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Calibration, Embedding and De-Embedding – Achieving Highly Accurate Impedance Results

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Agenda

Obtaining accurate impedance measurements is dependent on proper calibration, embedding, and de-embedding of the instrument, cables and fixtures. In this session we will show:

- Why most impedance measurement solutions don’t include accuracy specifications
- The differences between calibration, embedding, and de-embedding, and how they are used.
- Where the measurement errors are, and how calibration, embedding, and de-embedding can correct them or make them even worse
- What’s the difference between 50MHz and 450MHz in terms of calibration complexity and cost?
- What are the post calibration residual errors?
- Calibration methodologies for traditional VNAs and why they don’t work for the Bode 100/500 VNA
- Why calibrating for probes is so much more complex and error prone than for connectors
- Measuring ESL
- Calibrating Component Test Fixtures
- Summary: Closing in on the ‘Perfect’ Measurement

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Typical Required Range

Assuming our goal is to accurately measure the VRM and POL inductors and MLCC capacitors, we can determine the measurement range we need to accomplish

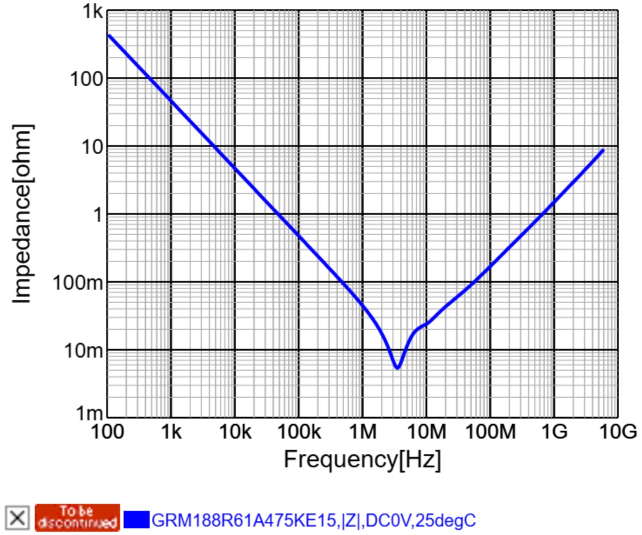
Wurth 744316330
3.3uH/5.75A
DCR=18.5mΩ
SRF=66MHz
C ≈ 1-2 pF

Electrical Properties:

Properties		Test conditions	Value	Unit	Tol.
Inductance	L	100 kHz/ 100 mV	3.3	µH	±20%
Rated Inductance	L_R	100 kHz/ 100 mV/ 5.75 A	2.25	µH	typ.
Rated Current	$I_{R,50K}$	ΔT = 50 K	5.75	A	max.
Performance Rated Current [1]	$I_{RP,40K}$	ΔT = 40 K	7.1	A	max.
Saturation Current @ 10%	$I_{SAT,10\%}$	$\vert\Delta L/L\vert < 10\ \%$	2.75	A	typ.
Saturation Current @ 30%	$I_{SAT,30\%}$	$\vert\Delta L/L\vert < 30\ \%$	5.8	A	typ.
DC Resistance	R_{DC}	@ 20 °C	18.5	mΩ	±10%
Self Resonant Frequency	f_{res}		66	MHz	typ.

[1] refer to IEC 62024-2-2020

Murata MLCC Capacitor
GRM188R61A475KE15E15
4.7uF/10V 0603 (1608) chip
ESR ≈ 4mΩ ESL ≈ 200pH



10% Accuracy	
C	100 fF
L	20 pH
R	12.5 µΩ

Pulse PA4990.101HLT Inductor
100nH/77A
DCR ≈ 125 µΩ

Electrical Specifications @ 25°C — Operating Temperature -40°C to +130°C [7]

Part Number	Inductance[1] @ $0A_{DC}$ (nH ±15%)	Inductance[2] @Irated (nH TYP)	Irated[3] (ADC)	DCR[4] (mΩ)	Saturation Current[5] (A TYP)			Heating Current[6] (A TYP)
					25°C	100°C	125°C	
PA4990.101HLT	100	100	77	0.125±10%	125	105	95	77
PA4990.121HLT	120	120	77		105	88	81	
PA4990.151HLT	150	140	77		83	78	71	
PA4990.331HLT	330	300	32		40	32	28	

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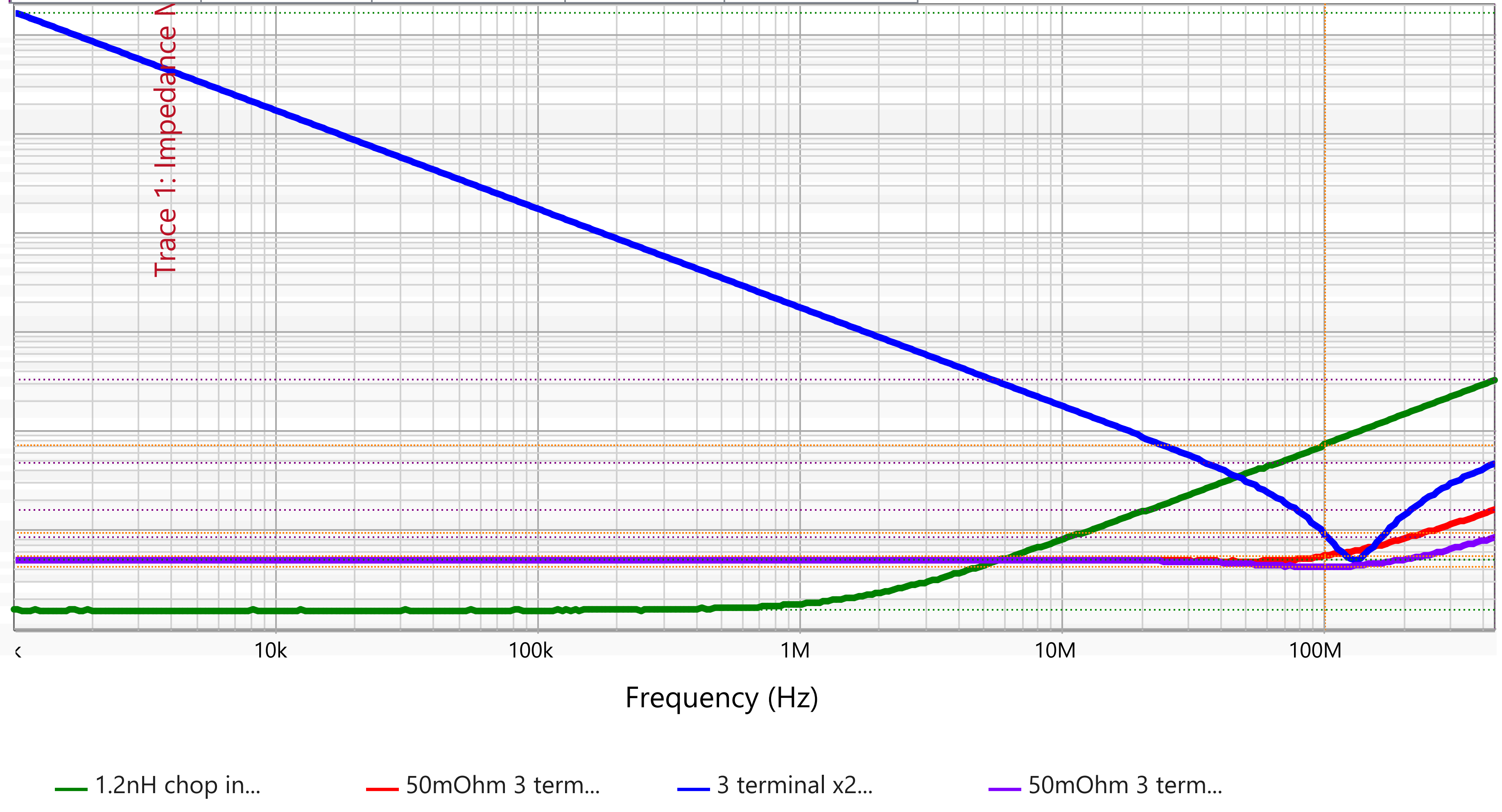
And Getting Harder All the time

Frequency	1.2nH chop in...	50mOhm 3 term...	3 terminal x2...	50mOhm 3 term...
450 MHz	1.169 nH	51.463 pH	165.386 pH	25.661 pH



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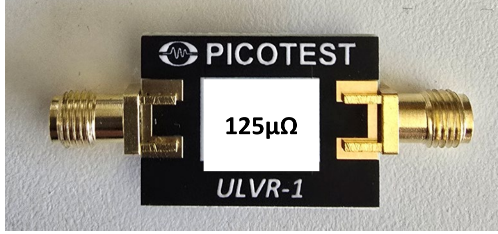
Measure Something You Know

Before we can measure an unknown, we need to measure something we do know, and close to the same magnitude. Sometimes that is easier said than done…

First, we'll make a few measurements of known devices without calibration to show the errors that need to be corrected.

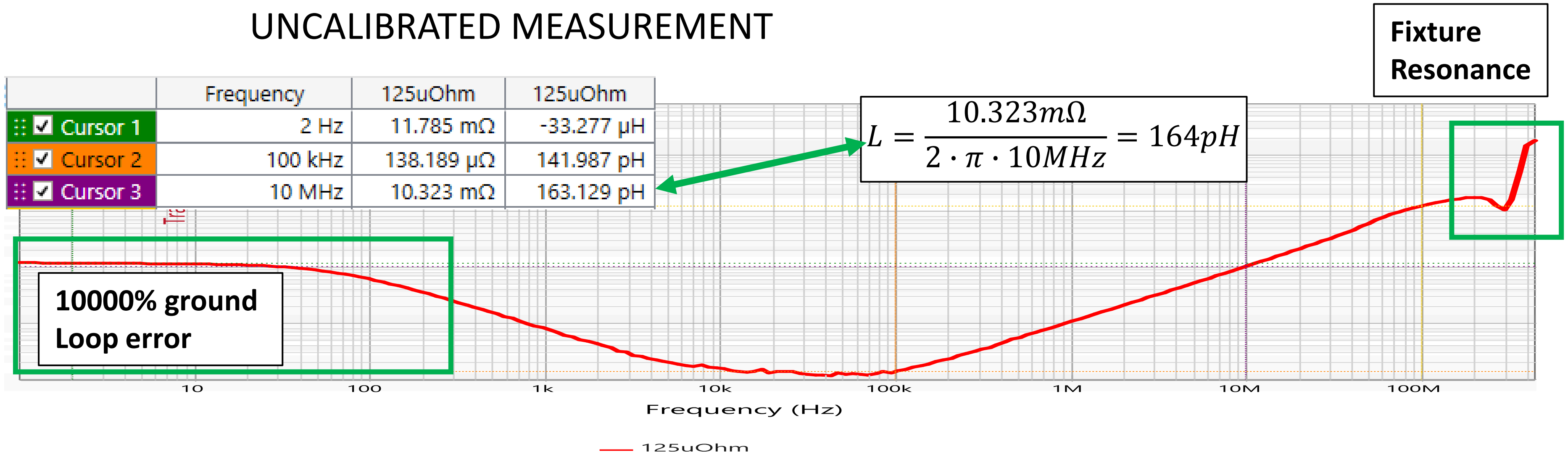
Resistor Measurement - Picotest ULVR1

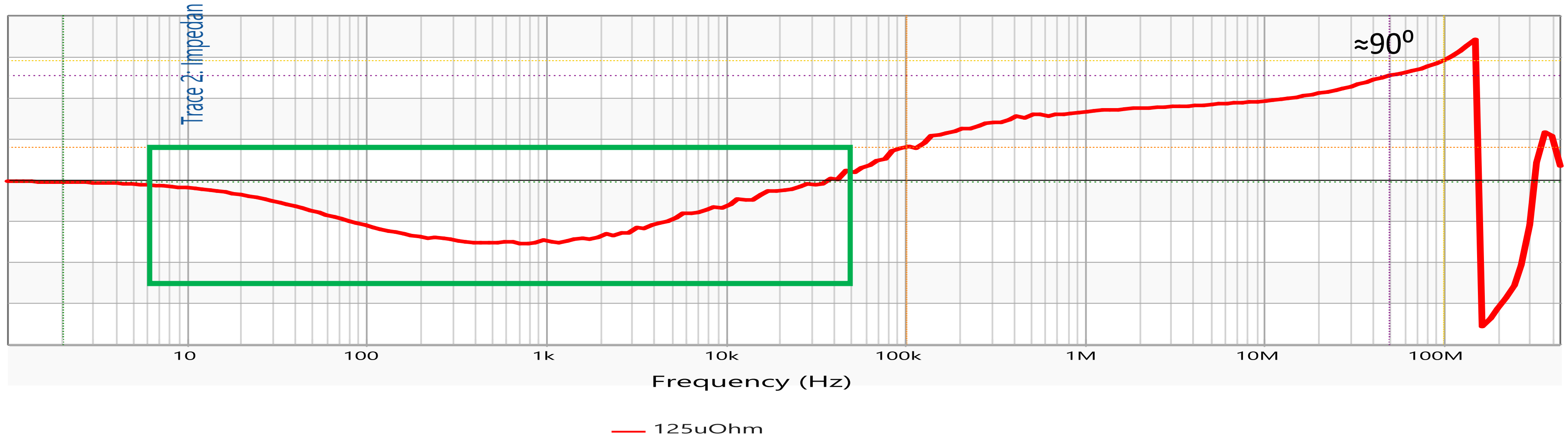


UNCALIBRATED MEASUREMENT

	Frequency	125uOhm	125uOhm
Cursor 1	2 Hz	11.785 mΩ	-33.277 µH
Cursor 2	100 kHz	138.189 µΩ	141.987 pH
Cursor 3	10 MHz	10.323 mΩ	163.129 pH

$$L = \frac{10.323m\Omega}{2 \cdot \pi \cdot 10MHz} = 164pH$$





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Can’t Correct with Calibration

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The low frequency ground loop error is nearly 10,000%. Calibration would subtract 11.66 mΩ resulting in the correct 125uOhm, but there are other material factors to consider.

Any changes due to the contact resistance, cable deformation or pressure sensitive probe pin resistance would be directly reflected in the measurement.

Adding a ground loop isolator will divide the error by the isolator CMRR prior to calibration greatly reducing the sensitivity to contact and probe pin resistance.

The fixture, which is any hardware beyond the calibration point (i.e., SMA cables) also must be properly designed and error terms minimized, or the calibration won’t be able to fully correct it.

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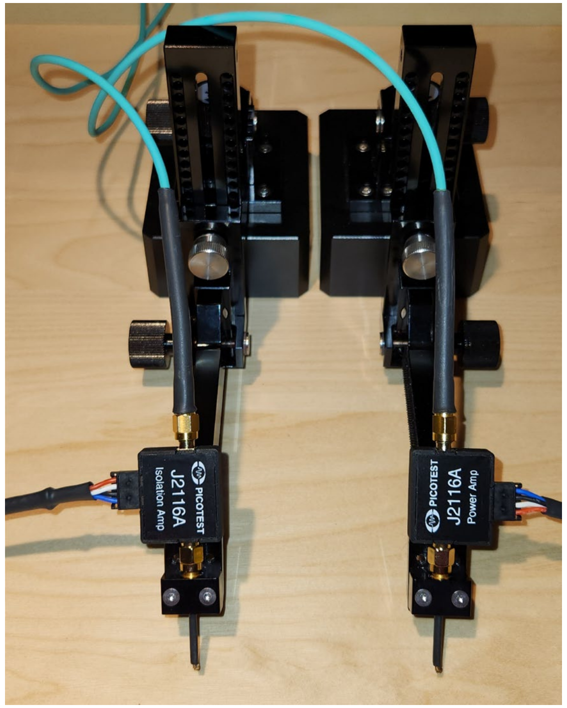
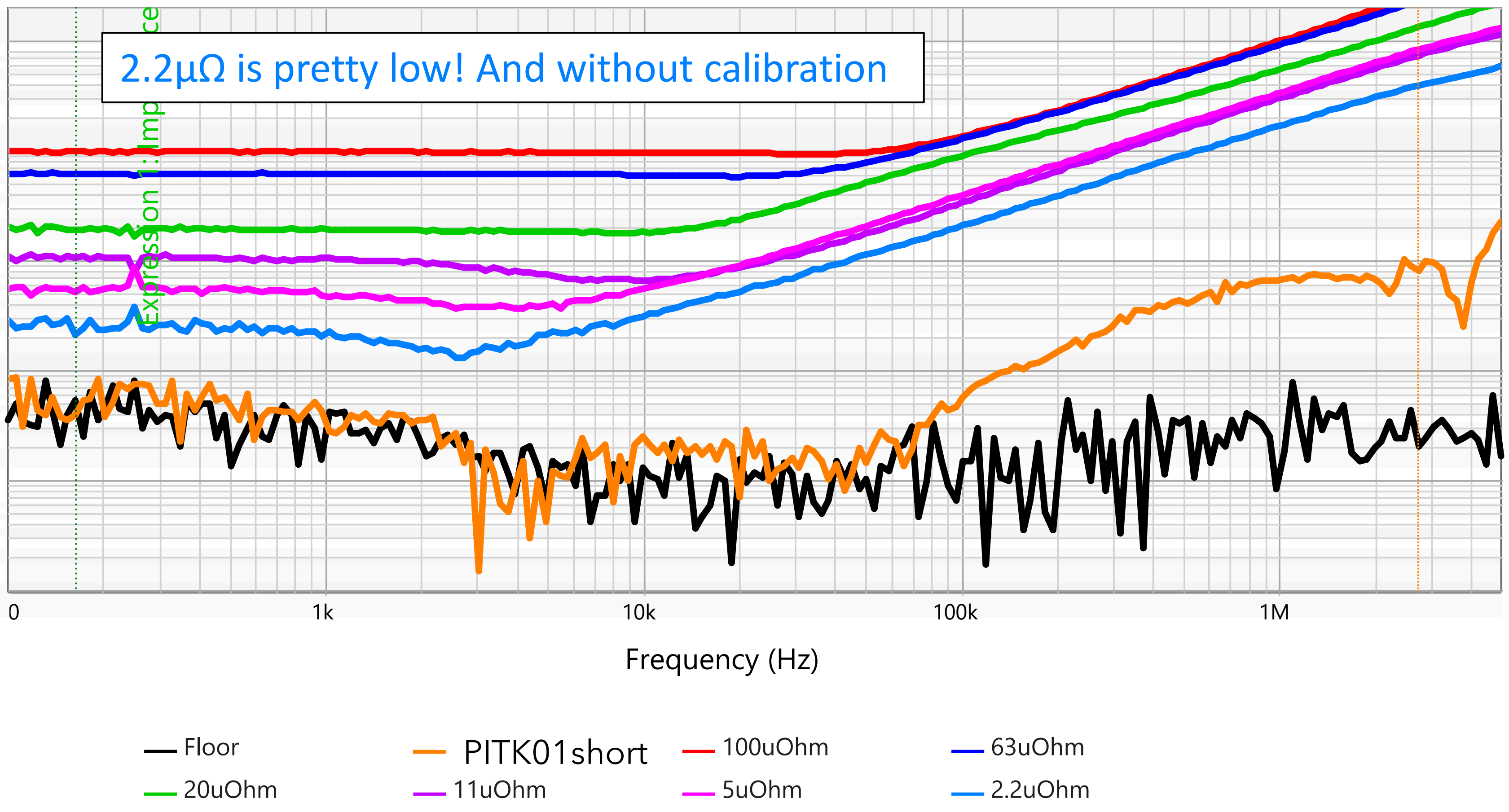
And Errors CAN Be Minimized



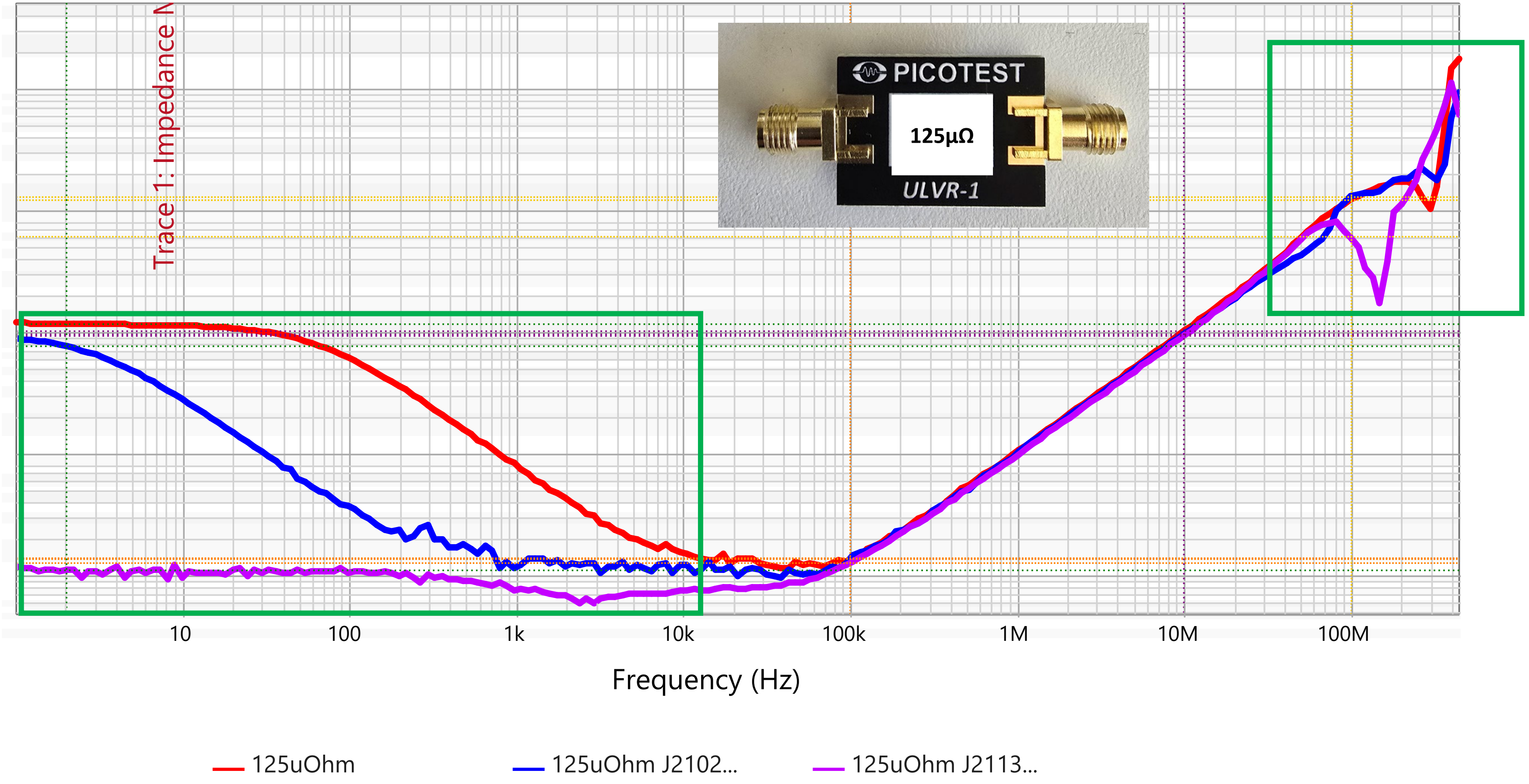
J2116A Source Power Amp and 100dB Ground Isolator Mounted on 1-port Microprobes

These 2-port Ultra-Low-Value Resistor measurements are PRE-CALIBRATION!



But WHICH Ground Loop Isolator??

The best balance is the J2102B – it can calibrate from ≈ 1kHz to ≈ 100MHz for most measurements



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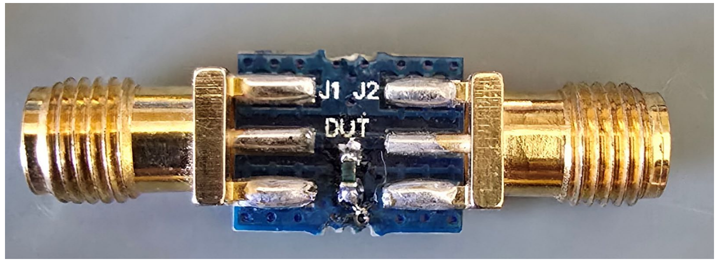
Chip Inductor

A representative 0603 (1608) chip inductor was chosen. While higher in value than we would like, 1.2nH ± 100pH (8%) provides a reasonable tolerance part in a size that is easy to hand solder to a PCB mount for measurement.



Lower value 1nH chip inductors are available, but with a larger percentage tolerance ±100 pH (10%) and in a size that is difficult to hand solder (0201).

1.2 nH Chip measurement - L06031R2BGSTR

	Frequency	1.2nH - L0603...	1.2nH - L0603...
Cursor 1	2 Hz	21.975 mΩ	-32.038 µH
Cursor 2	100 kHz	17.46 mΩ	1.549 nH
Cursor 3	10 MHz	86.838 mΩ	1.37 nH
Cursor 4	100 MHz	791.229 mΩ	600.579 pH

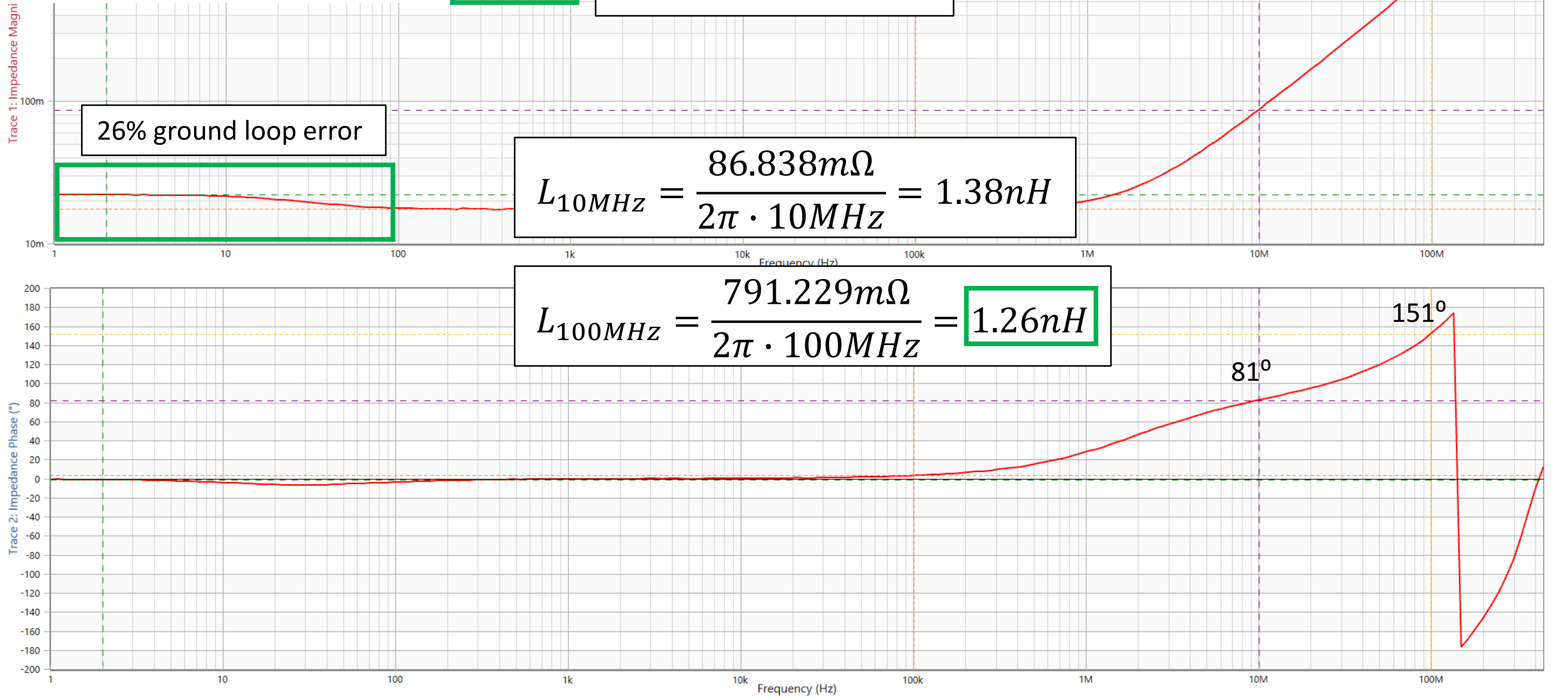
Calculations are correct, cursors are wrong!

50% inductance error

26% ground loop error

$$L_{10MHz} = \frac{86.838m\Omega}{2\pi \cdot 10MHz} = 1.38nH$$

$$L_{100MHz} = \frac{791.229m\Omega}{2\pi \cdot 100MHz} = 1.26nH$$



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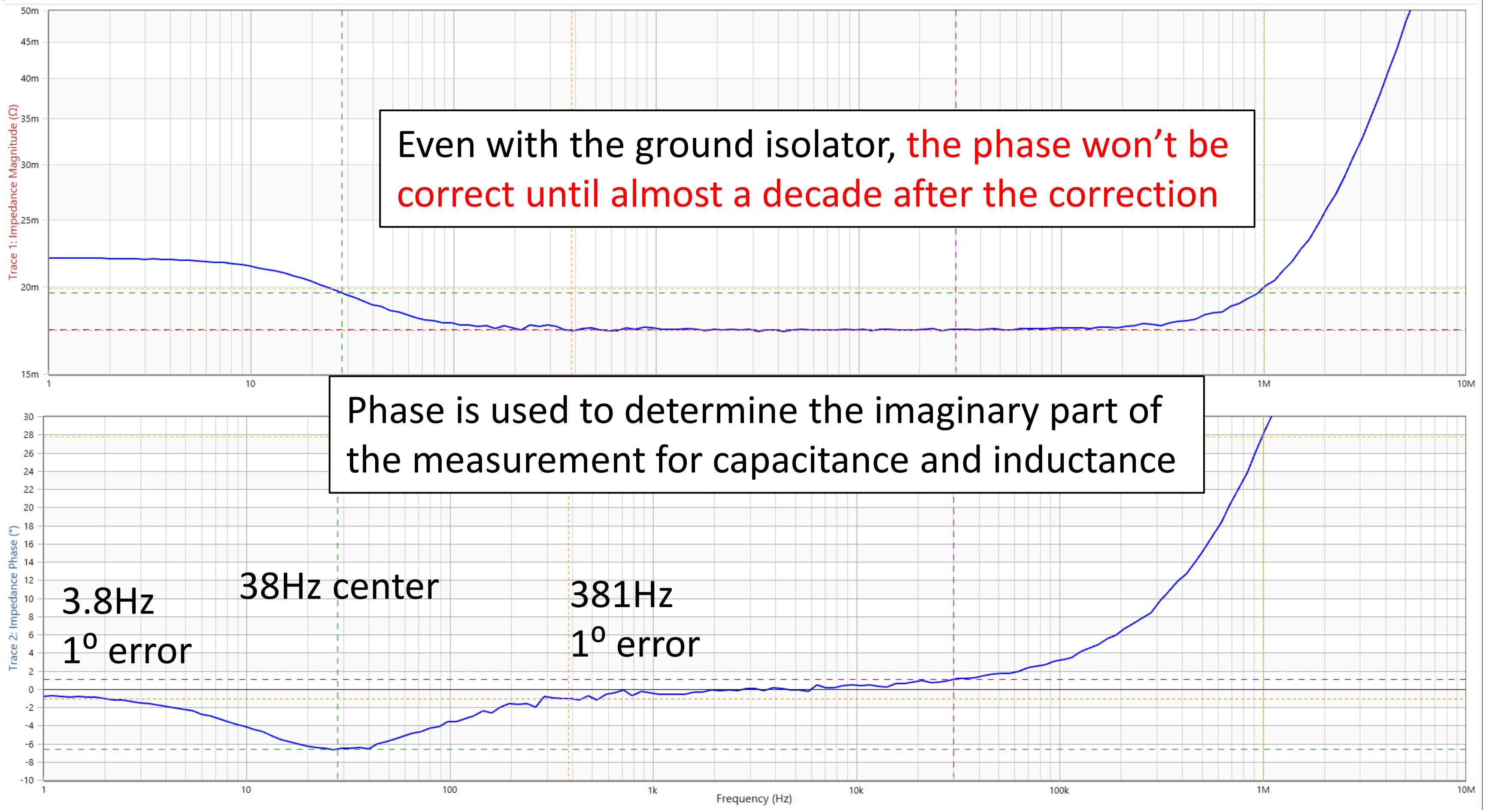
Because Phase Matters (For L, C, and Q)

	Frequency	1.2nH - L0603...	1.2nH - L0603...
Cursor 1	27.99 Hz	19.63 mΩ	-6.598 °
Cursor 2	381.07 Hz	17.334 mΩ	-1.024 °
Cursor 3	30.16 kHz	17.389 mΩ	1.052 °
Cursor 4	1 MHz	19.91 mΩ	27.775 °



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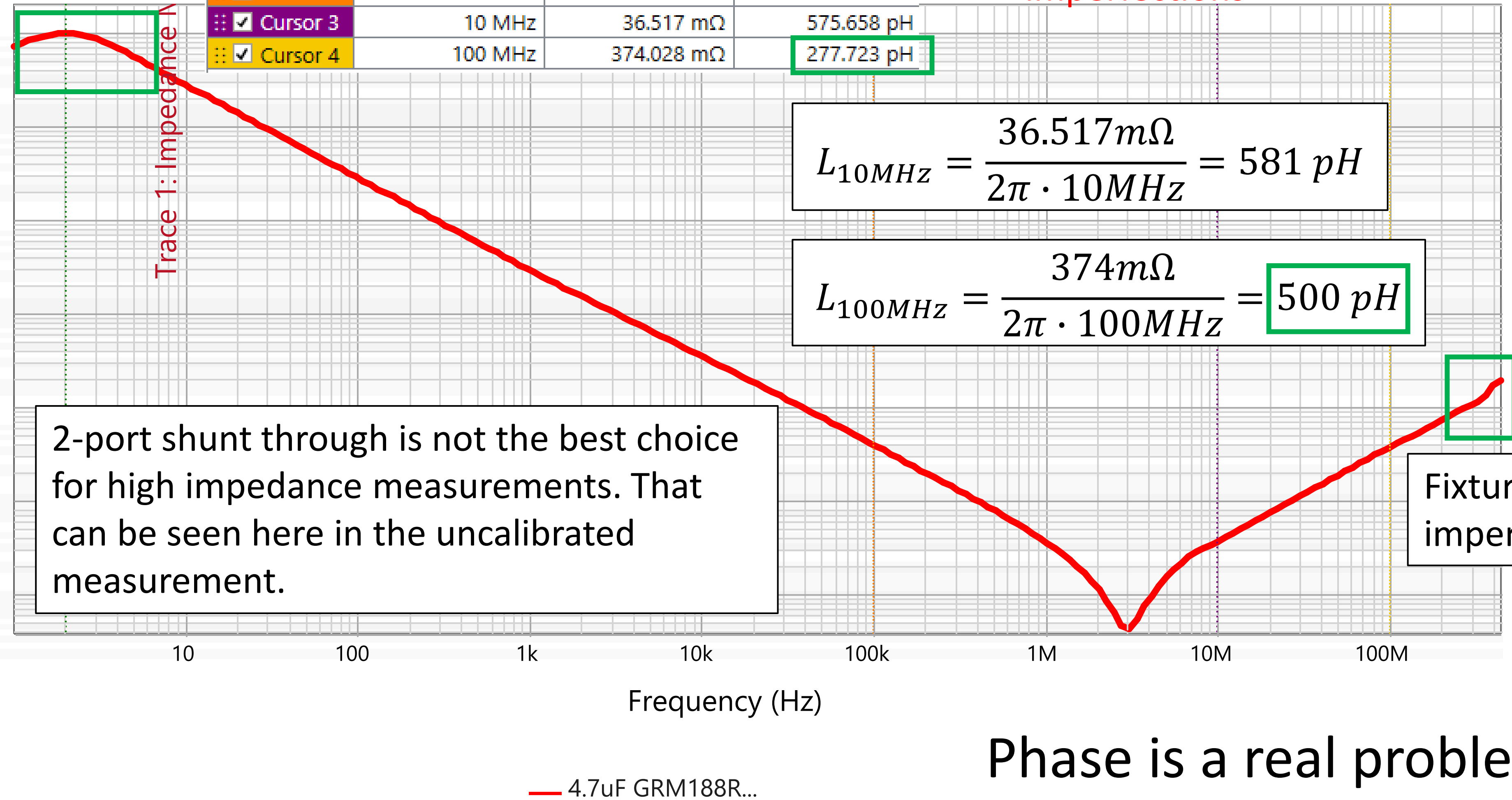
4.7uF/10V Capacitor GRM188R61A475KE15E15

Calibration will correct these two imperfections

	Frequency	4.7uF GRM188R...	4.7uF GRM188R...
Cursor 1	2 Hz	10.109 kΩ	-722.549 H
Cursor 2	100 kHz	404.382 mΩ	-646.42 nH
Cursor 3	10 MHz	36.517 mΩ	575.658 pH
Cursor 4	100 MHz	374.028 mΩ	277.723 pH



$$L_{10MHz} = \frac{36.517m\Omega}{2\pi \cdot 10MHz} = 581\ pH$$

$$L_{100MHz} = \frac{374m\Omega}{2\pi \cdot 100MHz} = 500\ pH$$

2-port shunt through is not the best choice for high impedance measurements. That can be seen here in the uncalibrated measurement.

Fixture imperfections

Phase is a real problem!

Let’s Define Our Terms

- **Embedding** is the addition of elements such as fixtures to a measurement
- **De-embedding** is the subtraction of elements, such as fixtures or EM-related artifacts
- **Calibration** is the correction of the setup and/or fixture, using a calibration device with known characteristics
- **Cal-Kits** are the software that describe the Calibration module to the VNA. Data-Based Cal-Kits are much more expensive, but include data for a specific calibration device (by serial #)

S911T Calibration Module

Electrical Data

Impedance	50Ω
Frequency range	DC to 9 GHz
Connector type	3.5 mm female

Open	Phase deviation, max.
DC - 4 GHz	≤ 1.5°
4 GHz - 9 GHz	≤ 3°

Short	Phase deviation, max.
DC - 4 GHz	≤ 1°
4 GHz - 9 GHz	≤ 2°

Load	
Resistance	50Ω ± 0.5Ω
Return Loss	
DC - 4 GHz	≥ 37 dB
4 GHz - 9 GHz	≥ 34 dB
Power rating, max.	0.5 W

Thru	
Electrical (Offset) delay	127.588 ps
Return loss	
DC - 4 GHz	≥ 34 dB
4 GHz - 9 GHz	≥ 28 dB
Insertion loss	
DC - 9 GHz	0.11 dB

Environmental Data

Operating temperature	5 °C to 40 °C
Storage temperature	-40 °C to +70 °C

Coefficients

Open	$C_0 = -7.425 \times 10^{[illegible]}$ F	
	$C_1 = 2470 \times 10^{[illegible]}$ F/Hz	
	$C_2 = -226 \times 10^{-24}$ F/Hz^2	
	$C_3 = 6.18 \times 10^{[illegible]}$ F/Hz^3	
	Offset delay	30.821 ps
	Offset length	9.24 mm
Short	$L_0 = 27.98 \times 10^{[illegible]}$ H	
	$L_1 = -5010 \times 10^{-24}$ H/Hz	
	$L_2 = 303.8 \times 10^{-33}$ H/Hz^2	
	$L_3 = -6.13 \times 10^{[illegible]}$ H/Hz^3	
	Offset delay	30.688 ps
	Offset length	9.2 mm
Thru	Electrical delay	127.588 ps
	Electrical length	38.25 mm

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Full 2-Port VNA Calibration for SMA

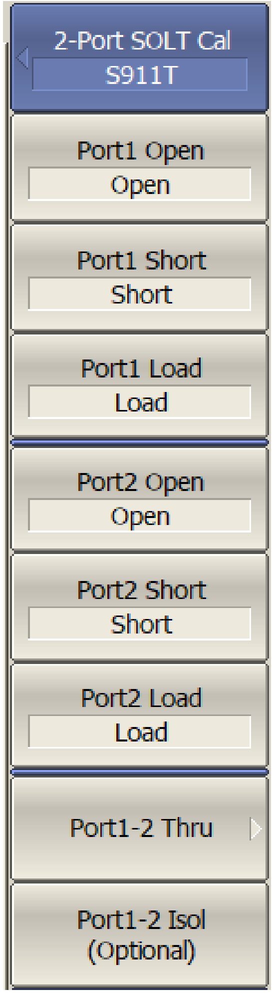
Use a torque wrench to ensure full and consistent engagement of the connectors

Select the calibration kit that matches the known calibrator

C? Start 9 kHz 201 Log

	Label	Description	Select	Predefined	Modified	#STDs
22	WR284	S-band 2.6-3.95G SSLT/TRL Waveguide (Flann Microwave)	☐	Yes	No	8
23	WR229	E-band 3.3-4.9G SSLT/TRL Waveguide (Flann Microwave)	☐	Yes	No	8
24	WR187	G-band 3.94-5.99G SSLT/TRL Waveguide (Flann Microwave	☐	Yes	No	8
25	WR159	F-band 4.64-7.05G SSLT/TRL Waveguide (Flann Microwave	☐	Yes	No	8
26	WR137	C-band 5.38-8.18G SSLT/TRL Waveguide (Flann Microwave	☐	Yes	No	8
27	N611/612	Type-N 50Ω 6GHz Cal Kit, S/N 4xx,5xx,6xx (CMT)	☐	Yes	No	8
28	N611/612	Type-N 50Ω 6GHz Cal Kit, S/N Axx, Bxx, 12xx (CMT)	☐	Yes	No	8
29	S911	3.5mm 9GHz SOL Cal Kit (CMT)	☐	Yes	No	5
30	S911T	3.5mm 9GHz SOLT Cal Kit (CMT)	☑	Yes	No	5
31	N1801	Type-N 50Ω SOLT 18GHz SOLT Cal Kit (CMT)	☐	Yes	No	5
32	S2611	3.5mm 26.5GHz SOLT Cal Kit (CMT)	☐	Yes	No	5
33	T4311	RPC-2.92 40 GHz SOLT Cal Kit [Jack] (CMT)	☐	Yes	No	5
34	Z5411	RPC-2.40 50 GHz SOLT Cal Kit [Jack] (CMT)	☐	Yes	No	5
35	N1802	Type-N Male 50Ω SOLT 18GHz Cal Kit (CMT)	☐	Yes	No	5
36	P2100A-CAL	Calibration Substrate (Picotest)	☐	No	Yes	5
37						

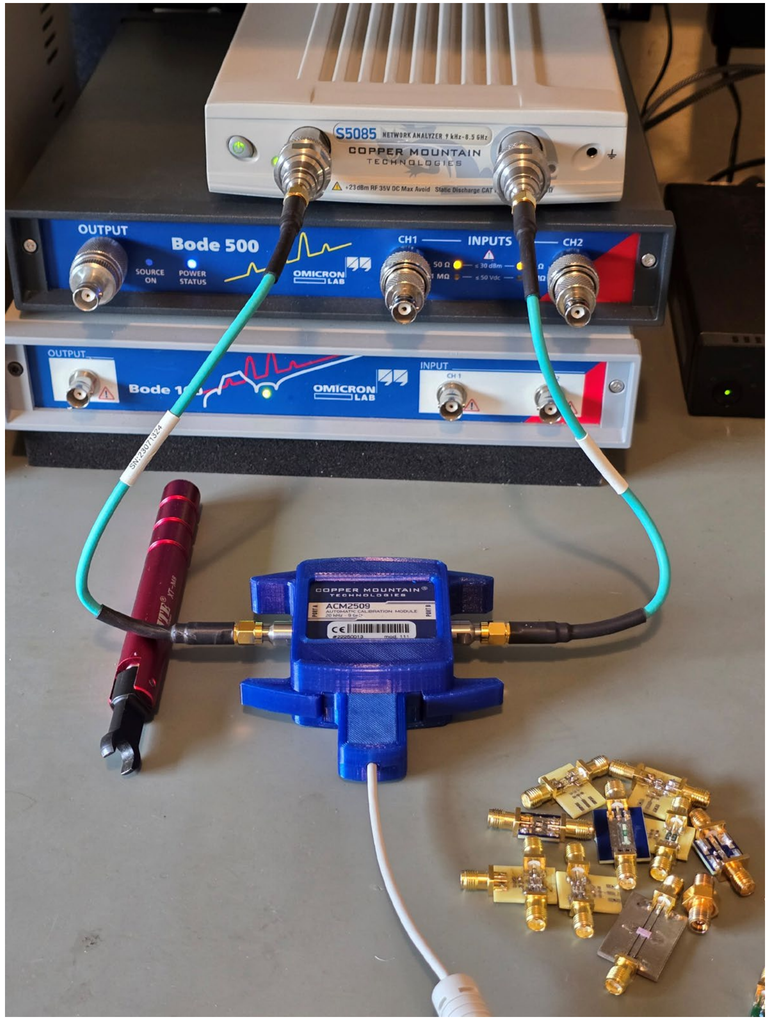
SOLR is generally better than SOLT. If UNKNOWN THROUGH is an available option, select that. This is a reciprocal method that will generally work with all passive THROUGH paths.



Perform 7 (8) calibrations

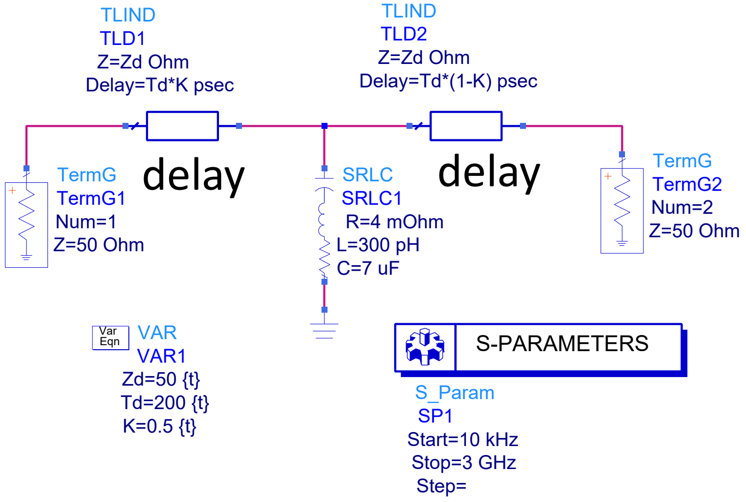
Automatic Calibration Modules

- Most traditional VNA manufacturers offer Automatic Calibration modules
- These are more accurate than mechanical calibrators, more time efficient, and easier on the fingers.
- These are also often traceable to national metrology institutes
- Many include a confidence check



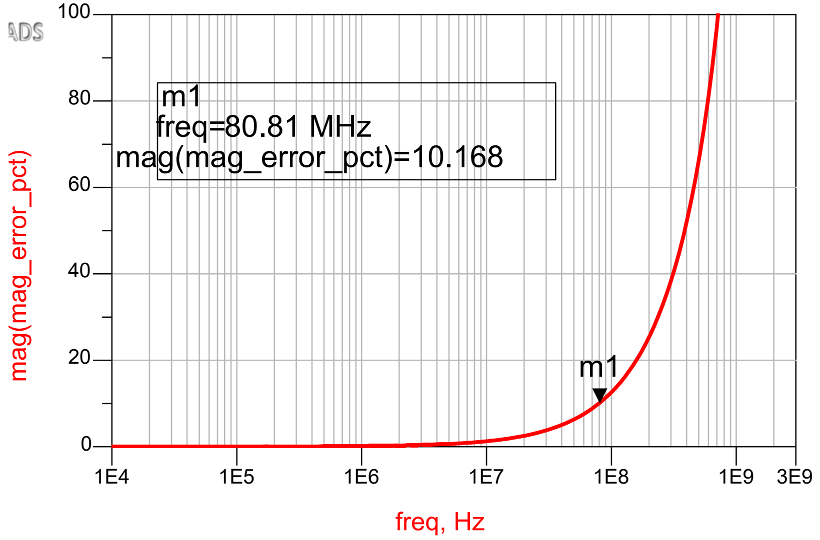
Full 2-Port and S21 are NOT the Same

Even in a very small PCB, the uncorrected ideal (lossless) delay error contributes 10% at 80MHz and 60% error at 450MHz

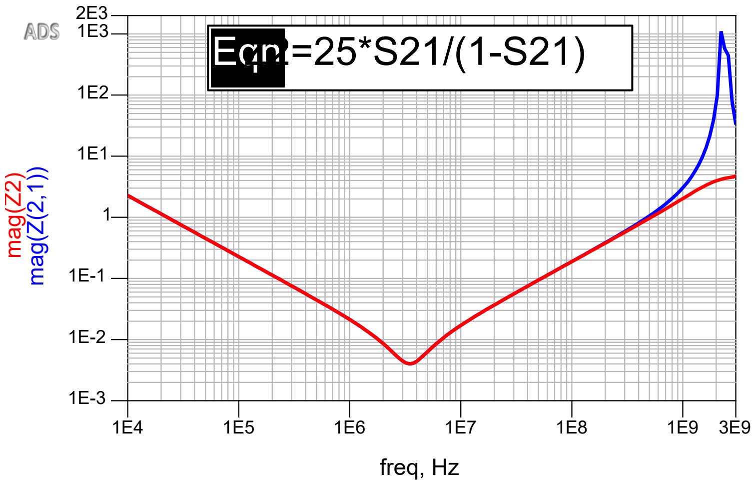


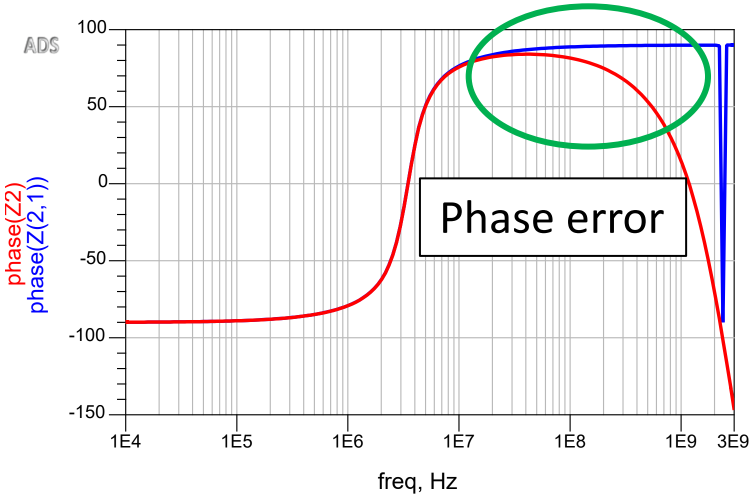
$200ps \sim 3cm\ (1.2")\ in\ FR4$

Magnitude % Error



Magnitude error





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Still Wrong!!! WHY? Electrons Move Slowly

- Nearly 300mm/ns in air, slower in cables & PCBs
- Delays shift phase but minimal impact on magnitude
- 0.2nH/mm requires 0.15mm accuracy for 30pH (1 Post-It) hence, the wrench to maintain repeatable engagement

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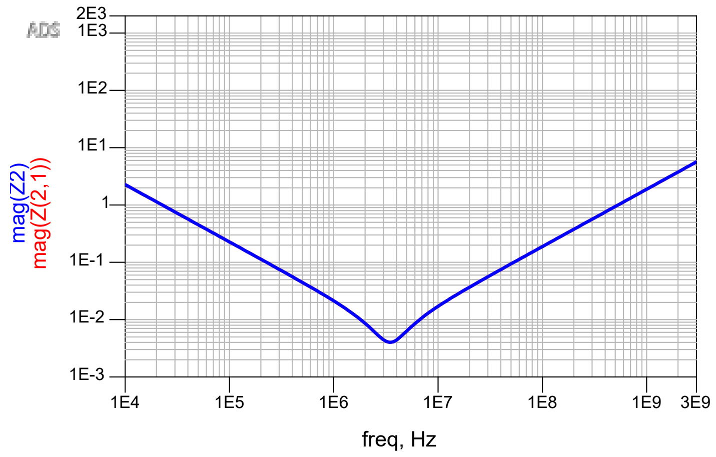
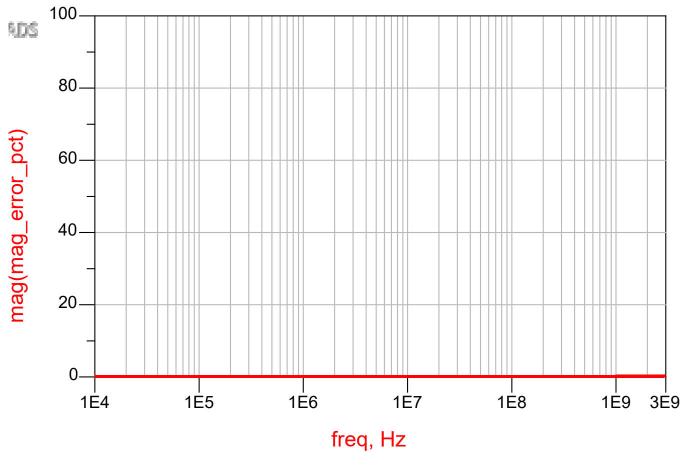
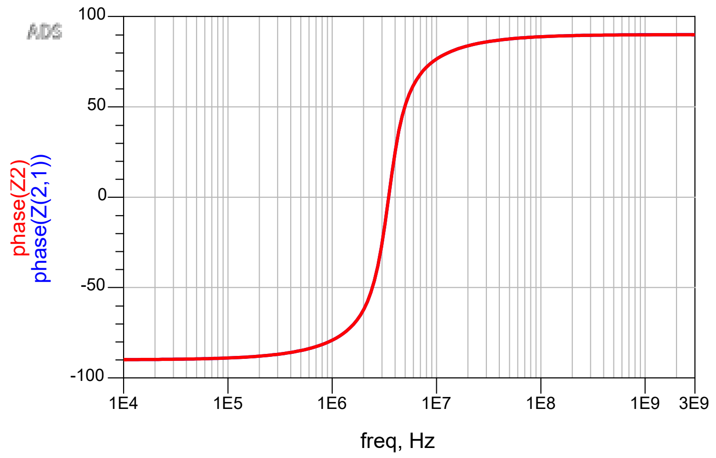
Reducing the Delay to 1ps Until They Converge





The delay is controlled by both the physical distance and D_k (E_r)

Smaller, RF material PCBs will have smaller phase error than FR4, but are also more expensive



Simulation of Z21 the S21 transform converge when the uncorrected delay gets very small

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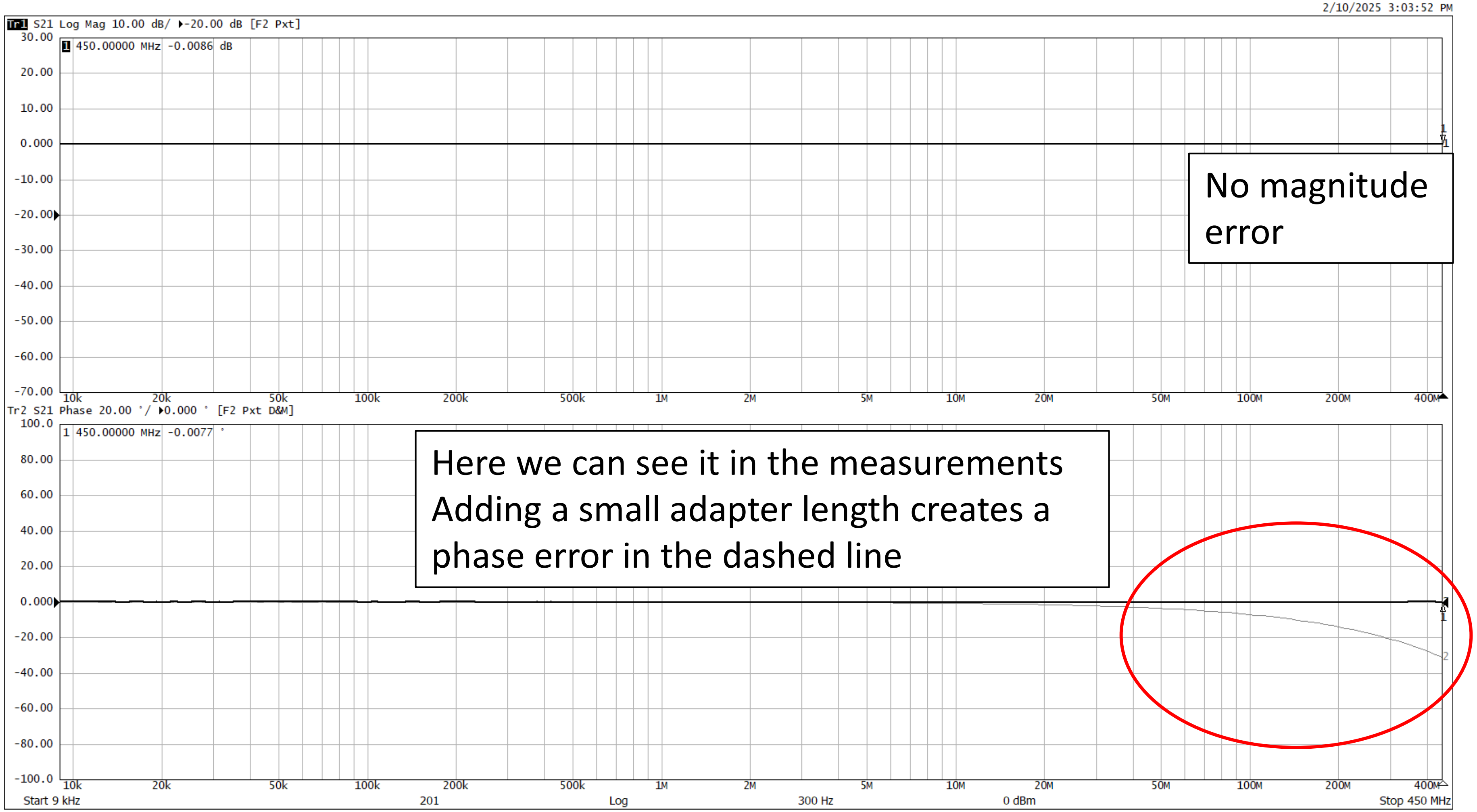
After calibration, the simple THROUGH measurement is still not good above 10MHz

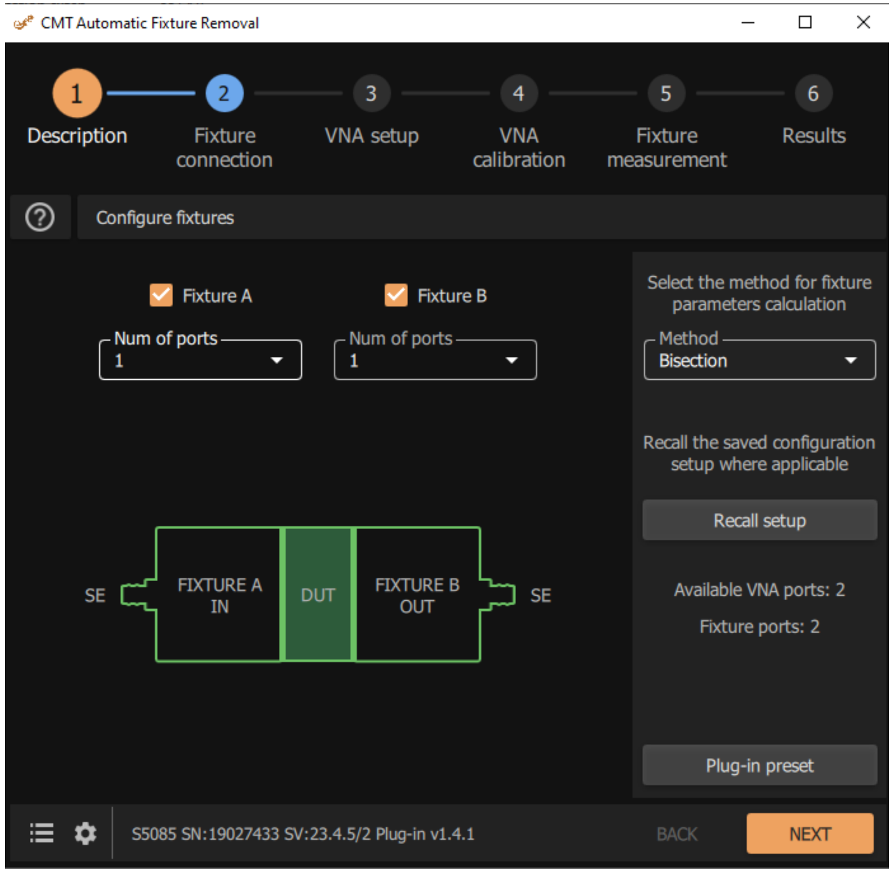


If the mount is **ideal** with 4-point contact and 50Ω traces, the phase can be corrected using "port extensions" in the VNA. CAN'T CORRECT REFLECTIONS

Port extensions "de-embed" the electrical length (phase) of the PCB mount from each port connector to the DUT

Ideally the DUT should be centered so that the port extensions are known to be equal

Automatic Fixture Removal



AFR Software is generally available from the VNA manufacturer

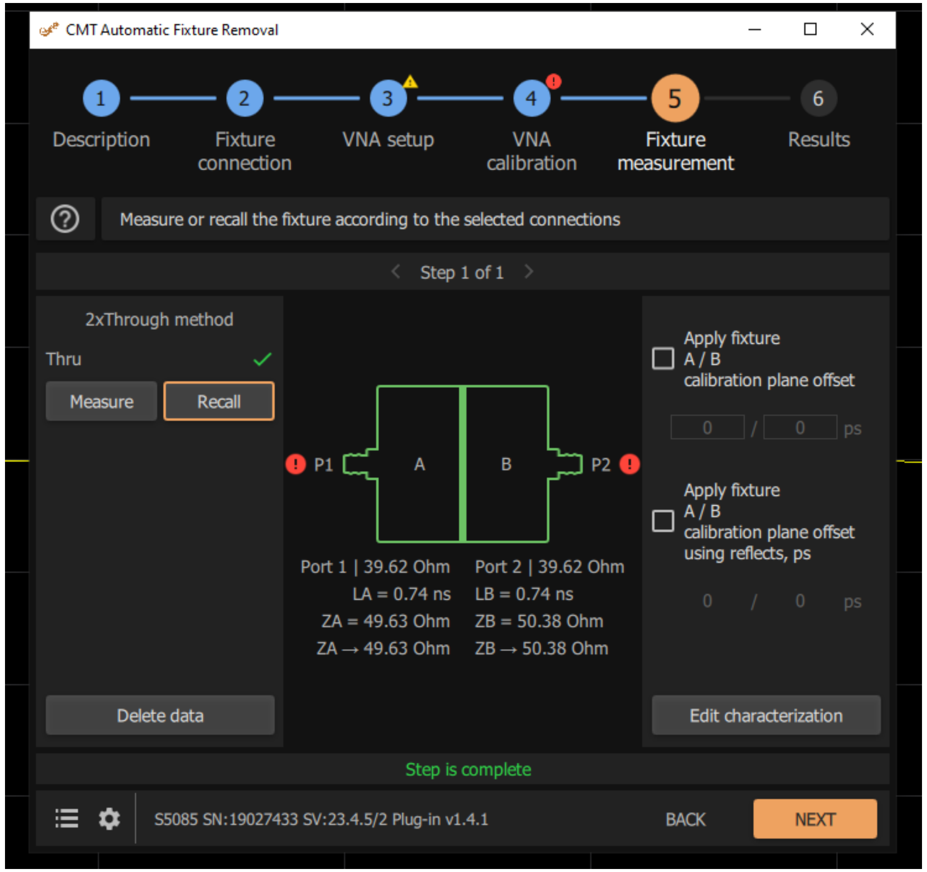
The software creates the port 1 and port 2 de-embed files from VNA measurements and applies the de-embedding to the measurement

The fixture de-embed files can also be saved for future use

NOTES:
The fixture needs to be good to much higher frequency than the desired measurement

Bisection is a good general selection

Relatively expensive add-on, but worth it if you can use it frequently



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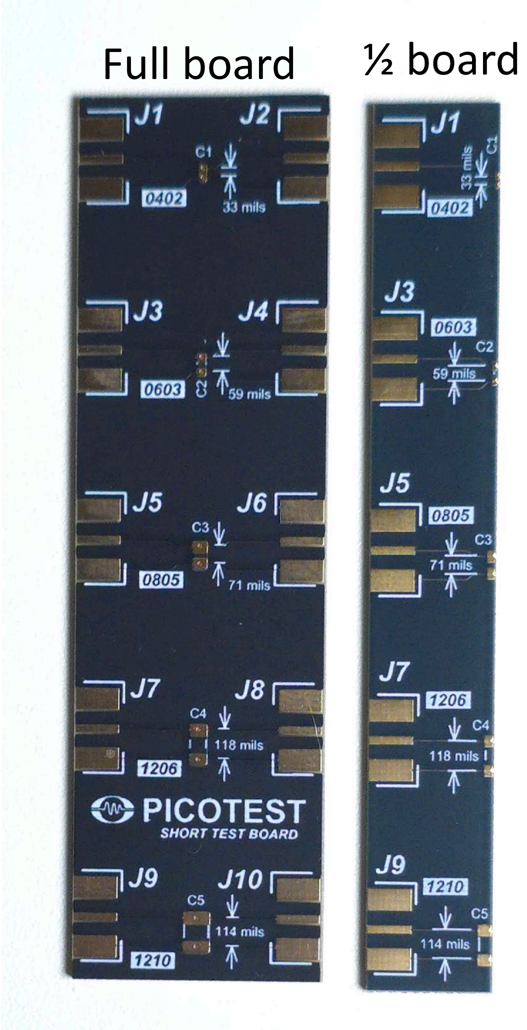
Half-Board Calibration



Fabricating a half-board, in addition to a full board, or cutting a board in half allows the calibration elements (OPEN, SHORT and LOAD) to be moved to the center of the DUT on the PCB.

These half boards are then used to perform the OPEN, SHORT, and LOAD calibrations, while the full PCB is used to perform the THROUGH calibration.

The advantage is that it corrects for the electrical length of the PCB, moving the calibration point from the SMA to the DUT.

The disadvantages are that the half boards do not have a known calibration kit and that extra half boards are required.

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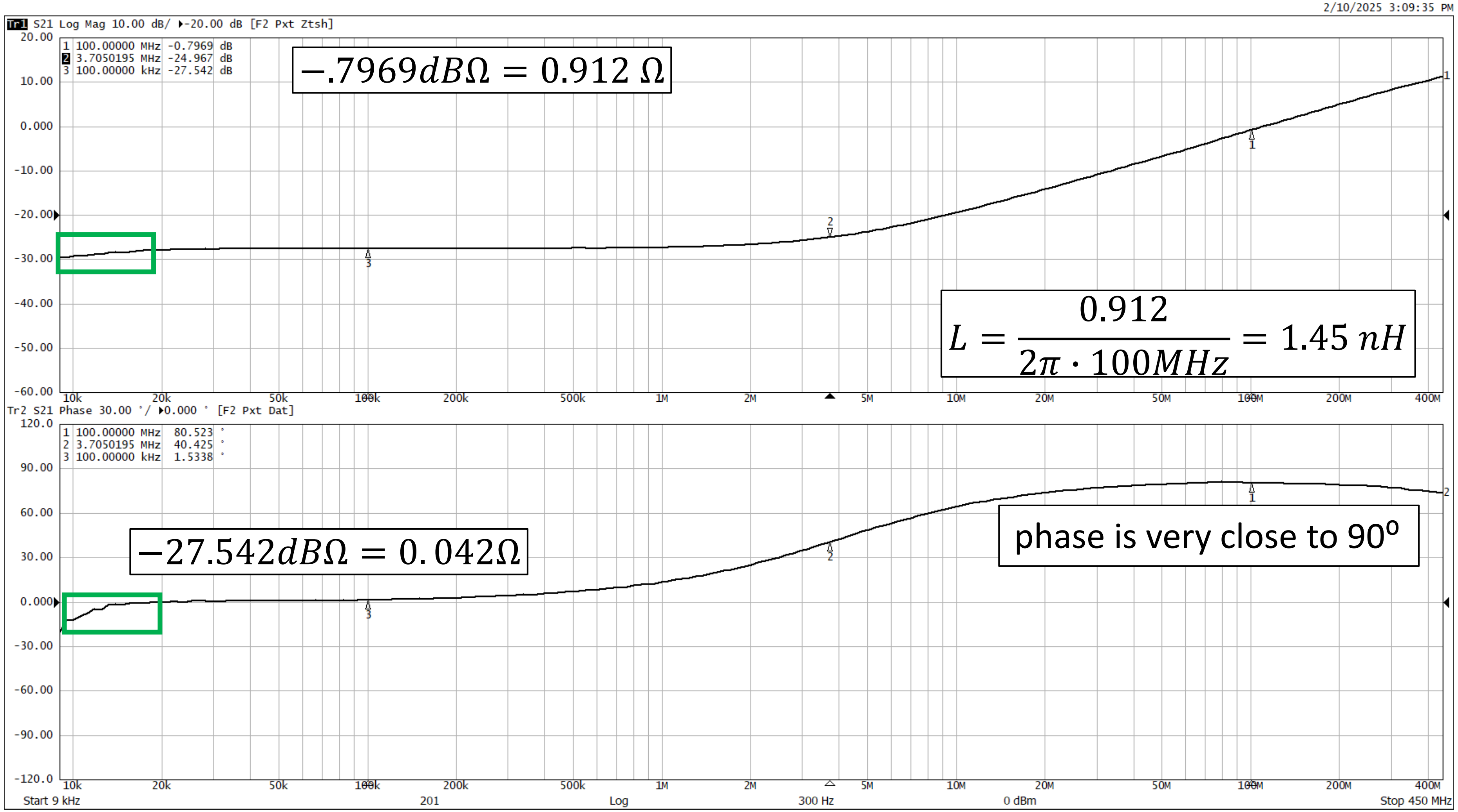
1.2nH Inductor Post Cal and Port Extension

Now this is a KNOWN value, since it is traceable to the cal-kit, and time corrected



After performing SOLR calibration and adjusting and applying port extensions to correct for the length of the PCB, the measurement is accurate within the cal-kit capability.

Databased calibrators, using a "Golden VNA" are more accurate, but this measurement is considered to be quite good.

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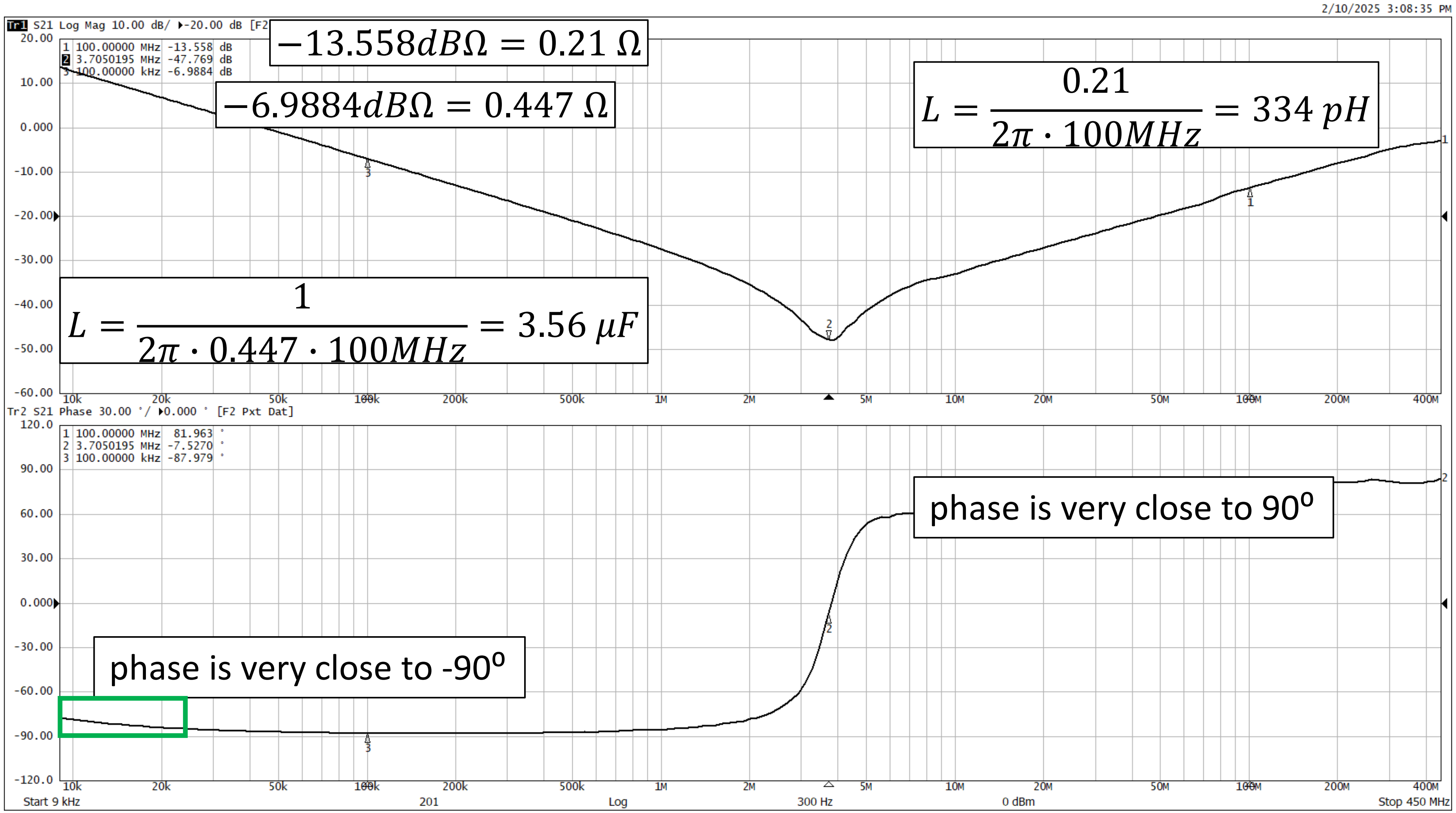
4.7uF Capacitor Post Cal and Port Extension



Next Steps

Next is to measure each component

- Without calibration and with 2-port shunt through calibration
- With calibration using SHORT and ISO-SHORT standards

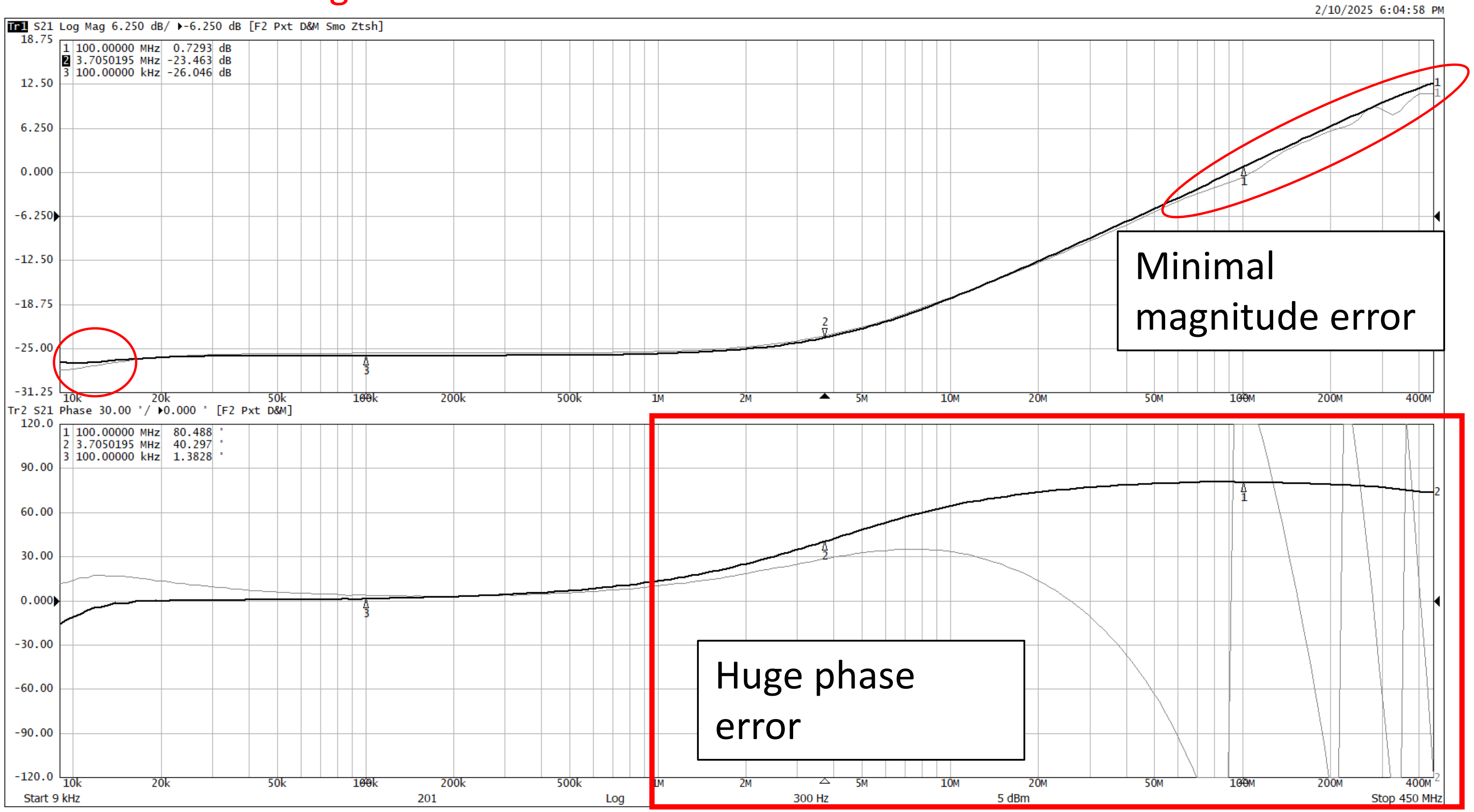
1.2nH Measurement W and W/O Calibration

Note the magnitude differences are minimal

Phase differences are large, even at 10MHz

First, correct most errors before calibration (such as the ground loop error using an isolator) and rely more on magnitude than on phase unless your measurements are phase corrected

Light trace is uncalibrated dark trace is calibrated



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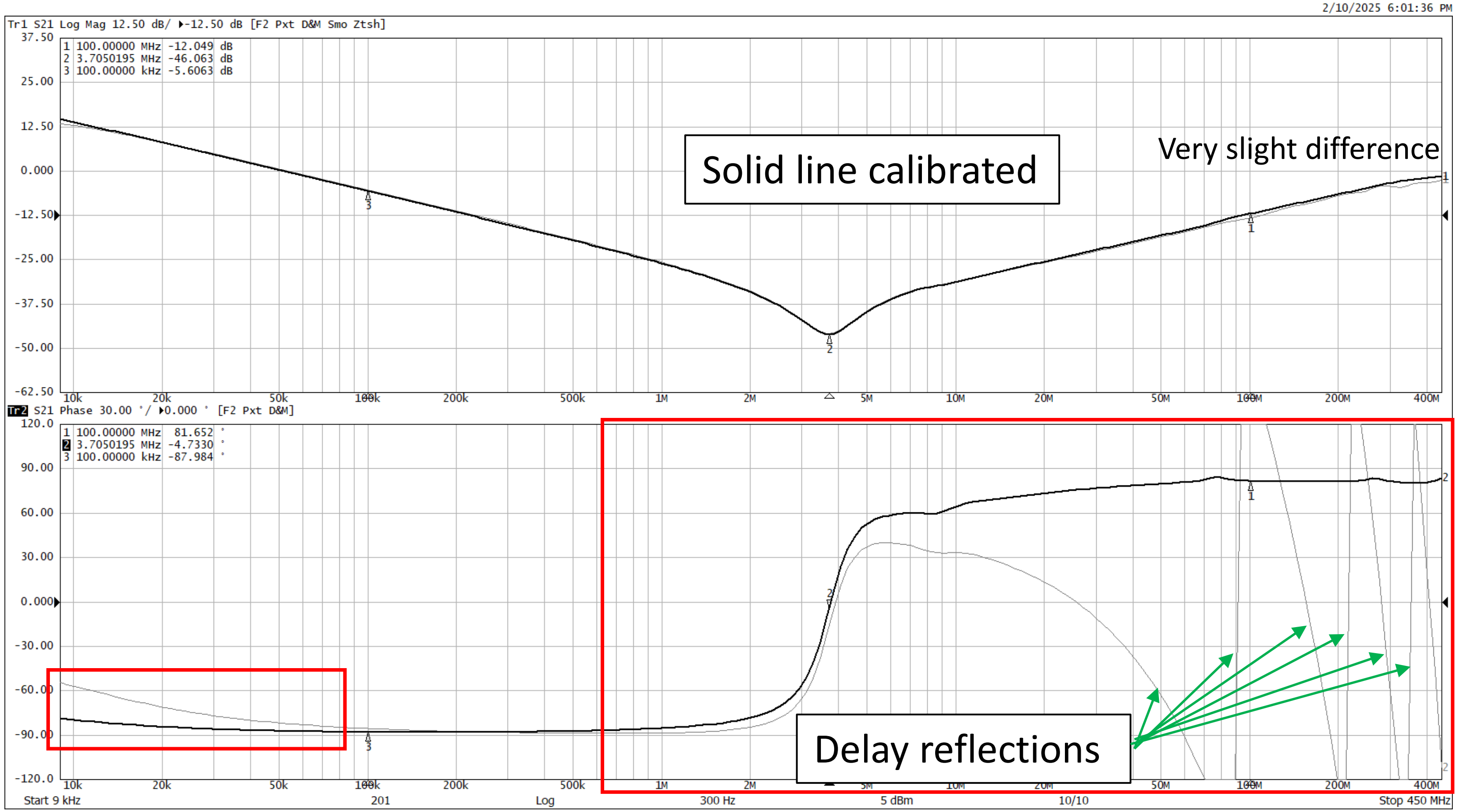
4.7uF Measurement With and W/O Calibration

Note the magnitude differences are minimal

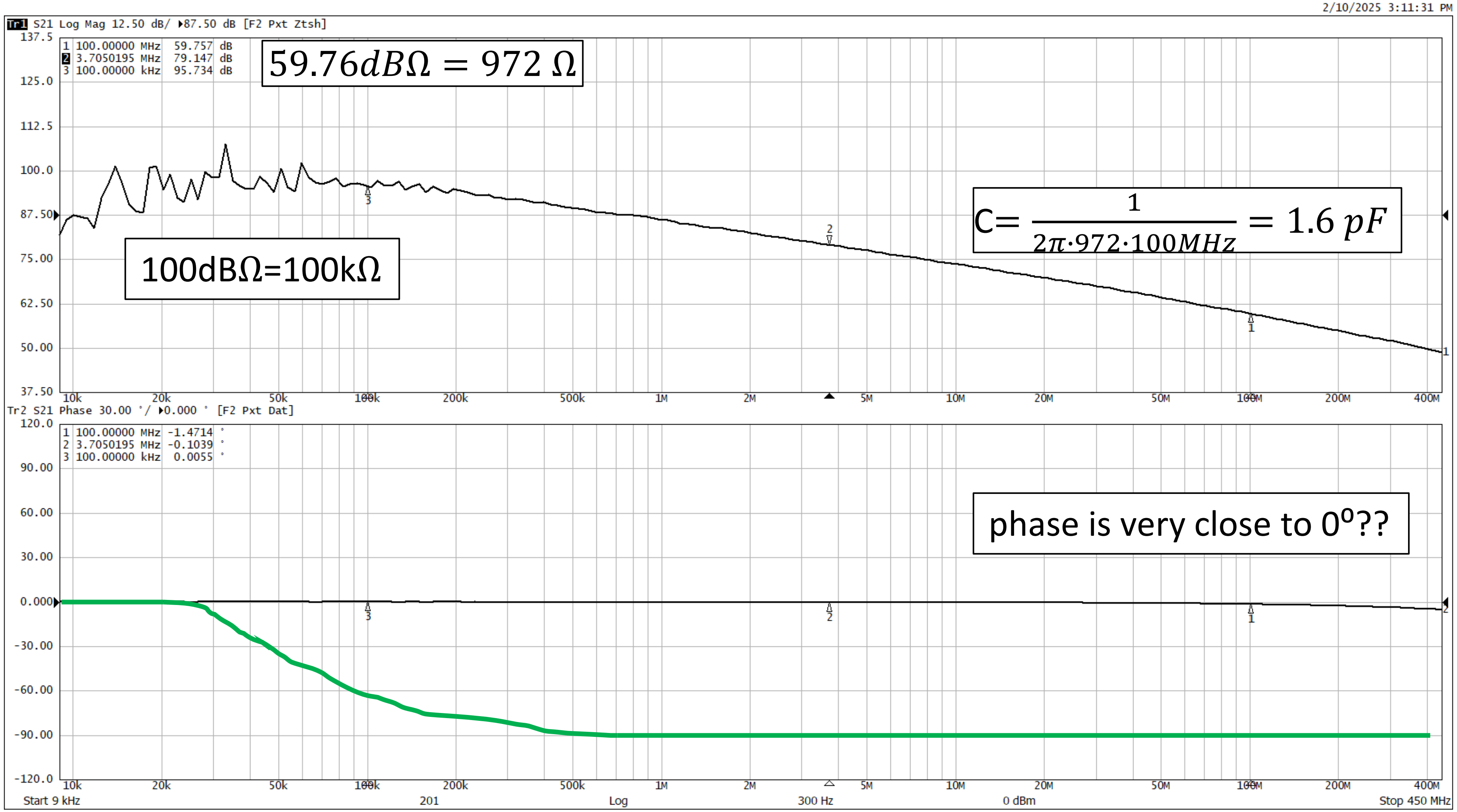
Phase differences are large, even at 10MHz

Correct most errors before calibration and rely more on magnitude than on phase unless your measurements are phase corrected



1.5pF – SHUNT THROUGH - NOT RECOMMENDED

Even with good calibration, 2-port shunt through isn't recommended above a few kΩ



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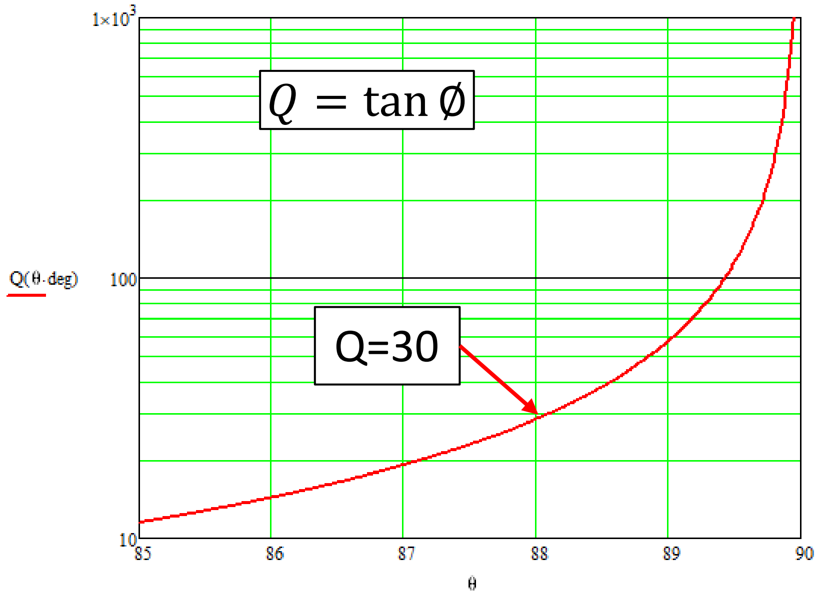
(Not) Measuring Q

At 450MHz 0.9mm FR4=1 degree

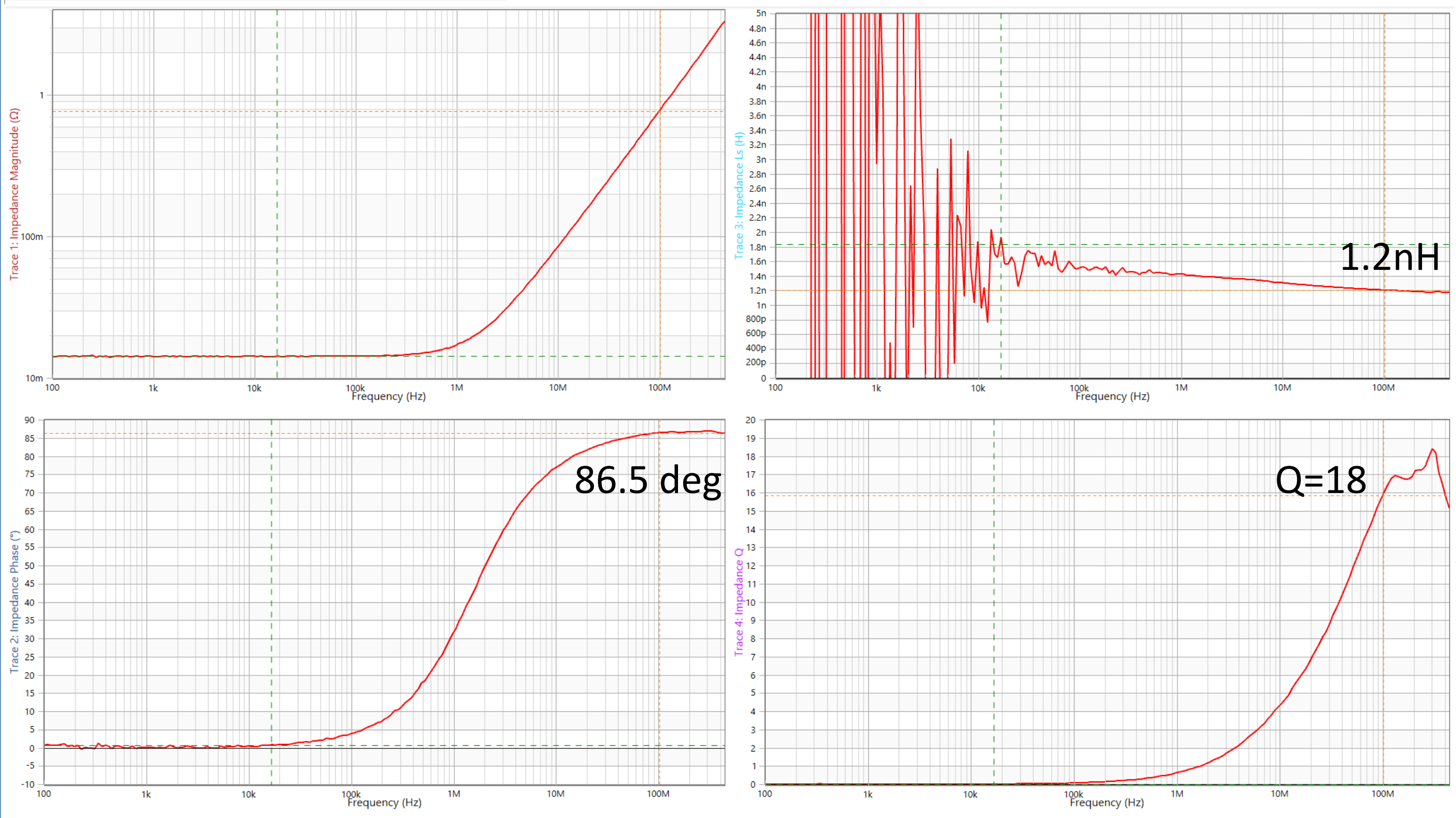
There is not a method of ACCURATELY measuring high Q

The phase accuracy of a typical VNA is 0.5-2 deg. At a 2 deg TOTAL accuracy, the maximum Q measurement is approximately 20

An LCR bridge is generally a better instrument



	Frequency	10mm cal 10mm...	10mm cal 10mm...	10mm cal 10mm...	10mm cal 10mm...
Cursor 1	16.5 kHz	14.224 mΩ	770.091 m°	1.838 nH	13.441 m
Cursor 2	101.782684 MHz	773.471 mΩ	86.392 °	1.207 nH	15.86
Delta C2-C1	101.766184 MHz	759.247 mΩ	85.622 °	-631.409 pH	15.847



Differences: Bode 100/500 vs Traditional VNA

- Doesn't offer calibration kit support
- Doesn't use SOLT or SOLR calibration for 2-port measurements
- Doesn't offer port extensions, fixture removal or embedding/de-embedding

BUT

- Uses a Z parameter calibration that is more direct. Lack of Cal-Kit support requires that we calibrate the measurement differently

PICOTEST

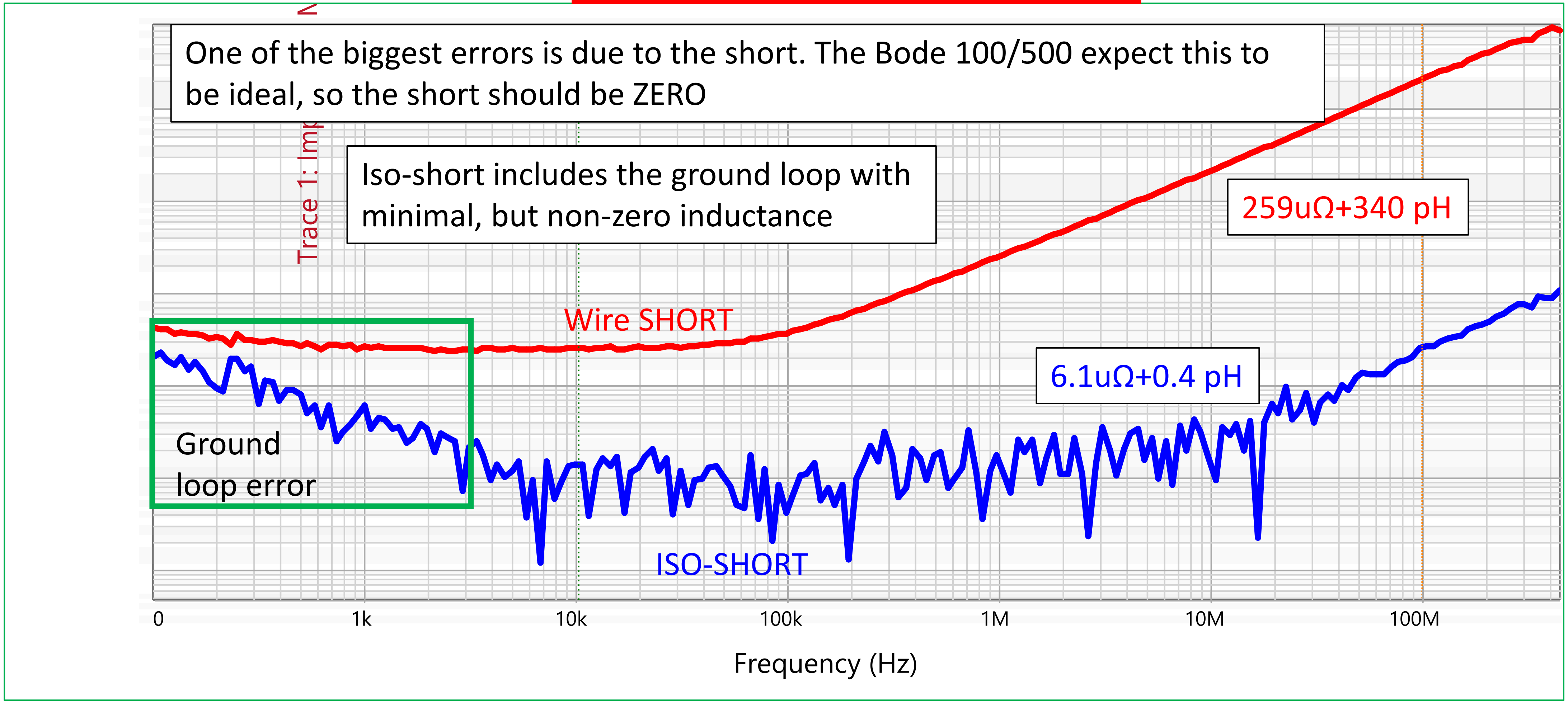
Modified SOL Calibration for Bode 100/500

- Perform OPEN using the PCB without a component installed
- Perform LOAD using the fixture (i.e. PCB) with a 49.9 Ohm resistor installed
- Perform SHORT using an ISO-SHORT calibration fixture the same size as the component fixture. This shorts each port to itself and connects the grounds together.

PICOTEST

How Short is Short

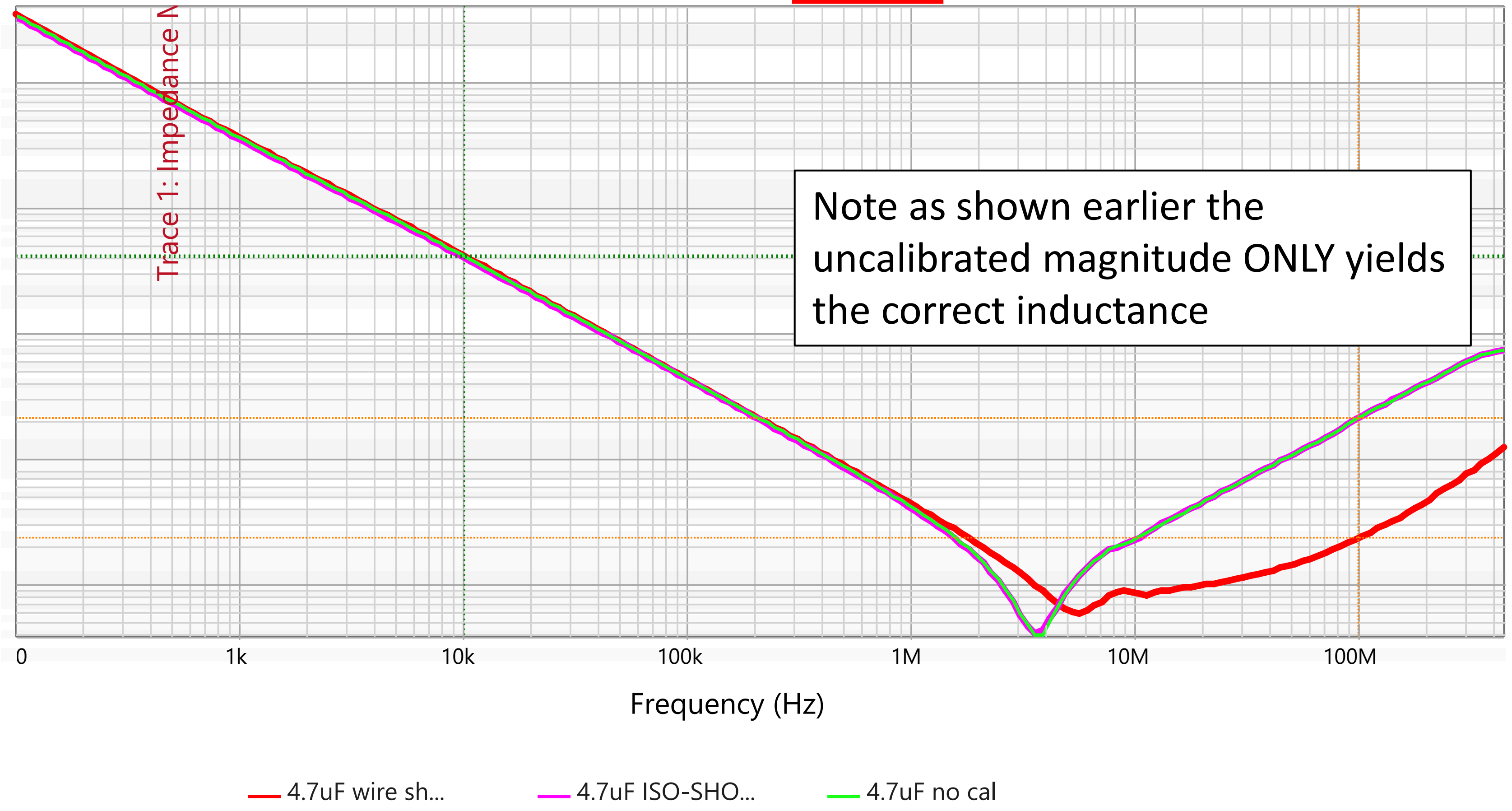
	Frequency	uncalibrated ...	uncalibrated ...	uncalibrated ...	uncalibrated ...
☑ Cursor 1	10 kHz	259.134 µΩ	6.084 µΩ	448.546 pH	92.045 pH
☑ Cursor 2	100 MHz	213.737 mΩ	7.24 mΩ	-135.101 pH	3.726 pH



PICOTEST

(Accidental?) De-embedding

Frequency	4.7uF wire sh...	4.7uF ISO-SHO...	4.7uF no cal	4.7uF wire sh...	4.7uF ISO-SHO...	4.7uF no cal
10 kHz	4.241 Ω	4.084 Ω	4.203 Ω	-67.571 µH	-65.047 µH	-66.951 µH
100 MHz	23.846 mΩ	214.335 mΩ	214.029 mΩ	-25.286 pH	340.499 pH	339.936 pH



The wire short removed the electrical length of the component

The measurement result is the inductance above the physical inductance. This is sometimes desirable (EM simulation)

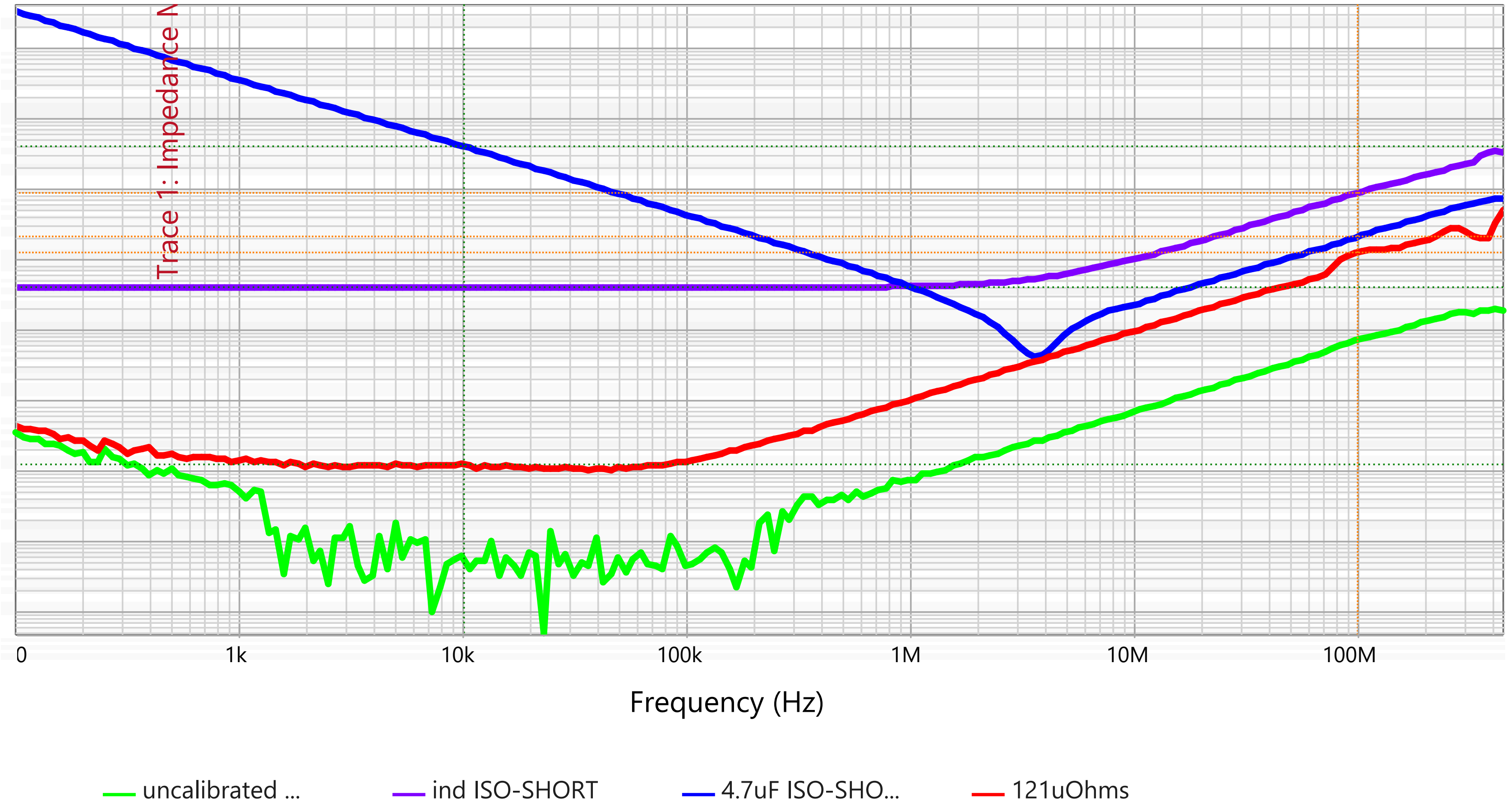
Results in a negative ESL???

Note calibration change is minimal, reflecting the fidelity of the traditional Kelvin PCB mount

PICOTEST

Bode 500 Pre/Post-Calibrated Measurements

Frequency	ind ISO-SHORT	4.7uF ISO-SHO...	121uOhms	ind ISO-SHORT	4.7uF ISO-SHO...	121uOhms
10 kHz	40.837 mΩ	4.084 Ω	124.612 µΩ	1.498 nH	-65.047 µH	-18.889 pH
100 MHz	889.596 mΩ	214.335 mΩ	126.855 mΩ	-719.672 pH	340.499 pH	-63.635 pH
50 MHz	450.483 mΩ	106.73 mΩ	43.527 mΩ	610.668 pH	336.373 pH	80.732 pH



From Magnitude ONLY

	R	L
4.7 µF	4.1 mΩ	341 pH
1.2 nH	41 mΩ	1.4 nH
121 µΩ	125 µΩ	138 pH
ISO-SHORT	6.1 µΩ	11.5pH

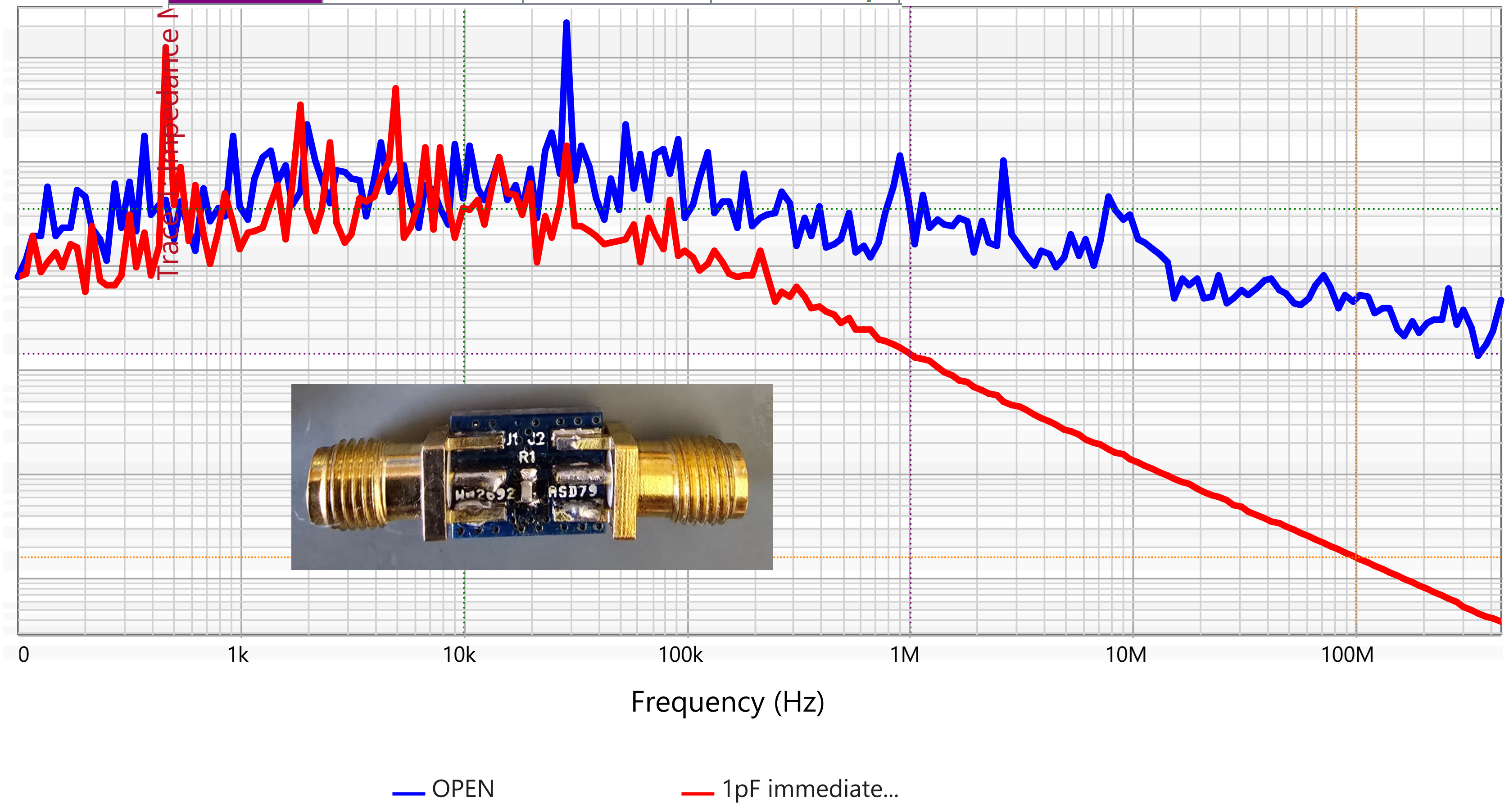
$$L_{4.7uF} = \frac{0.214}{2\pi \cdot 100MHz} = 341\ pH$$

$$L_{1.2nH} = \frac{0.89}{2\pi \cdot 100MHz} = 1.4\ nH$$

$$L_{floor} = \frac{0.00724}{2\pi \cdot 100MHz} = 11.5\ pH$$

Bode 500 Pre/Post-Calibrated Measurements

	Frequency	1pF immediate...	1pF immediate...
Cursor 1	10 kHz	3.534 MΩ	-10.506 pF
Cursor 2	100 MHz	1.601 kΩ	996.491 fF
Cursor 3	1 MHz	143.973 kΩ	1.107 pF



	C
1 pF	996 fF
Ceiling	3.33 fF

$$C_{1pF} = \frac{1}{2\pi \cdot 1.6k\Omega \cdot 100MHz} = 994 \text{ fF}$$

$$C_{ceiling} = \frac{1}{2\pi \cdot 479k\Omega \cdot 100MHz} = 3.3 \text{ fF}$$

PICOTEST

A Final Comparison

1.2nH chip inductor mounted on a Picotest component mount.

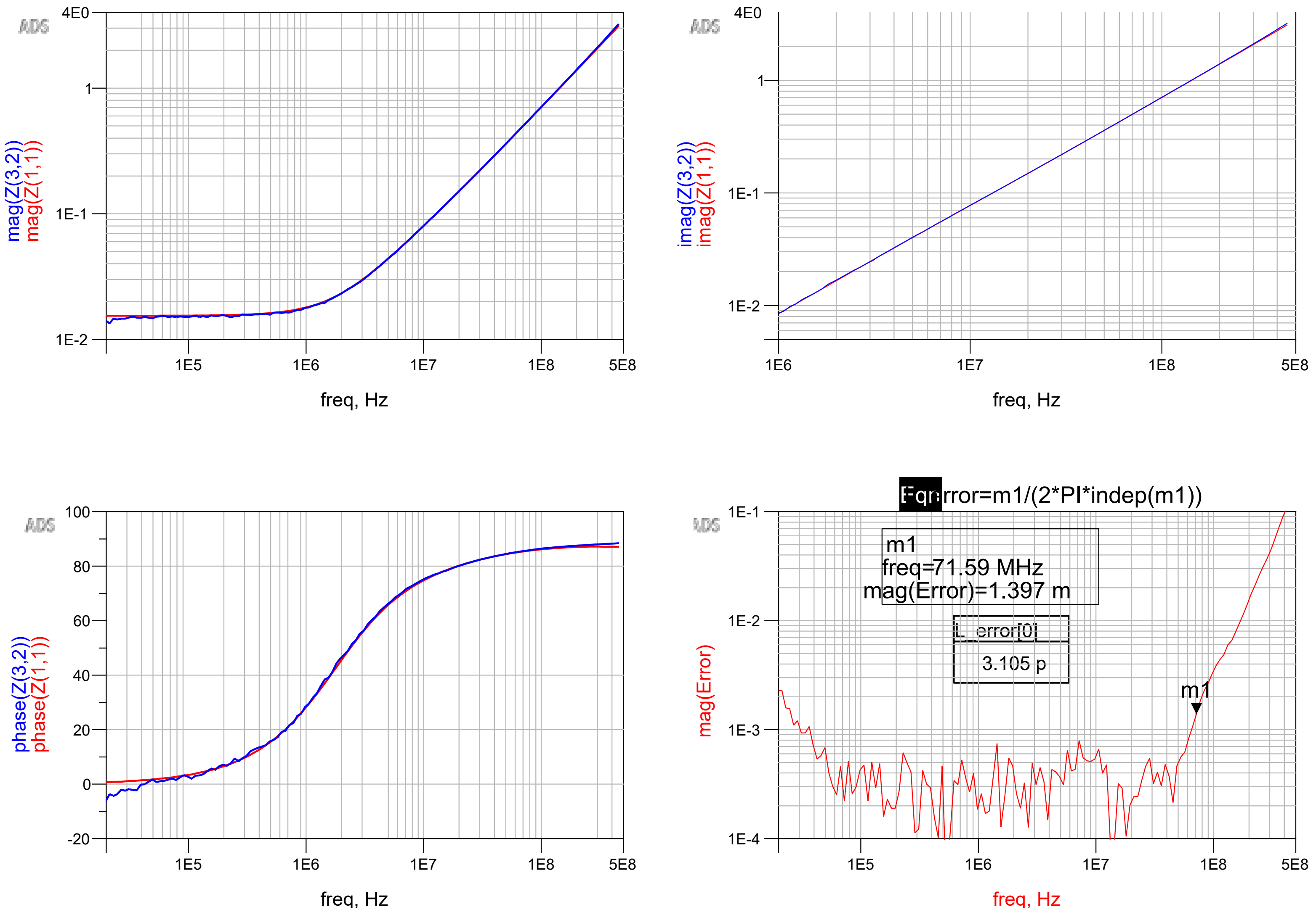
The same mounted chip measure:

With ACM2509 calibrated S5085 (blue) + port extensions for PCB

With Picotest UC10-2.92 calibrated Bode 500 (red)

Match to within 3.1pH!

Now THAT's ACCURATE!!

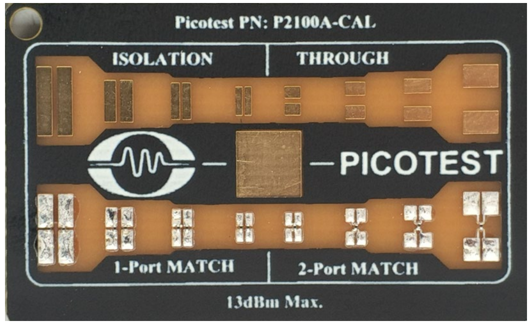


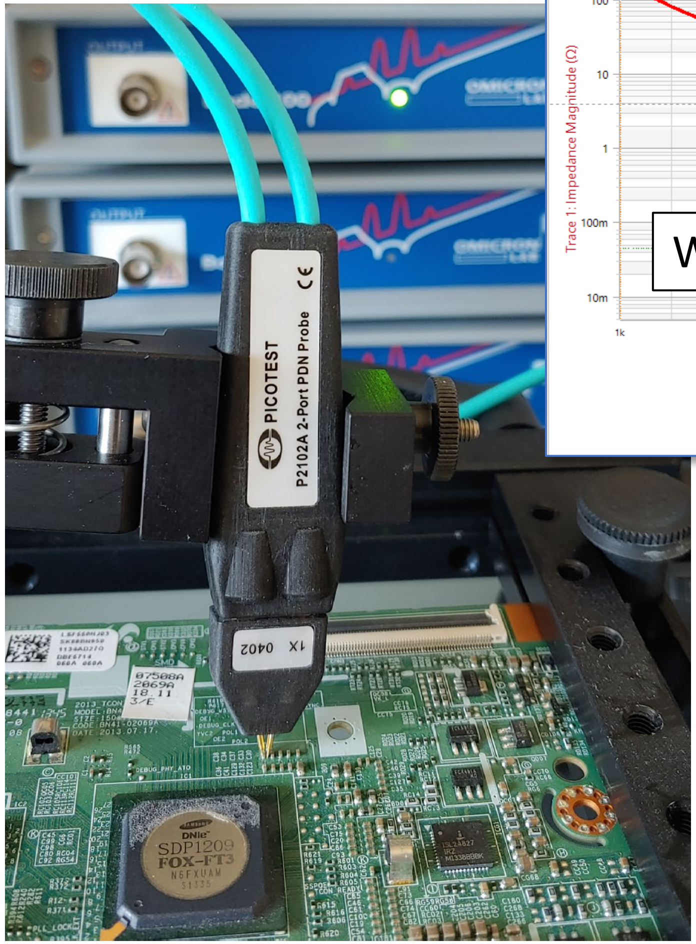
PICOTEST

What About Probes?

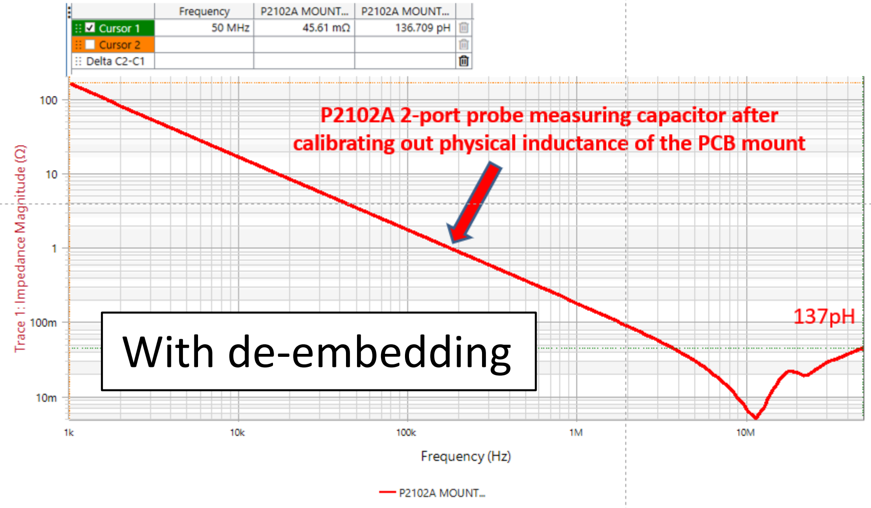
The Picotest P2102A performs a 2-port impedance measurement

The calibration procedure is the same as for the SMA connectors and calibration boards are included for the calibration methods presented here





Or Use a Probe for the Measurement



A 2-port probe provides 4 contacts on the capacitor termination pads. Using the 2-port shunt through impedance and performing a fixture removal (SOL) calibration for the probe simplifies the process.

Use a shorted PCB mount, the same size as the capacitor for the calibration.

The P2102A 2-port probe provides a direct reading display of 137pH, very close to the 144pH we measured using the PCB de-embedding

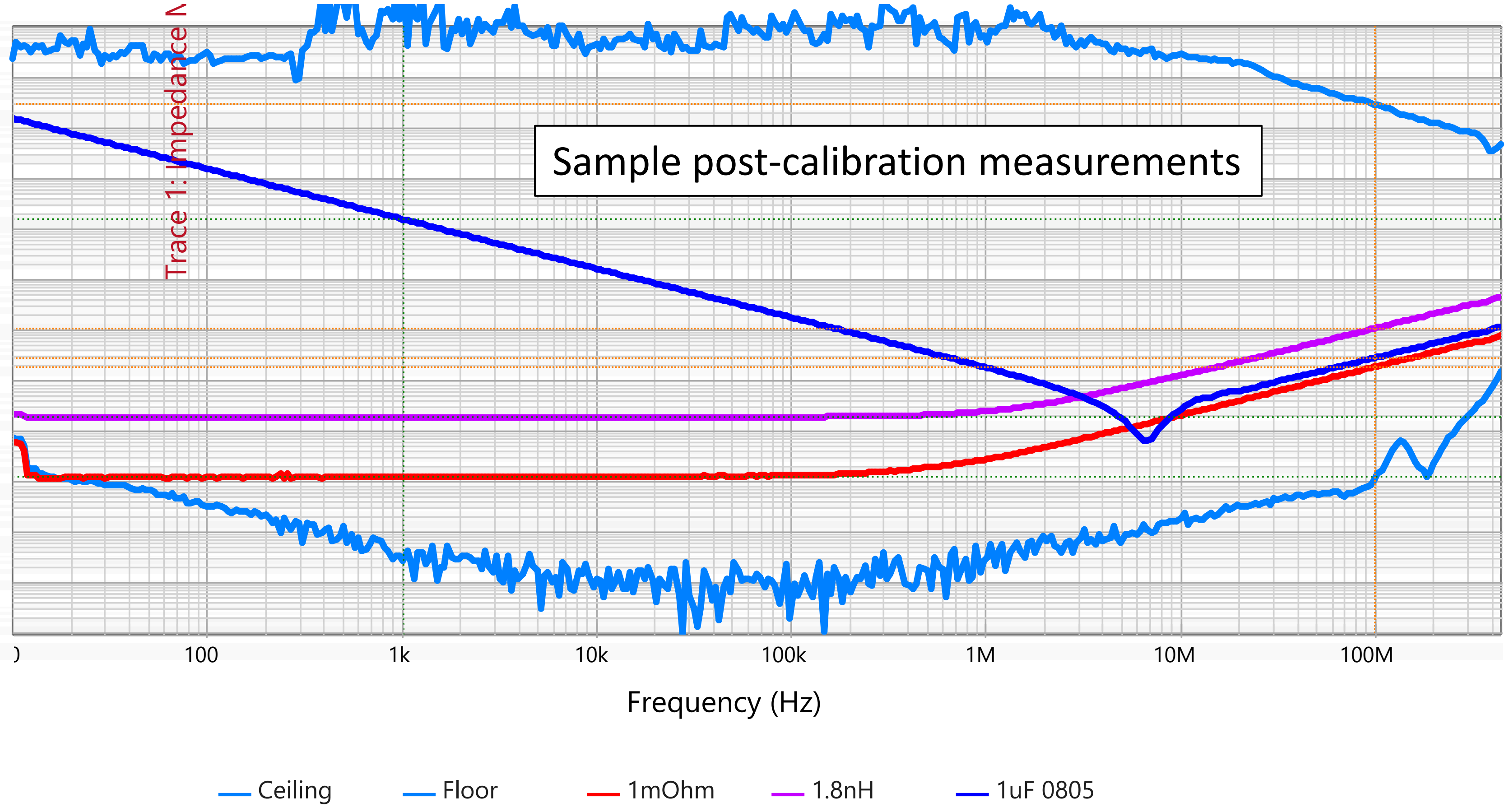
EDICON 2021 Partial Inductance

Probes have the added difficulties of

- Added pin resistance (that changes with contact pressure) exacerbating the ground loop error
- Added coupling between pins appears inductive, changes with pin length

Component Test Fixtures

	Frequency	Ceiling	1mOhm	1.8nH	1uF 0805	Ceiling	1mOhm	1.8nH	1uF 0805
Cursor 1	1.015 kHz	5.314 MΩ	1.258 mΩ	19.137 mΩ	159.208 Ω	113.763 H	1.033 nH	1.586 nH	-24.98 mH
Cursor 2	100 MHz	30.568 kΩ	186.592 mΩ	1.084 Ω	281.41 mΩ	-48.255 µH	296.837 pH	1.723 nH	444.927 pH

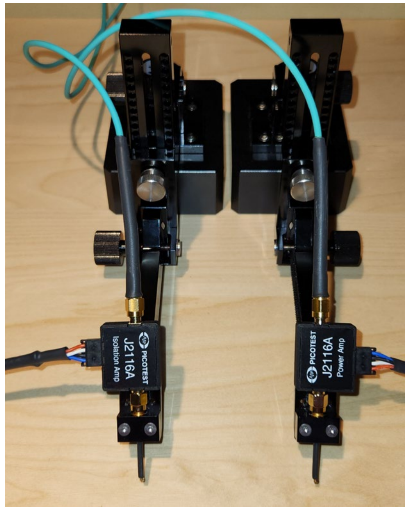


The Picotest Component Test Fixture includes the coaxial isolator and performs a 2-port impedance measurement

The calibration procedure is the same as for the SMA connectors and the calibration boards will be available for the calibration methods presented here

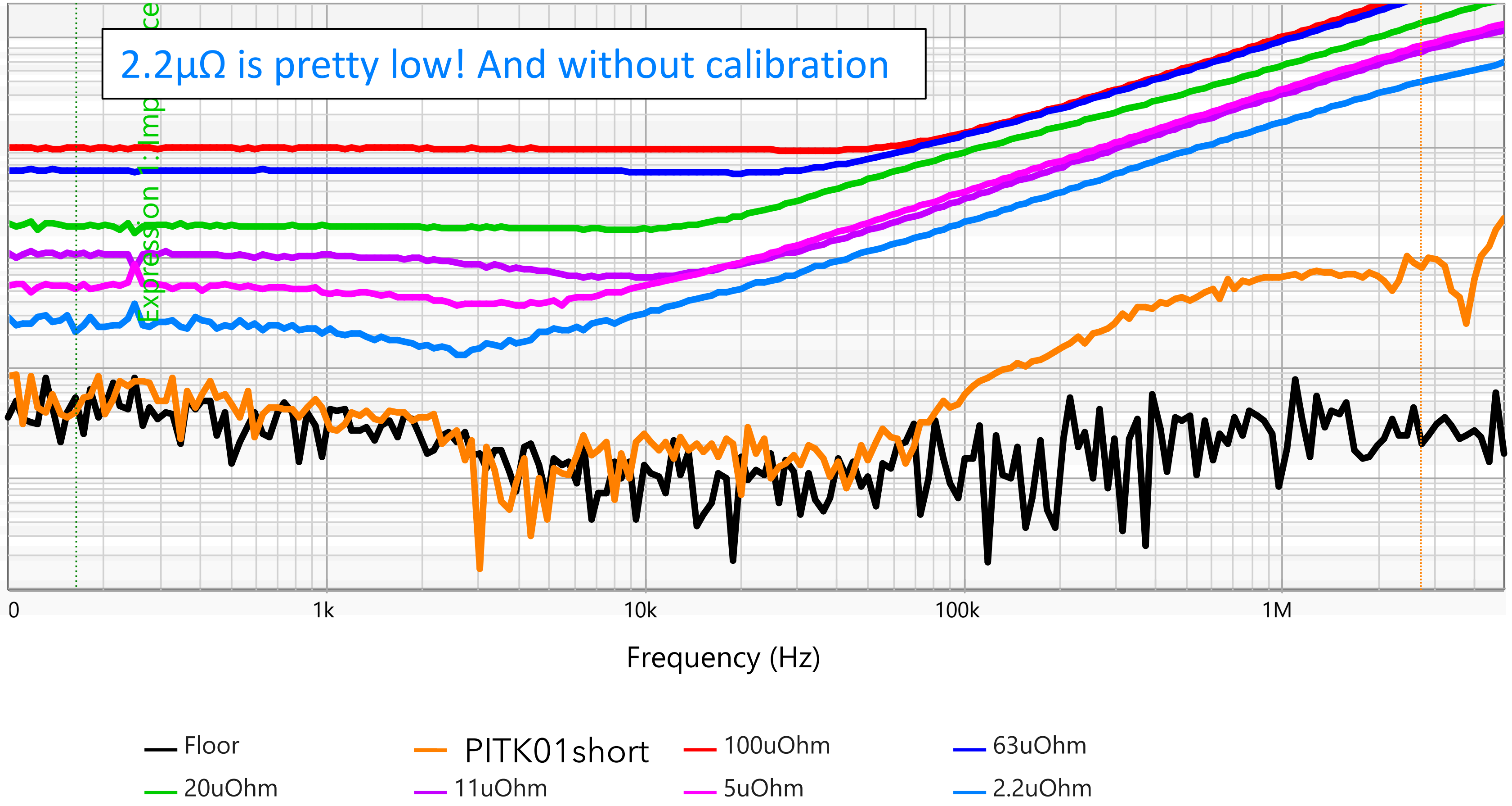
PICOTEST

And Example of Embedding



The J2116A Source Power Amp and Isolator offer flat precise gain

Calibrate to the cable SMAs and EMBED the two amplifiers using an expression trace to multiply by the gain terms



PICOTEST

Top Tips

- Use properly designed 50Ω Kelvin mounts
- Use short, phase stable cables, ideally screw type and properly torqued
- Choose isolators based on required CMRR and frequency range
- Remove as many errors as possible in the setup and fixture FIRST, calibration corrections should be minimal
- Calibration can also degrade measurements. It is often a good idea to first look at the results with and without calibration
- Measure something you know first and same magnitude if you don’t have a known calibration kit
- Be careful not to unintentionally de-embed any elements
- It is often better to avoid using phase data when measuring extremes. Phase changes a DECADE earlier than magnitude
- When measuring extremes, measure quickly after calibration and do most important calibration last

PICOTEST

Thank You!

- Q&A
- Learn more about the products and accessories we discussed today:
  - www.picotest.com
  - www.omicron-lab.com
- Stay Connected! Follow Picotest on LinkedIn: https://www.linkedin.com/company/picotest
- Email info@picotest.com with any other questions

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