# The Simple Truth About Complex Impedance Probes

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11th Power Analysis & Design Symposium (Live Virtual Event)
March 9, 2022

# Agenda

- What motivates us to measure impedance
- What makes it difficult
- Why use probes
- Tips
- Demo



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# Let's Face It

IMPEDANCE is NOT the end goal!

But it **is** a quantifiable metric for assessing the end goal, which is compliant performance.



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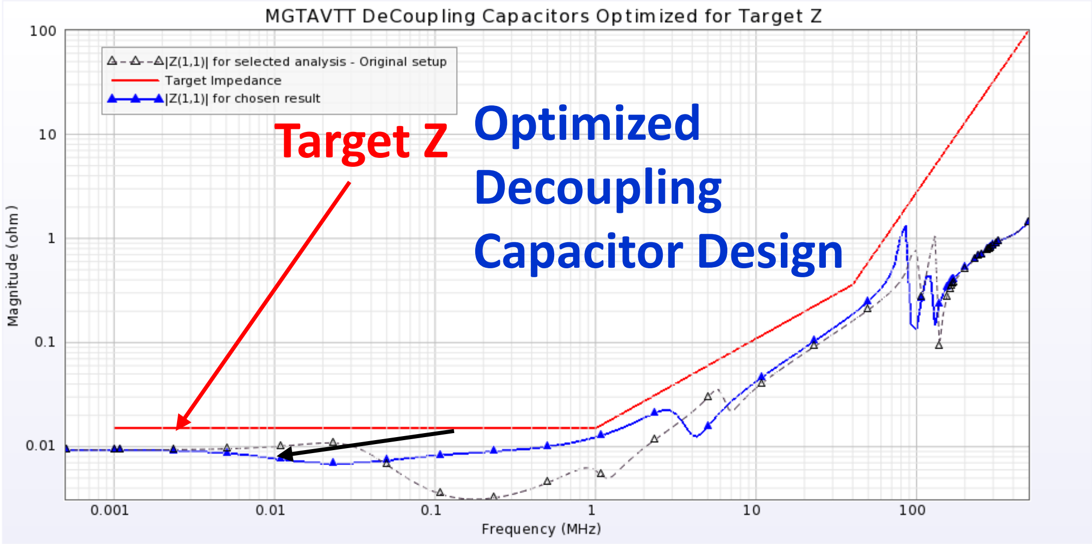
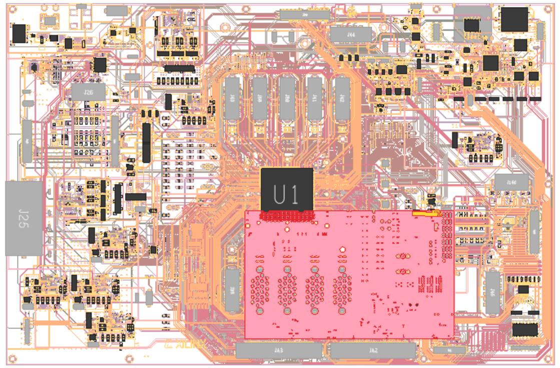
# Well, Unless You are Assessing Target Impedance

Power Integrity is focused on receiving the low frequency power electronics output and distributing it to the high-speed and sensitive circuits. This includes the filtering and decoupling to support the load current demands that are much higher in frequency than the power electronics circuitry.

The Power Integrity Engineer also has specific goals, and this (non-exhaustive) list identifies some of the most common:

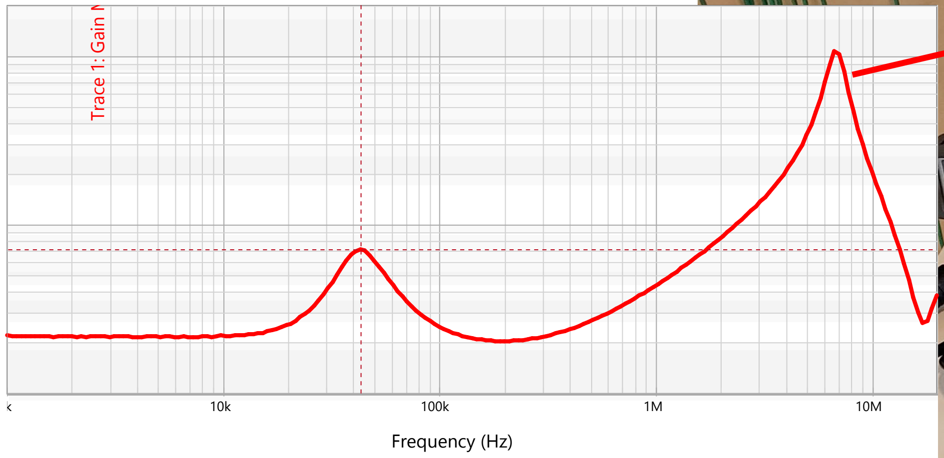
- Target **Impedance**
- Ripple Noise
- Excess Inductance

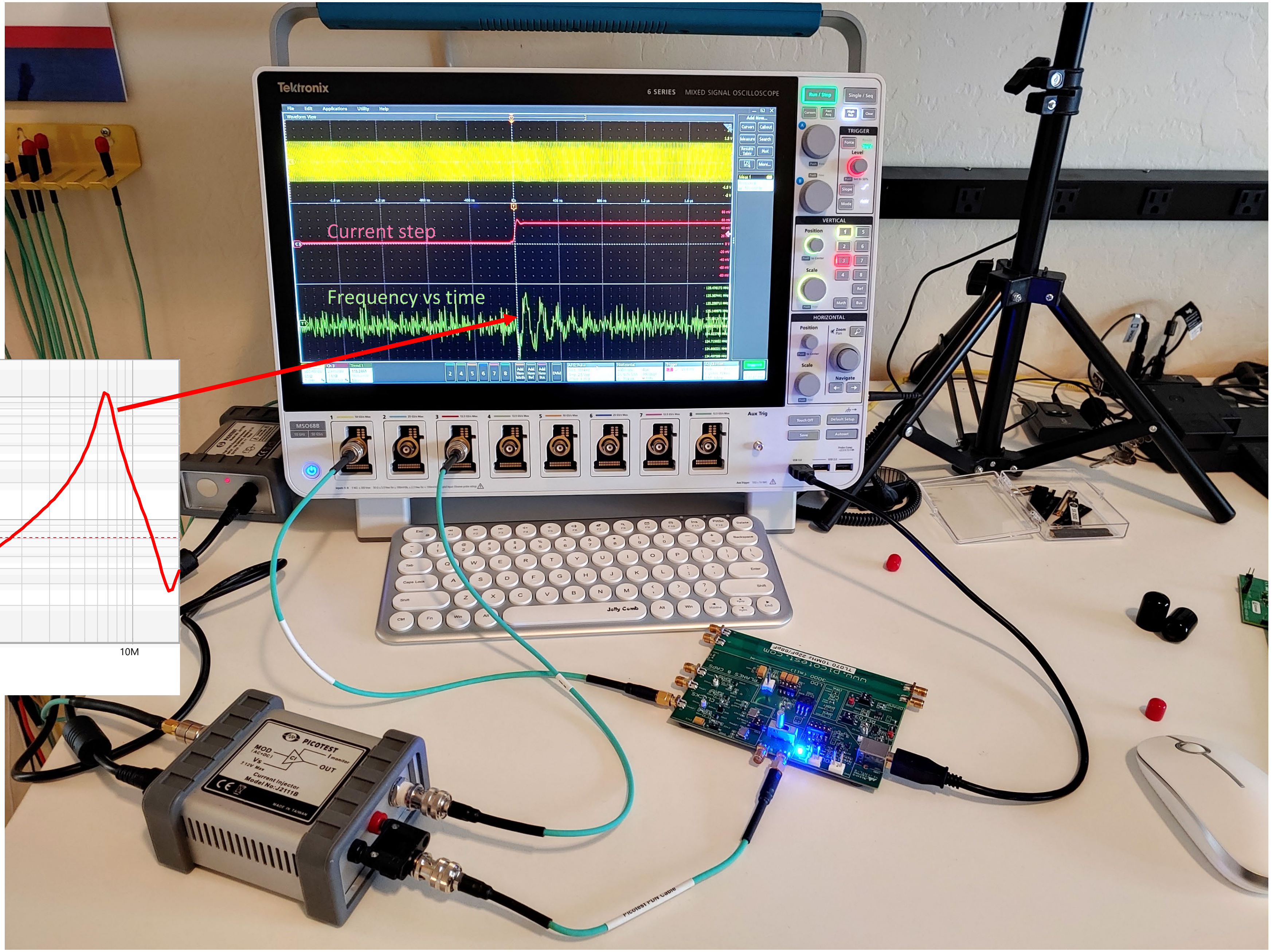



Images Copyright Keysight – Courtesy Heidi Barnes

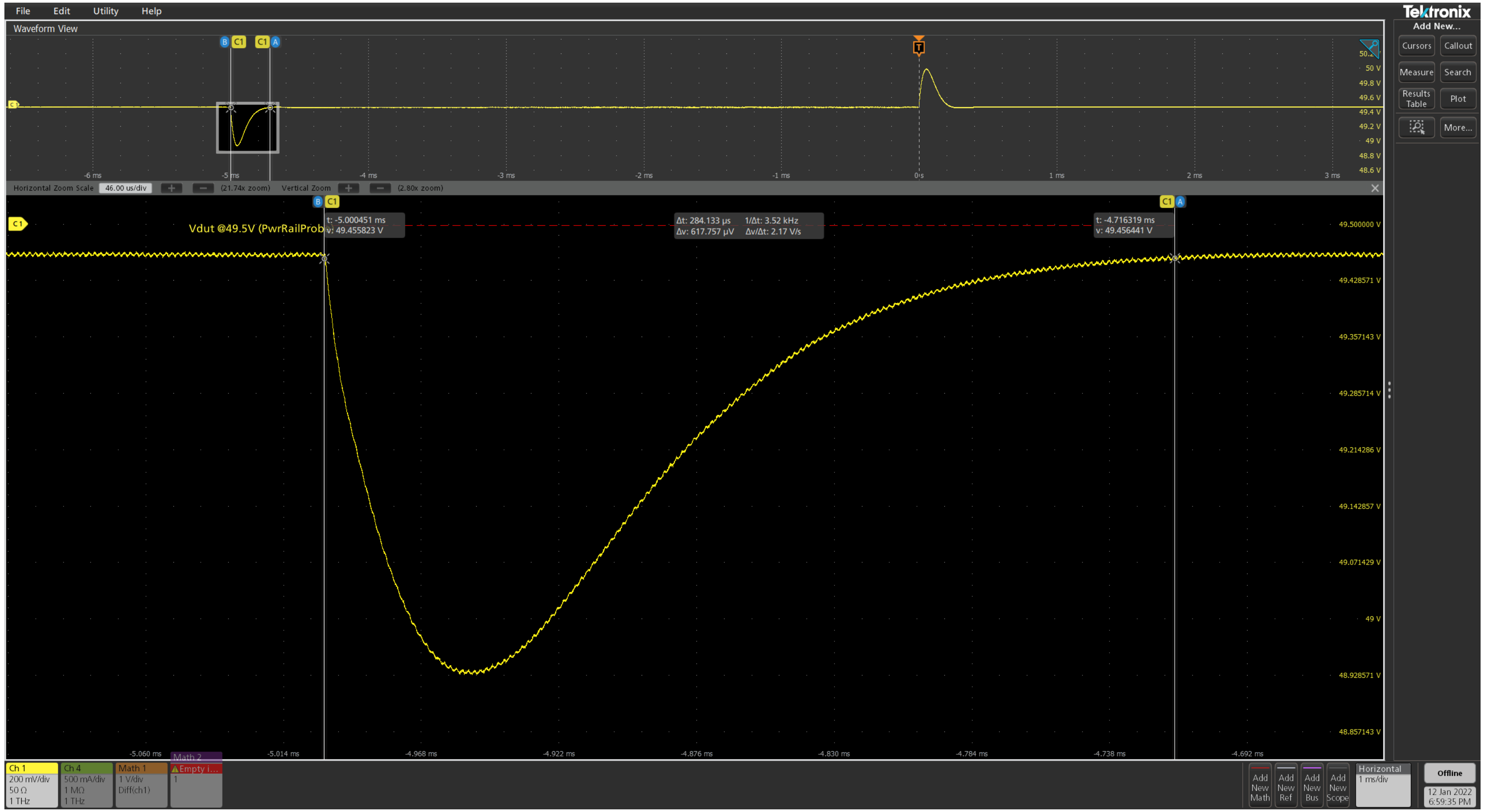
The step response also shows up in our critical circuits, including reference clocks, voltage references, phase locked loops, etc.



# Many of Us Are Familiar with Step Load

Which we frequently use to verify stable control loops





But this step load was performed by a very small probe. The probe gets closer to the DUT for better speed and fidelity.

50V 3A in this tiny probe is a challenge





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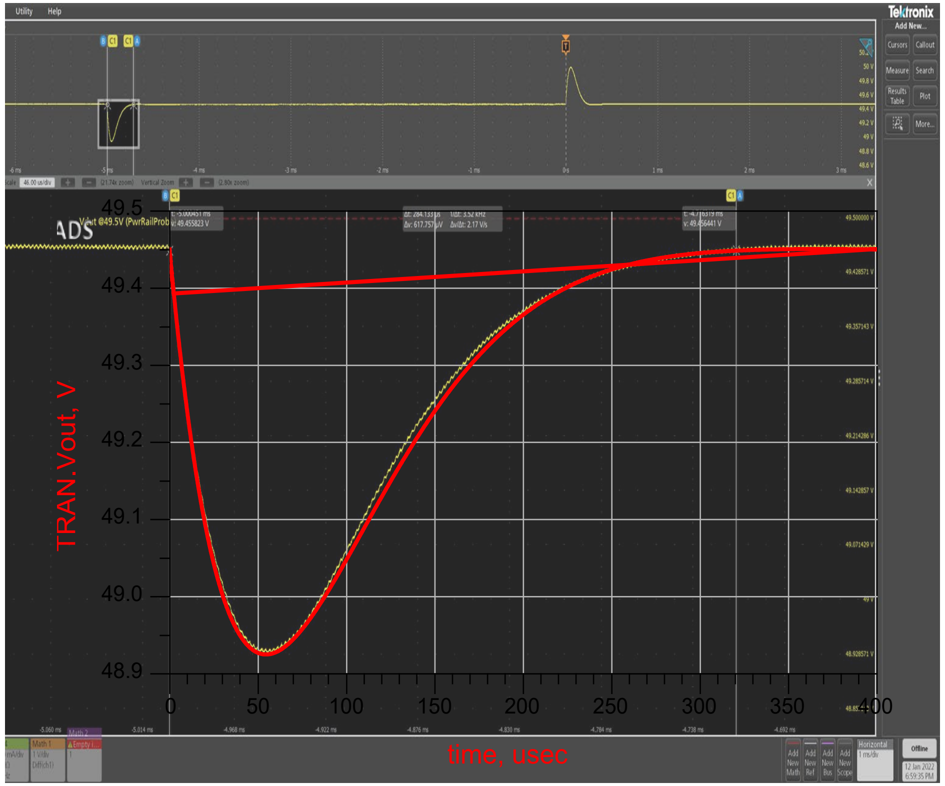
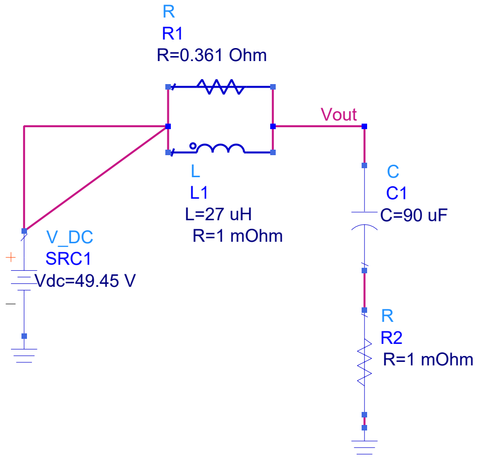
# Easy to Transform Time ⟷ Frequency

- Fourier gave us time to frequency conversion
- Laplace gave us frequency to time conversion

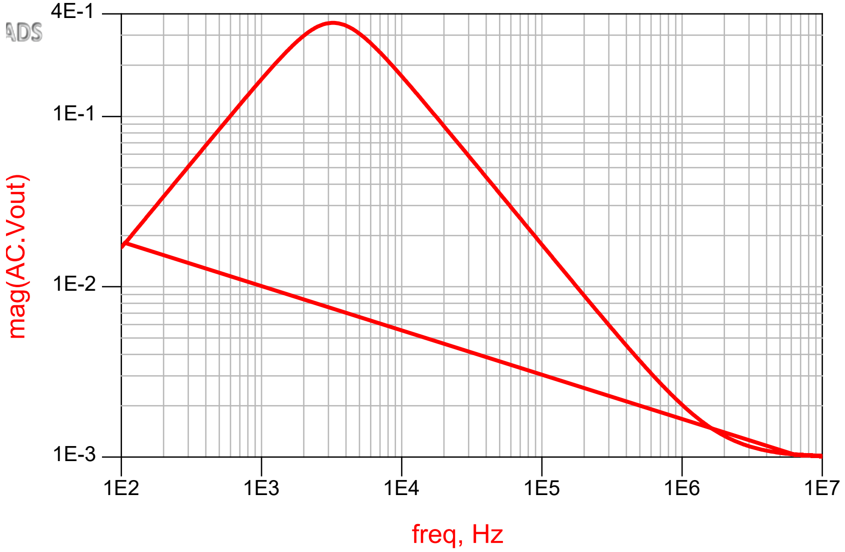
**Thanks guys!!**

# Time to Frequency Conversion (and Vice Versa)




Frequency Domain Result




Extracted using Picotest SEPIA software – hopefully coming to scopes soon



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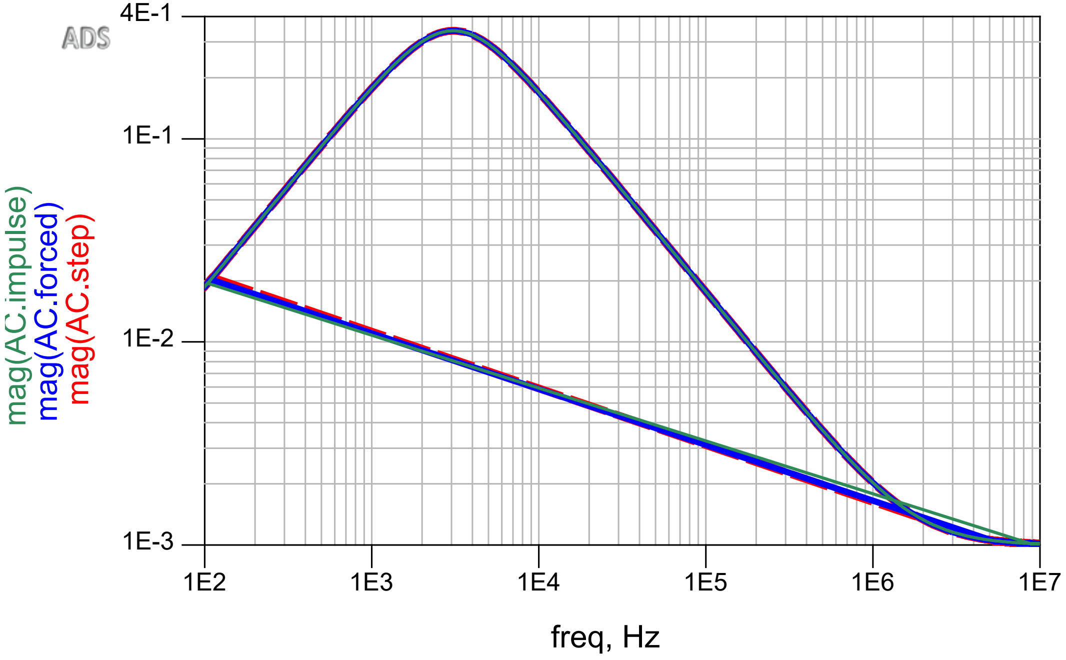
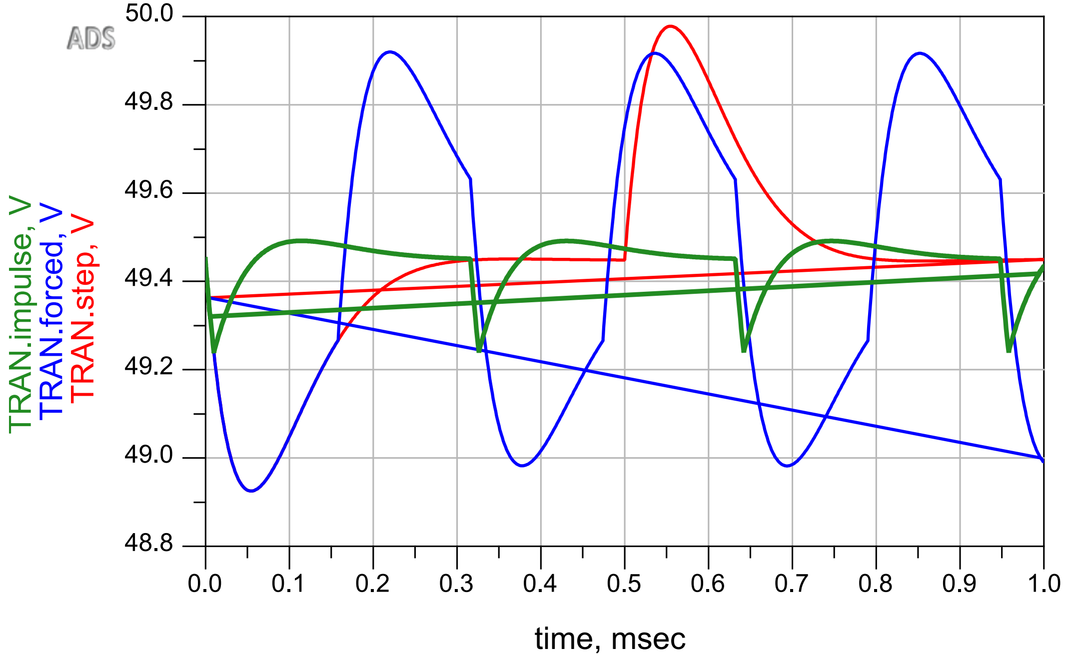
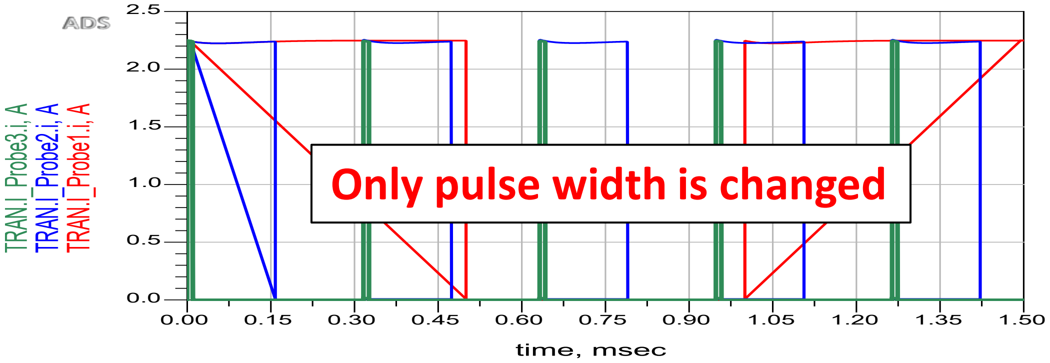
# One to Many Relationship

ONE IMPEDANCE PROFILE




MANY TIME DOMAIN PROFILES





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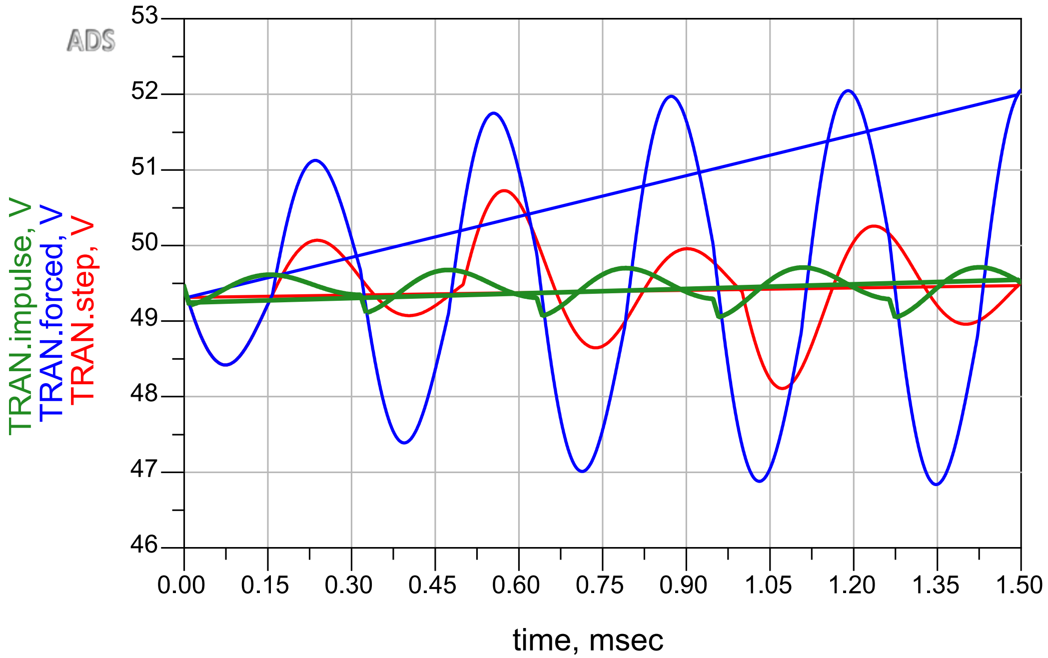
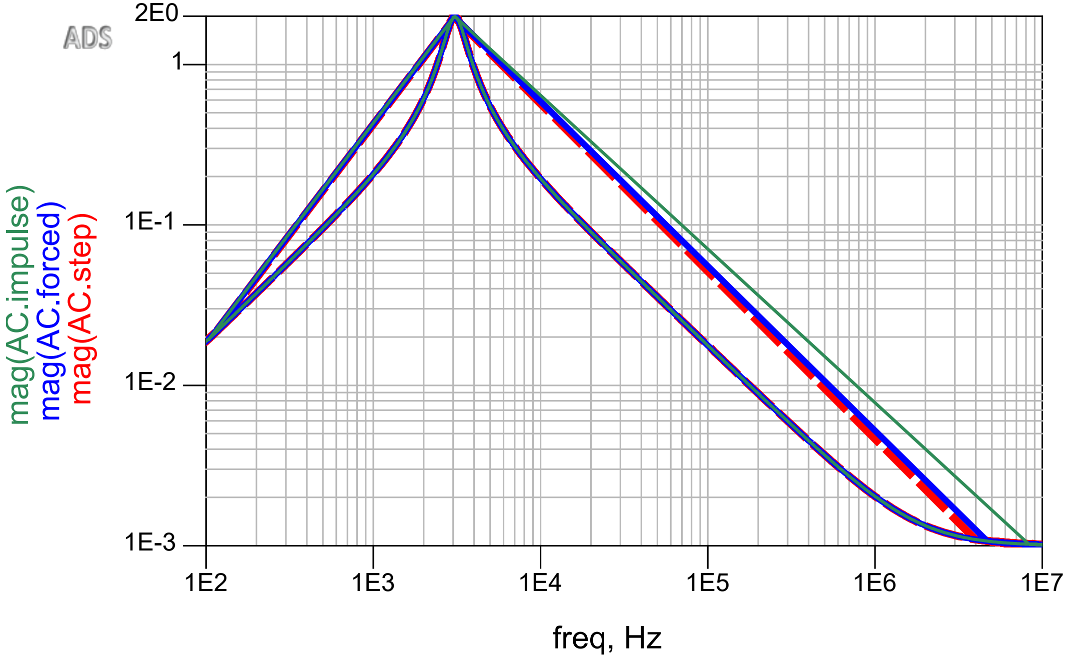
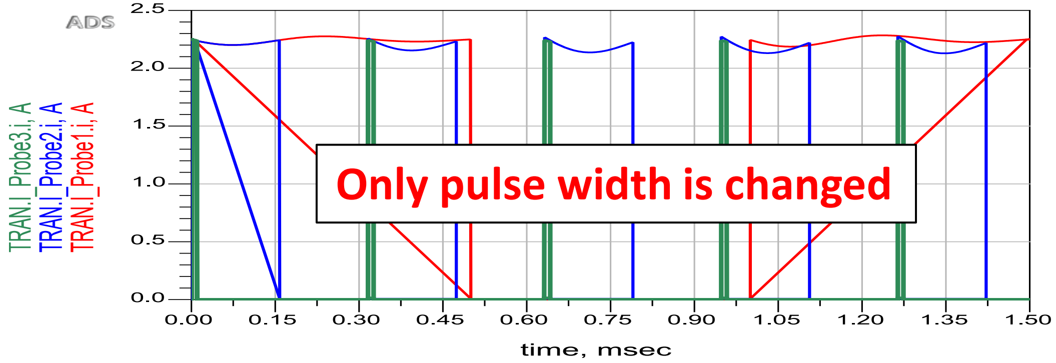
# Even More Dramatic at Higher Q

MANY TIME DOMAIN PROFILES




ONE IMPEDANCE PROFILE




And there can also be Rogue Waves!



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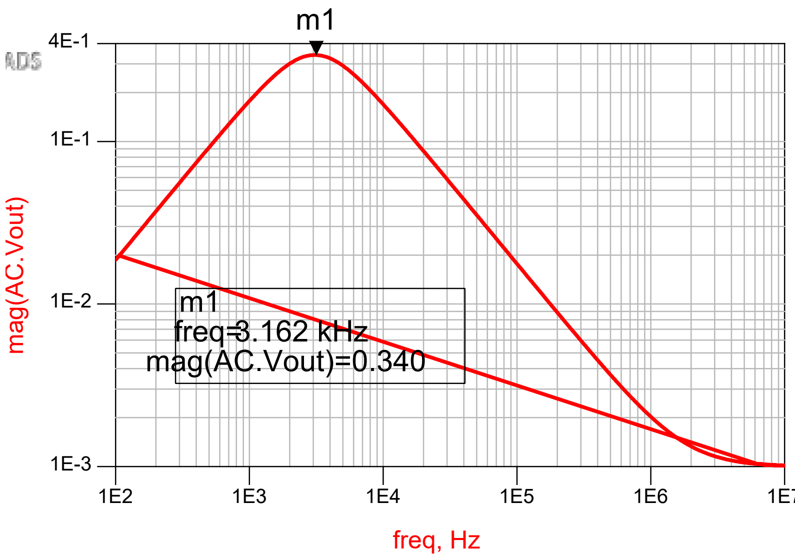
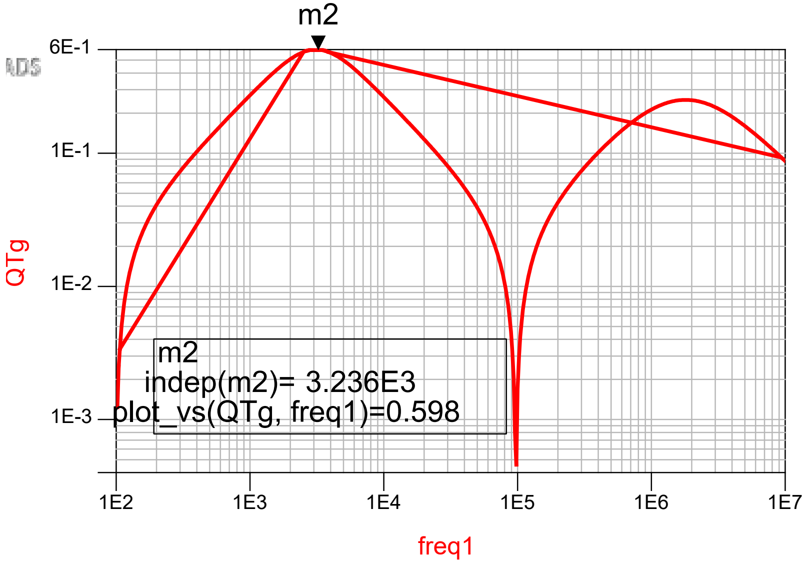
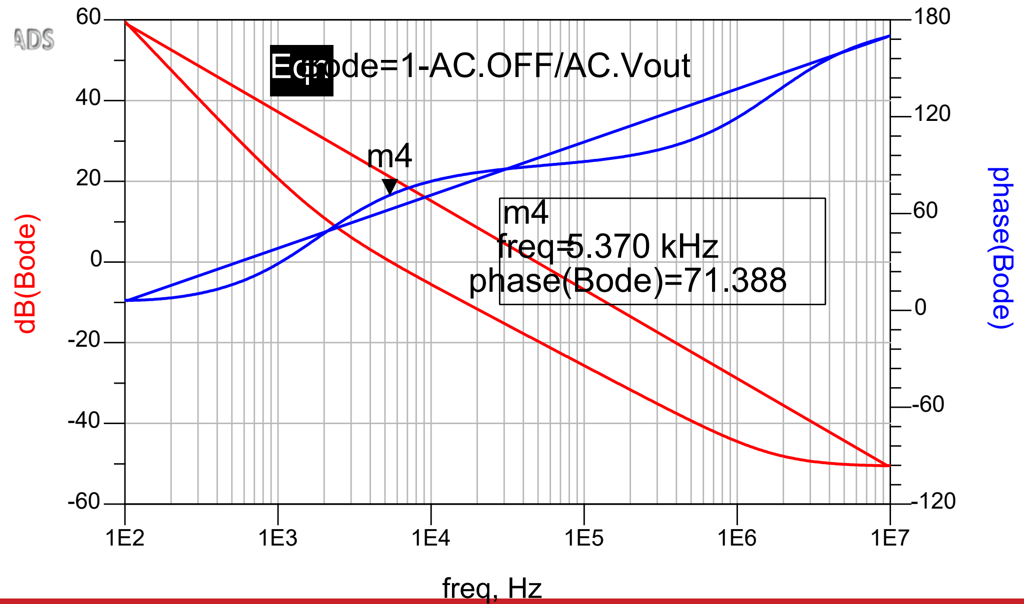
# NISM




| NISM_degrees |
|---|
| 68.700 |

Impedance also provides stability information – and can even provide Bode plots




Both solutions can be obtained directly from the Bode 100!!



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# So Why Frequency Domain (Impedance)?

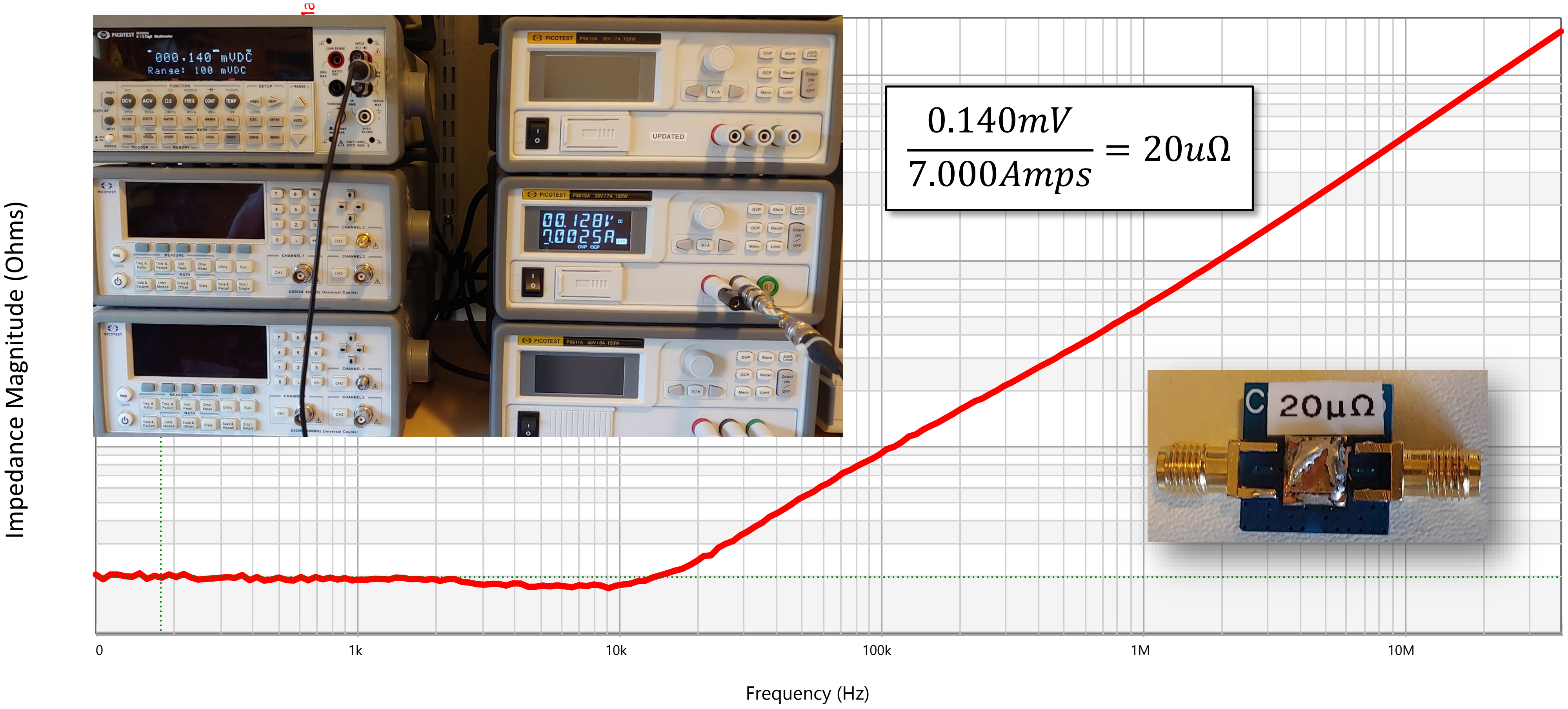
- Singular impedance response provides the MANY time domain responses
- Lower noise measurement yields much higher dynamic range
- Linear scales vs log scales
- Easily calibrated and wide band
- Easy to determine the worst-case stimulus
- Generating time domain stimulus can be hard

# Measuring (Low) Impedance

2-Port Shunt-Through

# Low Impedance Measurement is Challenging

But can be done with care




$$\frac{0.140mV}{7.000Amps} = 20u\Omega$$



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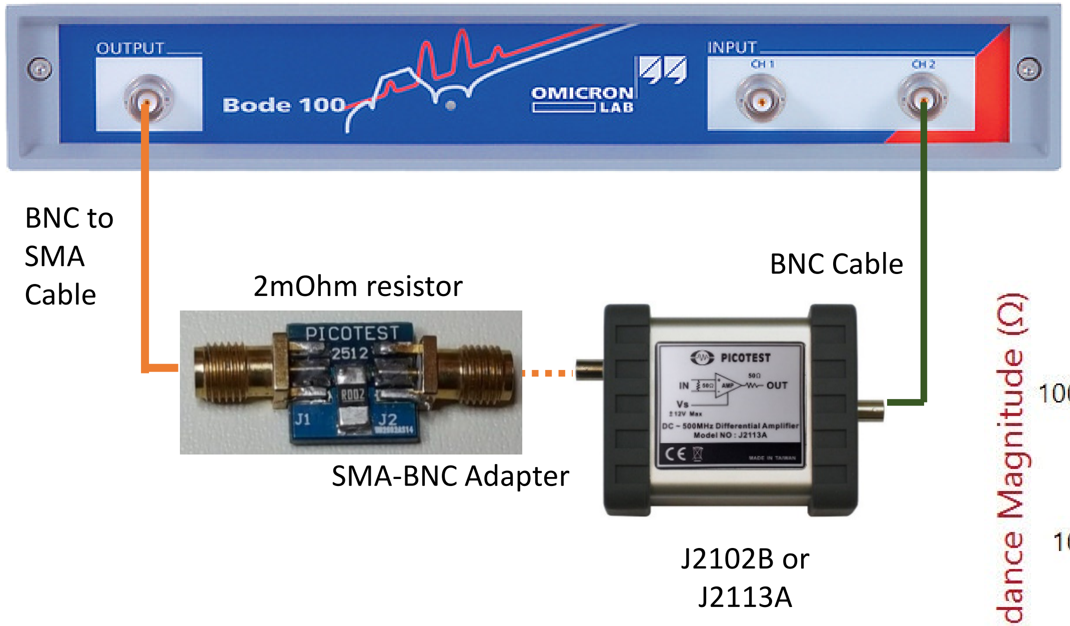
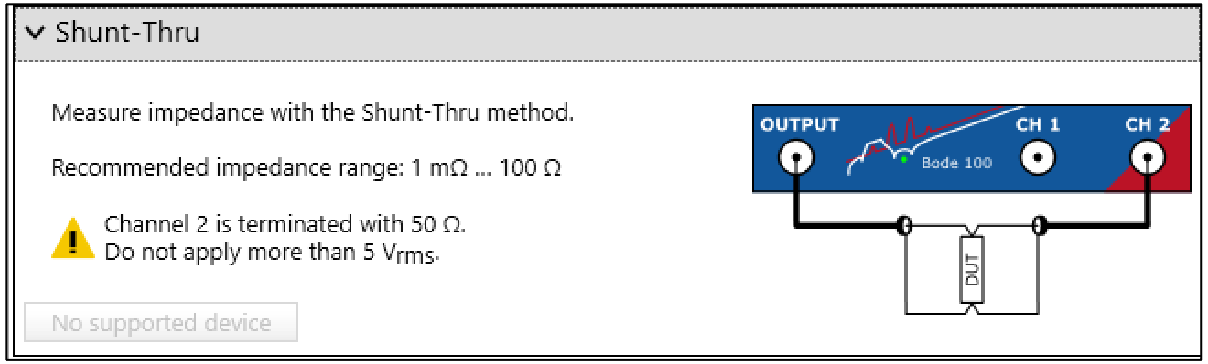
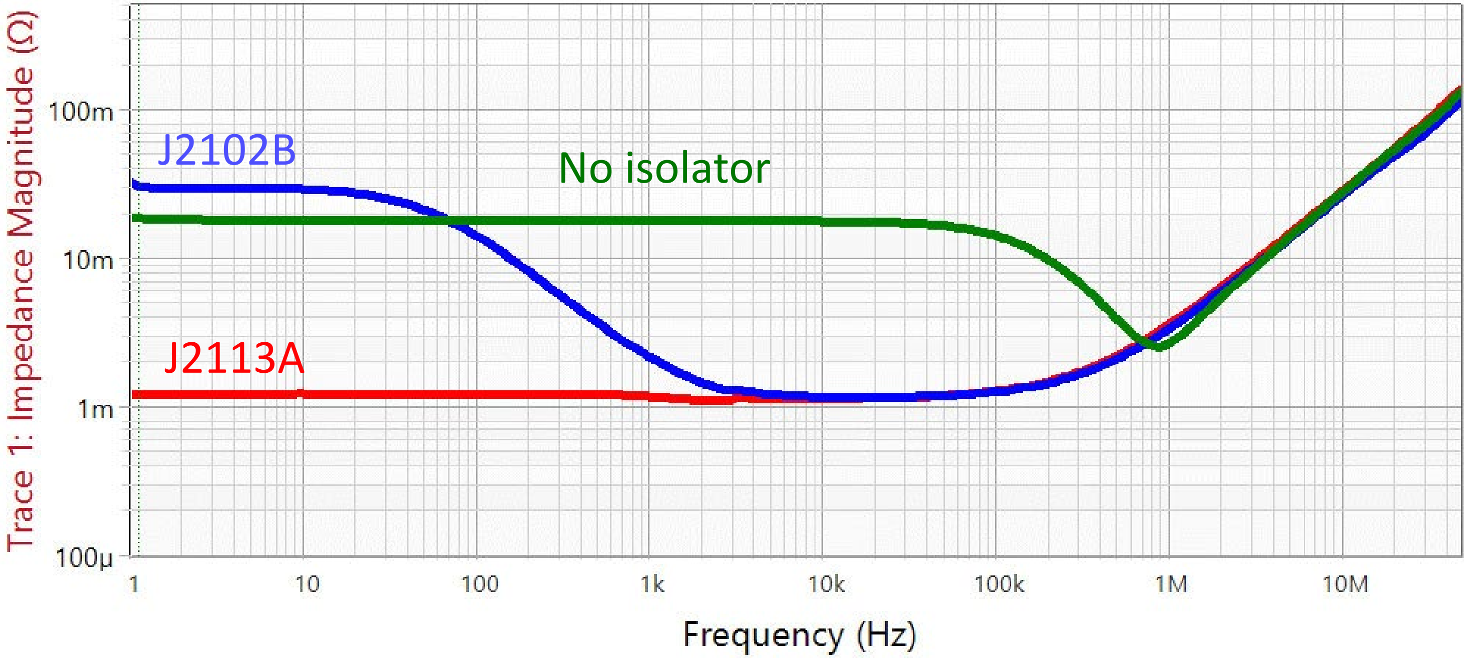
# 2-Port Shunt-Through Measurement




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



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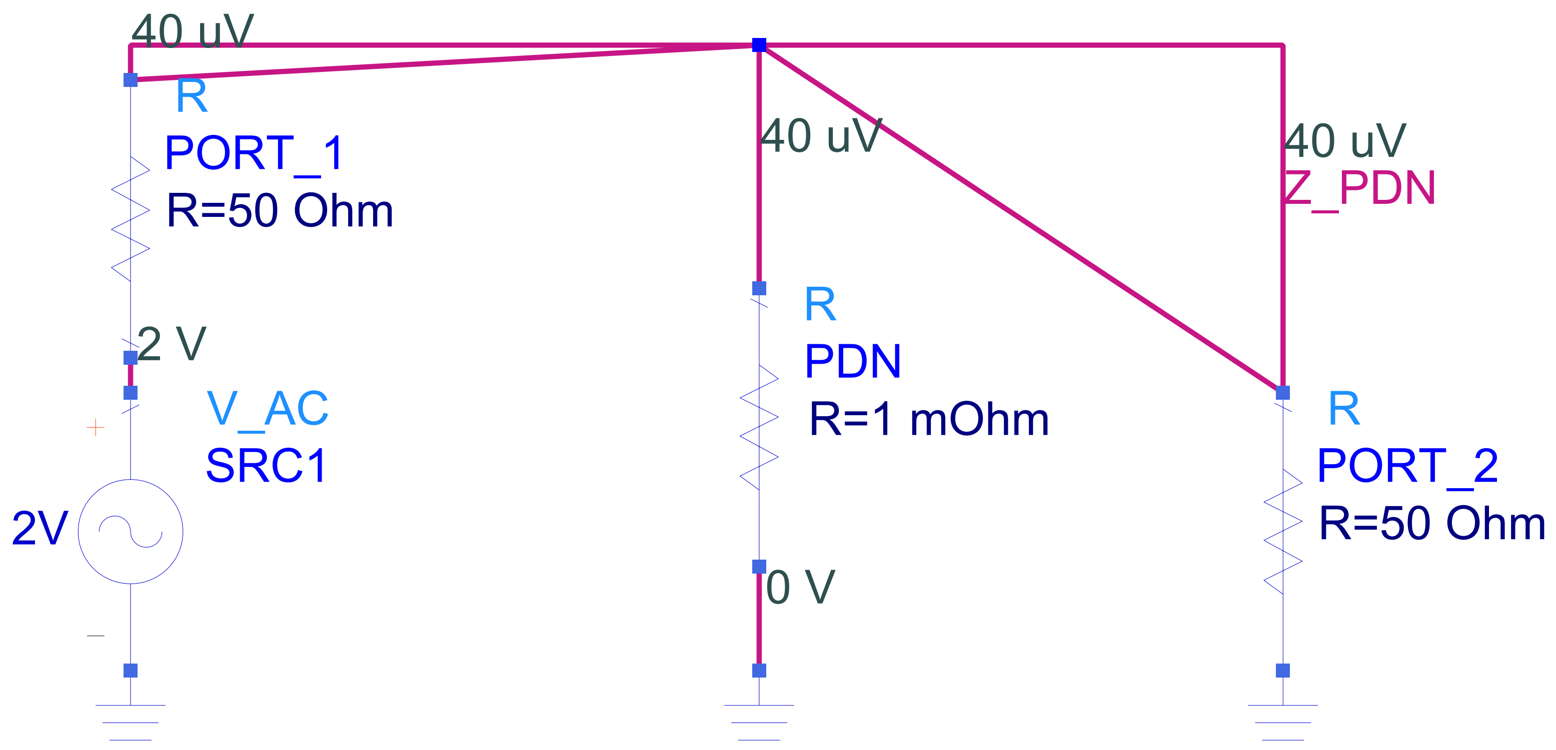
# 2-Port Shunt-Through Measurement

$$20 \cdot \log(40uV) = -87.96dB$$




$$S_{21} = \frac{2 \cdot DUT}{2 \cdot DUT + R_{port}}$$

$$DUT = \frac{R_{port}}{2} \cdot \frac{S_{21}}{1 - S_{21}}$$



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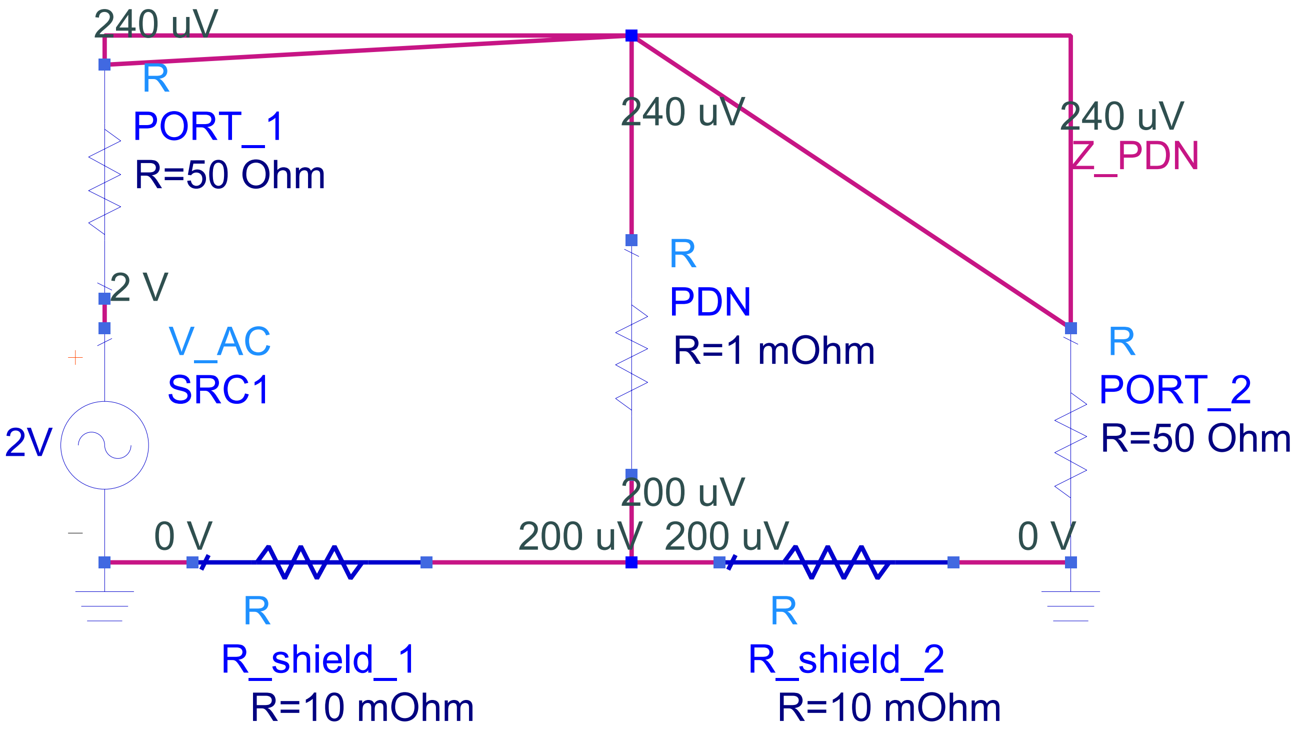
# Cable Shields Screw It All Up

The cable's outer conductors are in parallel with each other and in series with DUT




$$S_{21} \approx \frac{\frac{\mathrm{R\_shield}_1 \cdot \mathrm{R\_shield}_2}{\mathrm{R\_shield}_1 + \mathrm{R\_shield}_2} + DUT}{25 + \frac{\mathrm{R\_shield}_1 \cdot \mathrm{R\_shield}_2}{\mathrm{R\_shield}_1 + \mathrm{R\_shield}_2} + DUT} = 240u = -72.4dB$$

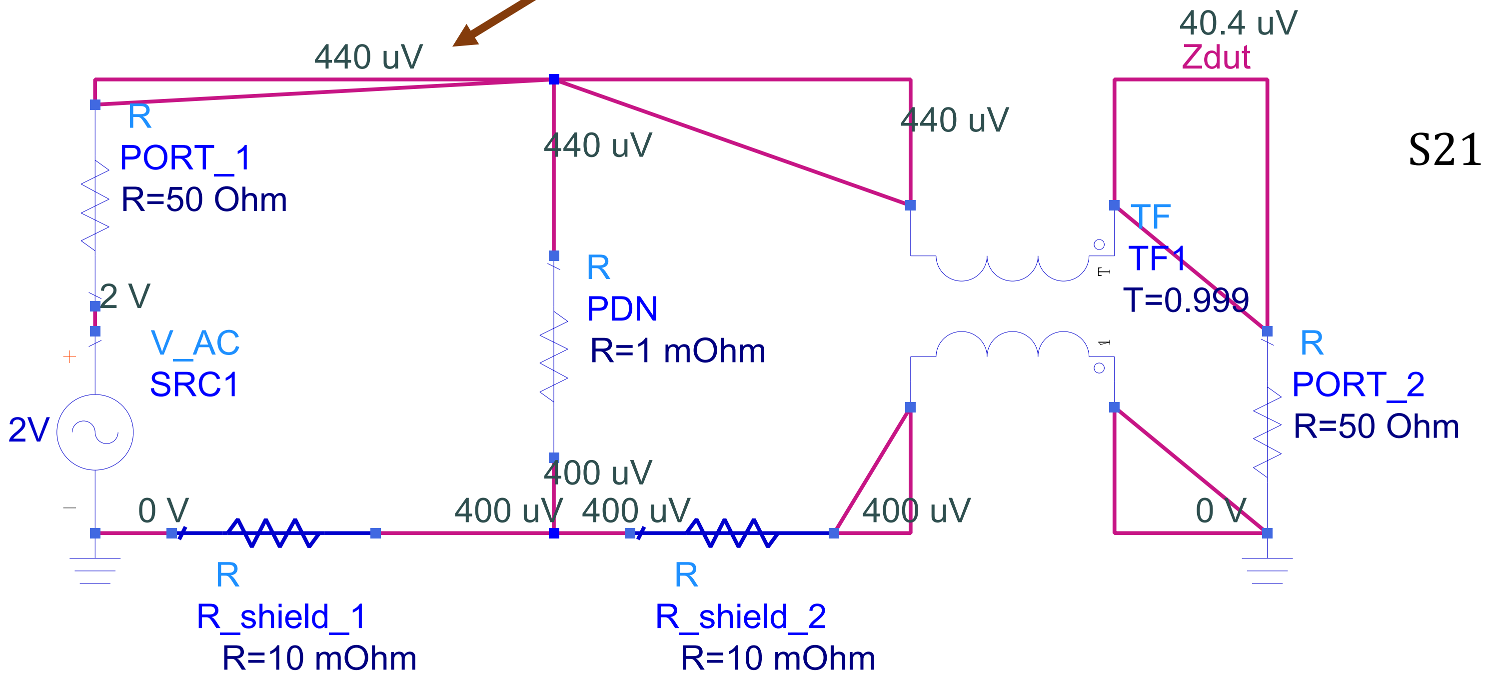
$$\mathrm{DUT} = \frac{25 \cdot 240\mathrm{u}}{1 - 240\mathrm{u}} \cong 25 \cdot 240\mathrm{u} = 6\mathrm{m}\Omega$$

$$10m\Omega || 10m\Omega + 1\mathrm{m}\Omega = 6m\Omega$$

$$Error = \frac{6m\Omega - 1m\Omega}{1m\Omega} = 500\%\ Error$$

# Ground Isolators Make It Better

Note that first it got WORSE, because now all the current returns through one shield, R_shield_1




Here the ground is isolated by the CMRR of the isolator

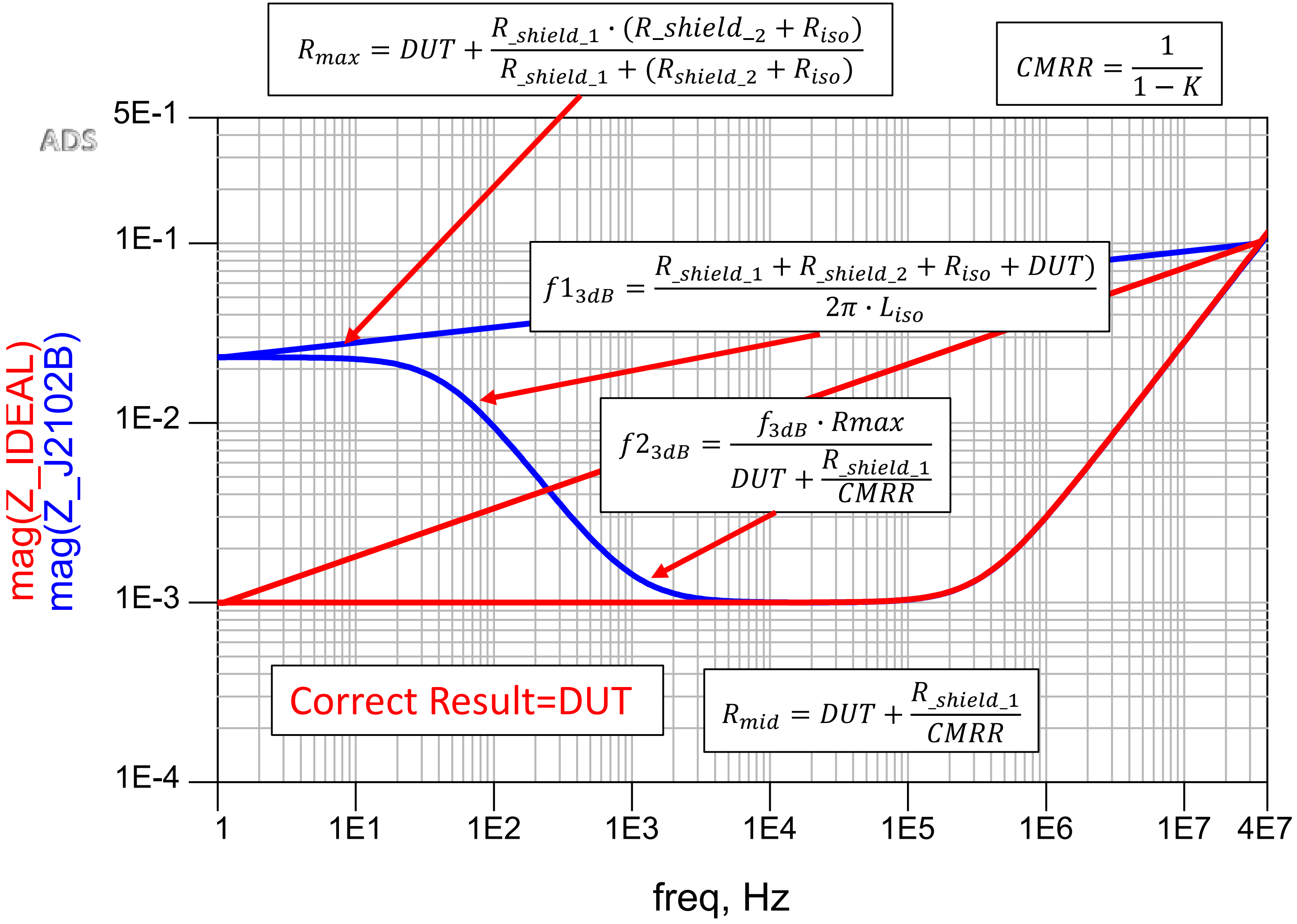
$$S21 = \frac{\text{R\_shield\_1} \cdot \left(\frac{1}{CMRR}\right) + DUT}{\frac{R_{port}}{2} + \text{R\_shield\_1} \cdot \left(\frac{1}{CMRR}\right) + DUT} = 40.4u$$

$$CMRR_{xfmr} = \frac{1}{1 - K}$$

$$DUT = \frac{50}{2} \cdot \frac{40.4u}{1 - 40.4u} = 1.01m\Omega$$

$$Error = \frac{1.01m\Omega - 1m\Omega}{1m\Omega} = 1\%\ Error$$

# Seeing It Mathematically




The transformer isolator is complex, but depends on excellent coupling for high CMRR, high isolation inductance and low DC resistance

The solid-state isolator is more straightforward and provides isolation down to much lower frequencies



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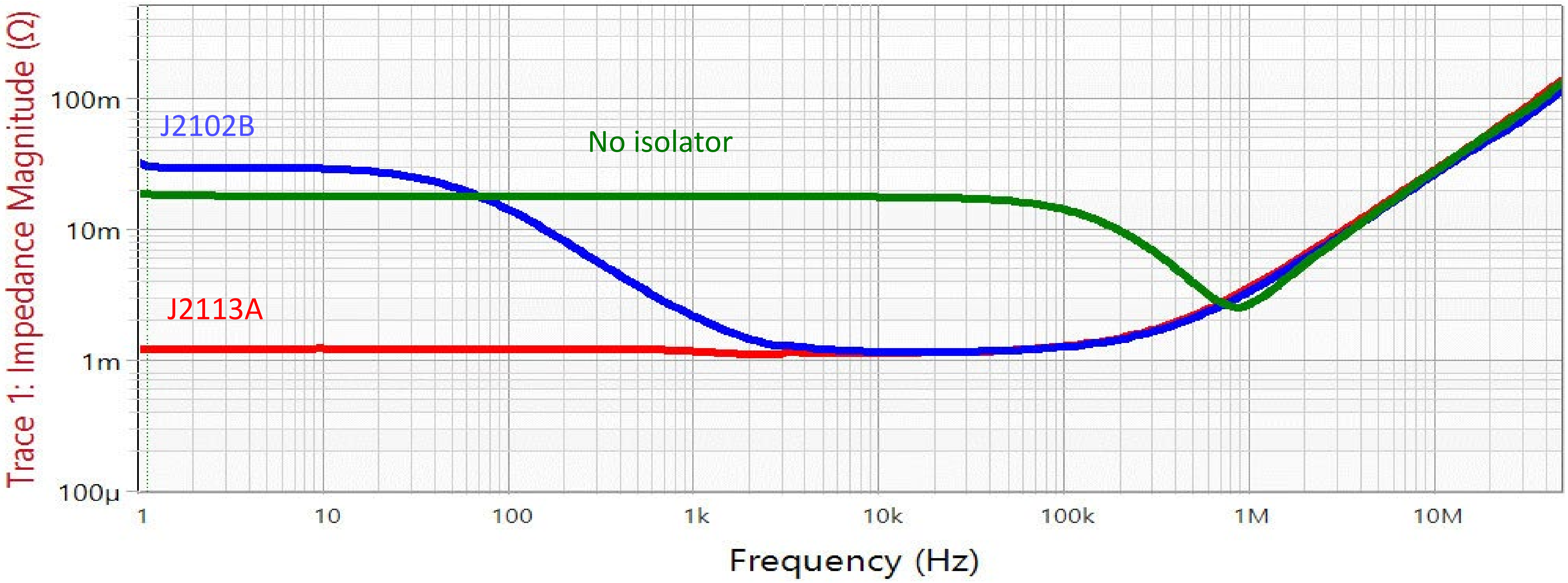
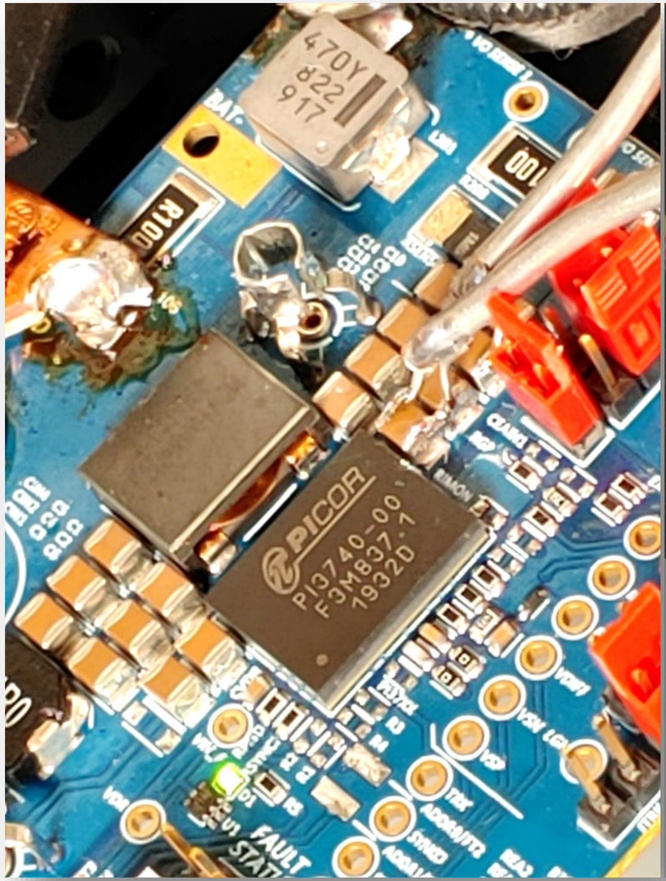
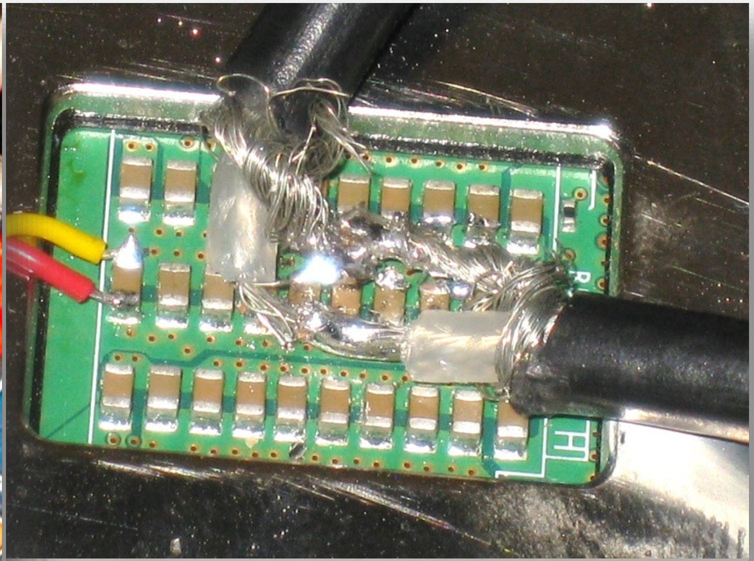
# Proving It Through Measurement



# Five Connection Options

- Solder down coax - pigtails
- Place RF connectors
- Place Headers or Probe Points
- Browser Probes
- Micro-Probes





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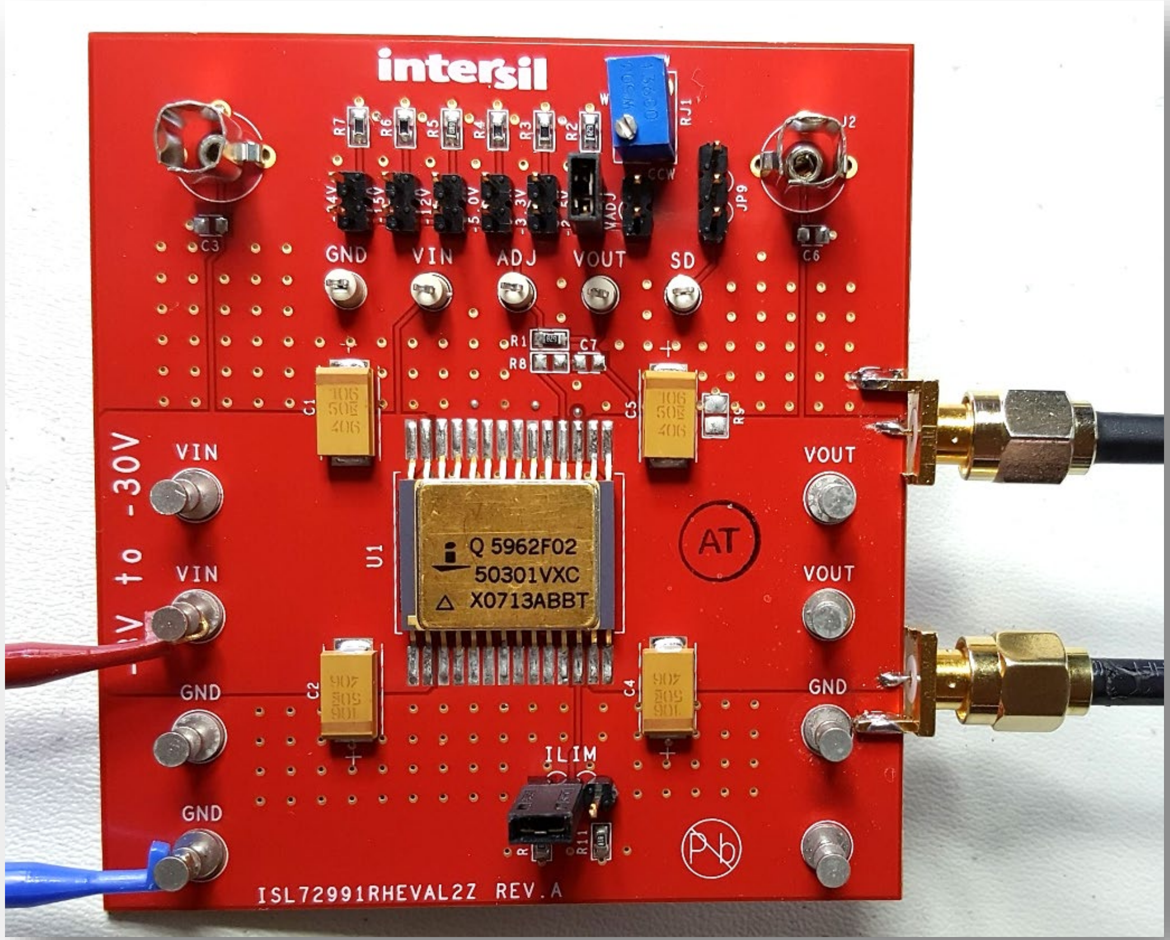
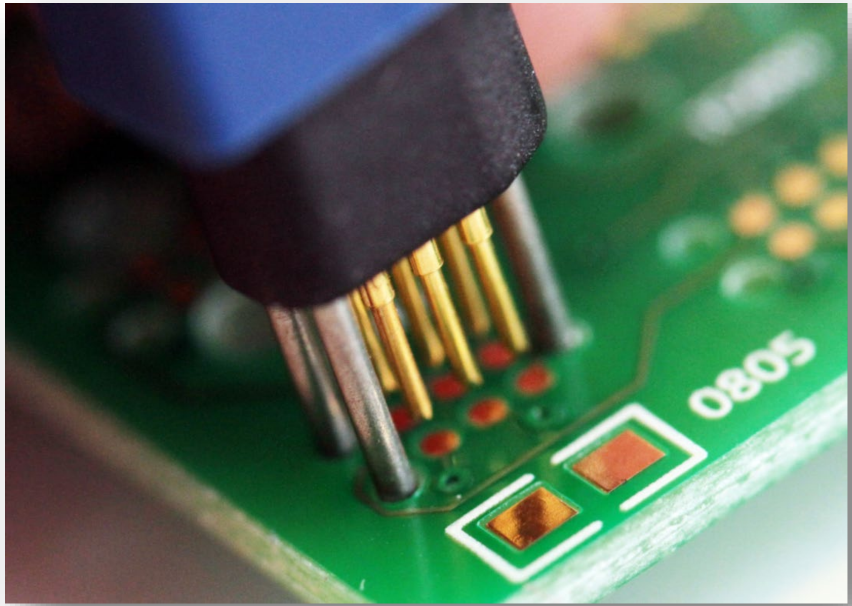
# RF Connectors

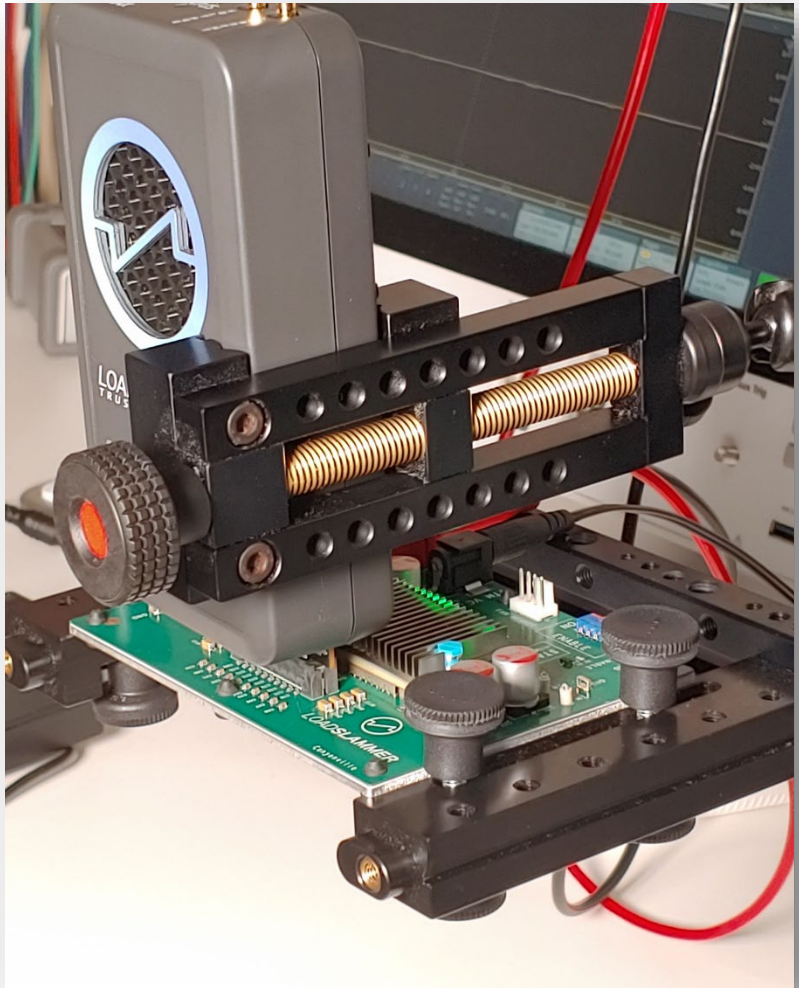



# Headers

Mill-Max

ThingamaFob



Samtec HSEC*-130-01-L-DV-A-WT-K-TR



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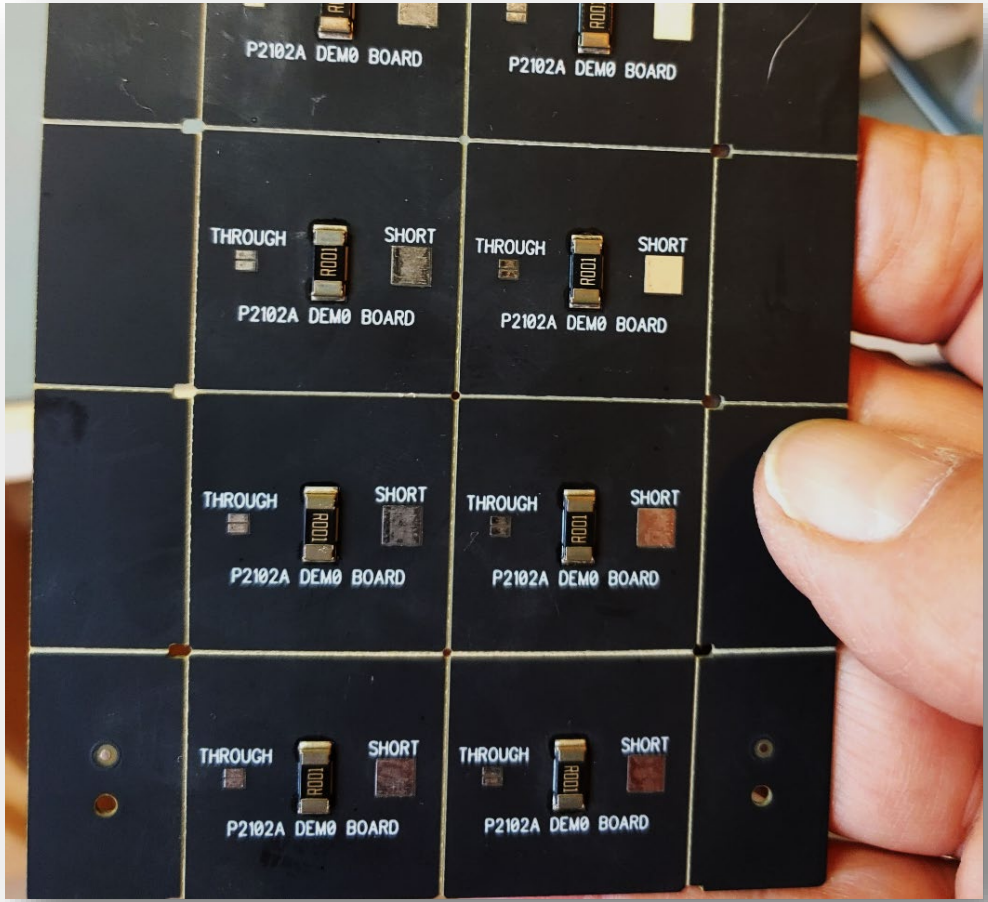
# Test Points

Test Points Can Be Tiny and placed on either side of the PCB





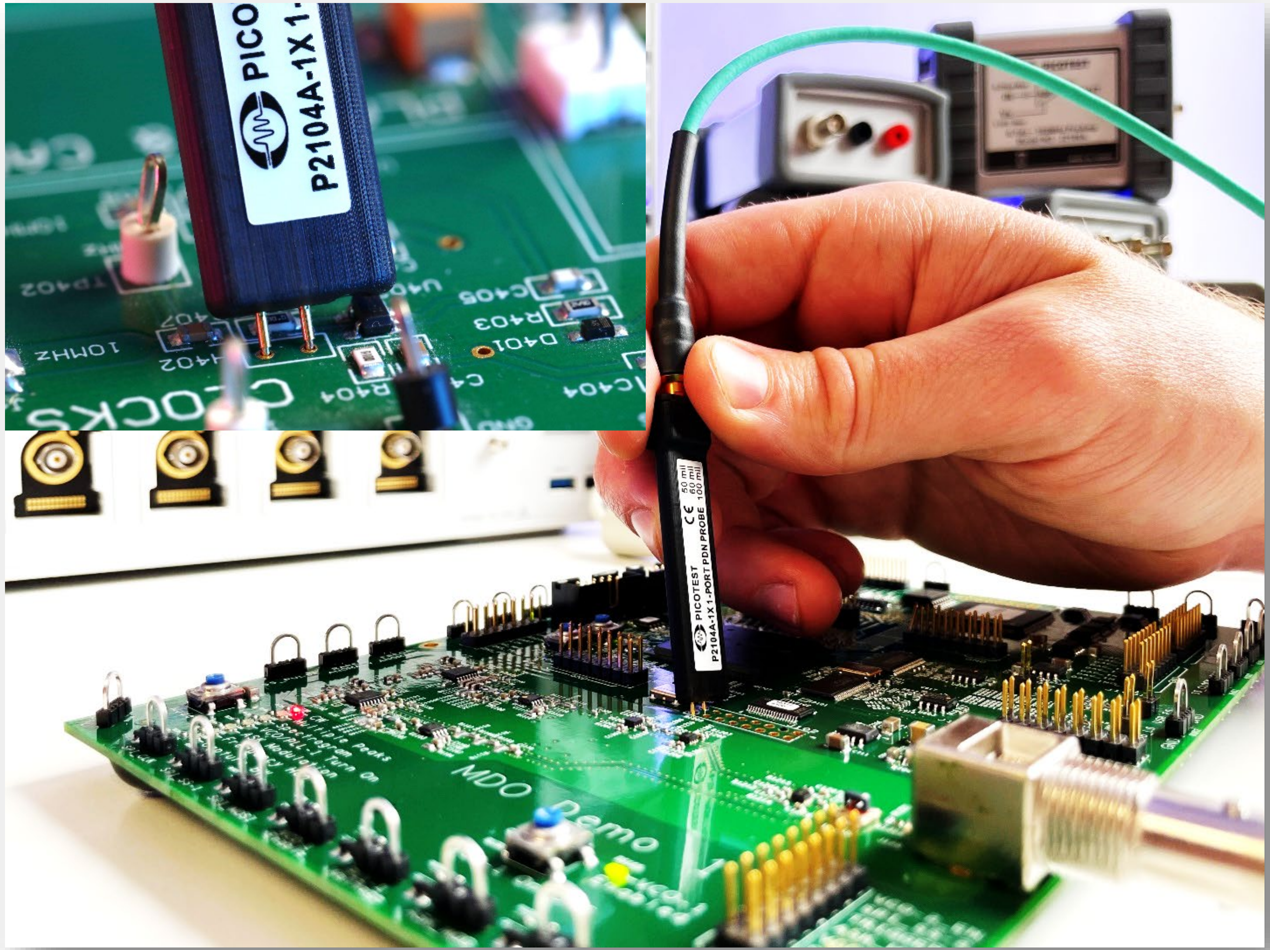
A 1 milliohm resistor is mounted on the topside of this demo board

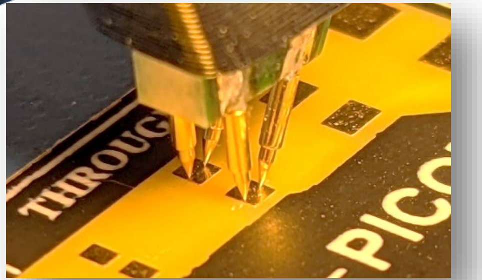
Four pads are placed on the back side to show that this resistor can be measured using an 0402, 0603, 0805, or 1206 probe head

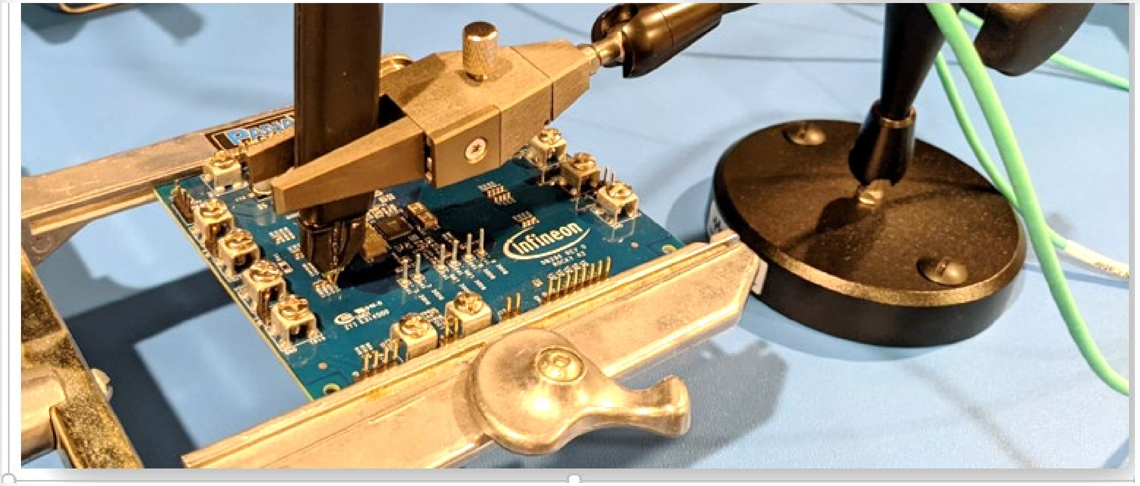
Each pad connects to the topside resistor with a separate via and trace

This maintains the 4-point Kelvin contact to the resistor

# 50 Ohm Probes – P2104A 1-Port & P2102A 2-Port



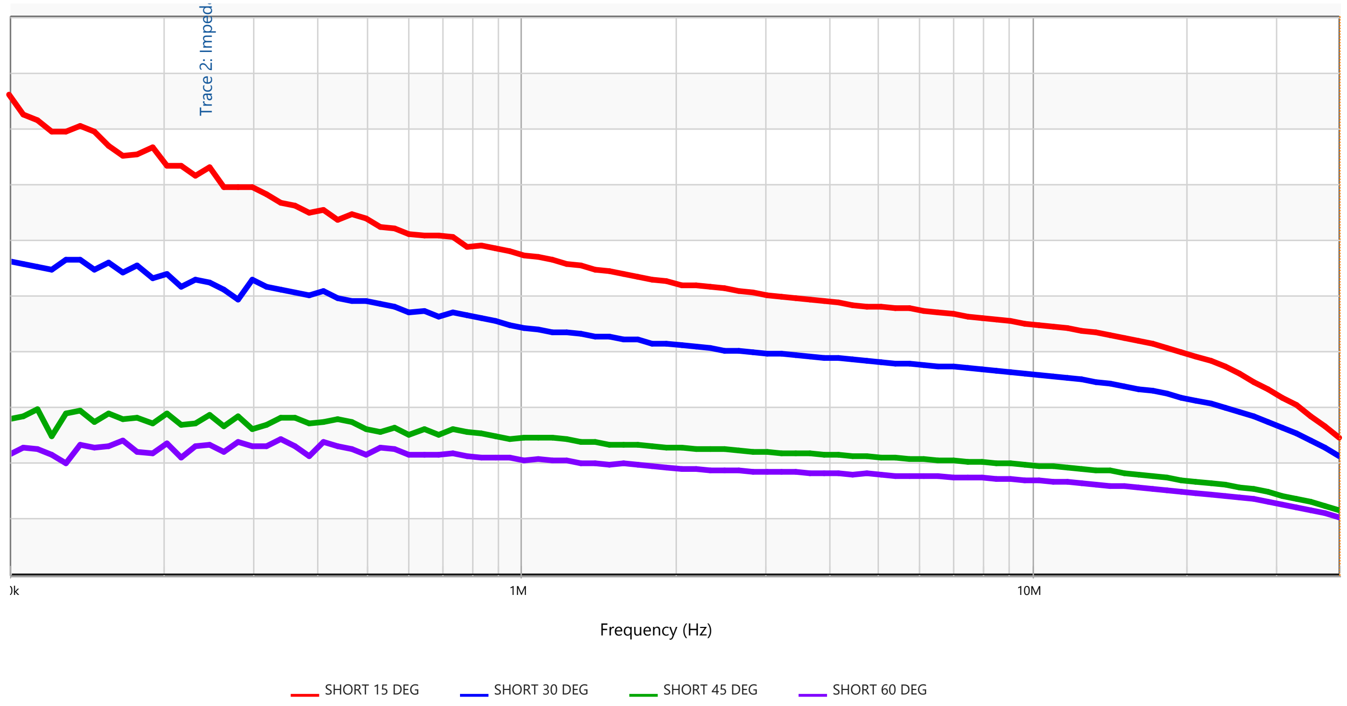



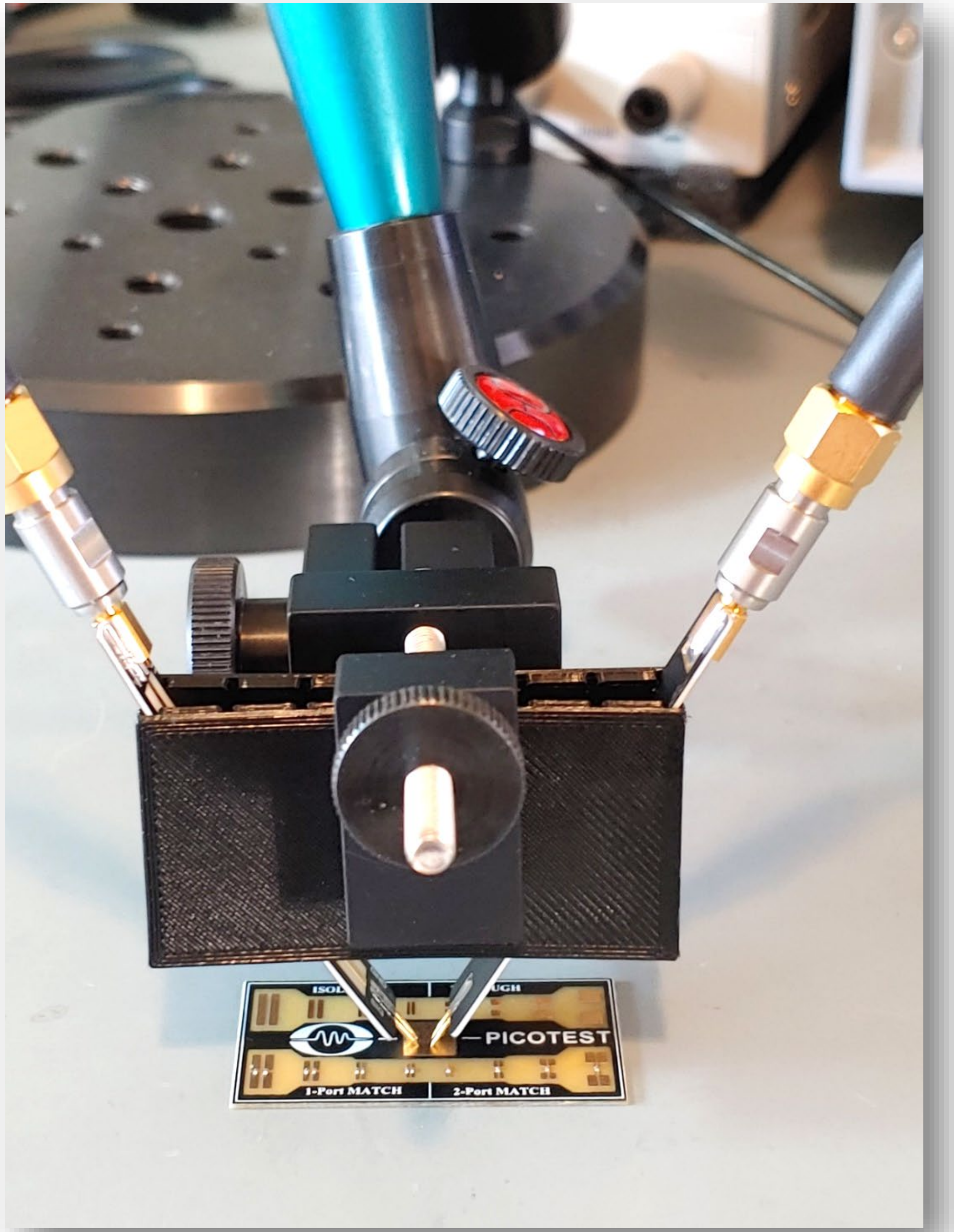


# But the Angles

Residual inductance varies with angle, so must be the same for calibration and measurement

2-port probe eliminates this variability



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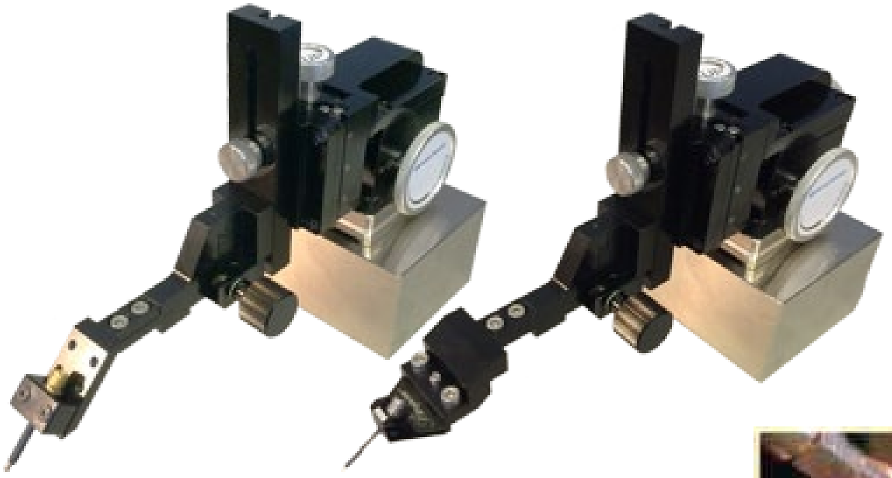
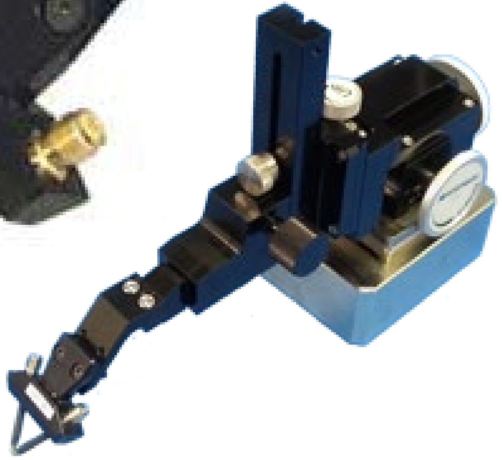
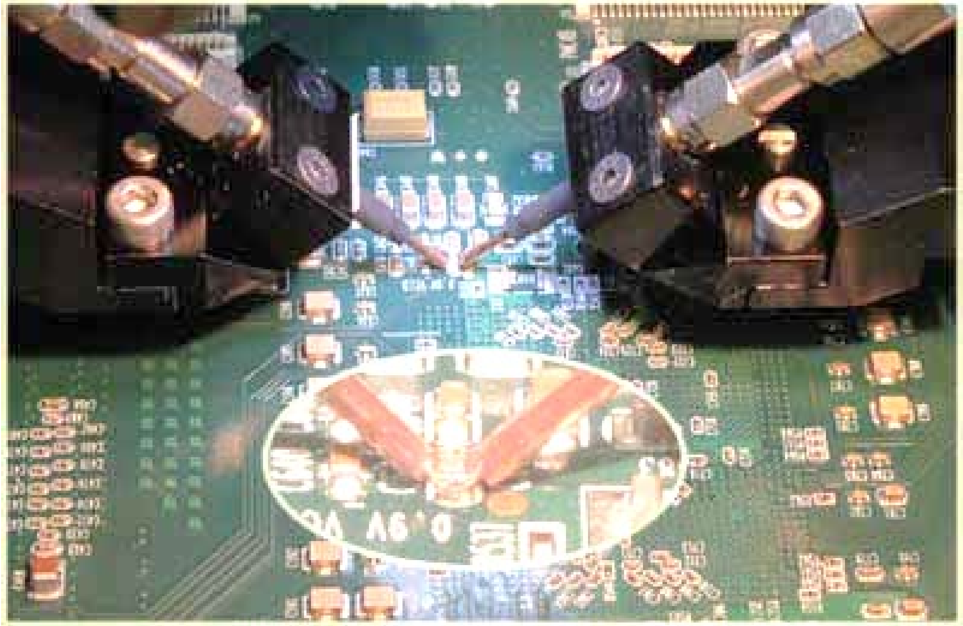
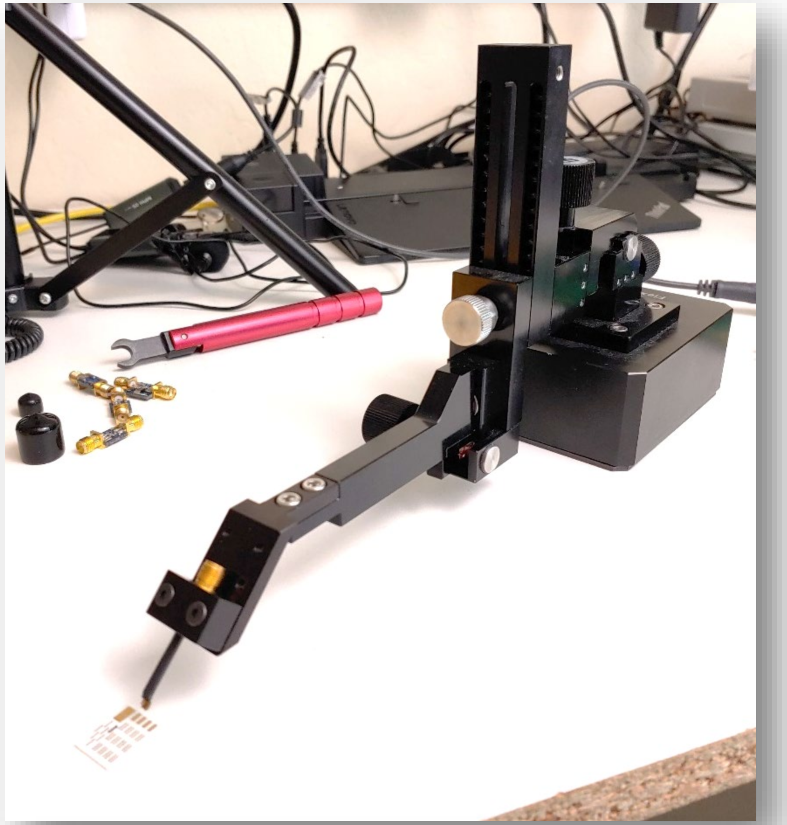
# Micro-Probes







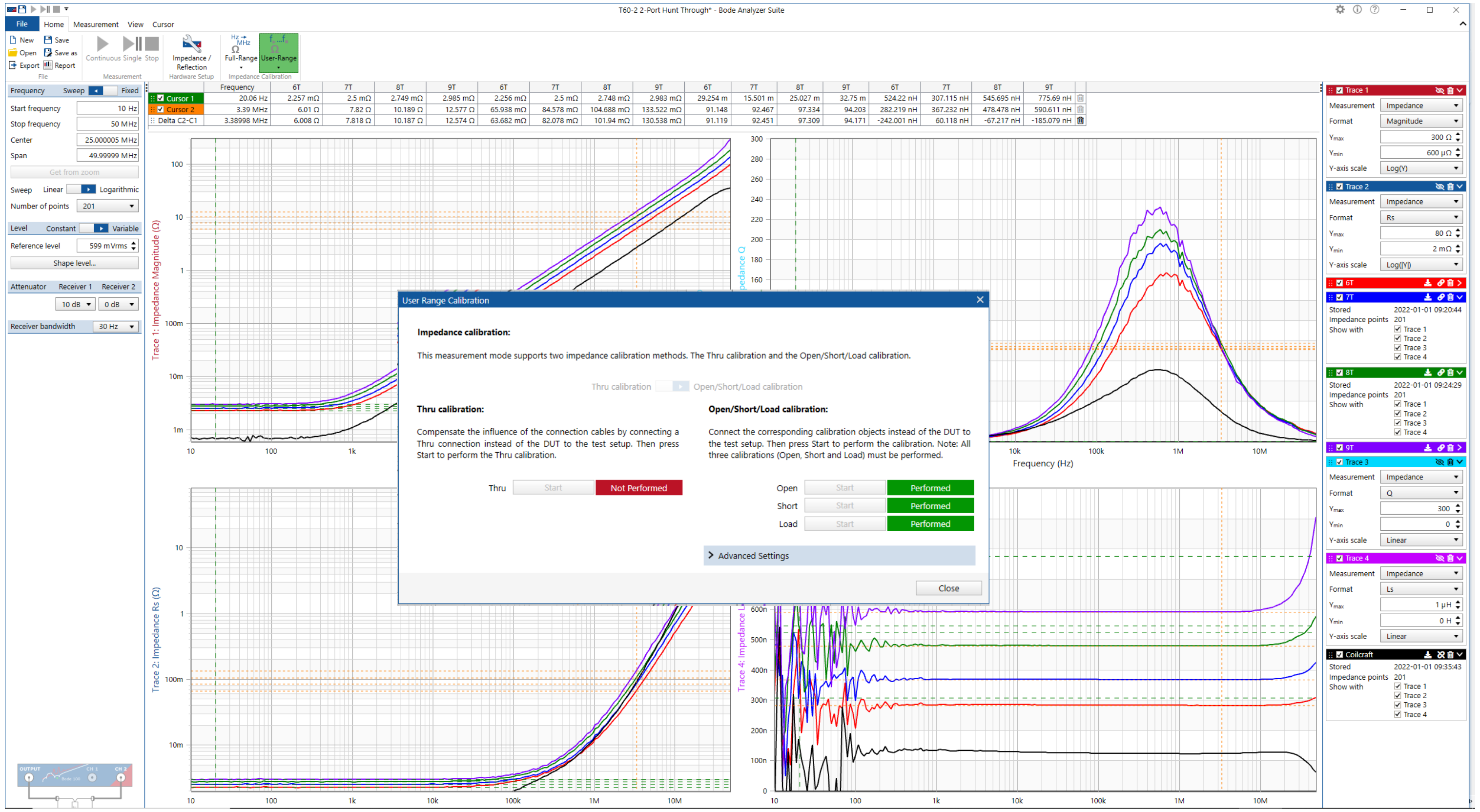


# Pros, Cons and Selection Criteria

| Connection | Ease | Measurement Repeatability | Cost | Accuracy | BW | Shield Resistance |
|---|---|---|---|---|---|---|
| Soldered Pigtail | Messy | Poor | Low | Poor | Limited | Very low |
| RF Connectors | Foresight | Excellent | Low | High | High | Very low |
| Browser Probes | Best | Very Good | Medium | High | High | Moderate |
| Micro-Probes | Holders<br>Microscope | Excellent | High | High | Best | Moderate - High |
| Headers | Foresight | Very Good | Low | Moderate | Moderate | Low |

The largest error is shield resistance, so spring pins and connector contacts add resistance
The cable also adds resistance, so choose wisely

# Calibrate!



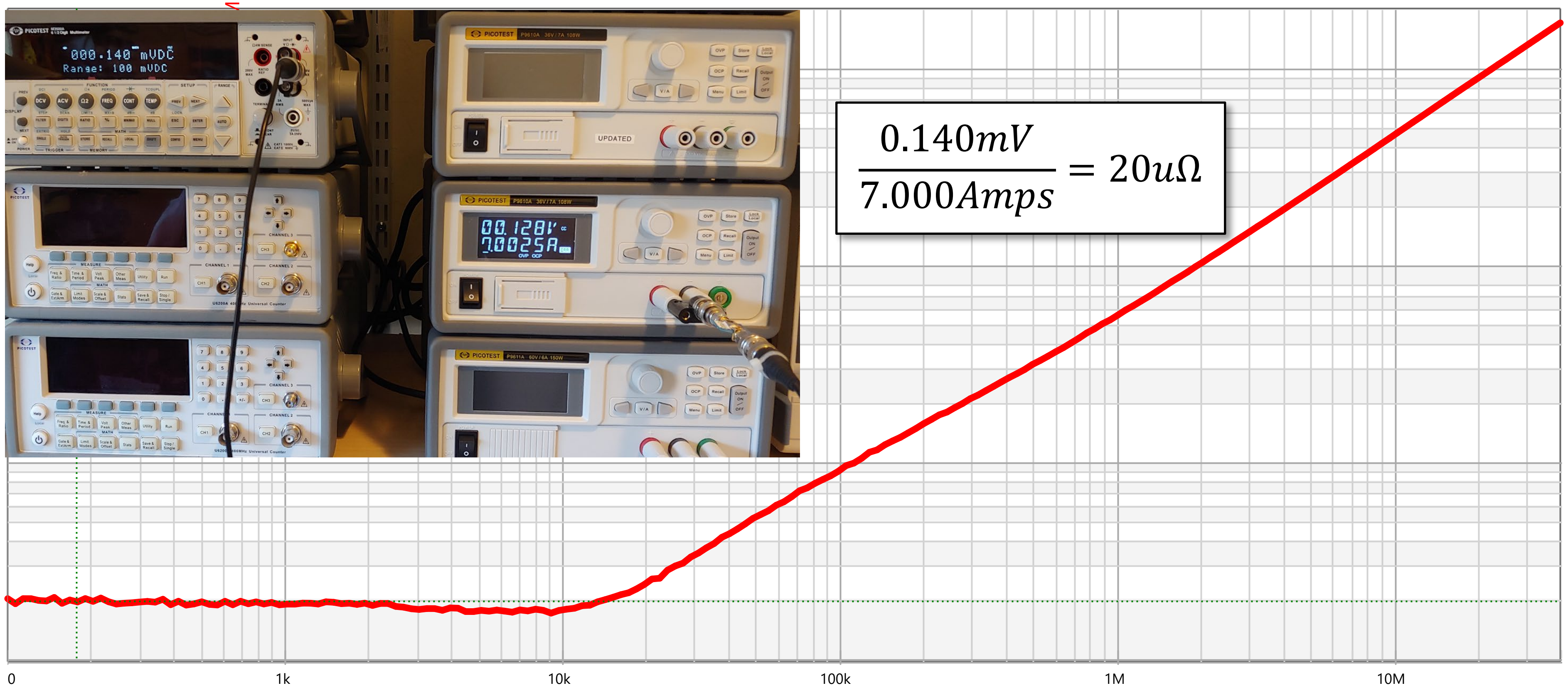

Frequency Domain (VNA) allows very simple and accurate calibration to correct for cable probe errors

Calibration can also be used to remove measurement parasitics that we don’t want to include

The Bode 100 provides Short, Open, Load calibration for 1-port AND 2-port measurements

# Calibration Allows Precise Measurements

At very low Impedance a B-AMP 12 on the Bode 100 OUTPUT can improve the measurement SNR

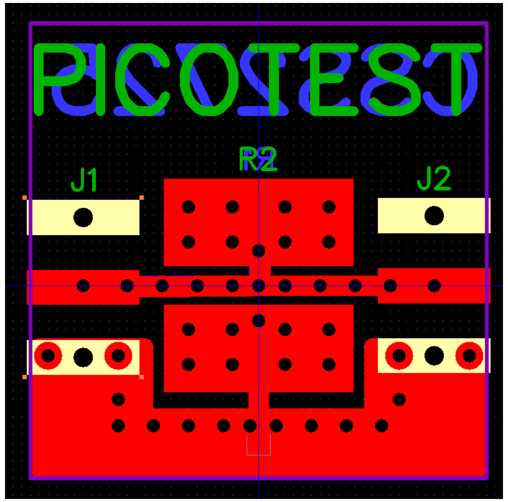


# Summary

- Several connectivity options are available. Different circumstances will warrant different selections
- Measuring a capacitor is NOT the same as measuring a circuit board plane
- Four-point connection is key. The P2102A 2-port probe is a four-point probe
- Calibrate appropriately
- Measure something you know, and of similar magnitude
- Cable shield and ground pin resistance $\mathrm{error}(\Omega) \approx \left(\frac{R\_GND\_1(\Omega)}{\mathrm{mag(CMRR)}}\right)$ so use low shield resistance cables, as short as possible, and a good quality common mode ground isolator – either solid state or passive

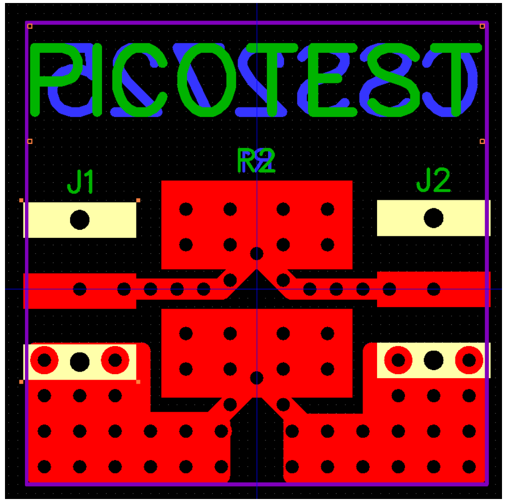
## Calibration is Essential

**2-point contact at DUT**




**BAD**

**4-point contact at DUT**




**GOOD**



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# Thank You for Attending!

- For demo equipment or quote requests, email info@picotest.com
- Want to become a certified measurement expert? Visit www.picotestonline.com
- Join the Power Integrity for Distributed Systems LinkedIn Group
- You can learn more about the products and accessories we discussed today by visiting:
    - www.picotest.com
    - www.omicron-lab.com



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# References

- The Influence of Connectivity on Low Impedance Measurements, EDICON 2021
- Target Impedance and Rogue Waves
- EDICON UNIVERSITY: How to Measure Ultra Low Impedance (100uOhm and Lower) PDNs, EDICON 2018
- Measuring uOhms and pH with the P2102A and the Bode 100
- Another Measuring uOhms and pH with the P2102A and the Bode 100



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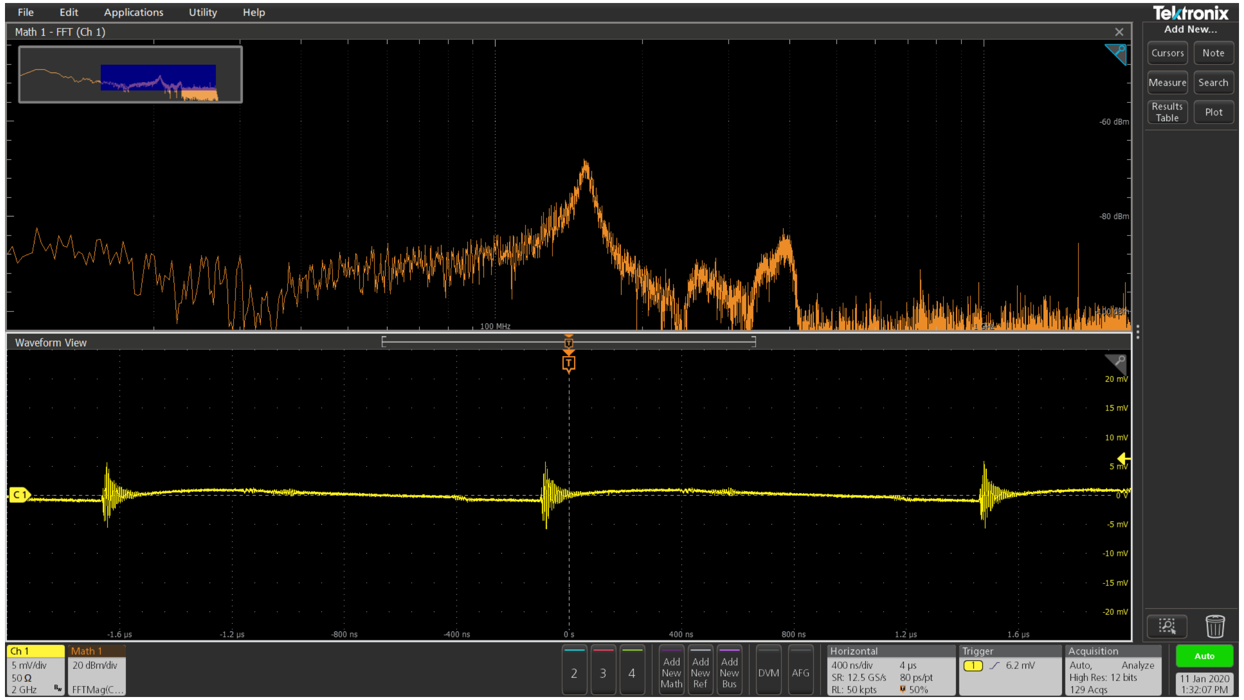
# Time Permitting

# Electromagnetic Interference (EMI)

EMI is focused on conducted and radiated signals that escape from the electronics circuitry where they can interfere with other circuits. For example, EMI in the 100MHz range might create noise in an FM radio, while 2.4GHz EMI might interfere with cell phone or Wi-Fi performance.

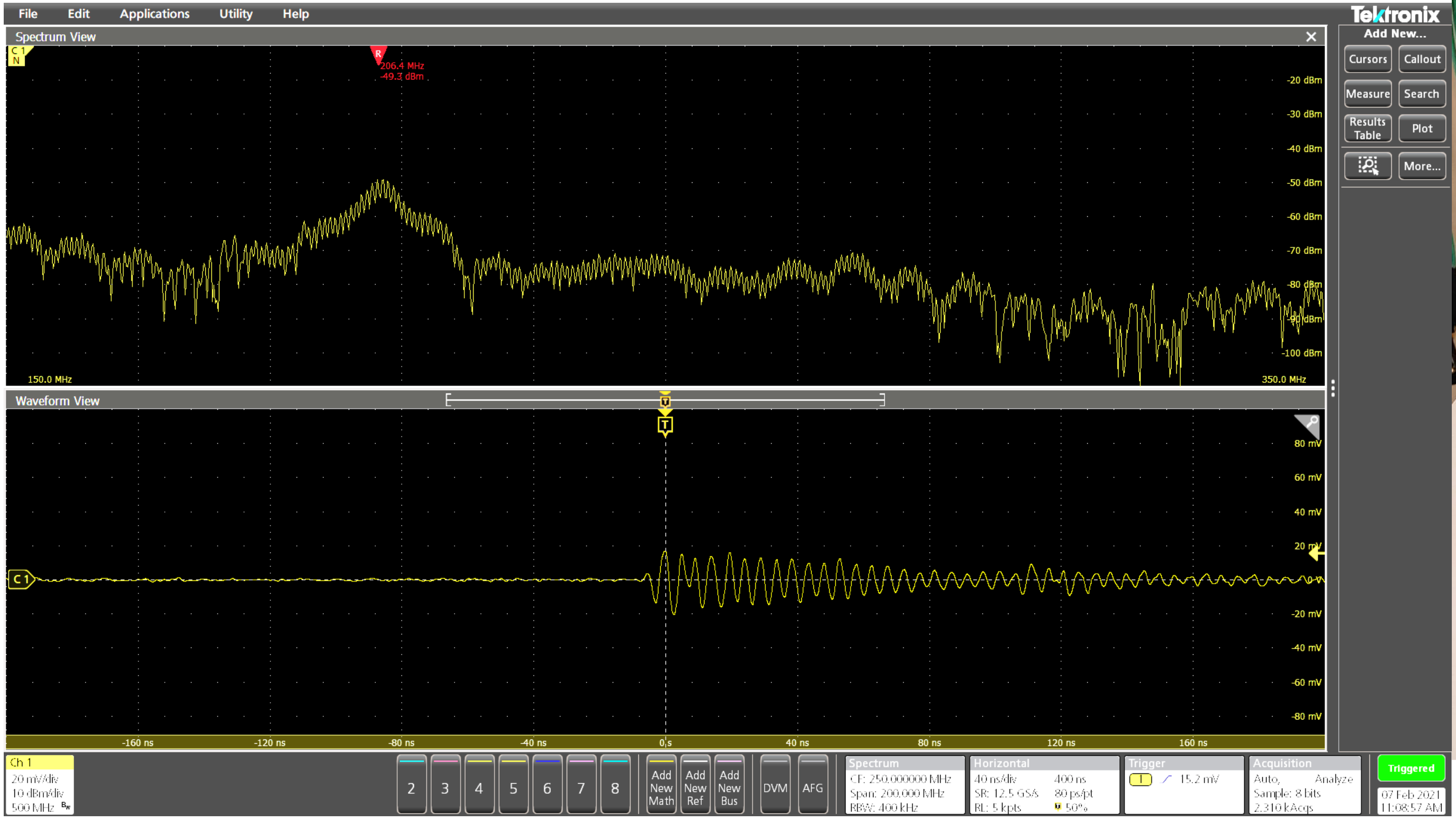
The EMI Engineer also has specific goals, and this (non-exhaustive) list identifies some of the most common:

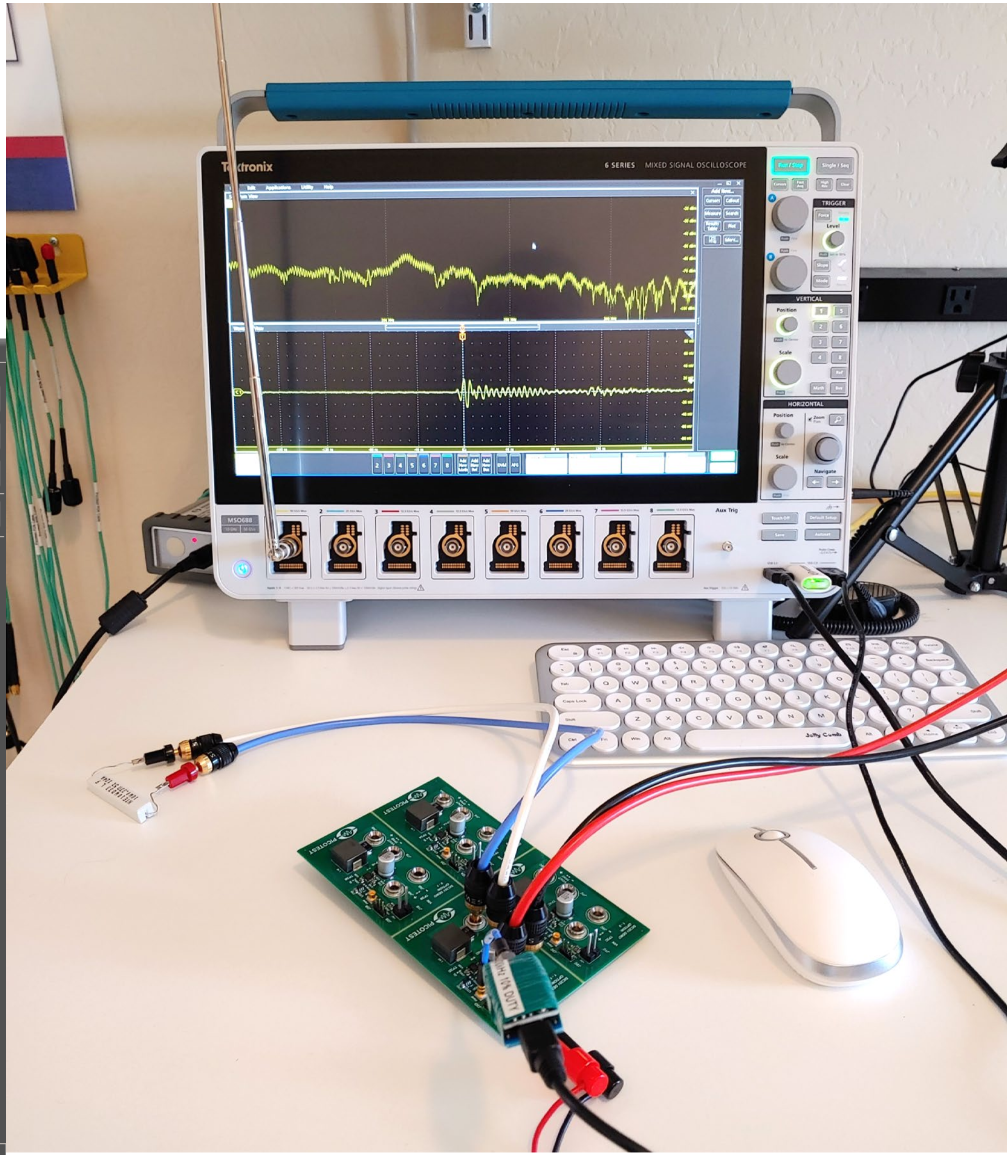
- Unbroken Return Paths
- Tightly Sealed Enclosure
- Minimum Coupling
- No High Q **Impedance** Peaks



# YEP, EMI

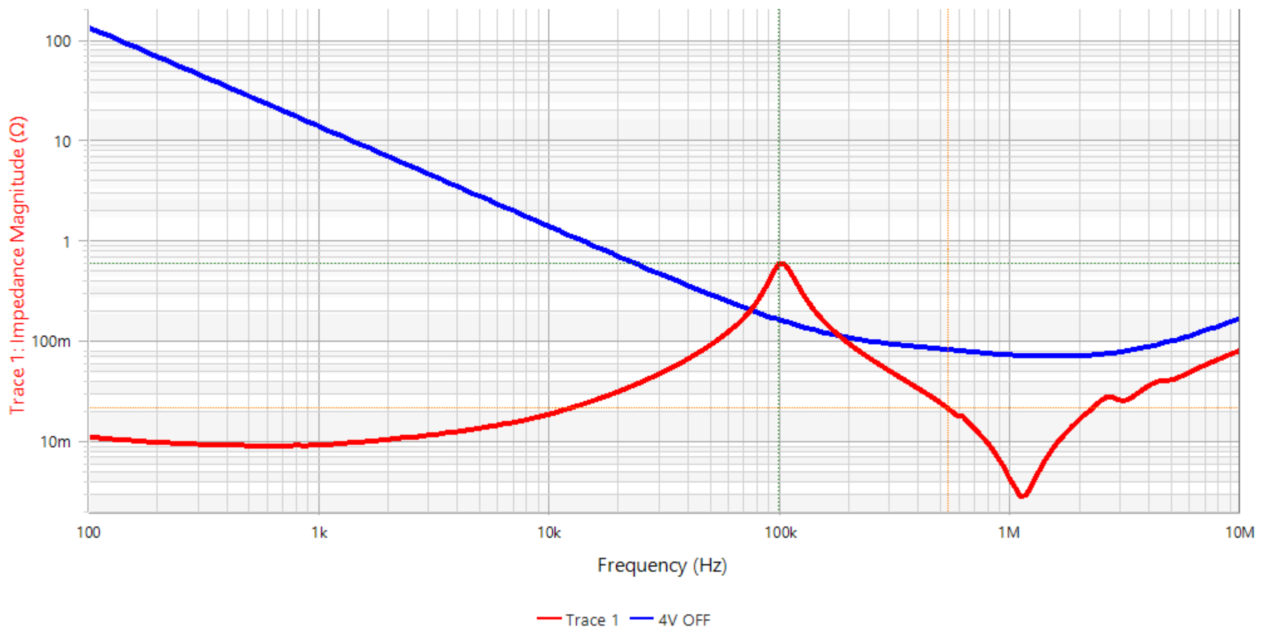
## Impedance -> Ringing -> EMI



# Impedance ⟷ Noise

## State Space Power Rail Impedance




## Measured Power Rail Noise Density nV/Hz