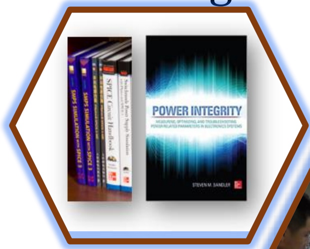
How to measure ultra-low impedance (100uOhm and lower) PDNs

October 17, 2018

And Just a Bit About Steve

- 40+ Years Experience (1977-present)
- AEi Systems – Founder and CTO (1995-)
- Picotest – Founder and Managing Director (2010-)
- Test Engineer of the Year (2012-2014)
- Experience: Space Shuttle, Space Station, GPS, Large Hadron Collider and many other military and commercial projects
- Primarily focused on RF, Analog, and Distributed Power Systems

I enjoy writing



lecturing

lab time

making pizza

Abstract Submitted

How to measure ultra-low impedance (100uOhm and lower) PDNs

Speaker: Steve Sandler

Who should attend:

All engineers that may be facing 100uOhm PDN's now or in the near future, or those that just have an interest learning new measurement techniques.

Prerequisites

None

Key Takeaways:

- Ultra-low impedance measurement basics
- Choosing between 2-port and 3-port measurement techniques
- Dealing with measurement ground loops
- The importance of interconnects and signal to noise ratio
- Self-impedance vs Transfer impedance
- Measuring something you know (close to 100uOhms)

Abstract Submitted

Measuring ultra-low impedance is a common requirement for assuring power integrity. This meant measuring 1 milliOhm to 2 milliOhm voltage regulator modules (VRM's) and power distribution networks or (PDN's). Every year we talked about how operating voltages are falling and frequency is increasing. Maybe some of us realized this meant higher operating current and therefore lower impedance.

Today, it is common to see 500uOhm power rails, but more recently the bleeding edge is below 100uOhms. Measuring 100uOhms is a significant challenge, even using the venerable 2-port shunt-thru measurement that has served as the staple of ultra-low impedance measurement. The dynamic range of the 100uOhm, 2-port, measurement is 108dB. An impedance dip to 30uOhms reduces this to 118dB. This dynamic range presses the limits of the noise floor for even the best VNA. The addition of operating voltage noise, including ripple and load-induced transients increases the challenge.

At these ultra-low impedance levels everything matters, from the quality of the instrument interconnects, to the quality of the ground loop isolator. In this tutorial, you'll learn some techniques that will improve the accuracy and fidelity of your sub 100uOhm measurements. You'll learn the pros and cons of the 2-port vs 3-port measurement technique. With a little bit of luck, we'll demonstrate a 100uOhm impedance measurement as well as showing some measurements highlight the challenges you'll face along the way.

Key Takeaways

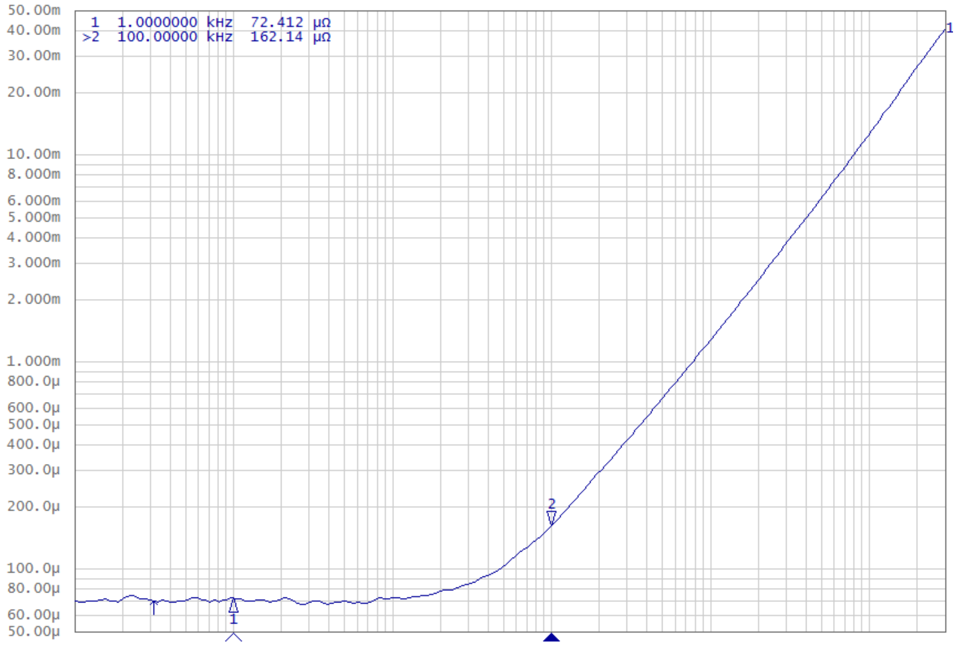
1. Ultra-low impedance measurement basics
2. Choosing between 2-port and 3-port measurement techniques
3. Dealing with measurement ground loops
4. The impedance of interconnects and signal to noise ratio
5. Self-impedance vs Transfer impedance
6. Measuring something you know (close to 100 uOhms)

Today's Agenda

1. What applications require 100 uOhm ?
2. What are the measurement options ?
3. What makes 100 uOhms so much more difficult than 1 mOhm ?
4. Tips for making good 100 uOhm measurements

Ultra-Low Impedance Measurement

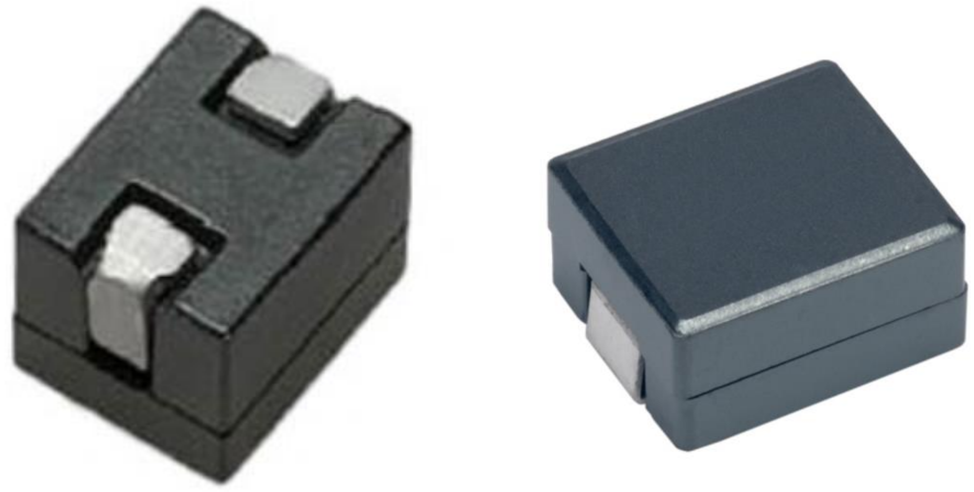
A quick introduction to the application and the measurement options



Filter Inductors

VRM power inductors often have DCR well below 1mΩ.

This device has a specified DCR of 90uΩ-110uΩ

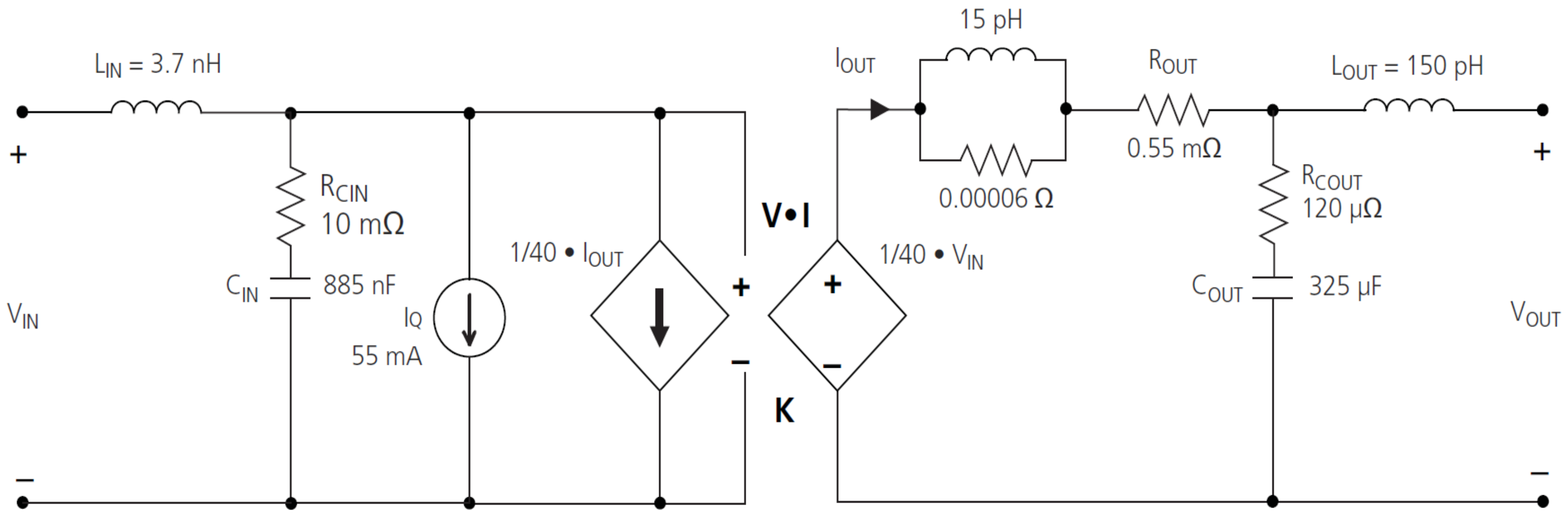


Part Number[8]	OCL[1] (nH) ±10%	FLL[2] (nH) minimum	I_{rms}[3] (amps)	$I_{sat}1$[4] (amps)	$I_{sat}2$[5] (amps)	$I_{sat}3$[6] (amps)	DCR (mΩ) ±10% @ 20°C
L1 Version							
FP1108L1-R105-R	105	76	64	81	77	72	0.10
FP1108L1-R150-R	150	108	64	57	49	45	0.10
FP1108L1-R180-R	180	129	64	47	41	37	0.10

Power Modules

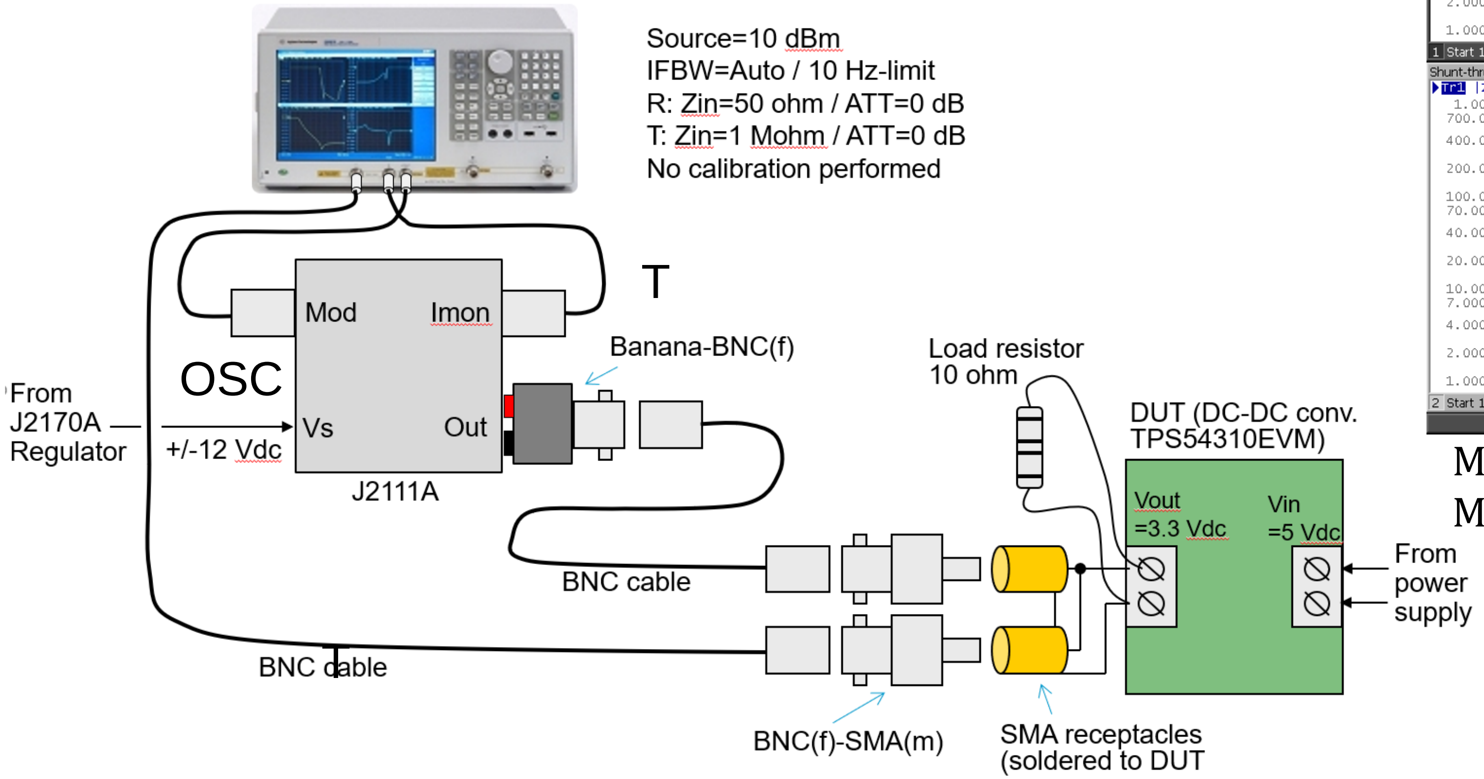
Common power modules can present impedance well below 1mOhm at DC and 120uΩ at higher frequency, in this case.

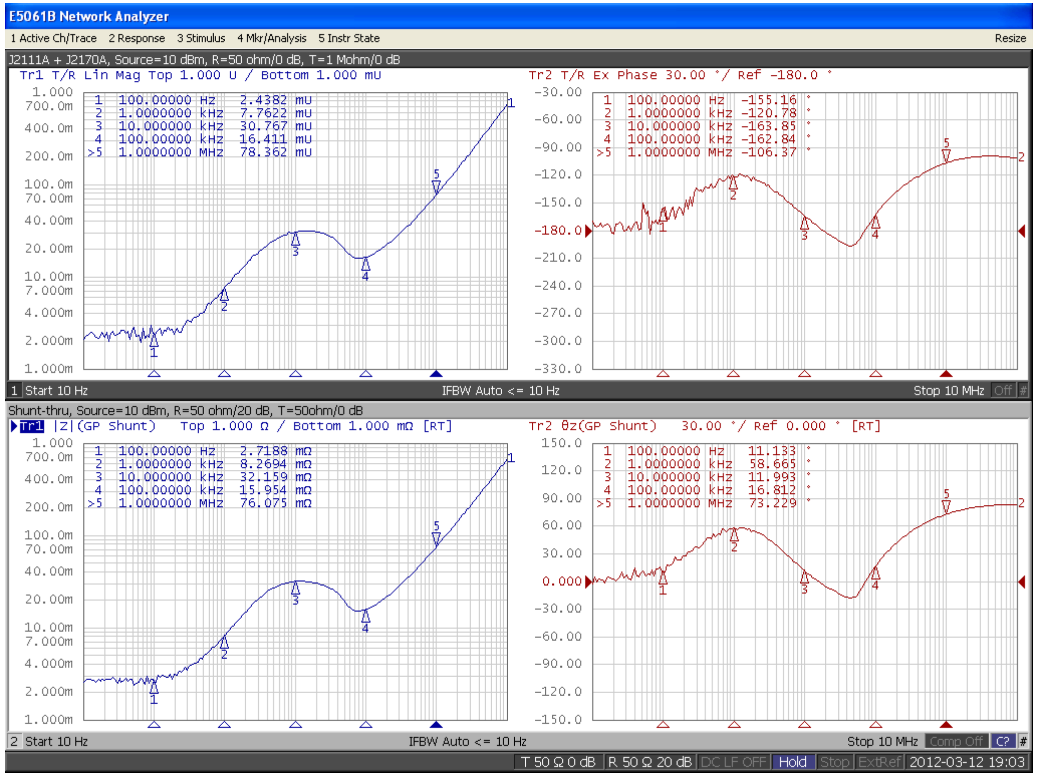
Many applications will use parallel power modules, reducing this impedance further.



www.vicorpower.com/documents/datasheets/VTM48EF012T130B01.pdf

3-Port Measurement

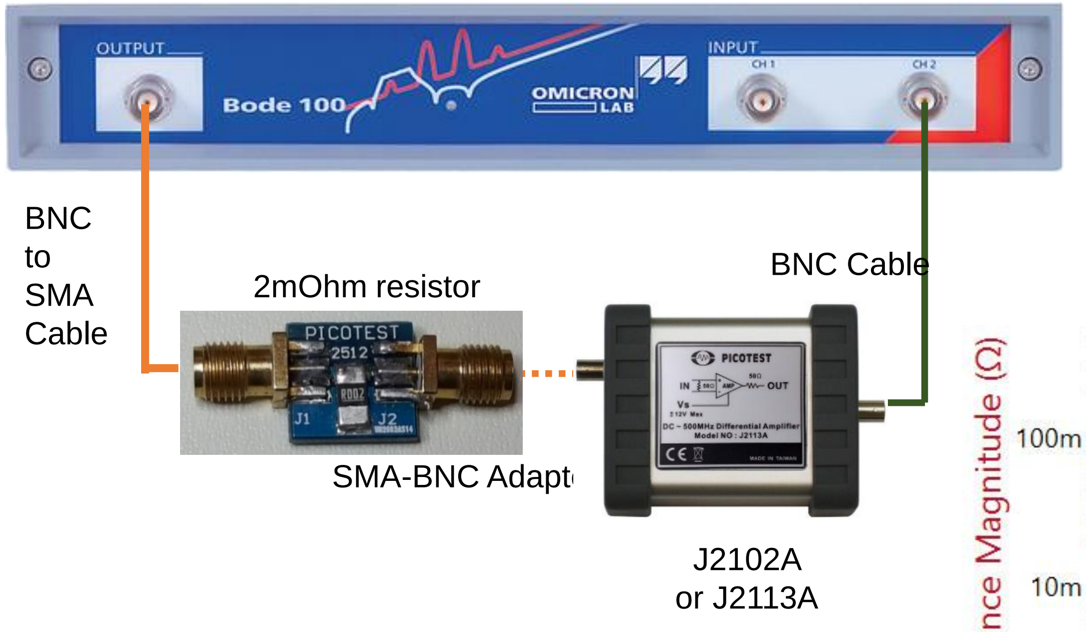


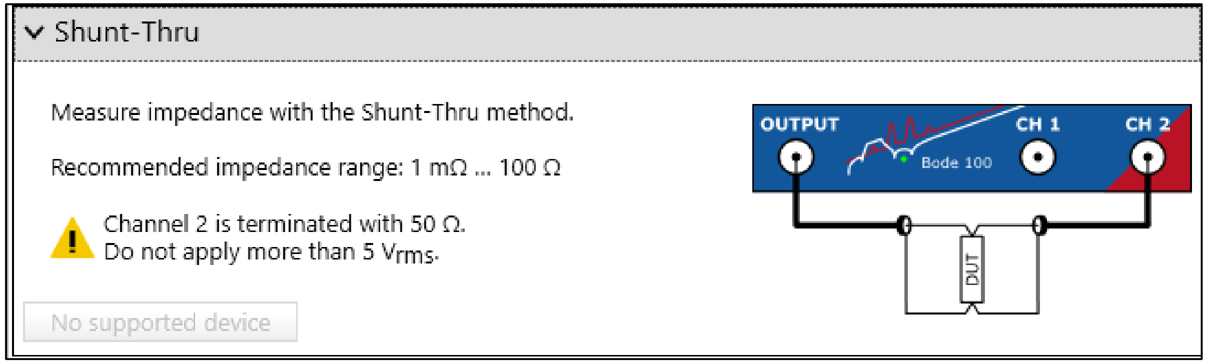


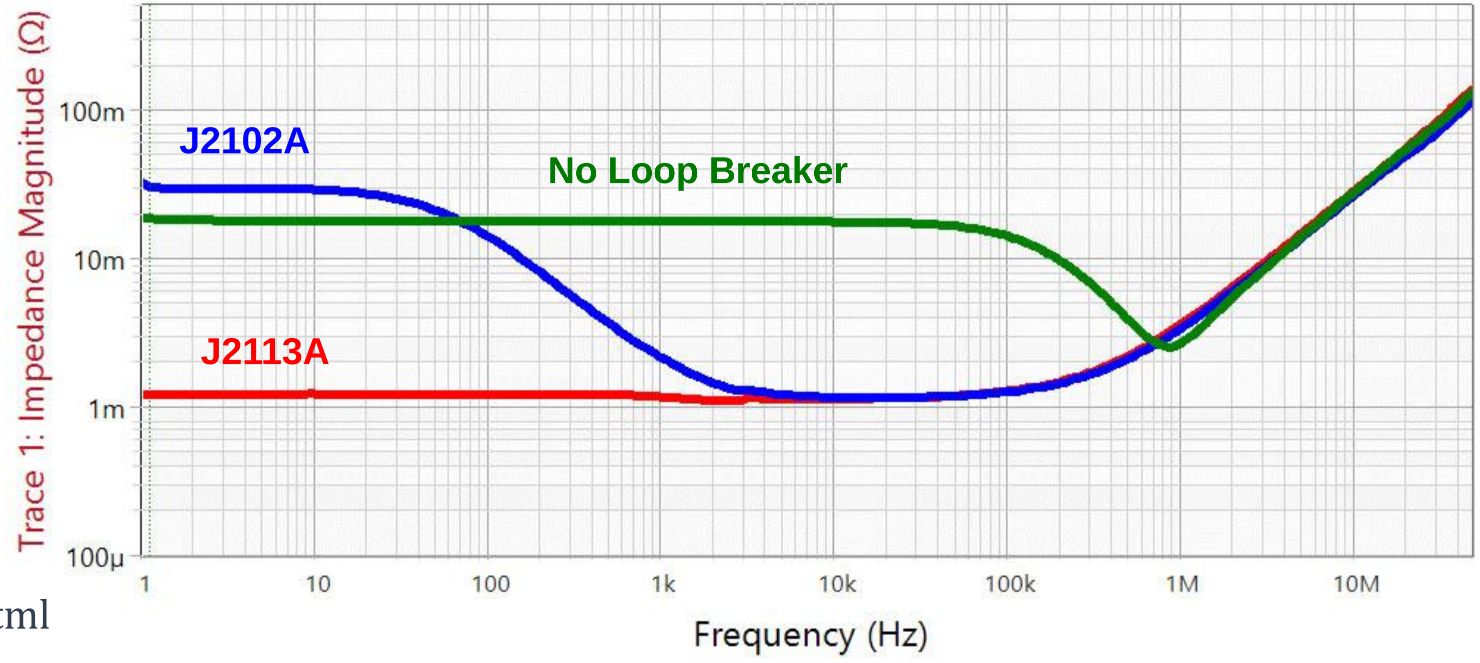
Measurement setup and data courtesy Yasuhiro Mori Keysight Technologies

$$Z = \frac{V}{I} = \frac{T}{R}$$

2-Port Measurement







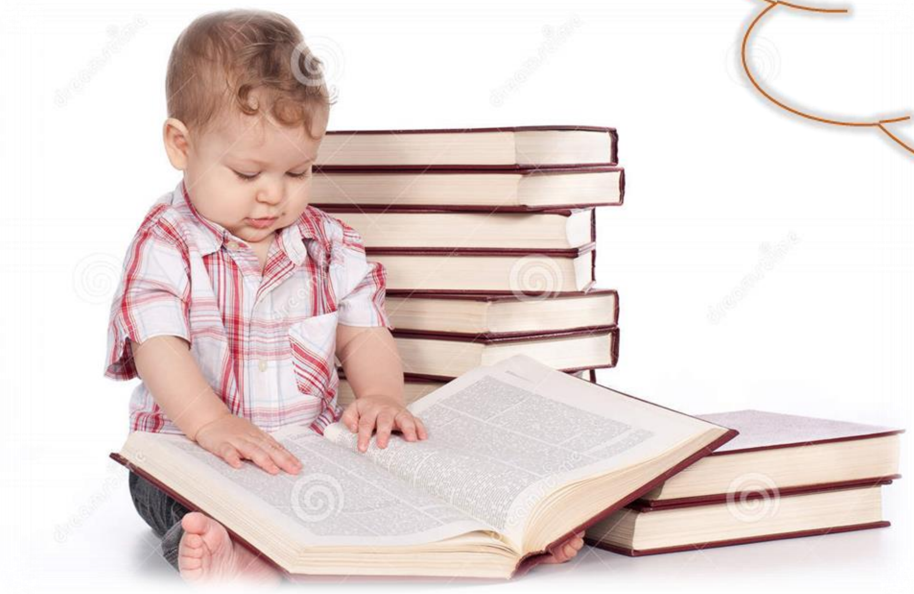
https://www.picotest.com/measurements/2-port.html

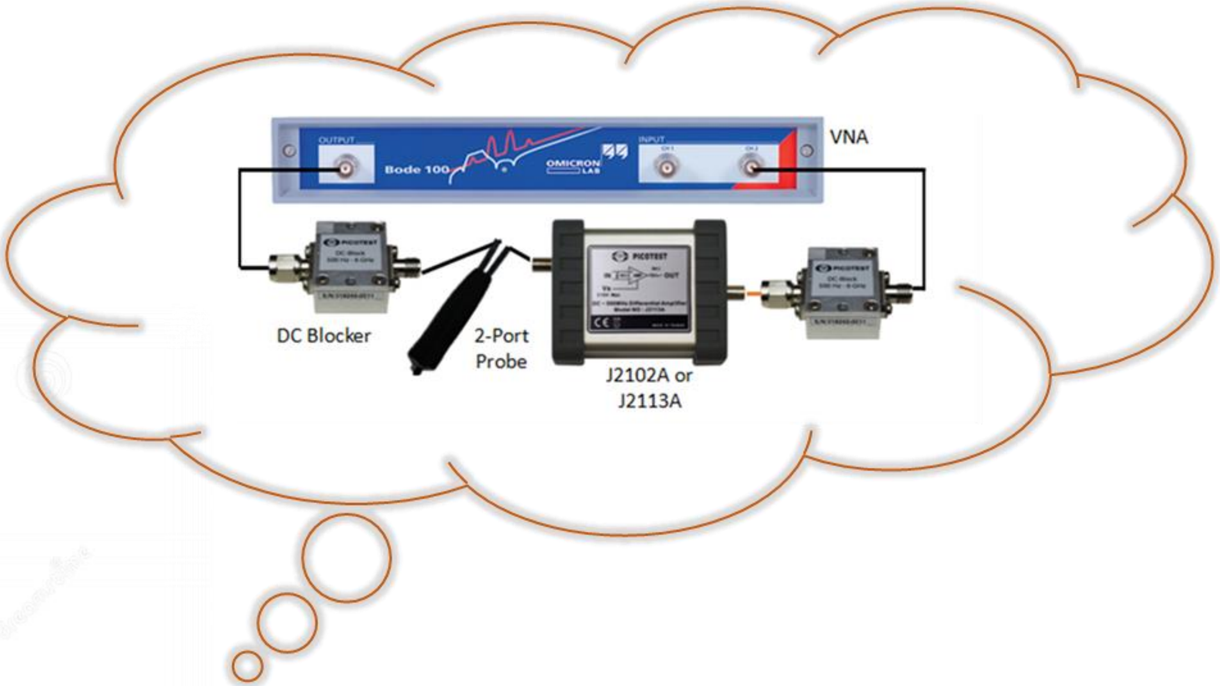
The Choice (for PDN) is Simple

2-Port		3-Port	
PROS	CONS	PROS	CONS
Can measure very low Z	Includes a ground loop	Can measure very low Z	Difficult to calibrate
Well supported calibration	Voltage limited	Many ways to implement	Includes a ground loop
Extended range-high Voltage	Limited max impedance	Can also serve as load	Limited in frequency
Extended range-higher Z	25Ω DC Loading	Supports NISM stability	
Extended range less loading		Can also serve as step load	
High frequency capable			
Supports NISM stability			
Simple connections			
DC Block Compatible			

For more info about NISM https://www.picotest.com/non-invasive-stability-measurement.html

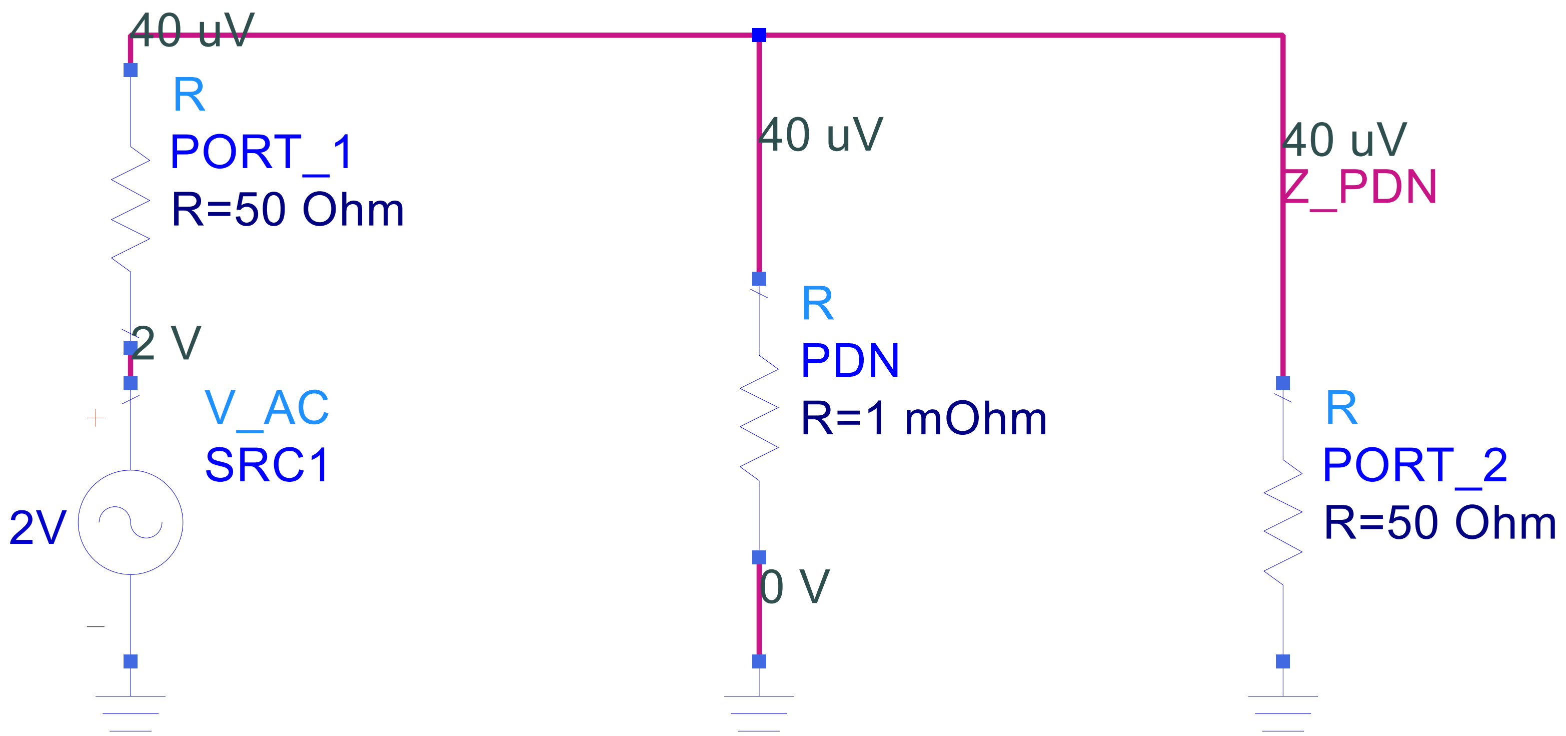
2-Port Shunt-Through Basics





The 2-Port Shunt Through Transforms

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

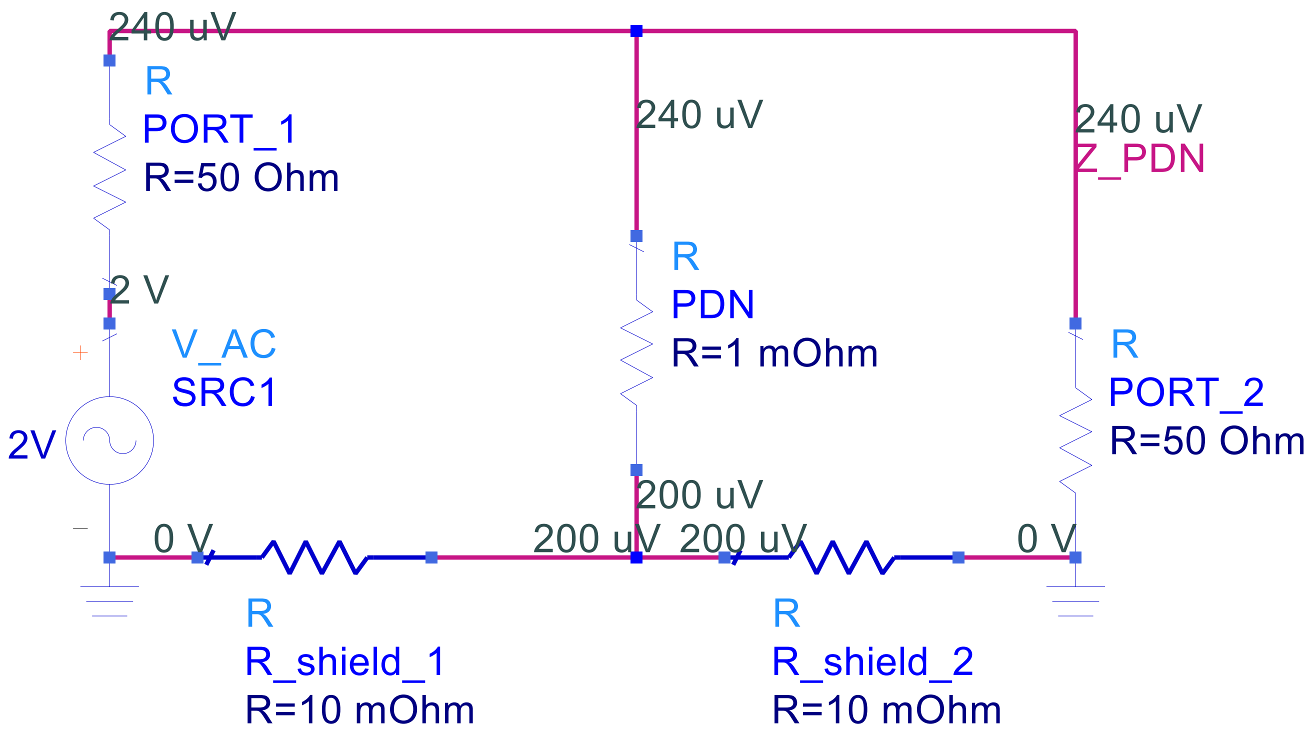


$$S_{21} = \frac{2 \cdot DUT}{2 \cdot DUT + R_{port}}$$

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

Cable Shields Mess Things Up

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

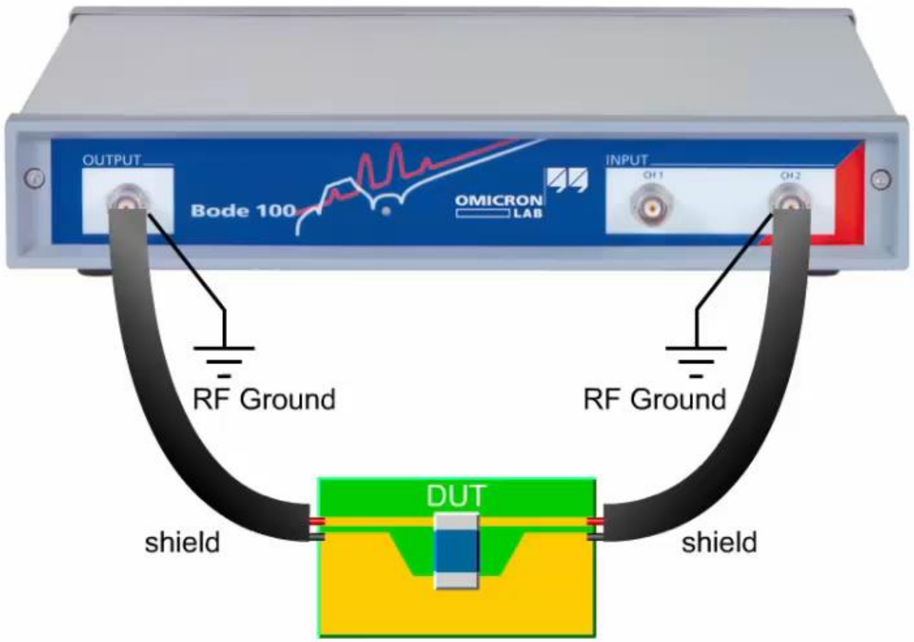


$$S_{21} \approx \frac{\frac{\mathrm{R\_shield_1 \cdot R\_shield_2}}{\mathrm{R\_shield_1 + R\_shield_2}} + DUT}{25 + \frac{\mathrm{R\_shield_1 \cdot R\_shield_2}}{\mathrm{R\_shield_1 + R\_shield_2}} + DUT} = 240u = -72.4dB$$

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

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

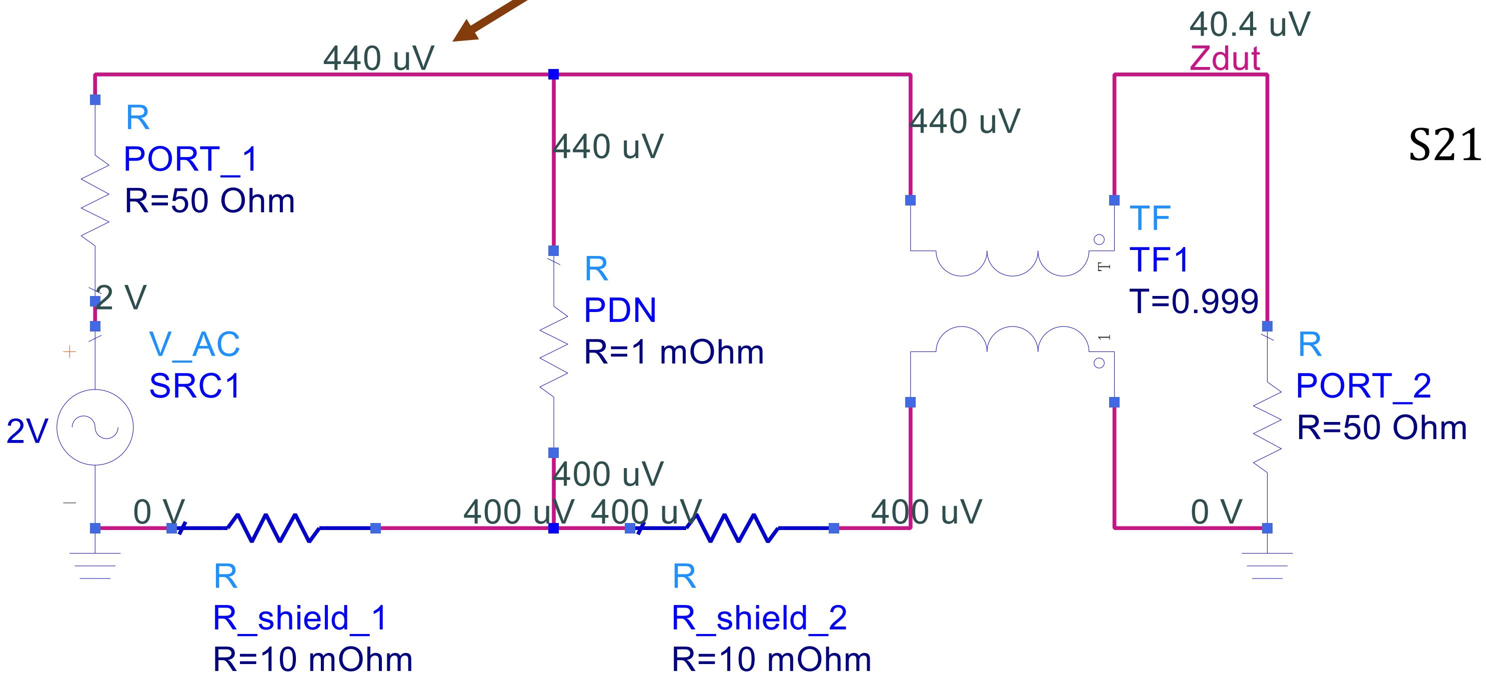
$$Error = \frac{6m\Omega - 1m\Omega}{1m\Omega} = 500\%\ Error$$


OUTPUT
Bode 100
OMICRON LAB
INPUT
RF Ground
RF Ground
DUT
shield
shield

Correcting the shield issue

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

Here the ground is isolated by the CMRR of the isolator.



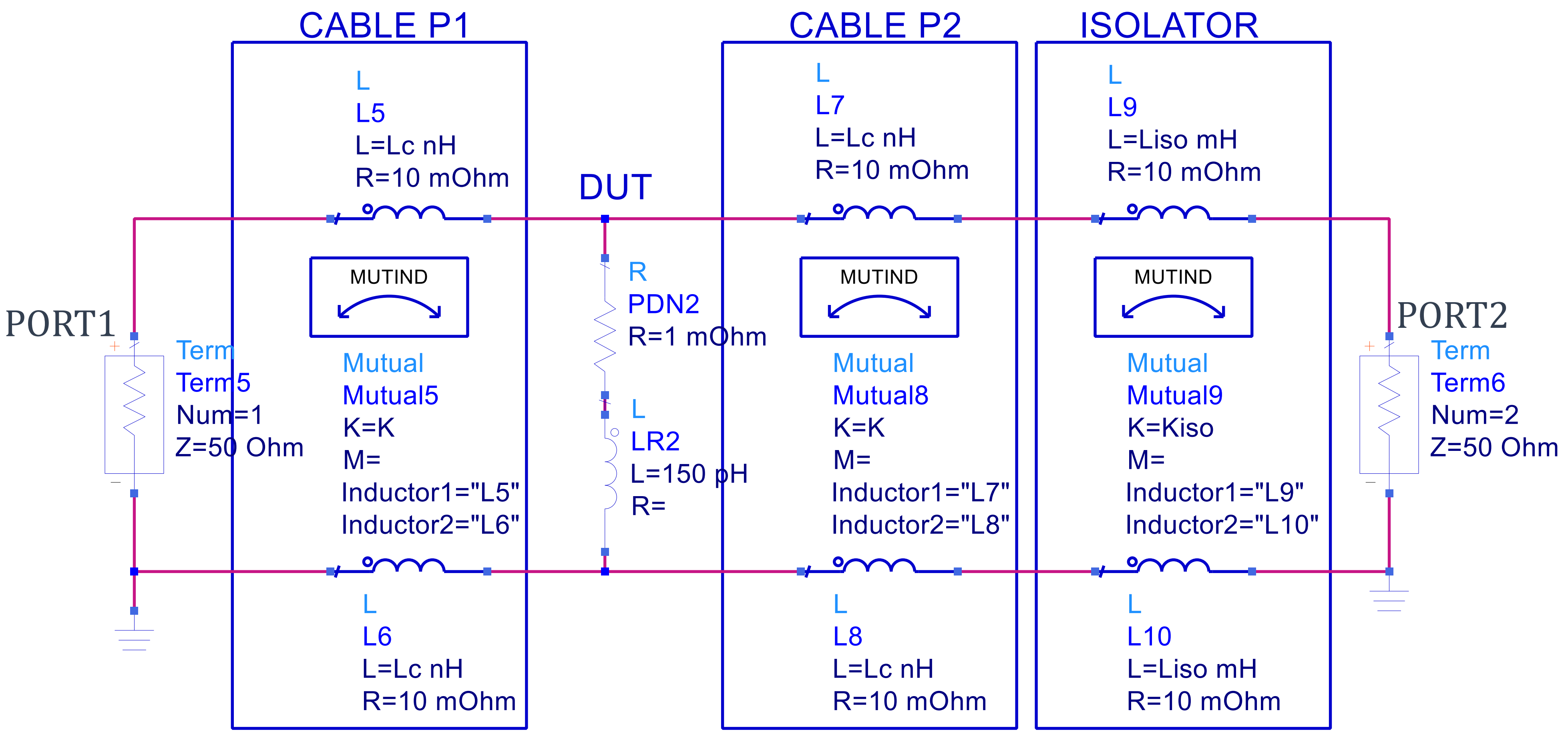
$$S21 = \frac{\text{R\_shield\_1} \cdot \left(\frac{1}{CMRR}\right) + DUT}{\frac{R_{port}}{2} + \text{R\_shield\_1} \cdot \left(\frac{1}{CMRR}\right) + DUT} = 40.4u$$

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

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

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

It's Really a Bit More Complex Than That



Cable Parameters

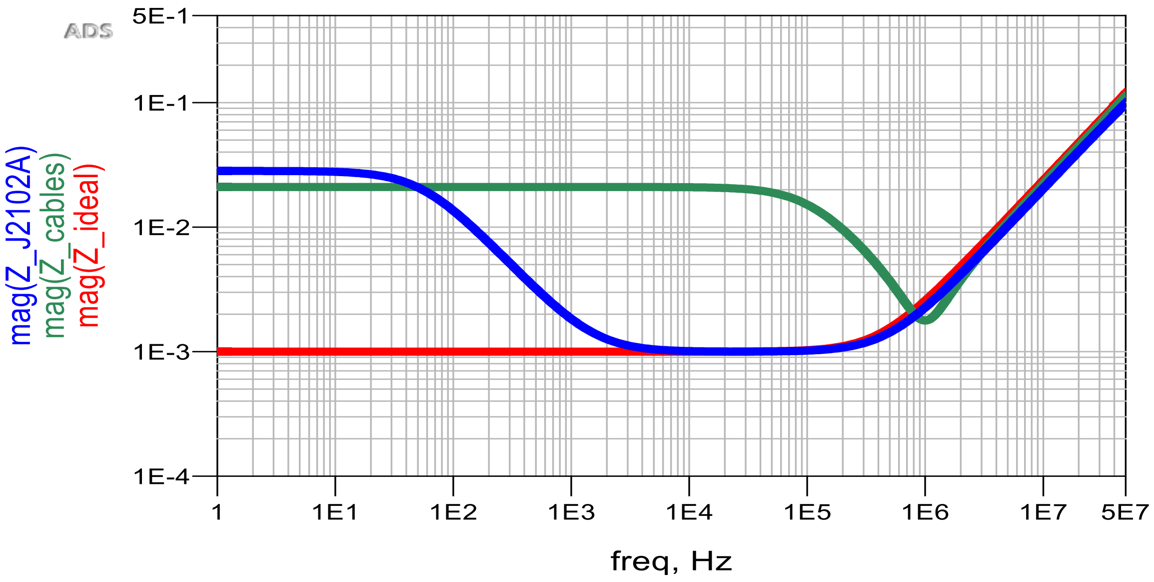
VAR
VAR1
K=0.98613
Lc=60

Isolator Parameters

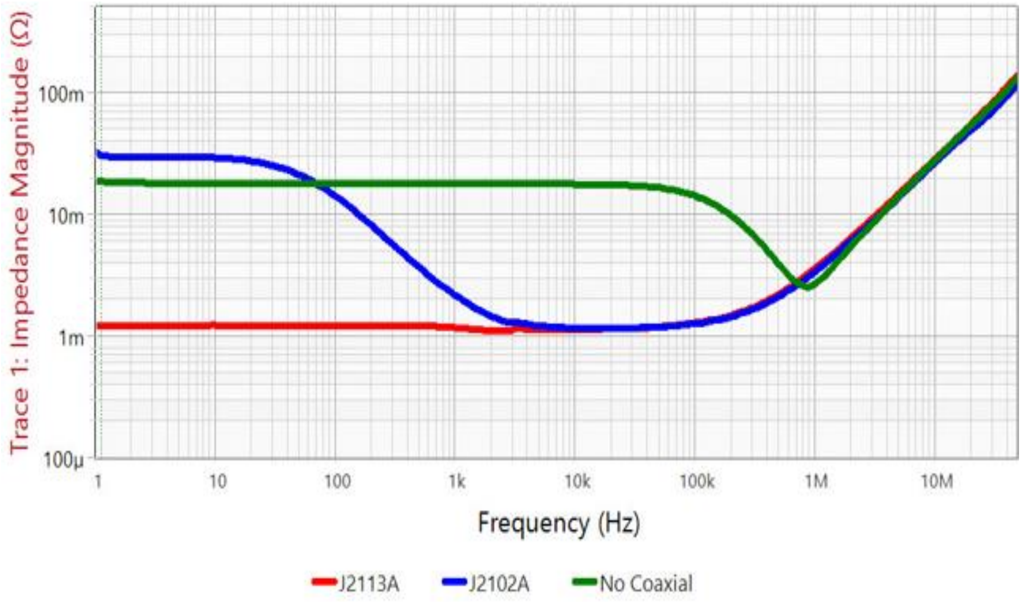
VAR
VAR2
Kiso=0.99993
Liso=0.32

The Proof is In the Testing

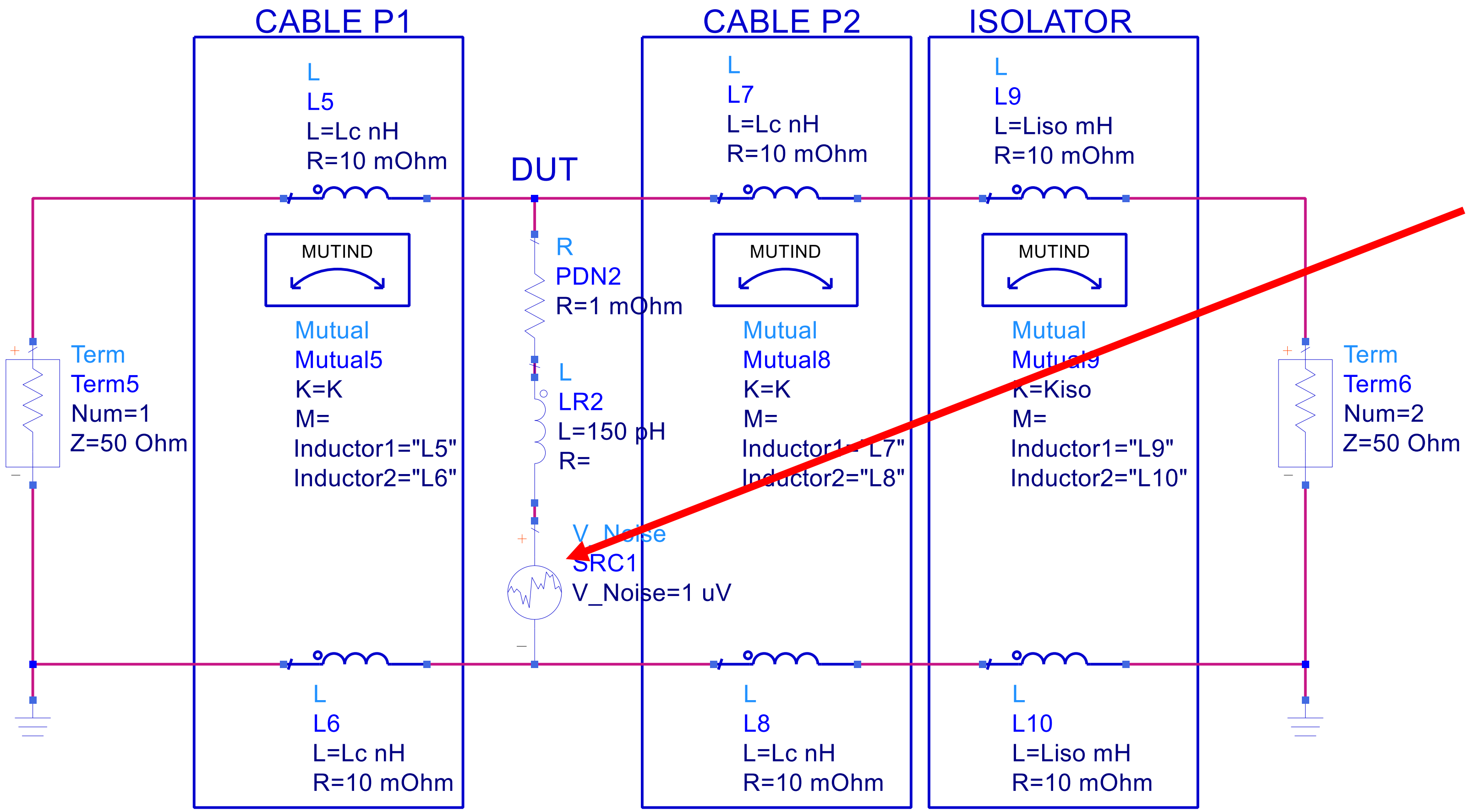
SIMULATED



MEASURED



Adding Yet Another Detail



The power rail includes noise due to switching ripple, load dynamics, switching frequency modulation noise and other system generated noise.

This noise is seen by VNA Port 2.

Converting to Port Voltages Provides Insight

$$S_{21} = \frac{V_{Port2}}{V_{Port1}} = \frac{2 \cdot DUT}{2 \cdot DUT + R_{port}}$$

The VNA source power is typically shown in dBm. And so calculating the associated RMS voltage at the VNA source

$$V_{rms}(dBm) = 0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}}$$

And the voltage received at VNA port 2 can be expressed, including all terms as

$$V_{measured} = 0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}} \cdot \frac{R\_shield\_1 \cdot \left(\frac{1}{CMRR}\right) + DUT}{\frac{R_{port}}{2} + R\_shield\_1 \cdot \left(\frac{1}{CMRR}\right) + DUT} + Instrument\_V_{noise} + PDN\_V_{noise}$$

And Also Allows Separation of Signal and Noise

$$V_{measured} = \underbrace{0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}} \cdot \left[\frac{DUT}{DUT + \frac{R_{port}}{2}} \right.}_{\text{Signal}} + \underbrace{\frac{1}{CMRR} \cdot \frac{R_{\_shield\_1}}{R_{\_shield\_1} + R_{port}}}_{\text{Error (Noise)}} + \underbrace{\left. \frac{1}{10^{\frac{Noise\_Floor}{20}}} \right]}_{\text{Error (Noise)}} + \underbrace{PDN\_V_{noise}}_{\text{Error (Noise)}}$$

Includes crosstalk

The only term not multiplied by the source signal

$$Measurement\_Error = \frac{\sqrt{\sum Error^2}}{Signal}$$

Short Break

Getting to 100uOhms (and lower)

Cable and Isolator Error Contribution

$$V_{measured} = 0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}} \cdot \left[\frac{DUT}{DUT + \frac{R_{port}}{2}} + \underbrace{\frac{1}{CMRR} \cdot \frac{R\_shield\_1}{R\_shield\_1 + R_{port}}}_{\text{Cable Error}} + \frac{1}{10^{\frac{Noise\_Floor}{20}}} \right] + PDN\_V_{noise}$$

The port 1 shield resistance needs to be as low as possible
Minimize the length of this cable
CMRR needs to be as high as possible.

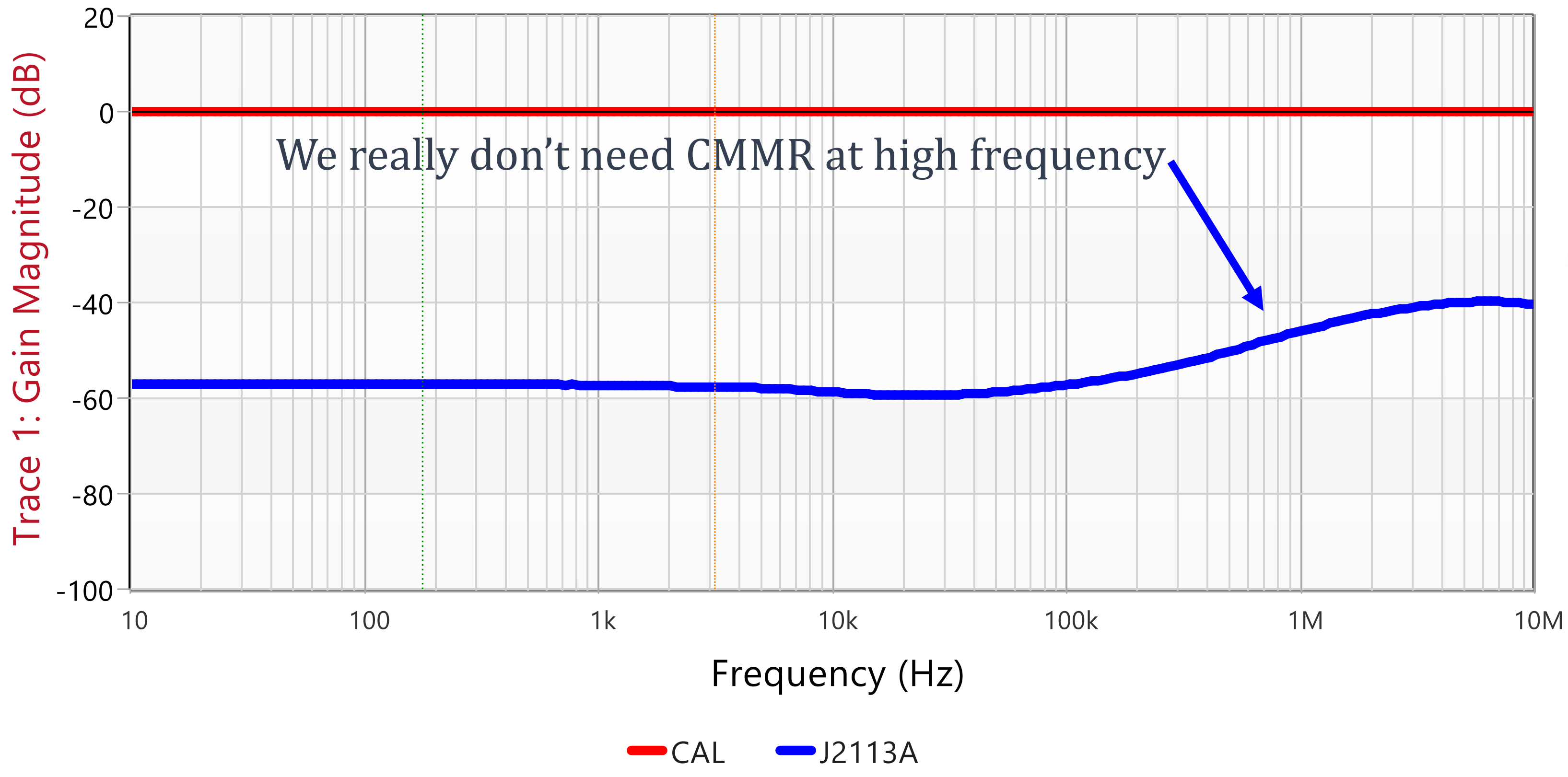
Choose Cables VERY Carefully

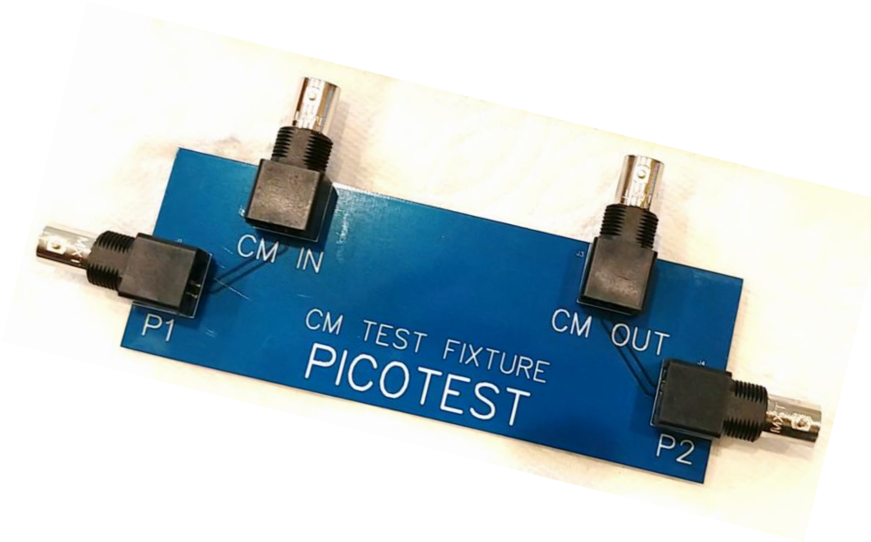
Many cable specifications don't include the outer conductor resistance. This is some data I was able to compile or measure. Crimps can often be highly resistive, so use soldered connectors. Connectors also have contact resistance.

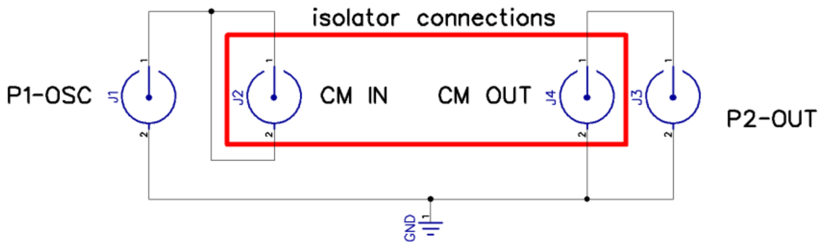
Cable	mΩ/ft	Dia (in)	Fmax	L(nH/ft)	C(pf/ft)	Shield	Comments
LMR400	1.65	0.405	5.8GHz	60.0	24	100%	EXCELLENT, but very bulky
RG316DS	3.95	0.186	3GHz	73.5	29.4	99%	Very Good bulky and stiff
RG405/AL	4.20	0.086	18GHz	73.8	29.5	100%	Formable, but stiff
LMR240	4.50	0.24	5.8GHz	60.0	24	84%	Bulky, flexible, poor shield
PICOTEST	4.70	0.102	5GHz	71.8	28.7	100%	ultra-flexible, triple shield
RG58	5.00	0.195	5GHz	72.0	28.8	78%	bulky, very poor shield
RG174	7.49	0.1	1GHz	77.0	30.8	90%	flexible
RG405	8.20	0.086	>33GHz	73.8	29.5	100%	double shield, semi-rigid
RG316	8.84	0.113	3GHz	73.5	29.4	95%	flexible
LMR100	9.50	0.1	8GHz	77.0	30.8	90%	Flexible, poor shield

Know Your CMRR

CMRR can be measured directly. A simple fixture was created to directly measure the CMRR of a J2113A solid state isolator. NOTE: solid state injectors introduce either a positive or negative error



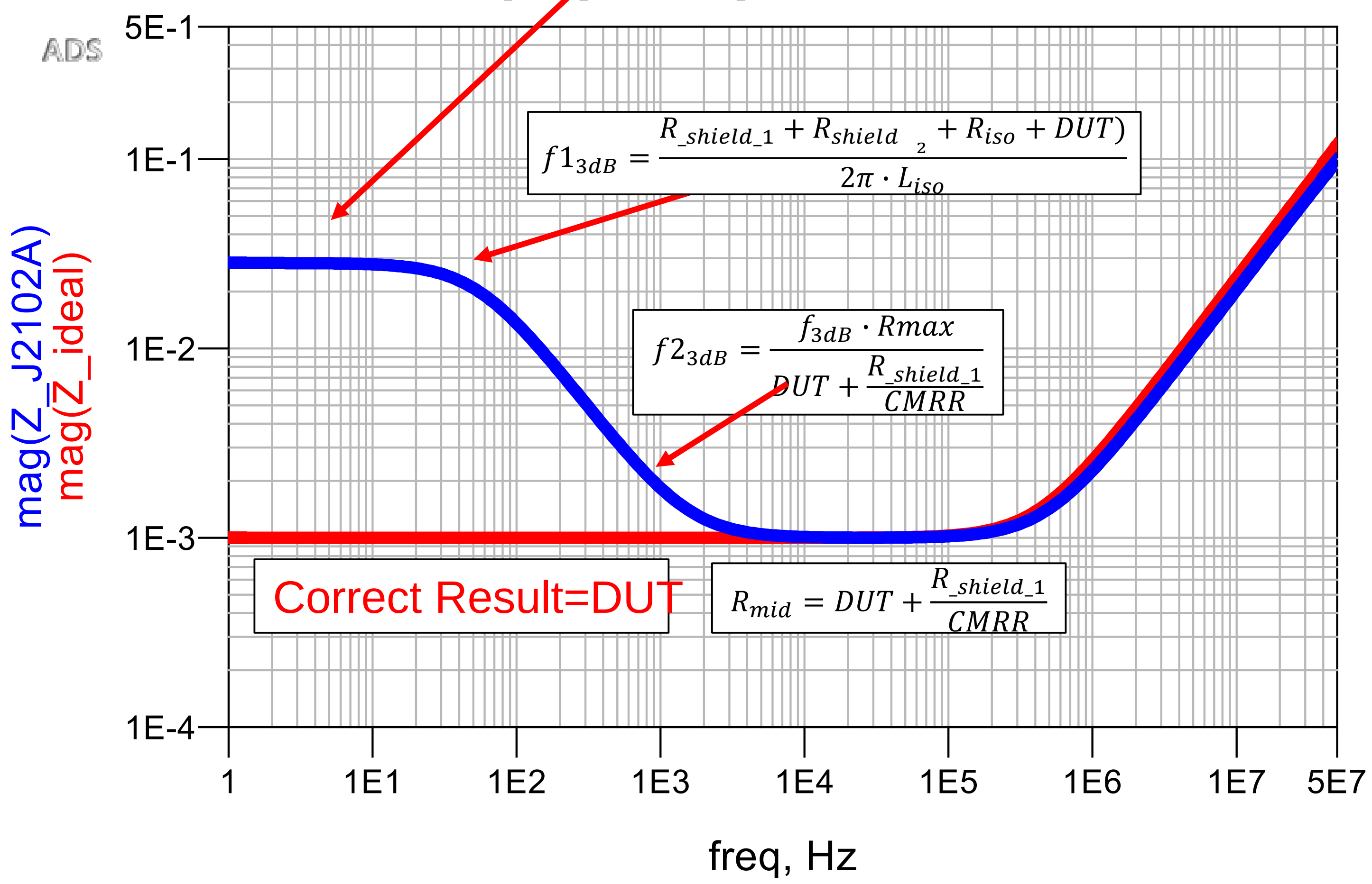




Transformer Isolator Relationships

$$R_{max} = DUT + \frac{R\_shield\_1 \cdot (R\_shield\_2 + R_{iso})}{R\_shield\_1 + (R_{shield\_2} + R_{iso})}$$

$$CMRR = \frac{1}{1-K}$$



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.

Cable and Isolator Error

$$Impedance\ Error = \left(\frac{R_{\_shield\_1}}{CMRR}\right)$$

$$Voltage\ Error = 0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}} \cdot \left[\frac{1}{CMRR} \cdot \frac{R_{\_shield\_1}}{R_{\_shield\_1} + R_{port}}\right]$$

In addition to minimizing the cable resistance

- Choose an Isolator with high CMRR

For example a 1ft Picotest cable with a 60dB CMRR (CMRR=1000) isolator contributes and error of

$$Impedance\ Error = \frac{4.7m\Omega}{1000} \cong 4.7u\Omega$$

This is a 4.7% error at 100uΩ

LMR400 cable is bulky, but would reduce this to approximately 1.5% error

Noise Floor Error Contribution

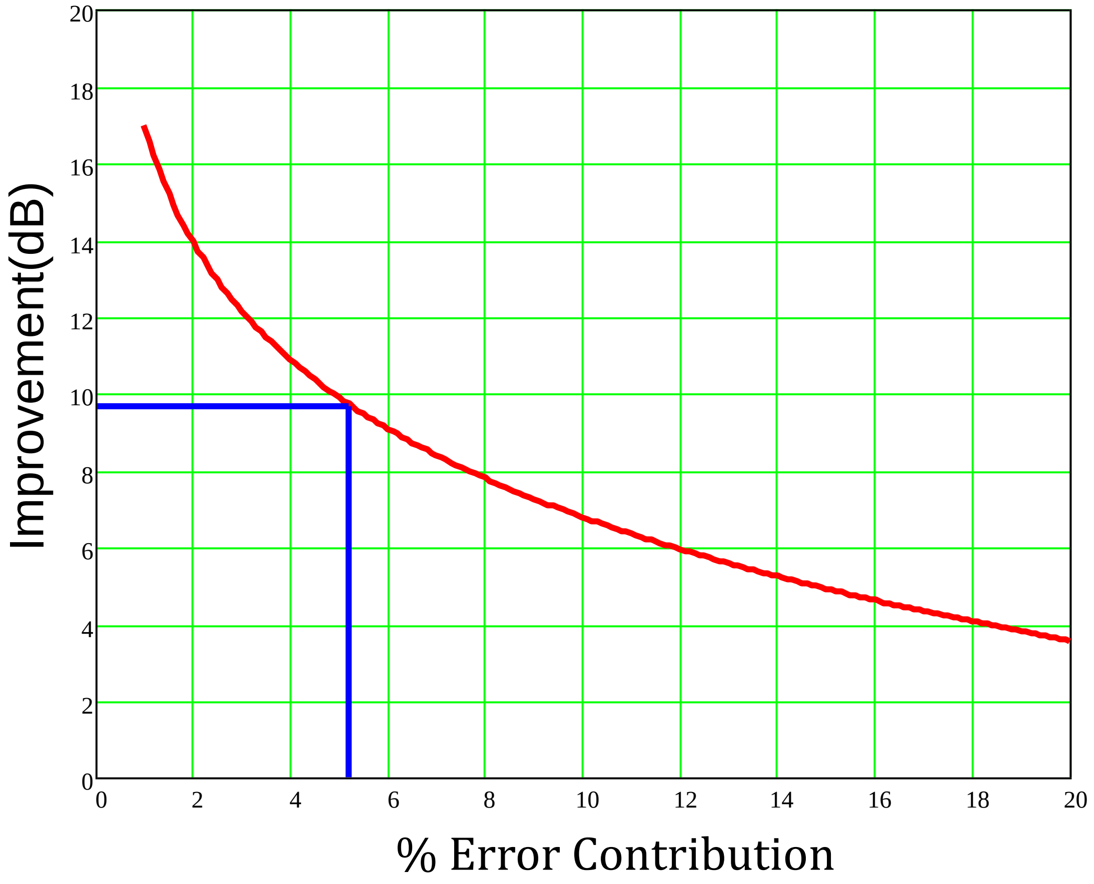
$$S_{21} = \frac{V_{Port2}}{V_{Port1}} = \frac{2 \cdot DUT}{2 \cdot DUT + R_{port}} = \frac{2 \cdot 100u\Omega}{2 \cdot 100u\Omega + 50\Omega} = 4u = -108dB$$

The noise floor needs to be lower than the measurement.

$$Error = 100\% \cdot \sqrt{1 + \left[\frac{1}{10^{\frac{dB\_improvement}{20}}}\right]^2} - 1$$

For example a 5% error contribution requires a noise floor 9.98dB lower than the measurement or approximately -118dB.

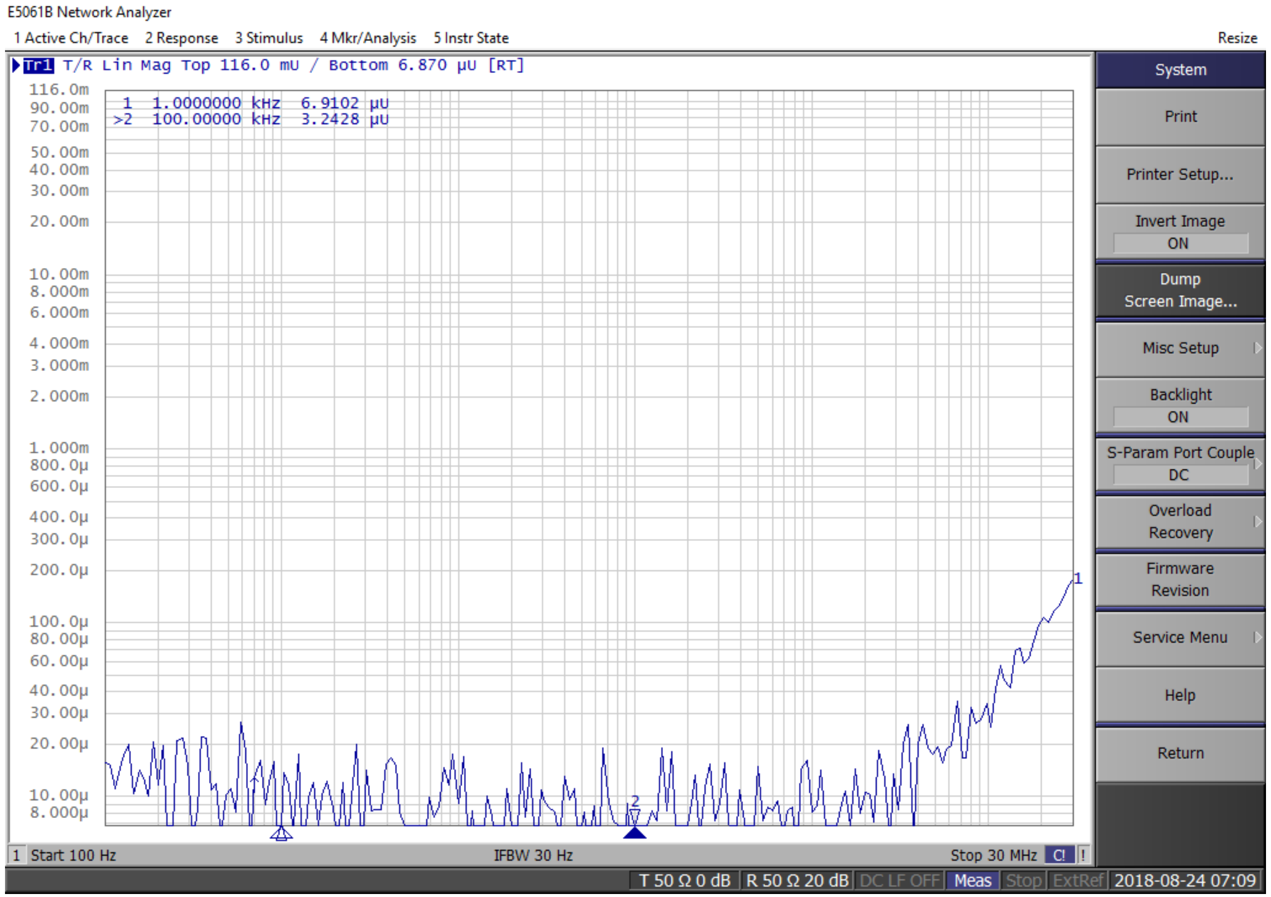
$$V_{noise\_floor} = 0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}} \cdot 10^{\frac{dB_{noise}}{20}}$$



Measuring Your Noise Floor

- Connect cables to Port 1 and Port 2 of the VNA.
- Place a SHORT plug at the far end of each cable
- Set the source power to the MAXIMUM level
- Set the Port 2 attenuator to 0dB

- Additional improvements can be made by
- Applying trace averaging
- Reducing receiver or (sometimes referred to as IF bandwidth)



Power Rail Noise Contribution

$$V_{measured} = 0.223 \cdot \sqrt{e^{0.2306 \cdot dBm}} \cdot \left[\frac{DUT}{DUT + \frac{R_{port}}{2}} + \frac{1}{CMRR} \cdot \frac{R_{\_shield\_1}}{R_{\_shield\_1} + R_{port}} + \frac{1}{10^{\frac{Noise\_Floor}{20}}} \right] + \underbrace{PDN\_V_{noise}}_{\text{Error (Noise)}}$$

There isn't much to be done about the PDN noise if the system is operating. The best method for determining the average noise is to measure it.

Noise density is typically measured with a 1Hz receiver bandwidth. Here it makes more sense to use an oscilloscope with FFT or a spectrum analyzer. Measure it with the same receiver bandwidth (and trace averaging if applicable) you have the VNA set for.

Making Connections at the DUT

Accurate 2-port shunt through measurements is a *four* wire measurement, no more and no less.

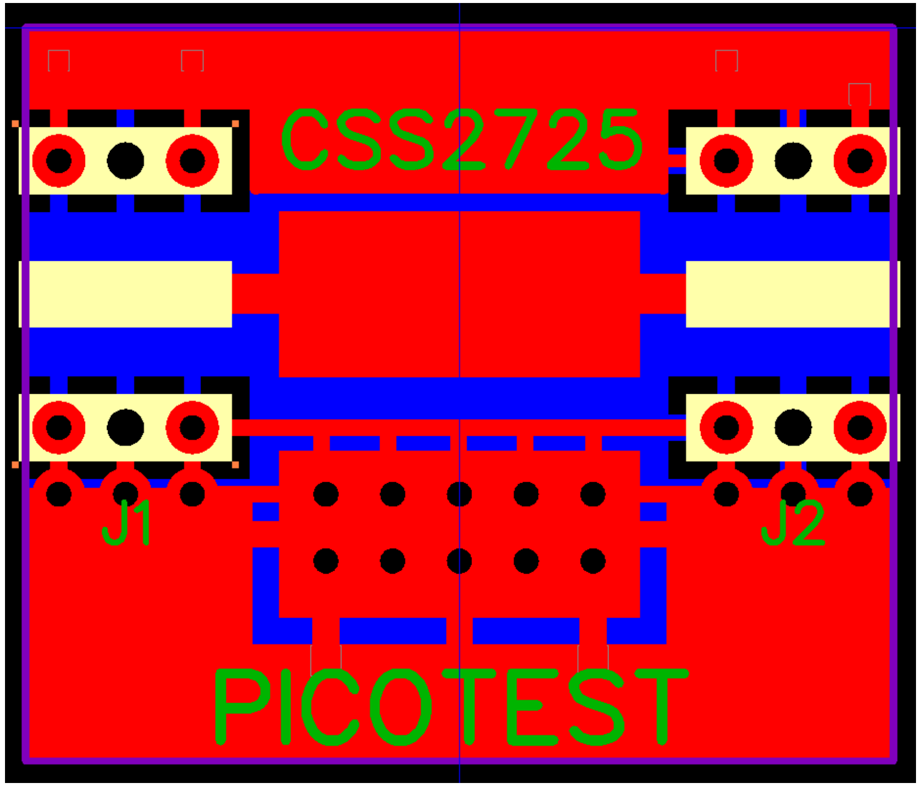
This board uses SMA connectors attached to a SHUNT resistor.

Too many ground connections provide alternate current paths, so this does not result in an accurate measurement for ultra-low impedance.

The two port tips are contacting the DUT in two different places, resulting in *transimpedance* rather than *impedance.*

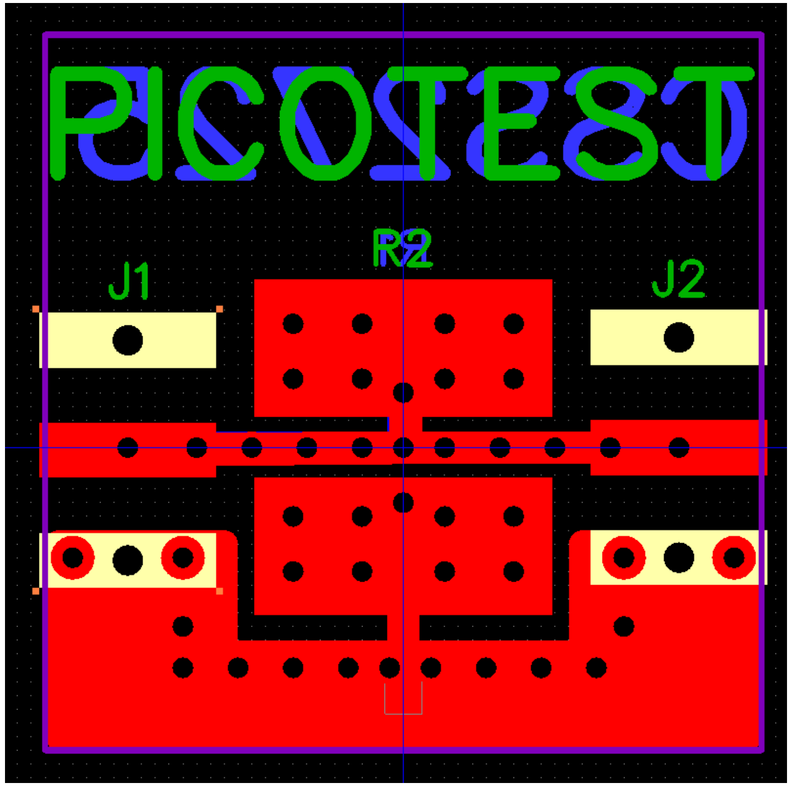
Many point contact at DUT

BAD



DUT Connections

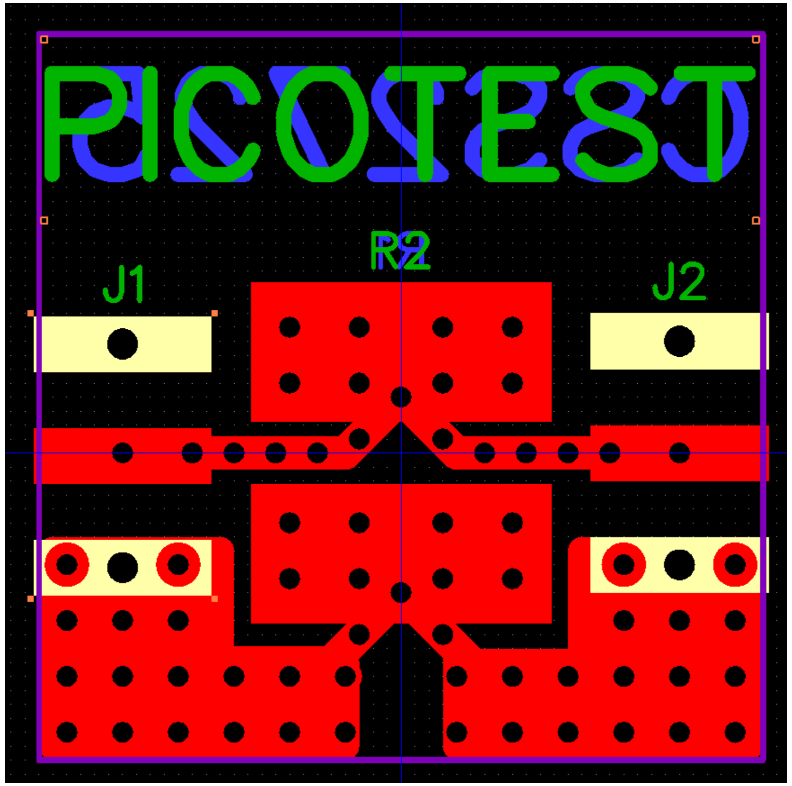
2 point contact at DUT



BAD

4 point contact at DUT

GOOD

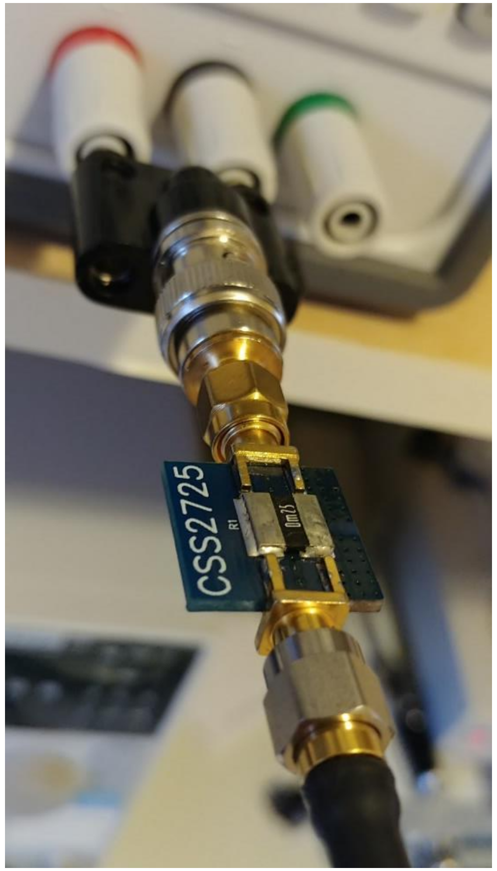


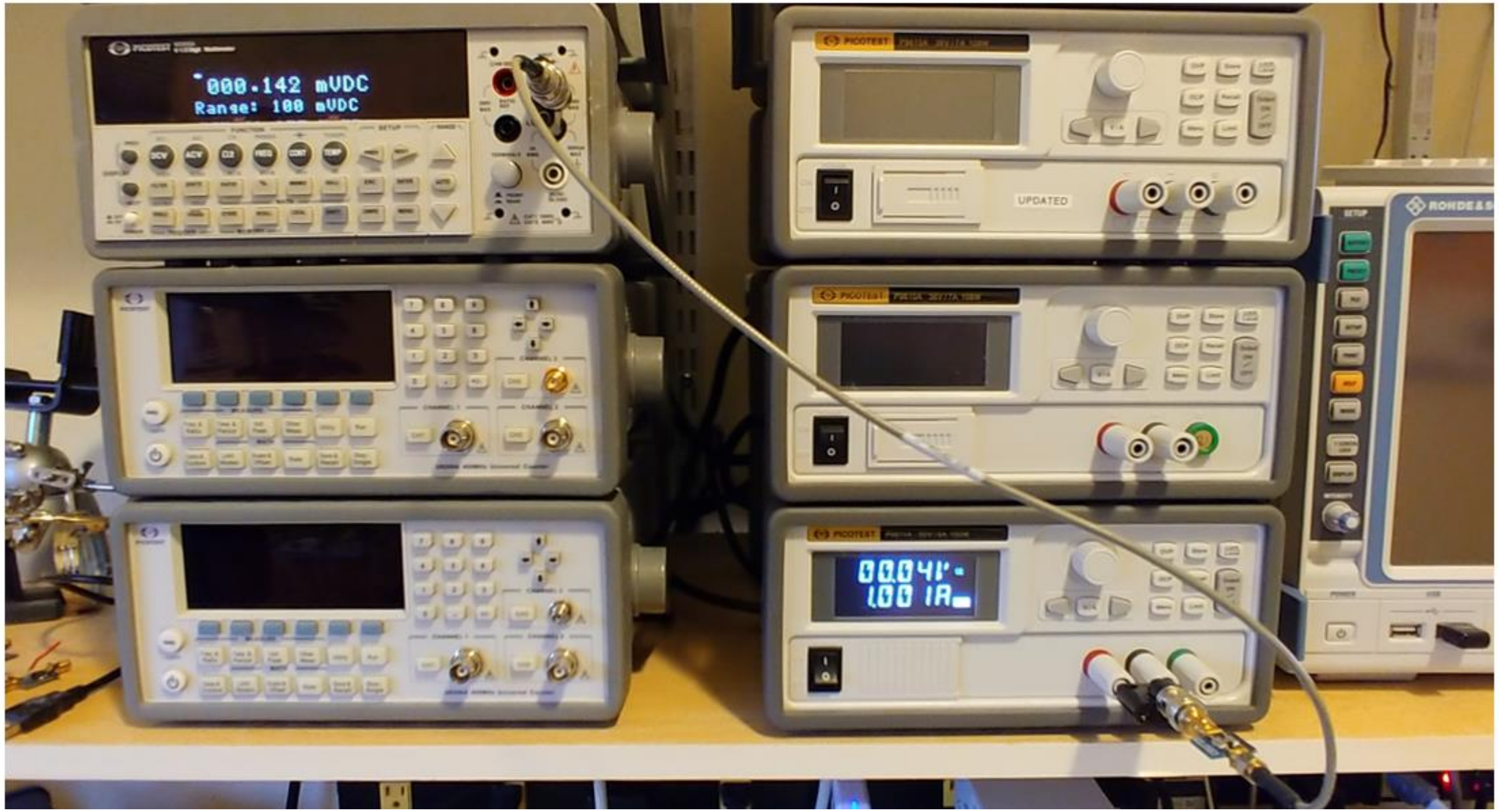
Angled traces minimize crosstalk

Tips for Successful Measurements

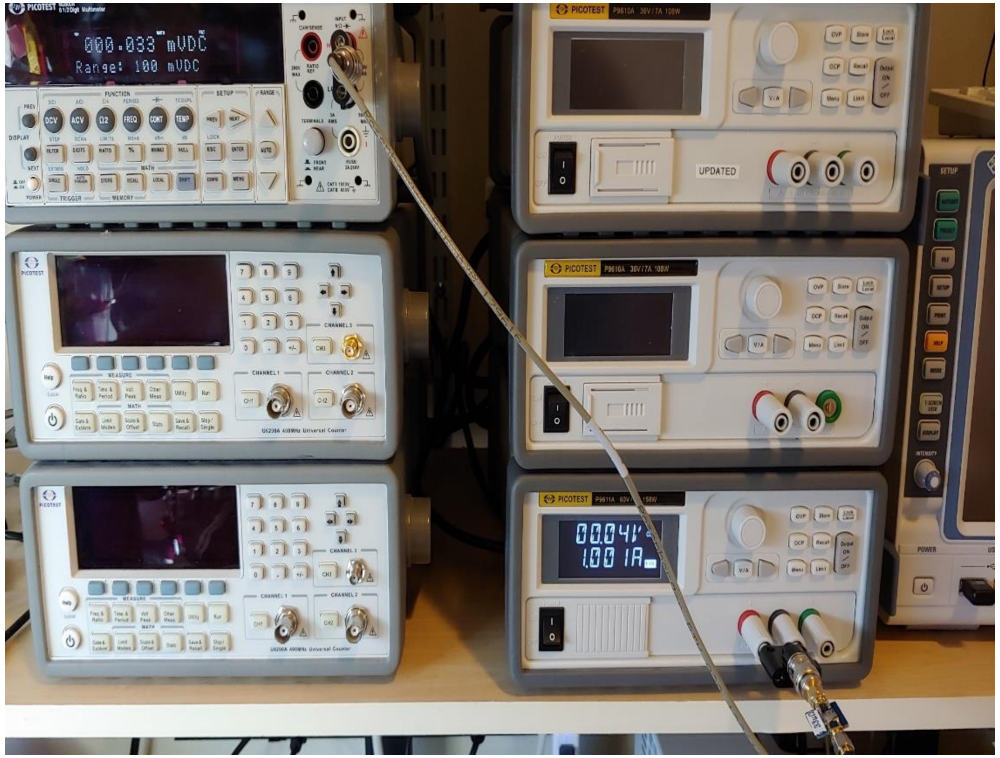
Measure Something you Know EVERY Time

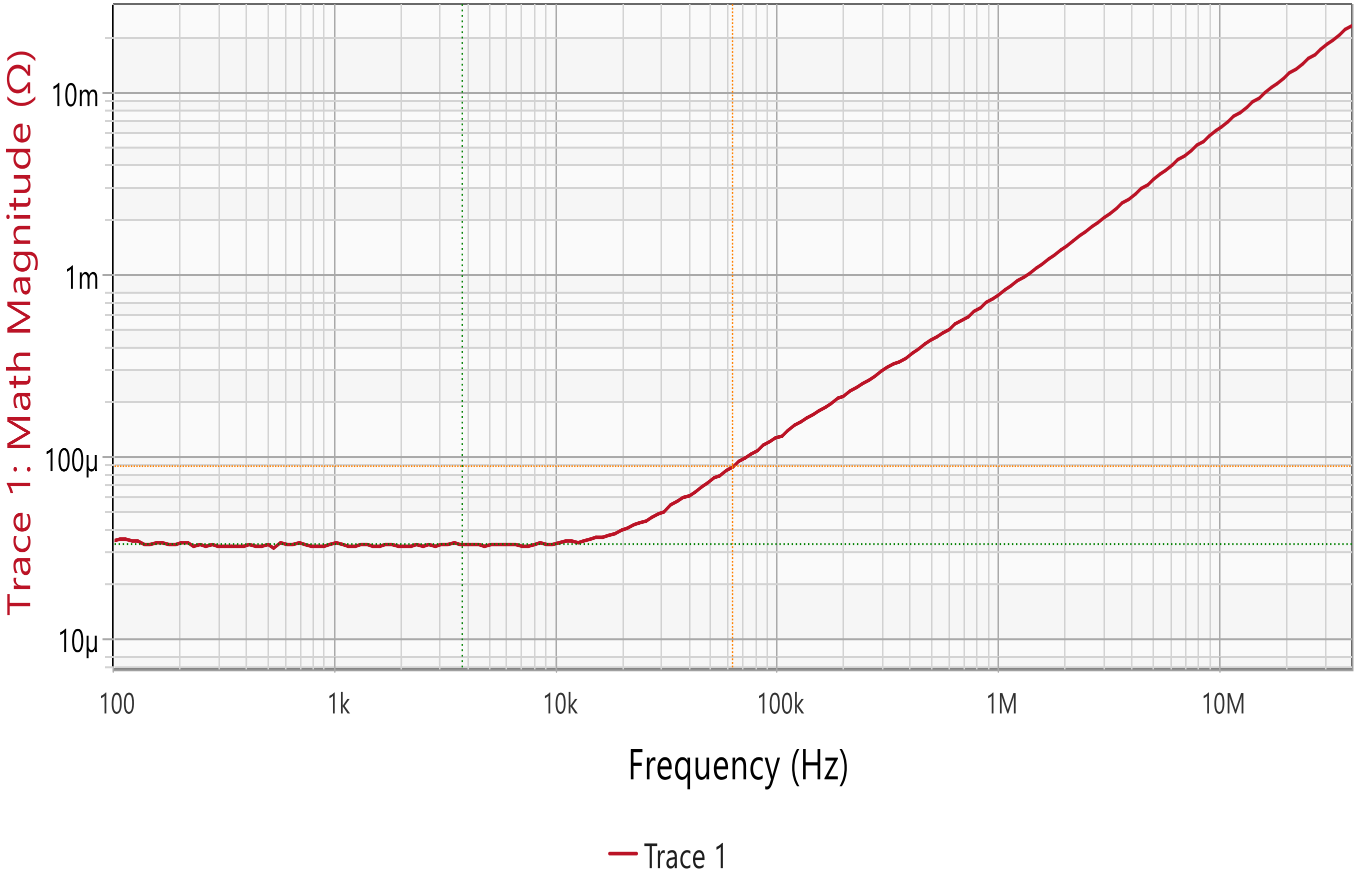
Constant current power supply and precision DMM provides the correct low-frequency result





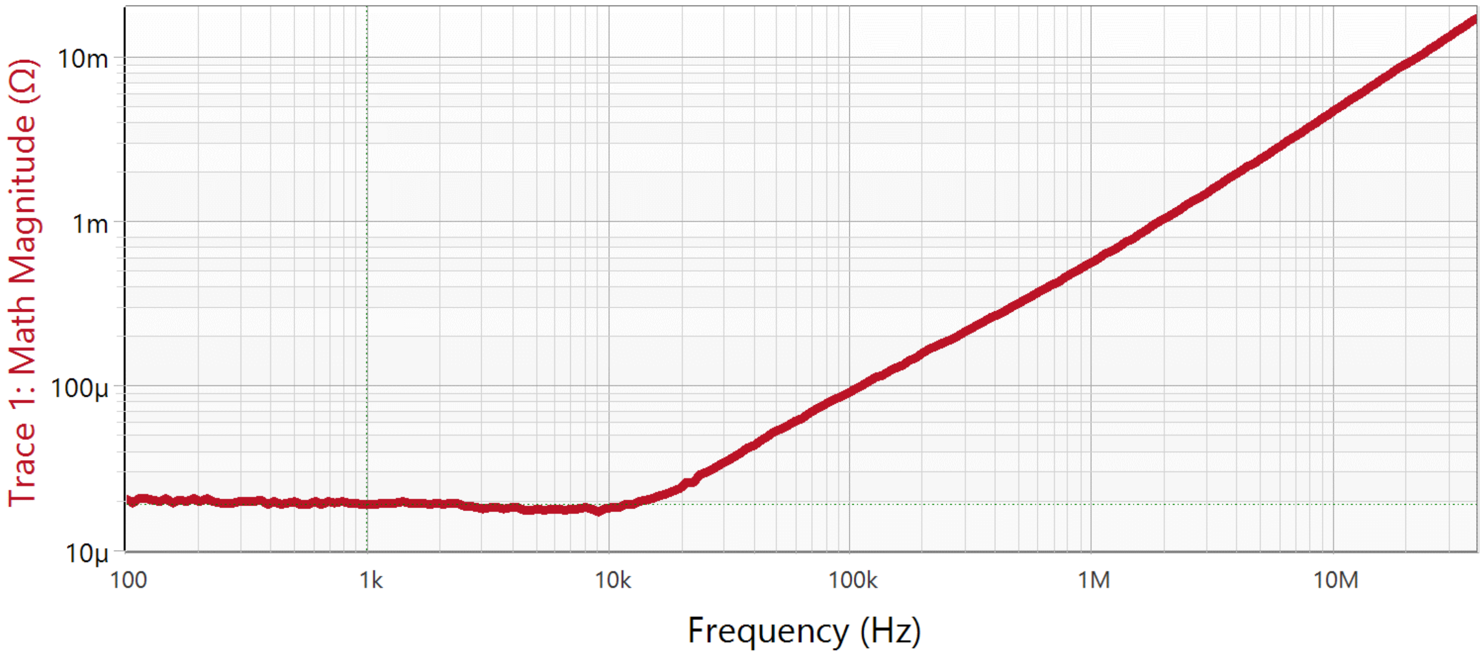
Yep! 33uΩ





The combined error of the current source, voltmeter and VNA are less than 1.5%.

Even lower! 20uΩ



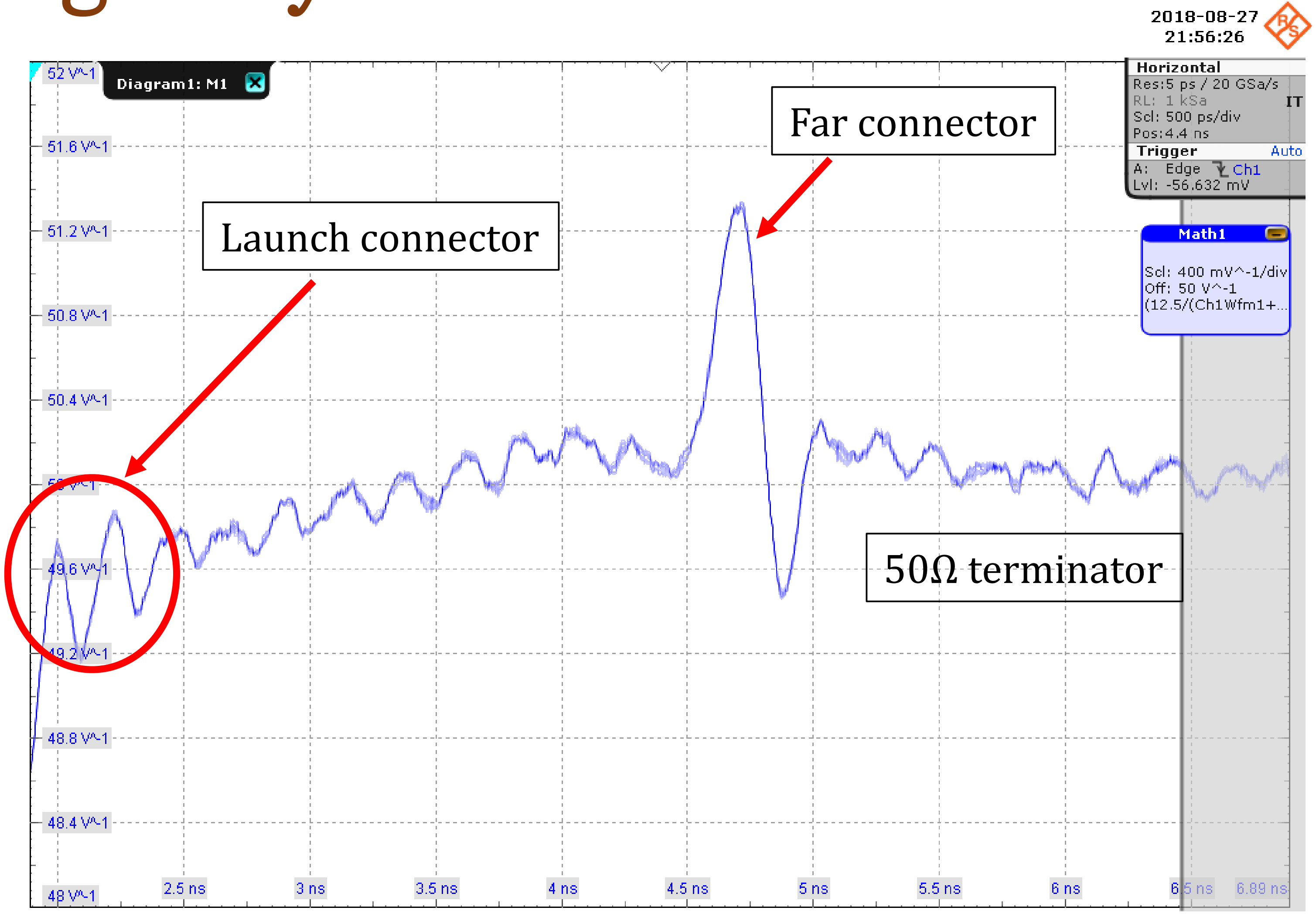
Test Your Cables Regularly with TDR

The weak spot in most cables is the connector to cable interface.

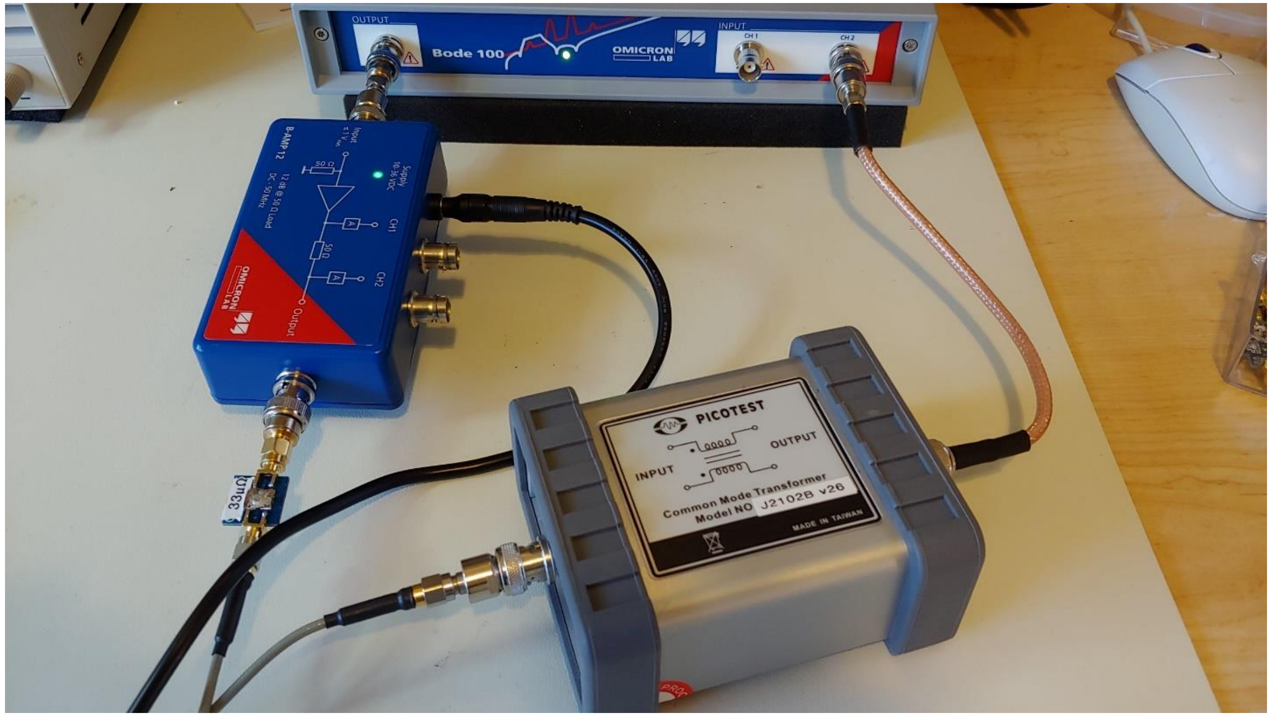
Use soldered connectors or solder them after receiving the cable

Test new cables when you get them

Torque them properly



Add an Amplifier (Somewhere)



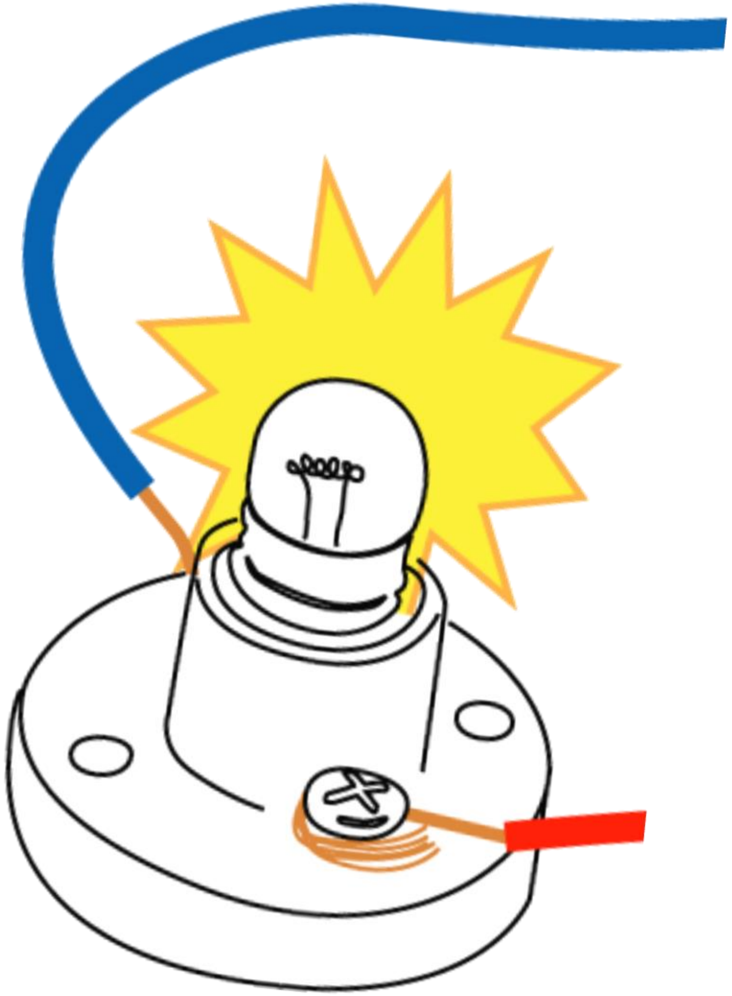
Adding an amplifier can improve the signal to noise ratio, which can improve the measurement accuracy.

I generally like to keep the port 1 connection pristine, and put all accessories between the DUT and port 2. The measurement is less sensitive to impedance on this port.

HOWEVER, Placing the amplifier here amplifies both the signal and the DUT noise

Placing the amplifier between port 1 and the DUT will amplify the signal without amplifying the noise, likely providing more benefit.

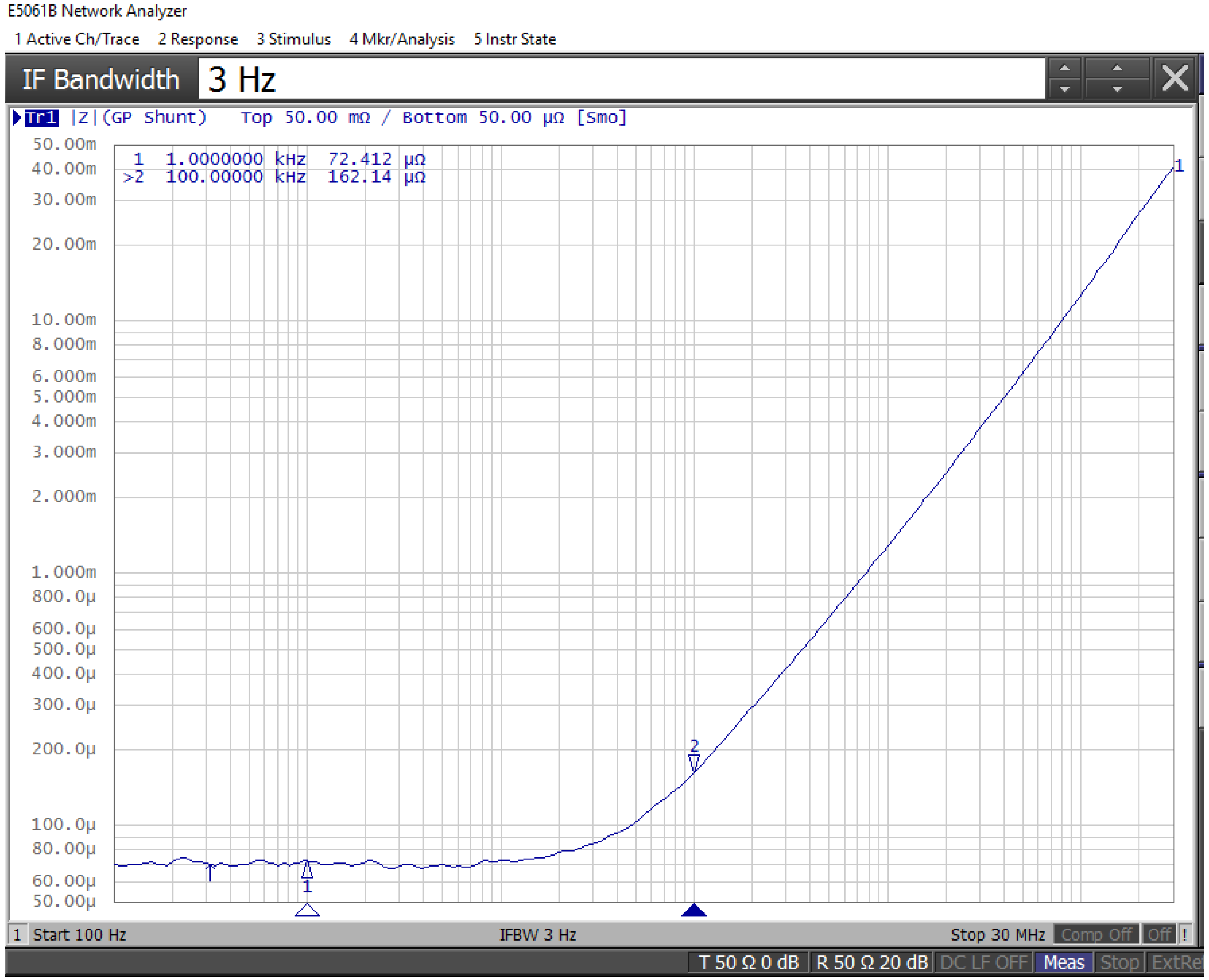
Demonstrations



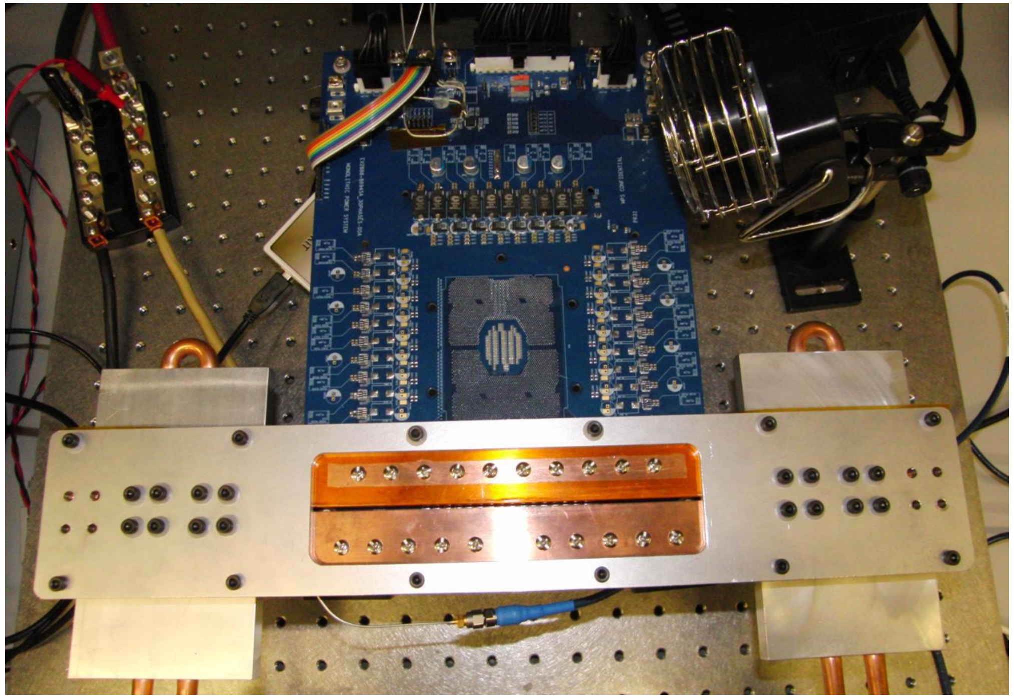
Putting it To the Test

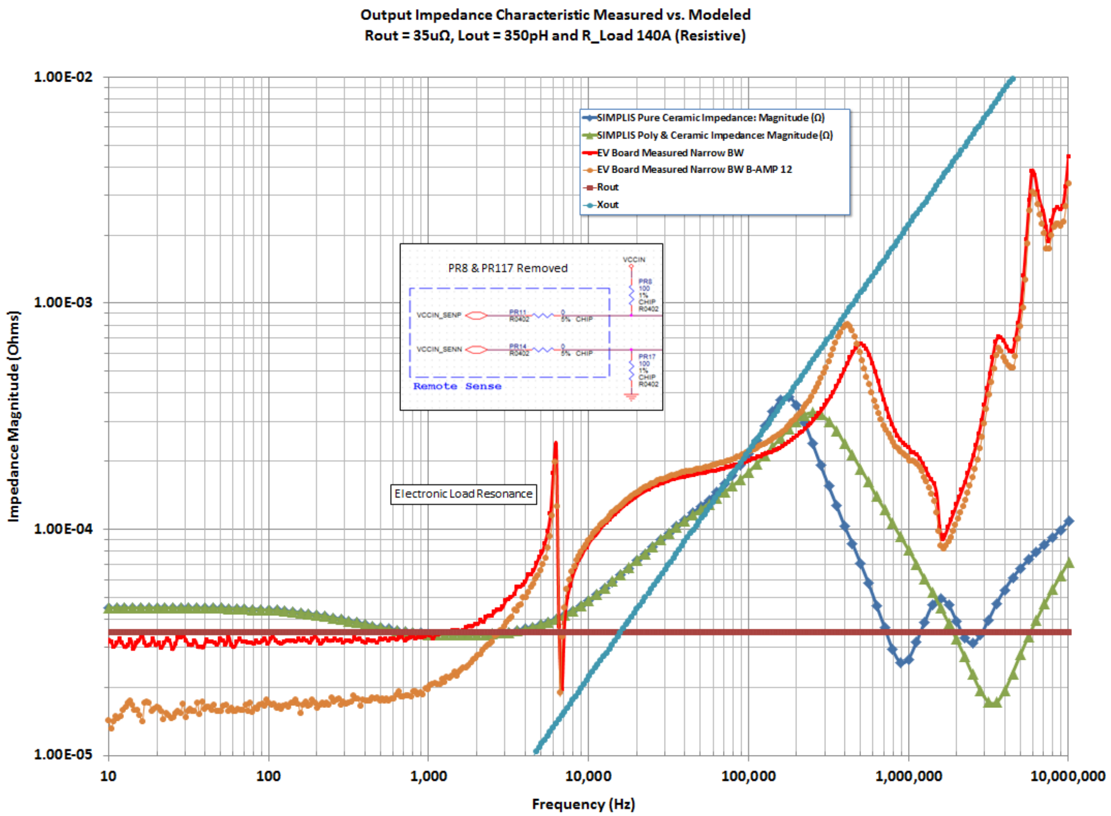
Using these techniques, we can very accurately measure impedance even below 100uOhms, as this example shows.

- Use HIGH QUALITY cables (and check them regularly)
- Know your isolator CMRR
- Know your instrument noise floor
- Plan measurement contact points carefully
- Add a source power amp for better SNR
- Measure a KNOWN of the same magnitude



Case study Rout = 35 uOhm, Lout = 350 pH





References

1. Steve Sandler, “Measure small impedances with Rogowski current probes”, EDN, February 05, 2014, www.edn.com/design/test-and-measurement/4427931/Measure-small-impedances-with-Rogowski-current-probes
2. Istvan Novak, “Simulating and Measuring Microohms”, DesignCon 2015, http://electrical-integrity.com/Paper_download_files/DC15_11_TH4_Paper_Simulating_and_Measuring_Microohms.pdf
3. Picotest, “The 2-Port Shunt-Thru Measurement and the Inherent Ground Loop” https://www.picotest.com/measurements/application-notes/The%202-Port%20Shunt-Thru%20Measurement%20app%20note.pdf
4. [9] Keysight “New impedance measurement solutions and applications using a Vector Network Analyzer”, https://www.keysight.com/upload/cmc_upload/All/E5061B_Zseminar_Expo.pdf
5. S.M. Sandler, “Power Integrity: Measuring, Optimizing, and Troubleshooting Power Related Parameters in Electronics Systems”, McGraw-Hill, NY, 2014 https://www.amazon.com/
6. OMICRON-Lab , “Battery Impedance Measurement”, https://www.omicron-lab.com/fileadmin/assets/Bode_100/ApplicationNotes/Battery_impedance/App_Note_Battery_Impedance_V2_0.pdf

Thanks for Attending this Session!

In this session I shared

- An introduction to the 2-port shunt-through measurement
- The major measurement obstacles at 100uΩ
- How to verify the setup
- A few of my top tips for designing power for sensitive circuits
- A live measurement demonstration

EDICON UNIVERSITY
Where HIGH FREQUENCY MEETS HIGH SPEED

Connect with me on LinkedIn or via email at Steve@Picotest.com

Learn more at www.picotest.com

PICOTEST