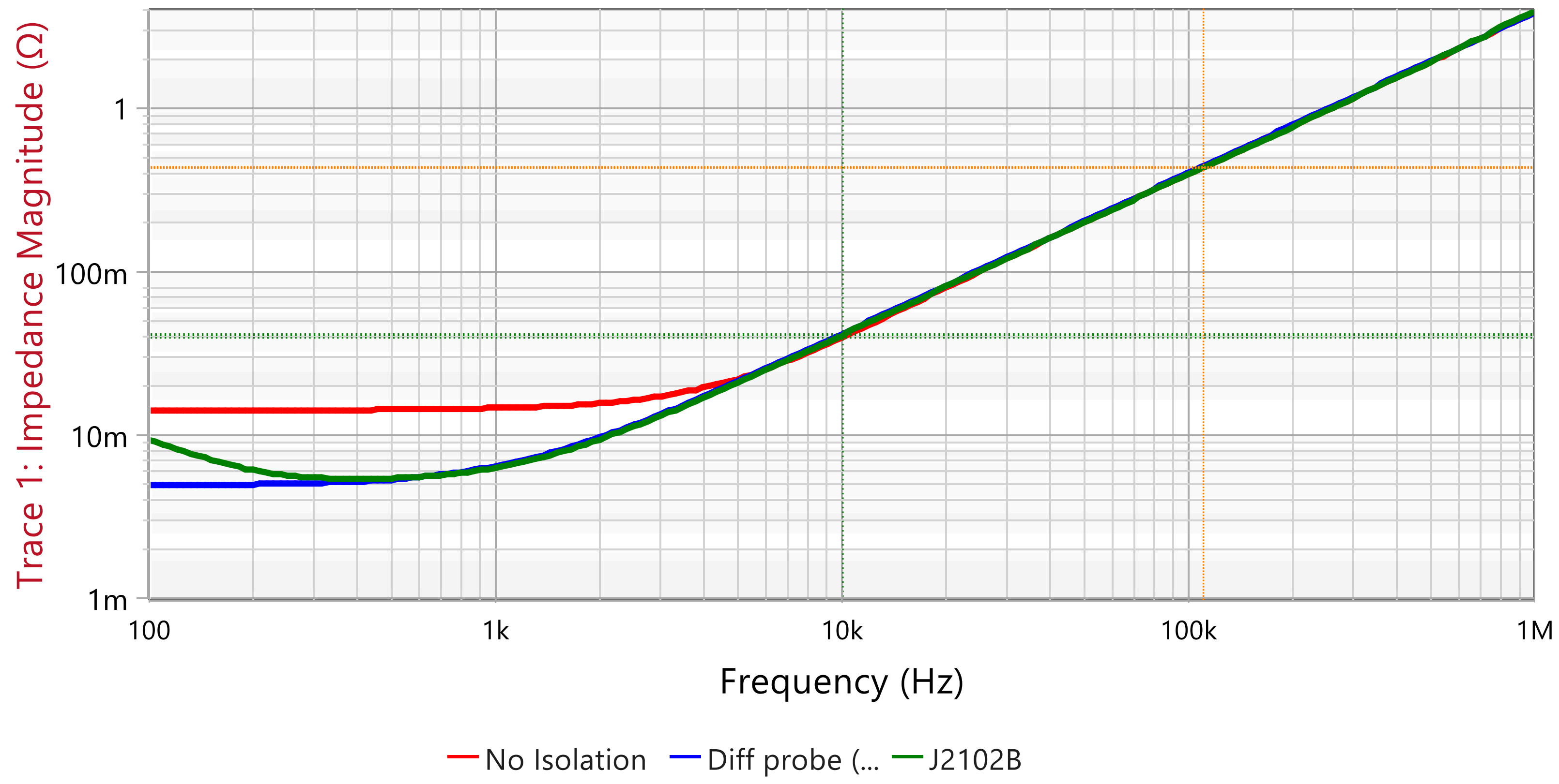
620nH / 5.1 mOhm Comparison

	Frequency	No Isolation	Diff probe (...	J2102B	No Isolation	Diff probe (...	J2102B
Cursor 1	200.54 Hz	14.203 mΩ	4.993 mΩ	6.091 mΩ	536.338 nH	644.307 nH	-1.378 µH
Cursor 2	100.242 kHz	394.504 mΩ	399.844 mΩ	392.634 mΩ	625.711 nH	634.106 nH	622.87 nH



- Use high quality, low resistance cables, such as PDN Cables
- Keep interconnects as short as possible
- For accurate low frequency measurements, use a coaxial isolation transformer (J2102B), semi-floating amplifier (J2113A) or low noise differential probe

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Advantages and Disadvantages

Advantages

- Can usually measure at operating switching frequency
- Same setup can measure negative DC-DC input impedance

Disadvantages

- Requires external modulation of the voltage source
- Limited Frequency range
- Requires high current power supply and interconnects
- Ground loop, requires differential probe or isolation transformer

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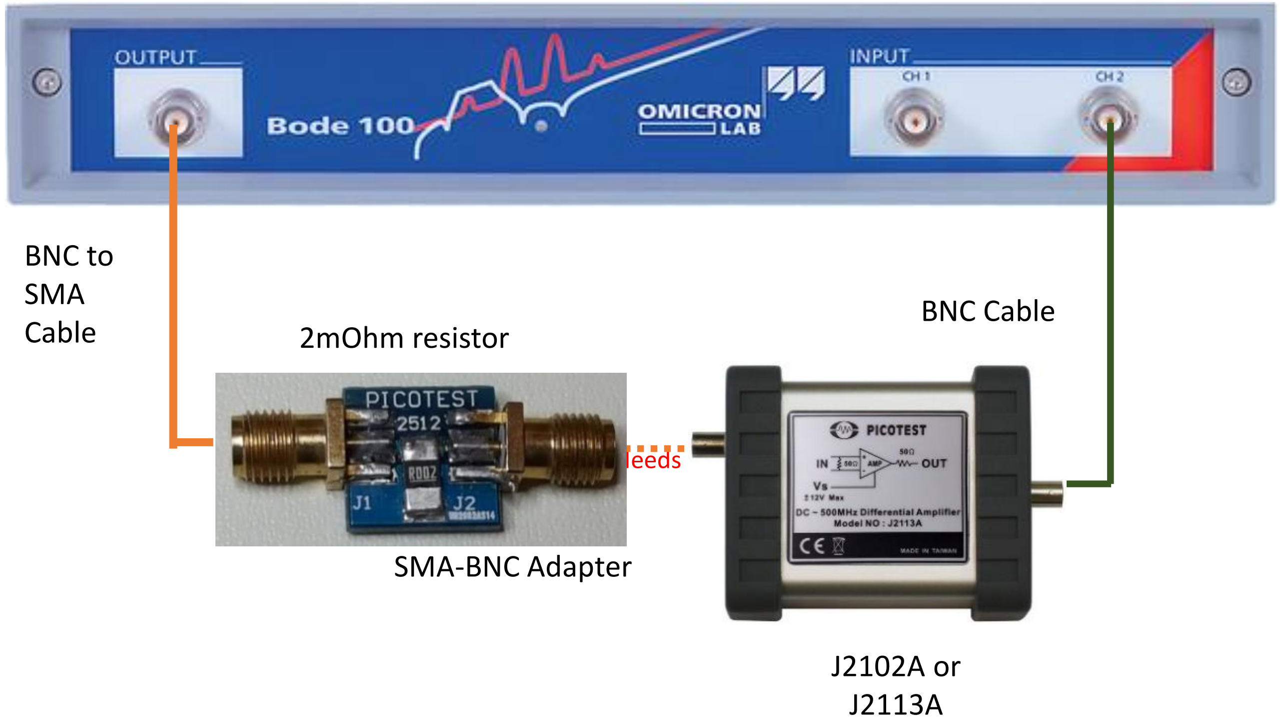
2-Port Shunt-Through Measurement



Using a 2-Port VNA, the device is measured in shunt with the 2-ports

An inherent DC ground loop is broken using either a coaxial transformer (J2102B) or a solid-state isolator (J2113A)

S21 scatter parameter is transformed to impedance within the VNA

The 2-Port Shunt-Through measurement can be used for impedance from 10's of uOhms to 100's of Ohms

https://www.picotest.com/measurements/2-port.html

https://www.picotest.com/measurements/2-portUltralowImpedance.html

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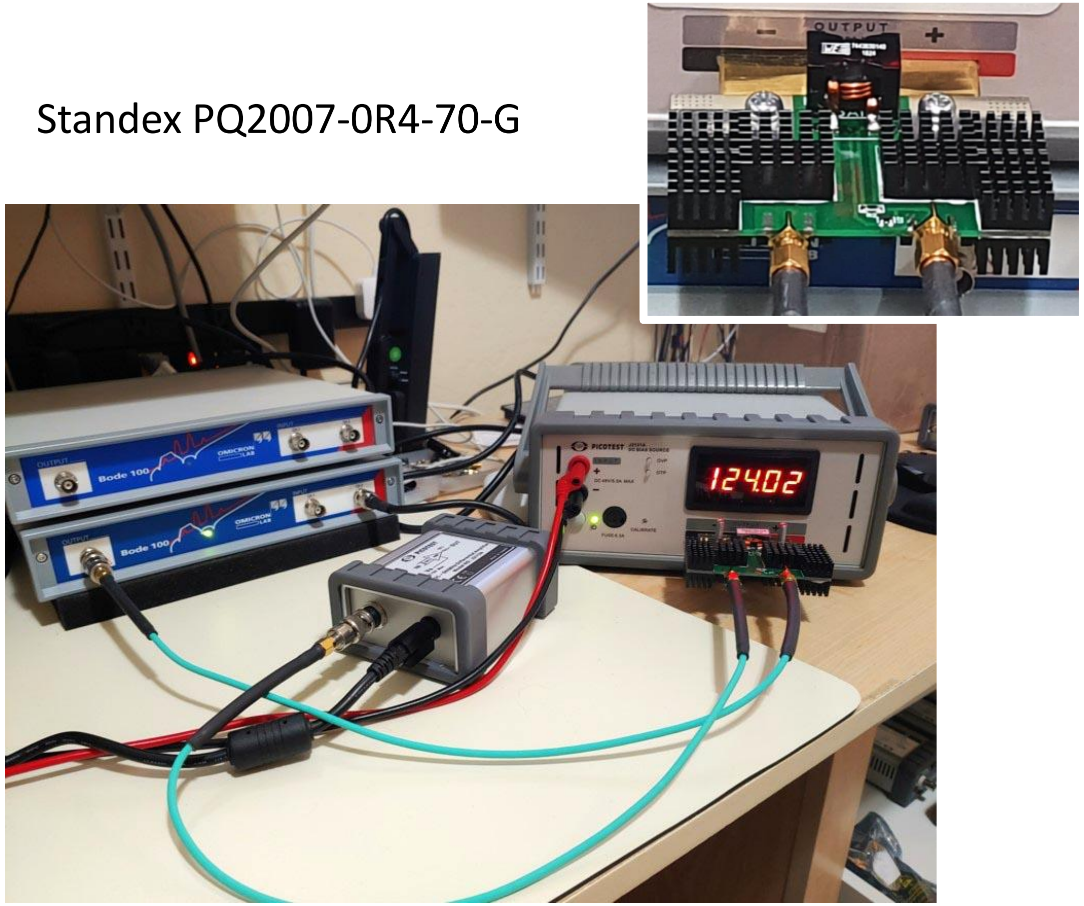
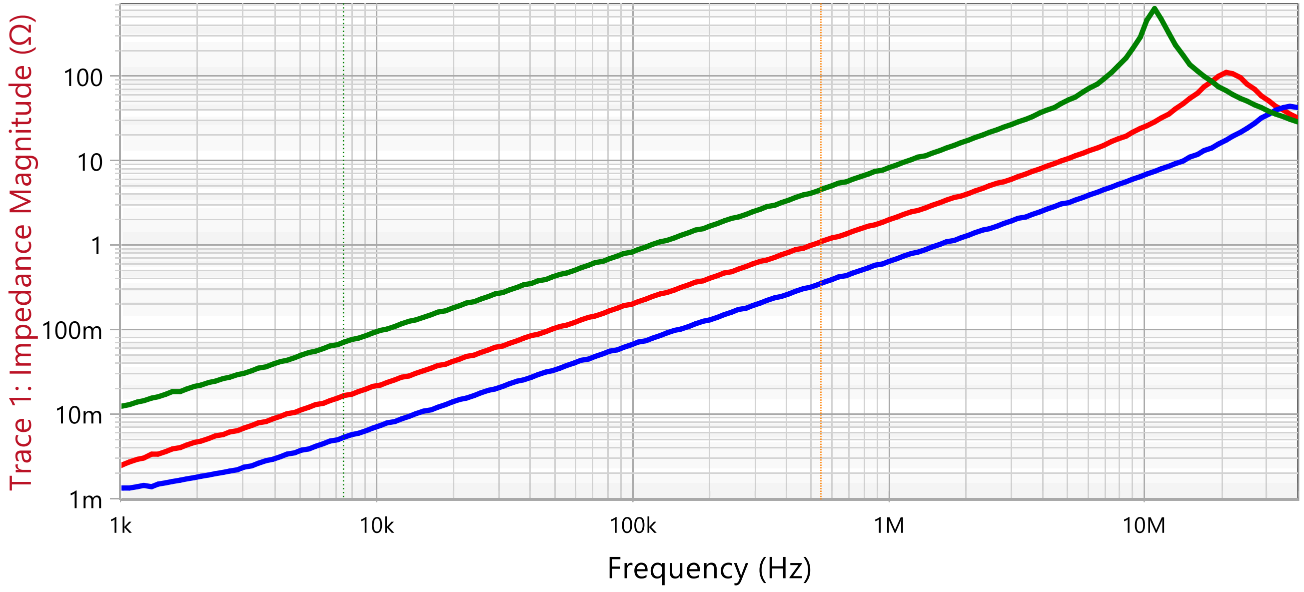
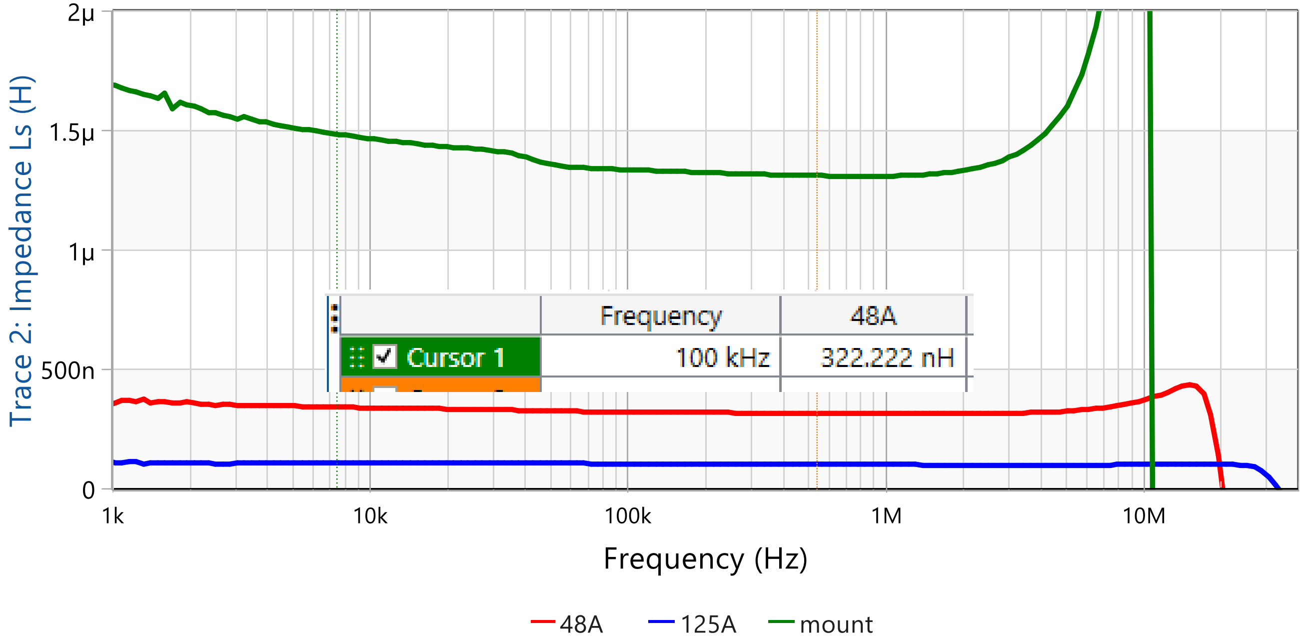
Example 400nH/70A

Standex PQ2007-0R4-70-G







The raw 400nH Measurement is 20% below nominal value

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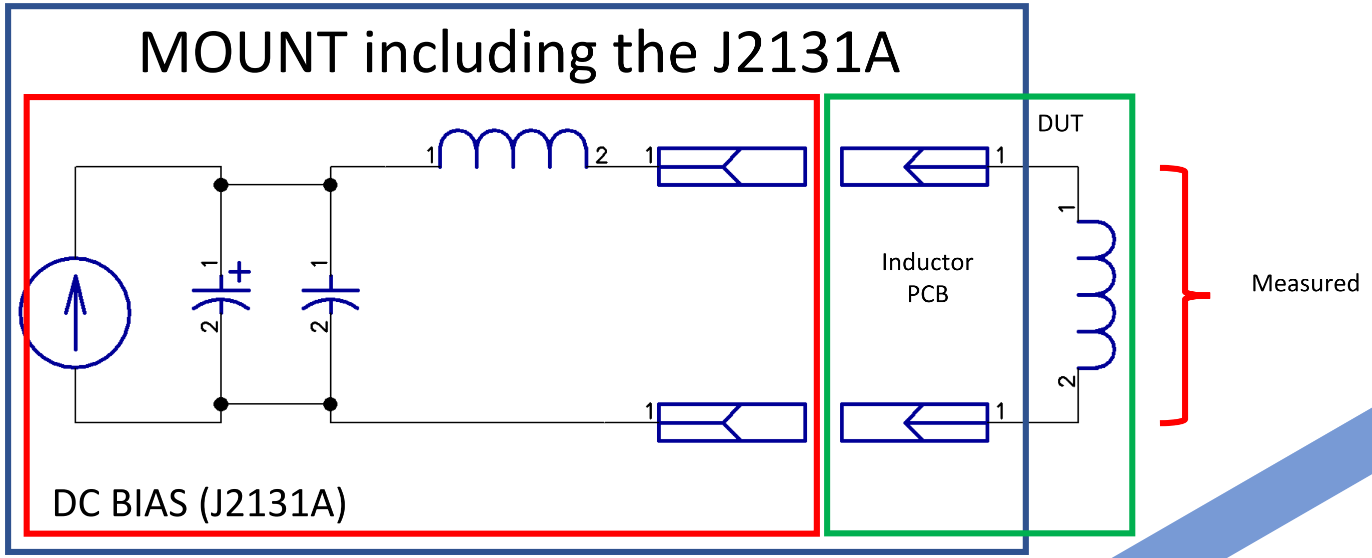
De-embedding

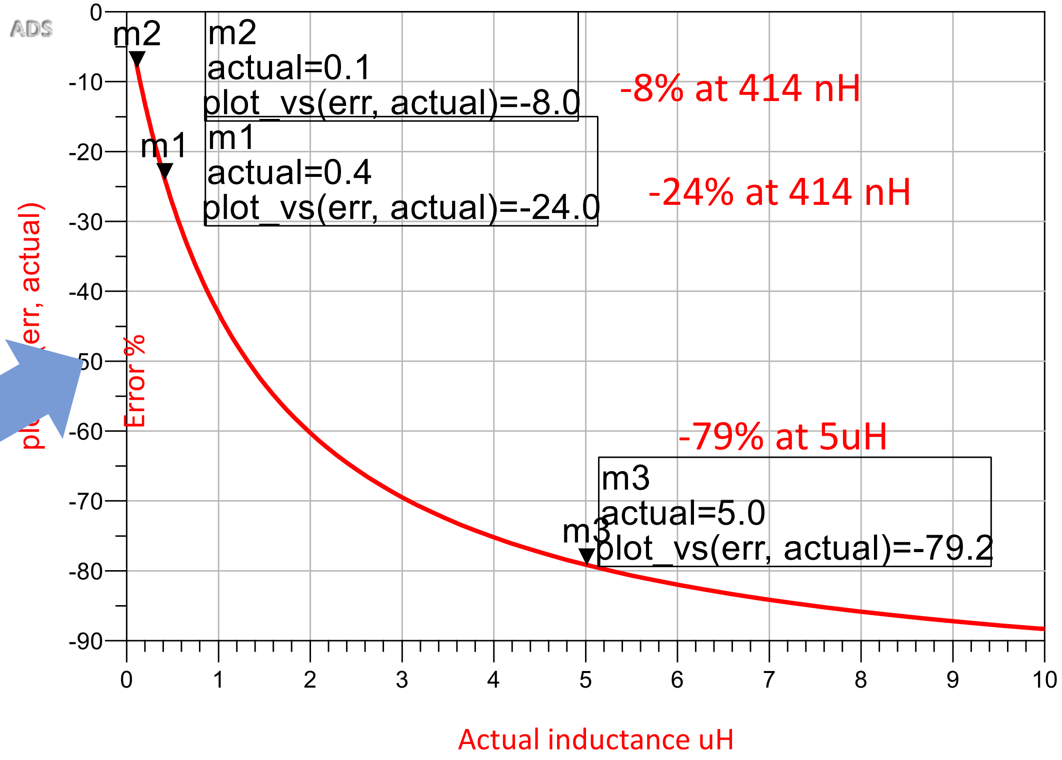
$$Measured = Mount \,||\, DUT = \frac{Measured \cdot Mount}{Mount + Measured}$$

$$De\text{–}Embedded\ DUT = \frac{Measured \cdot Mount}{Mount - Measured}$$



$$Uncorrected\ Error = \frac{mount}{DUT + mount} - 1$$

Raw % Error vs Inductance in uH



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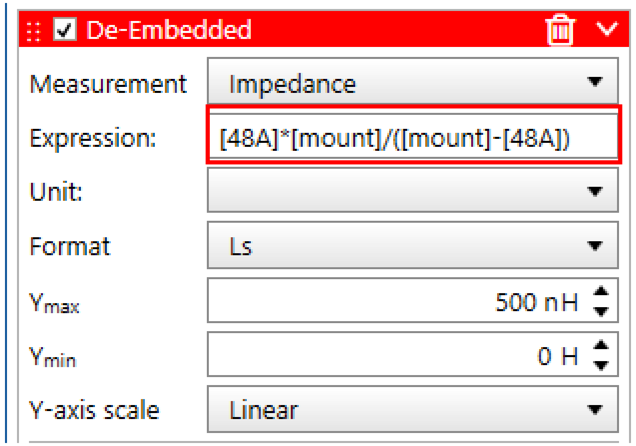
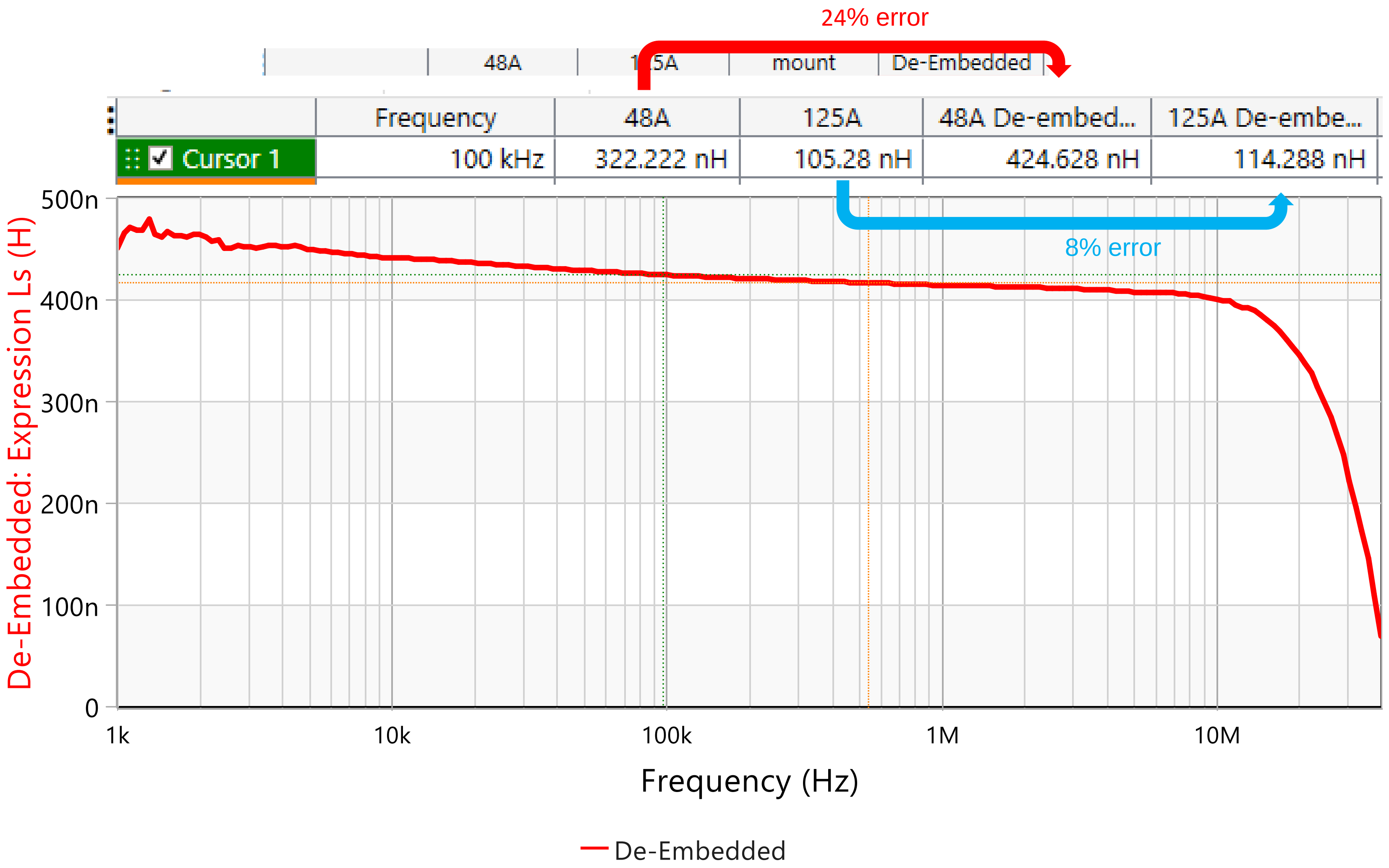
Post De-Embedded Measurement

A simple math expression can be applied to separate the DUT from the measurement that includes the mount (J2131A and PCB)

De-Embed expression for the 48A measurement





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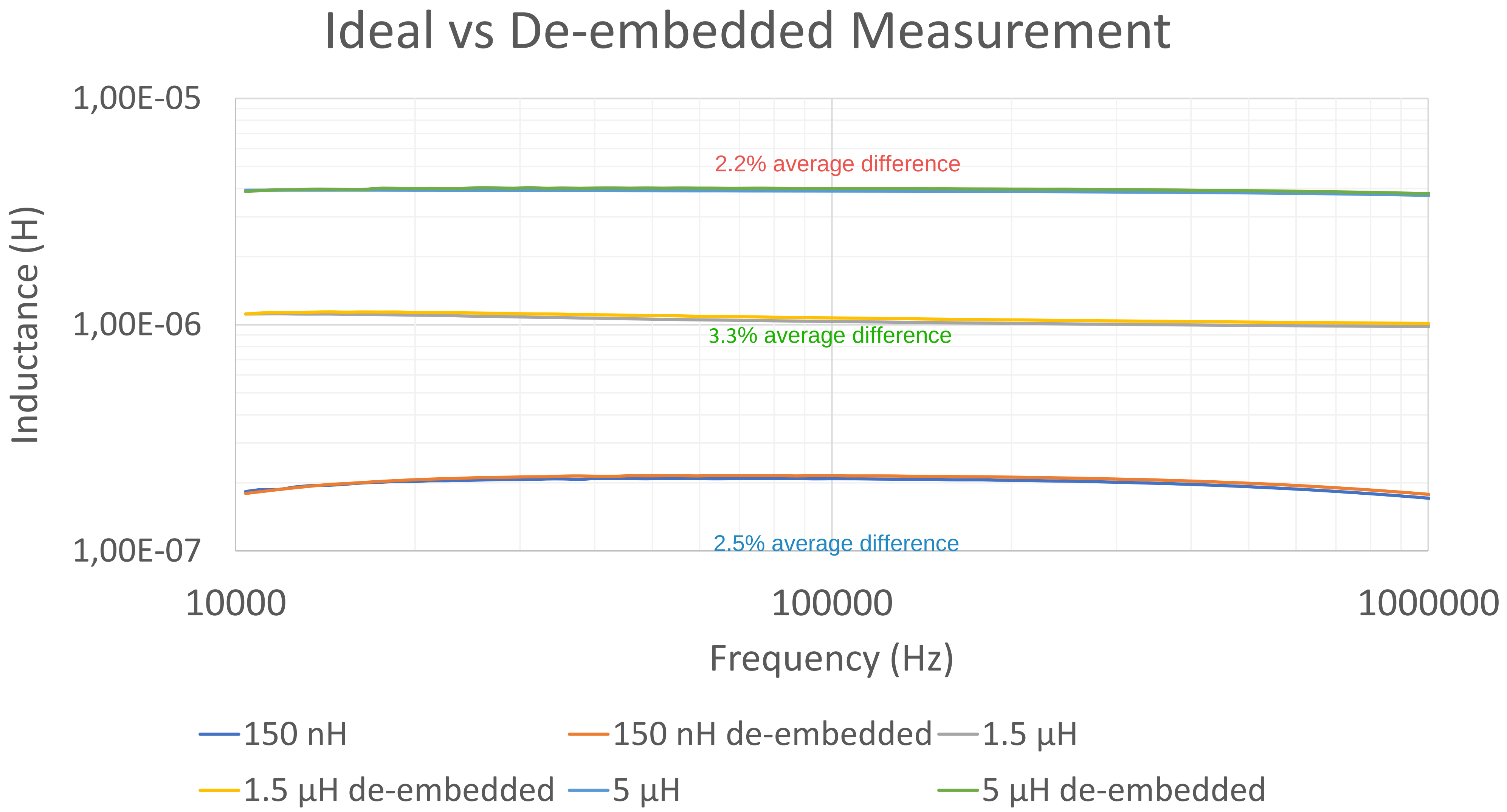
De-embedding Comparison



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Advantages and Disadvantages

Design, Fabrication, and Characterization of Package Embedded Solenoidal Magnetic Core Inductors for High-Efficiency System-In-Package Integrated Voltage Regulators

Advantages

- Can measure at operating switching frequency
- Wider frequency range
- No external modulator is required
- Measured using VNA which is better calibration for improved accuracy
- A source amplifier allows measurement with larger AC sources for core loss and Q dependencies
- Much lower current power supply

Disadvantages

- Requires a ground isolator
- Requires de-embedding

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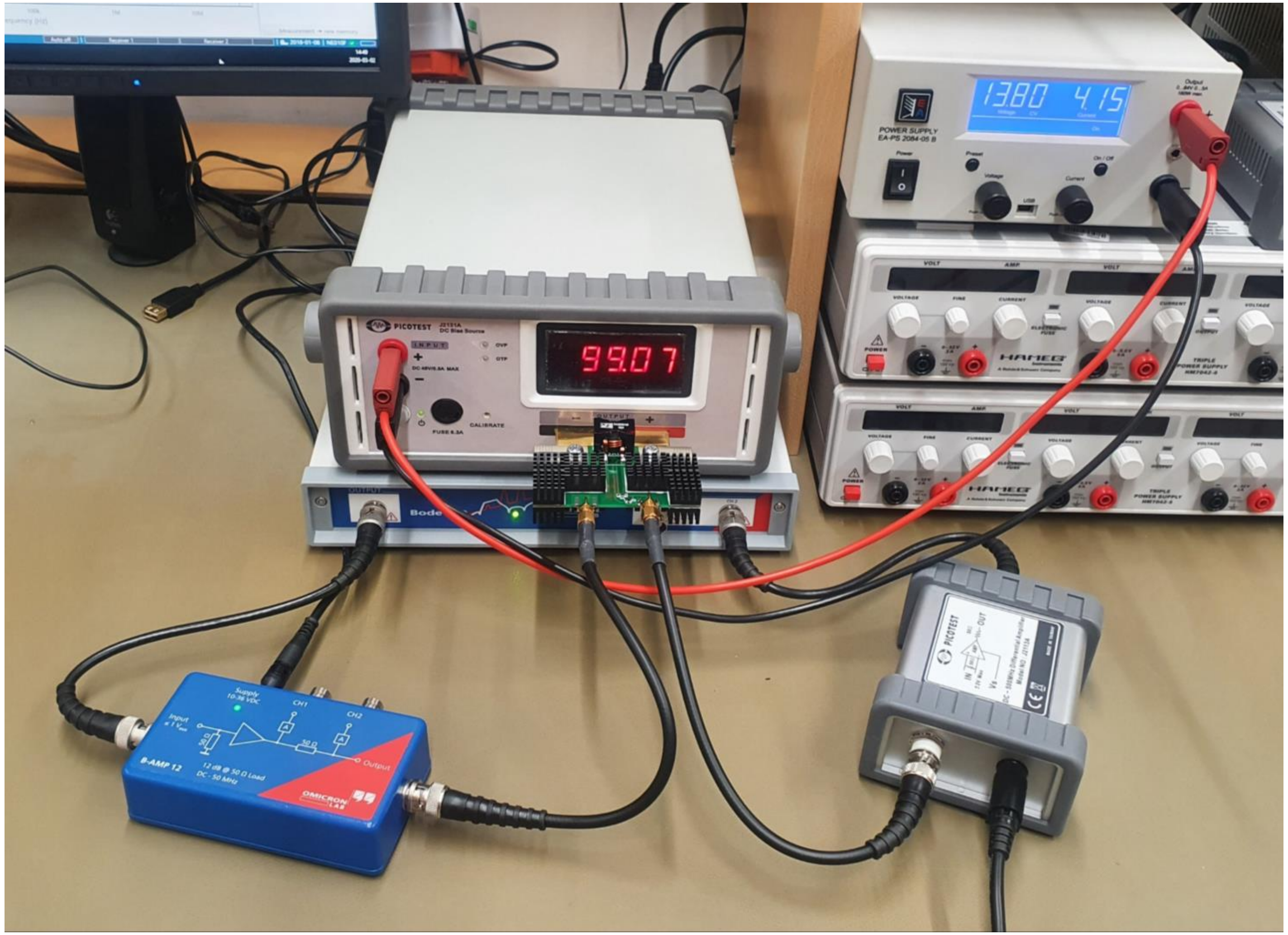
Measuring at Higher Signal Levels



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Summary

- Two simple methods for measuring frequency dependent inductance with bias were shown
- Up to 20 Amps, the 3-port FRA measurement works well
- Up to 125 Amps, the 2-port shunt-through using a Bias Source works well
- Above 125 Amps, it is possible to parallel Bias Sources

Be careful about self heating which can impact the results. Fewer datapoints, higher receiver bandwidth and limited frequency range all result in faster sweeps. Automation could enable bias, sweep, disable bias

It is possible to damage the VNA if the inductor breaks or becomes desoldered during testing. The energy stored in the bias source is substantial

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- You can learn more about the products and accessories we discussed today by visiting:
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  - **www.omicron-lab.com**
- YouTube Videos: How to Design for Power Integrity
  - **Tinyurl.com/pi-videos**
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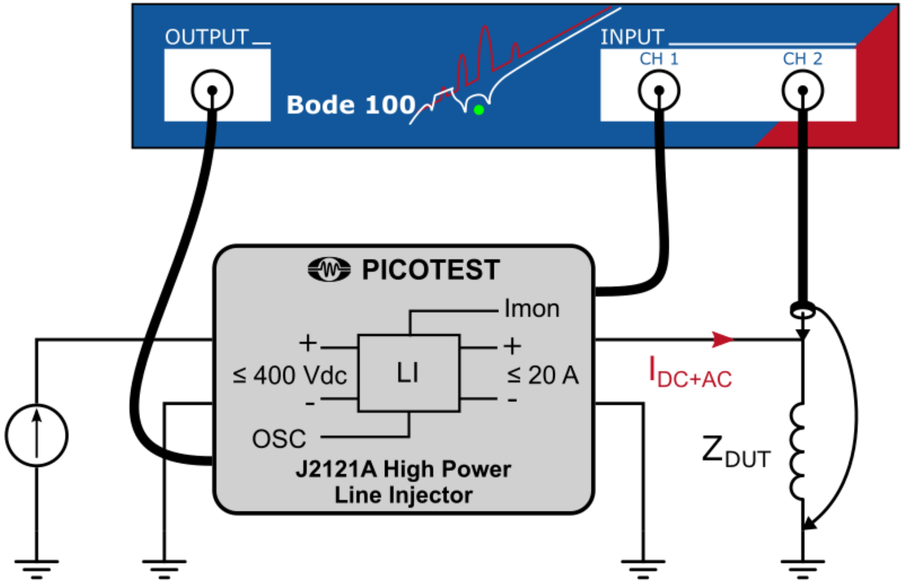
Live Hands-On Measurements

- DC-Biased Inductor Measurement using Picotest J2121A



DUT 1:

$L = 1.5\ \mu H$

$R_{DC} = 15\ m\Omega$

$I_R = 4.3\ A$

$I_{SAT} = 7.3\ A$

DUT 2:

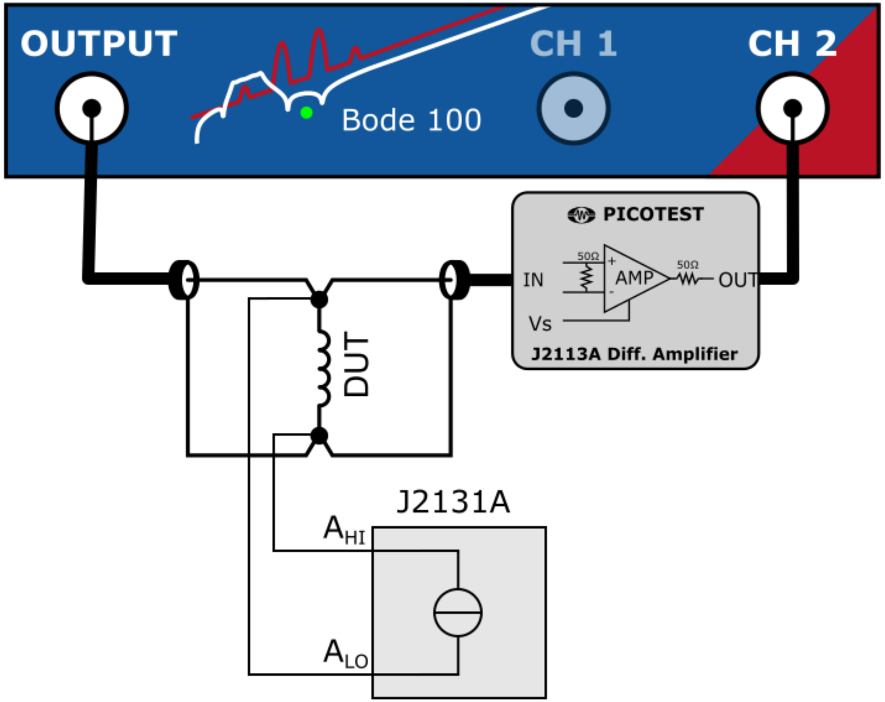
$L = 10\ \mu H$

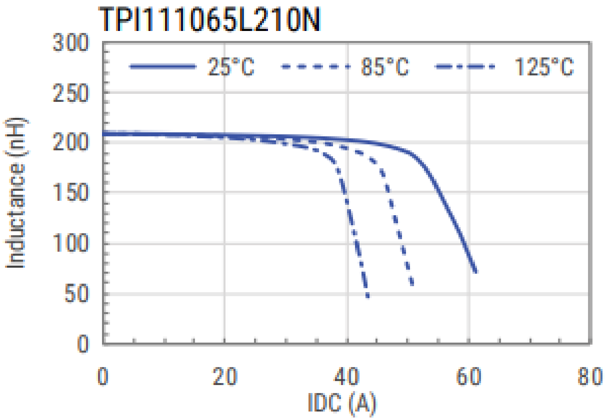
$R_{DC} = 10\ m\Omega$

$I_R = 2.5\ A$

Live Hands-On Measurements

- DC-Biased Inductor Measurement using Picotest J2131A + J2113A
  - DUT is a 210 nH Inductor with Isat = 54 A (@ 25 °C)





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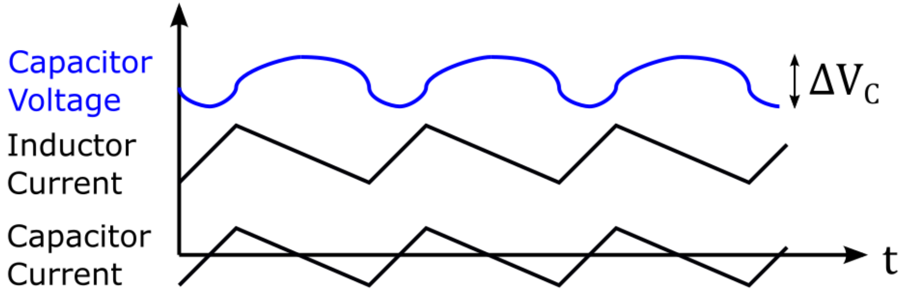
Capacitors with DC Voltage

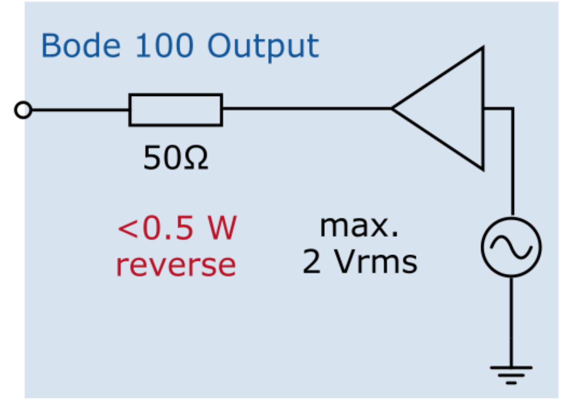
- Filter capacitors in power supply applications are charged with DC voltage
- Only AC ripple "flows thru" the capacitor
- Capacitance at 0 VDC is often useless

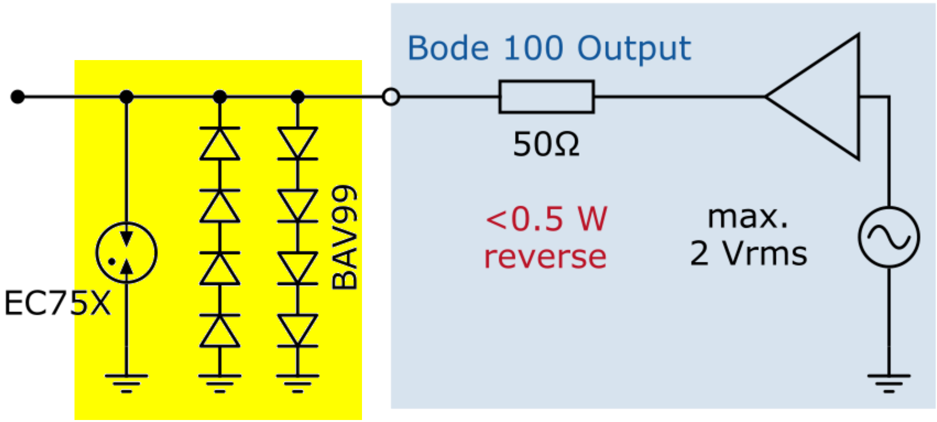
PWM Converter Example:



Bode 100 Output Stage Limits

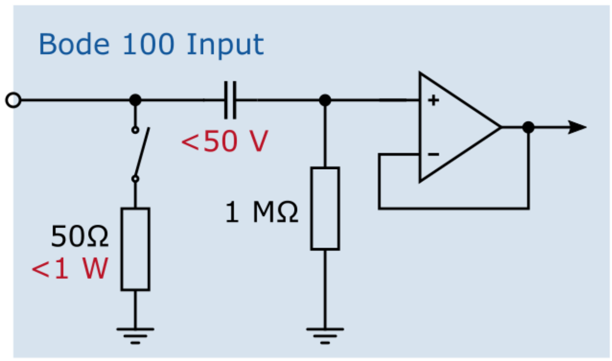
- < 0.5 W reverse power
- < 5 V reverse voltage
- ≤ 3.3 V recommended
- Sensitive to transients!
- Use external transient protection if necessary e.g. antiparallel diodes





Bode 100 Input Stage Limits

- Max. 1 W when set to 50 Ω
  → max. 7 V_{RMS}
- Max. 50 V_{DC} when set to 1 MΩ
- Maximum AC voltage at 1 MΩ depends on frequency!
  - < 50 V_{RMS} (1 Hz – 1 MHz)
  - < 30 V_{RMS} (1 MHz – 2 MHz)
  - < 15 V_{RMS} (2 MHz – 5 MHz)
  - < 10 V_{RMS} (5 MHz – 10 MHz)
  - < 7 V_{RMS} (10 MHz – 50 MHz)

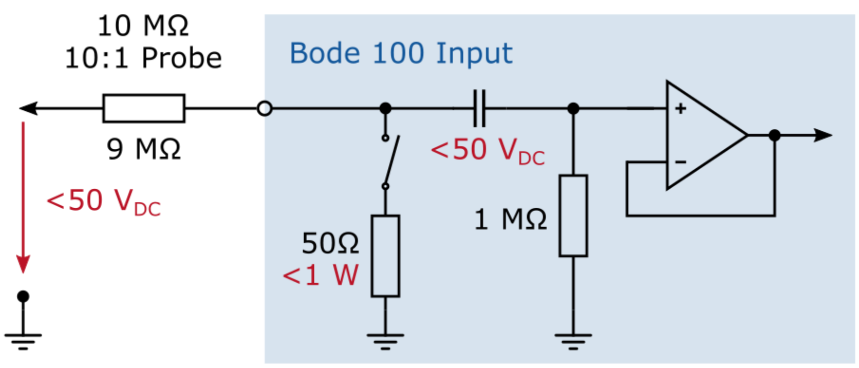


Note: Bode 100 can’t measure more than 10 V_{RMS} anyhow...

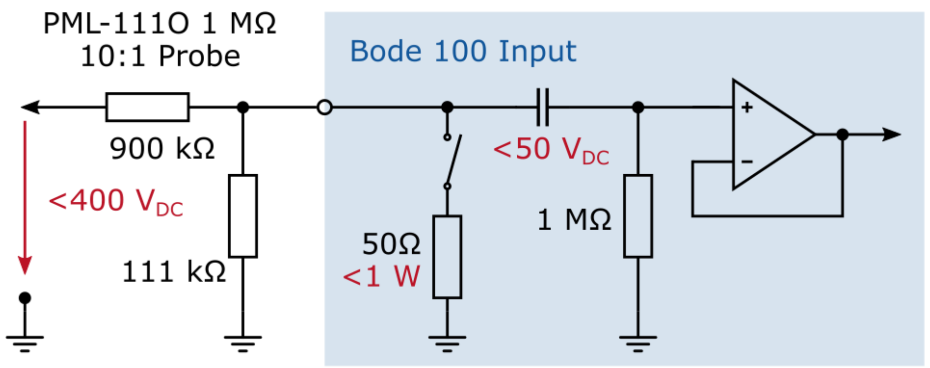
Using External Passive Probes

- Take care that inputs are AC coupled!
- Standard passive 10:1 probes don't increase DC limit!
- Use active probes or special 1 MΩ probes

Standard Passive Probe:

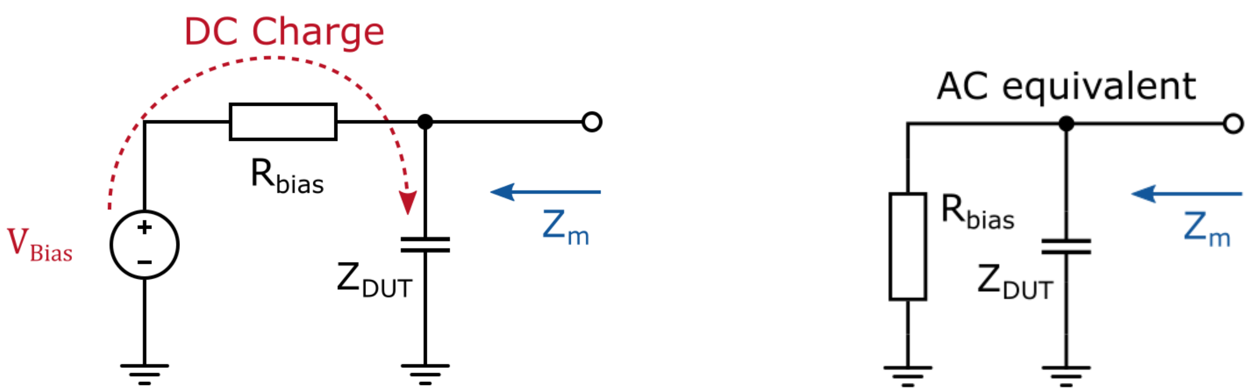


Special 1 MΩ Probe:

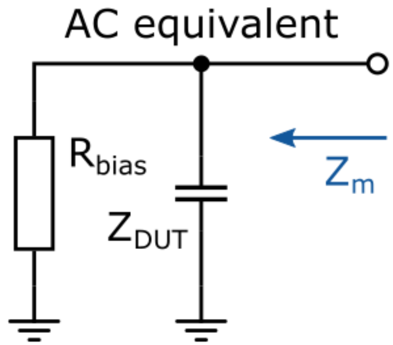


Voltage Biasing

- Bode 100 needs to be protected from the DC voltage
  → DC Blocking (capacitor)
- Charging a capacitor can be done via voltage source
  → generally via a resistor R_{bias} to reduce current
- Voltage source $Z \approx 0$
  → R_{bias} reduces measurement error when $|R_{bias}| \gg |Z_{DUT}|$



Bias Source Measurement Error



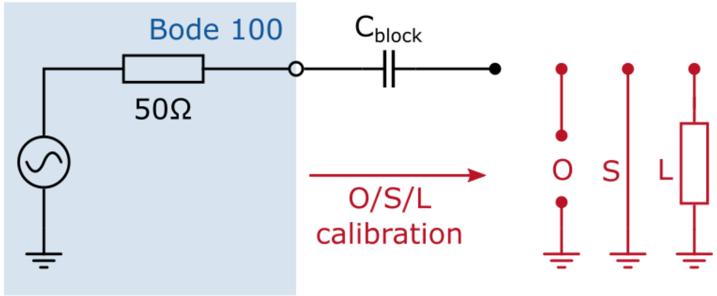
C_{DUT} and R_{bias} form a parallel circuit

$$Z_m = \frac{R_{bias}}{1+sR_{bias}C_{DUT}} \rightarrow f_c = \frac{1}{2\pi R_{bias}C_{DUT}}$$

- At f_c magnitude error is ≈ -3dB (≈ -30%)
  phase error ≈ 45°
- At $10 \cdot f_c$ magnitude error is already < 0.05 dB (<0.5%)
  phase error ≈ 4.5°
- At $100 \cdot f_c$ magnitude error is negligible
  phase error ≈ 0.45°

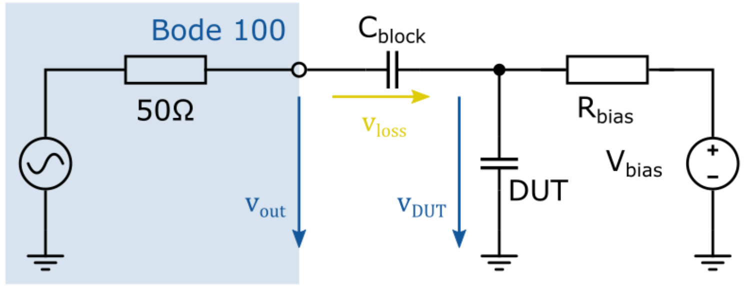
DC Blocking via Capacitor

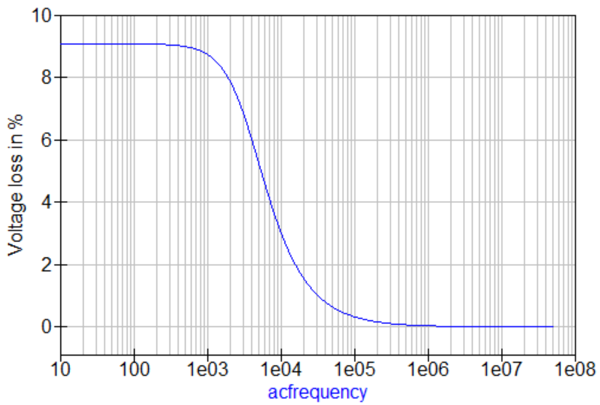
- C_{block} can be used to protect Bode
- Reference plane can be shifted to neglect C_{block} using O/S/L calibration



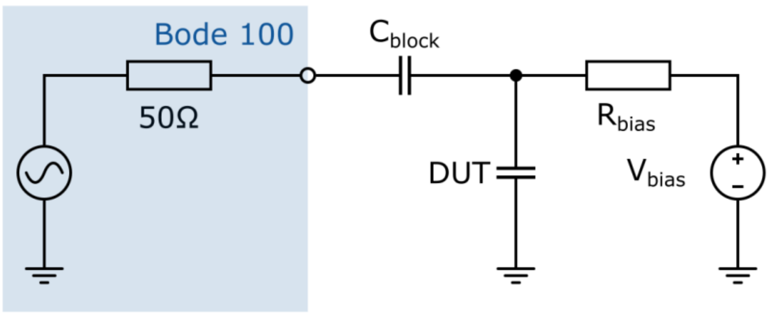
- Use linear capacitors such as NP0, G0G, Film (little DC sensitivity)
- Note that C_{block} will reduce SNR at low frequencies! Example:

$$C_{block} = 10\ \mu F \gg C_{DUT} = 1\ \mu F$$



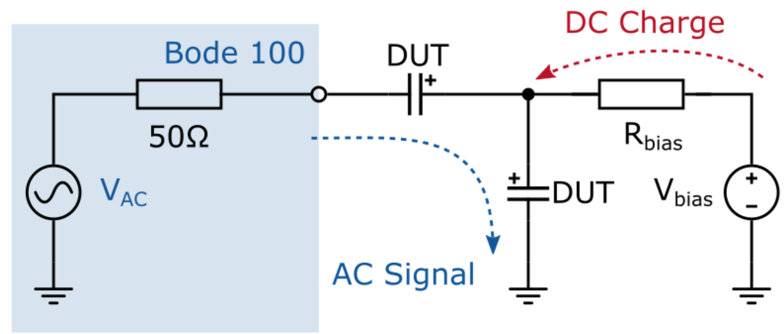


Measurement Setups



Using a DC block capacitor

- ☺ Only one DUT needed
- ☺ $Z_{DUT} = Z_m$
- ☺ Simple for low voltages
- ☹ $C_{block} \gg C_{dut}$ (>factor 10)
- ☹ DC block is never 100% linear



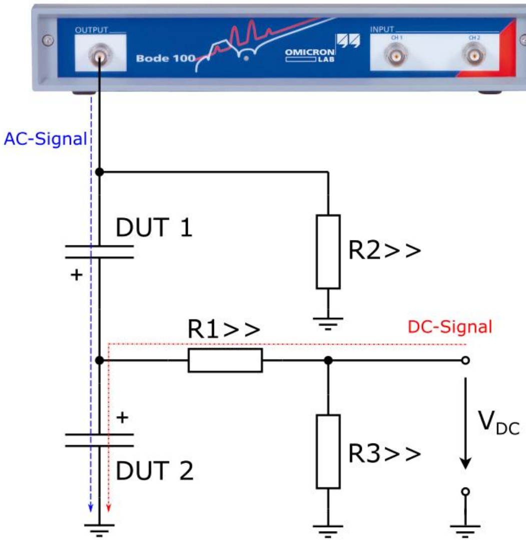
Using two similar DUTs

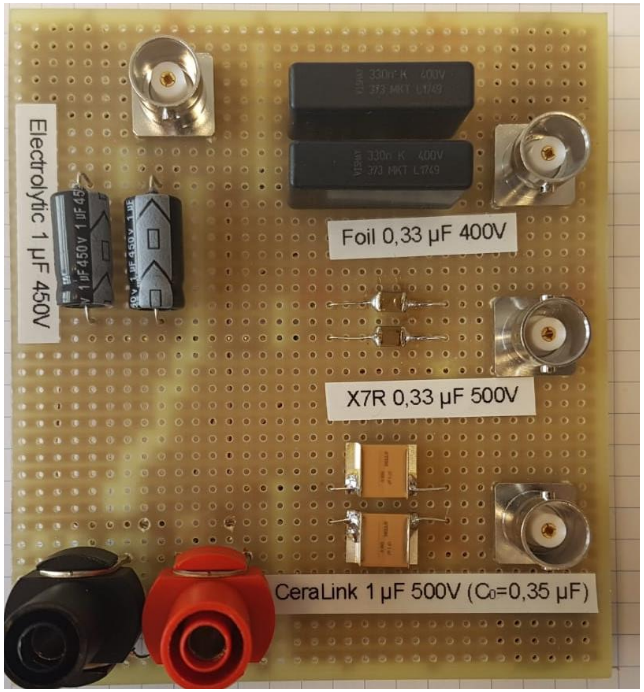
- ☺ No extra DC block needed
- ☺ Suitable for higher voltages
- ☹ $Z_m = Z_{DUT} \cdot 2,\ C_{DUT} = C_m \cdot 2$
- ☹ Two similar DUTs required

Measurement Example

Type (Electrolyte)	Nominal Voltage	Nominal Capacitance	Picture
Aluminum electrolytic	450 V	1 µF	
Film (MKT)	400 V	0.33 µF	
Ceramic (X7R)	500 V	0.33 µF	
Ceramic (CeraLink™)	500 V	1 µF (0.33 µF C_0)	

Dual DUT Method



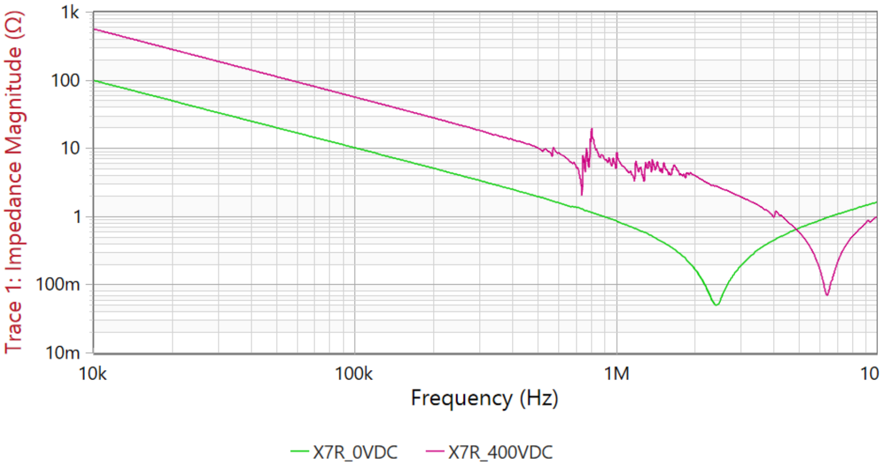


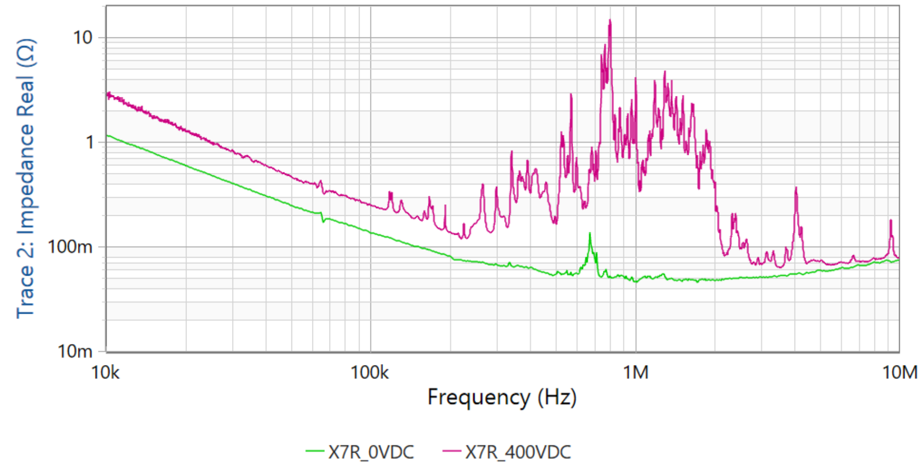
- One-Port Measurement
- R1 = R2 = R3 = 340 kΩ (R2 & R3 for discharging)
- $f_c = \dfrac{1}{2\pi R_{bias} C_{DUT}} \approx 0.5\ Hz$

Notice!

- Always take appropriate safety measures when working on hazardous voltages!
  - Connect Bode 100 housing to protective earth
  - Use isolated DC voltage source to reduce risk of shock
  - Cover live parts such that they cannot be touched
- Connect the complete test setup (including Bode 100) before powering the DC Voltage and don’t change when charge on the DUT is applied!
- Check if the charging / bias resistors can handle the maximum voltage
- Wait until capacitors are discharged! ($> 3\,\tau = 3 \cdot RC$)

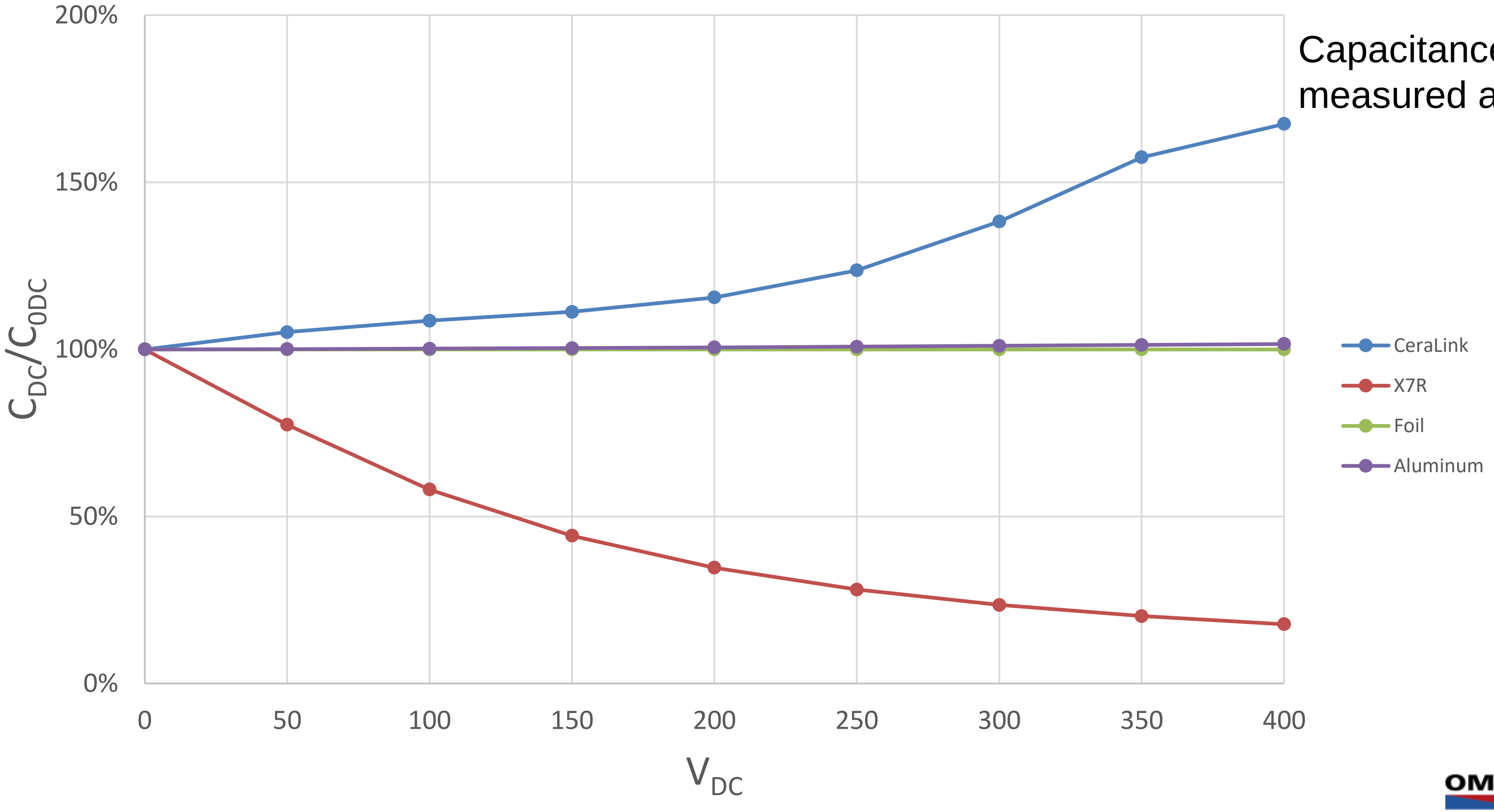
X7R Mechanical Self-Resonance





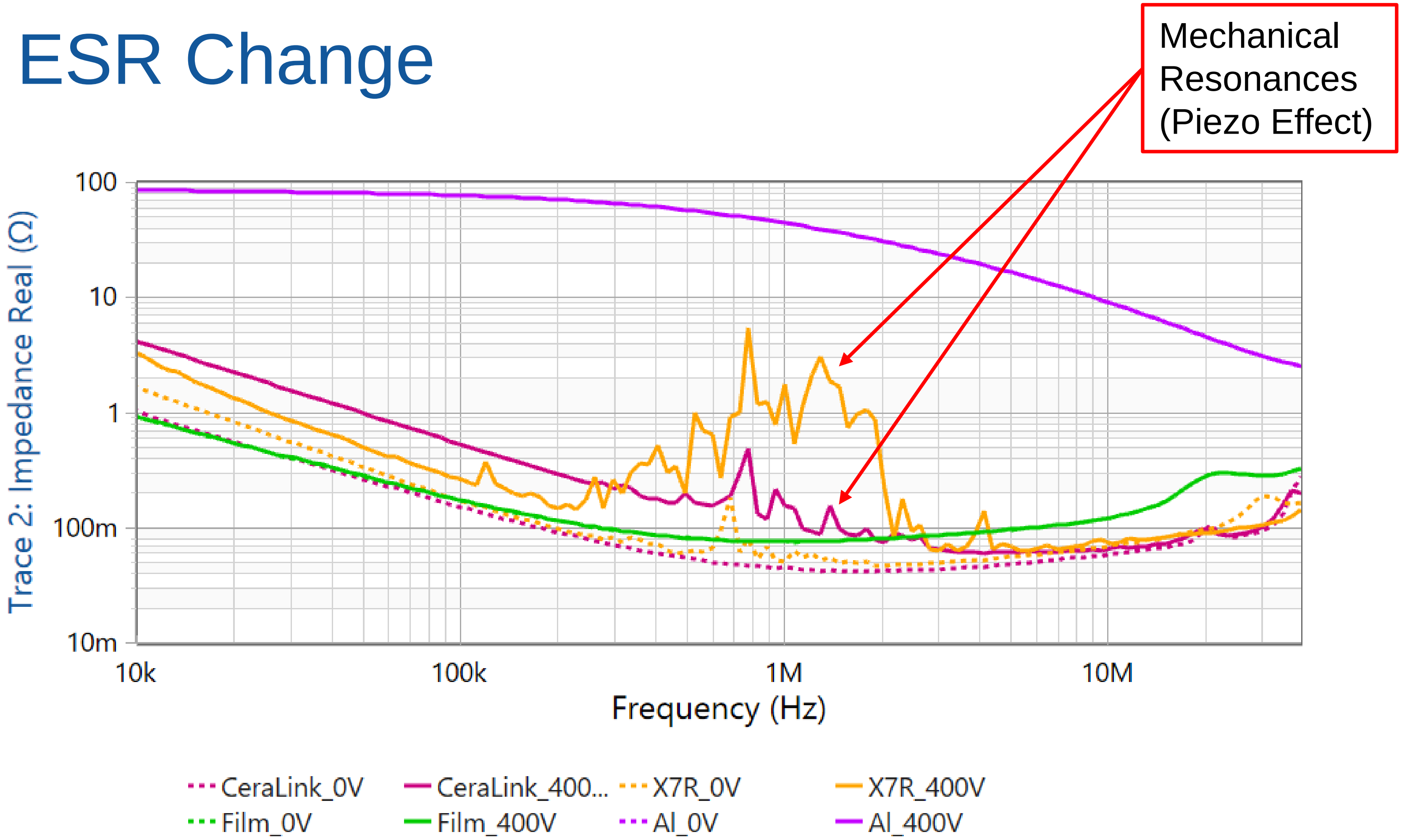
- Increases with DC bias voltage
- Increases losses (ESR @ 800kHz from 25 mΩ to 5 Ω)
  → Can impact filters designed with 0 V_{DC}

Capacitance Change with DC Bias



Capacitance measured at 1 kHz

ESR Change



Mechanical Resonances (Piezo Effect)
Trace 2: Impedance Real (Ω)
100
10
1
100m
10m
10k
100k
1M
10M
Frequency (Hz)
CeraLink_0V
CeraLink_400...
X7R_0V
X7R_400V
Film_0V
Film_400V
Al_0V
Al_400V

Summary

- Impedance measurements under DC bias are possible
- Not always straight-forward
- Setups are subject to systematic errors
- Simulation helps to identify and estimate the errors

References and further reading:

[1] Alexey Tyshko and Saulius Balevicius (2016), *Specifics of the X7R capacitors application in the high frequency inverters.* 267-270. 10.1109/ELNANO.2016.7493065.

[2] Günther Klenner, Johanne Wu (2017), *Verfahren und Messanordnung zur Ermittlung einer Impedanz in Abhängigkeit eines Gleichstroms.* DE102017209063B3

[3] QUCS (2019-03), Quite Universal Circuit Simulator is a free-software electronics circuit simulator software released under GPL - http://qucs.sourceforge.net/

[4] Voltech (2019-03), https://www.voltech.com/Products/DC1000A/Overview.aspx

[5] Picotest (2019-03), https://www.picotest.com/

[6] OMICRON Lab, DC voltage Biased Impedance Measurements, https://www.omicron-lab.com/applications/detail/news/dc-voltage-biased-impedance-measurements/

Feel free to ask questions via the Q&A function...

If time runs out, please send us an e-mail and we will follow up.

You can contact us at: info@omicron-lab.com

Thank you for your attention!

OMICRON LAB