2-Port Impedance Measurement using the P2102A Probe and Bode 100 VNA

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High speed Printed Circuit Board (PCB) design requires well designed Power Delivery Networks (PDN) to support today's FPGAs and custom mixed-signal ASICs. The PDN contains important impedance information that can tell a designer how a system will react to dynamic currents and the impact of PCB layout. If we consider the PDN as a transmission line between the Voltage Regulator Module (VRM) and the load (ASICs), then a starting point for a good PDN design is the VRM.

Today VRMs need to supply power to multiple VDD cores to support FPGAs and/or custom ASICs using multi-gigabit ethernet, PCIe, and DDR memory interfaces. With that being said, vendor information for a VRM's output impedance is not available and not always accurate when it is supplied. Further, measuring ultra-low impedance on multiple VRMs or multi-topology DC-DC regulators is a challenge for any design engineer.

The 2-port shunt-through impedance measurement is the gold standard for measuring a VRM's output impedance in the microOhm and milliOhm region [1]. However, it is not always possible to make these measurements with direct coaxial connectors designed into the PCB or Device Under Test (DUT). Therefore, when a designer makes these types of measurements with a Vector Network Analyzer (VNA), the method of connecting the DUT requires attention to detail to ensure inductance and various error sources are minimized to allow an accurate measurement. To get the most out of your VNA, you need to use the right probes and accessories to ensure your particular measurement application is successful. With a browser probe like the P2102A you can quickly characterize multiple VRMs to ensure stability or even check if your model is accurate during your initial PDN design.

The Picotest P2102A 2-port PDN transmission line probe is a browser probe that achieves a very low inductance at the tip to mitigate space constraints on a dense PCB, while eliminating the need to solder COAX, to add additional coaxial connectors, or other test points necessary for impedance measurements. It is especially useful when there are dozens of rails to assess and there isn't time, or PCB iterations available to provide test point implementations for each. Repeated measurements are simplified because connection is by simply touching the tip to an existing output capacitor pad. This browser probe comes with 4 probe tips to allow measurement across a variety of SMD packages on a PCB such as 1206, 0805, 0603, or 0402. The P2102A probe tips are available with 1X, 2X, 5X, and 10X attenuations. This allows flexibility for users to measure across a wide range of voltages. For instance, the 2X probe can measure 6Vrms without DC blocks. The tradeoff is the attenuation increases the impedance floor. In short, this 2-port P2102A probe is best suited for VRM, power plane, and decoupling measurements. An added benefit is that you can use Non-Invasive Stability Measurement (NISM) to assess power supply's stability at the same time as you assess the PDN [2].

The goal of this document is to show design and test engineers the process of how to set up and use the Bode 100 VNA with the Picotest P2102A browser probe to accurately measure the impedance of any VRM or power rail efficiently and quickly. This will also show you how to use this browser probe as a quick GO/NO-GO tester. In this application note, two DUTs will be measured as detailed by the process shown in Figure 1.

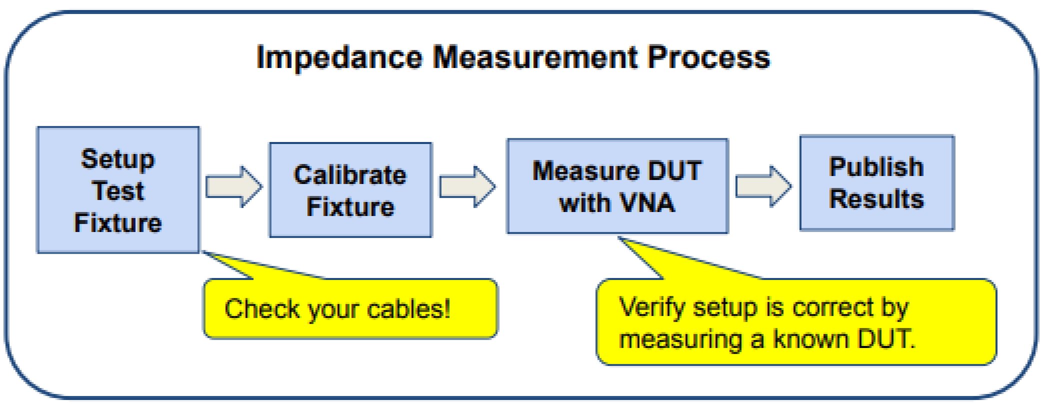


Fig. 1 - Impedance Measurement Process.

1.0 Test Equipment List

Description	Model	QTY
Vector Network Analyzer	OMICRON Lab Bode 100 [3]	1
2-port PDN Transmission Line Probe Kit	Picotest P2102A-2X [4]	1
Common Mode Transformer	Picotest J2102B-N [5]	1
Picotest PDN Cable®, BNC-BNC, 0.25 meter	BNCJ/BNCJ-250 [6]	1
SMA Female to N Male Adapter	Pasternack PE9081 [7]	1
SMA Female to BNC Male Adapter	Pasternack PE9073 [8]	1
BNC Female to N Male Adapter	Pasternack PE9002 [9]	1
3D Probe Positioner	Keysight N2787A [10]	1
VRM Demo Boards (Flat and Varying Impedance)	LM20143B [11]	1
VRM - Infineon PS5401 Eval (DUT)	EVAL_PS5401-INT [12]	1
Calibration Board/Substrate	Included in Picotest P2102A kit	1

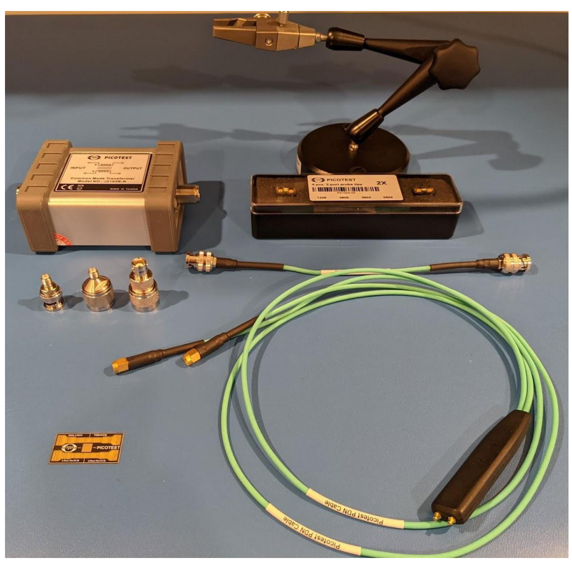


Fig. 2 - Picotest PDN cables, J2102B ground isolator, calibration substrate, P2102A probe, P2102A probe tips, and probe holder for measurement.

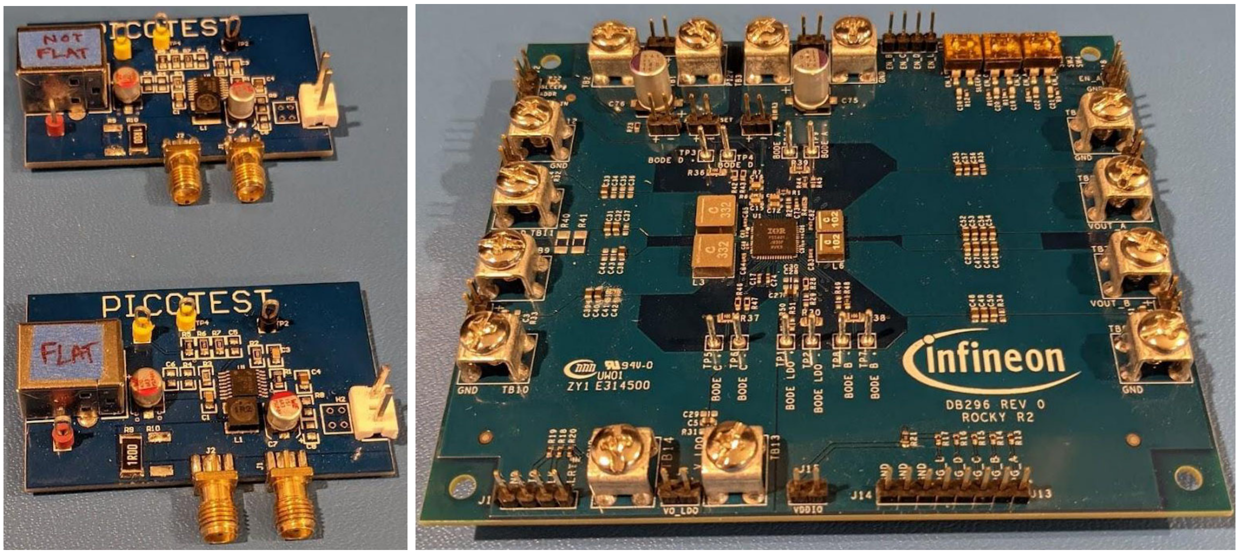


Fig. 3 - Picotest LM20143 DUTs (left) and Infineon PS5401 Eval DUT (right).

Note: The Picotest LM20143 test board may be referred to as Flat DUT and Not Flat (NF) DUT throughout this document.

2.0 Measurement Setup

The P2102A-2X probe tips include 50 Ω series resistors (Rs), which can be set up/accounted for in the Bode Analyzer Suite software. Figures 4 and 5 provide a depiction of how the DUT is connected to the 2-port P2102A probe with the Bode 100.

For the other P2102A-#X probe tip models, set Rs as defined below in the Bode Analyzer Suite:
P2102A-1X - Rs = 0Ω
P2102A-5X - Rs = 200Ω
P2102A-10X - Rs = 450Ω

Note: For the P2102A-1X probe tip, in the Bode Analyzer Suite the Shunt-Thru method can also be used instead of the Shunt-Thru with series resistance since Rs = 0Ω.

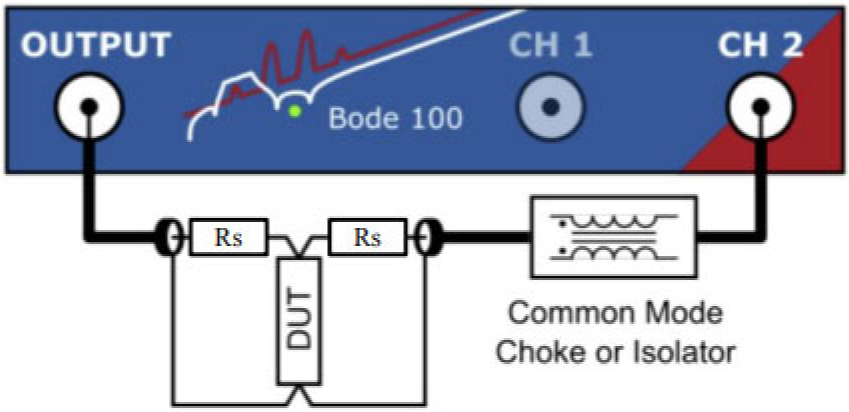


Fig. 4 - 2-port Shunt-Thru with series resistance impedance measurement setup using Bode 100 and Picotest ground isolator J2102B.

Many 2-port probe users already own a microprobe station, however the commitment to setting up the camera, microscope, calibration, etc. is a much bigger commitment than sometimes necessary for simple VRM impedance or even stability measurements. This is where the P2102A browser probe provides a great option on-the-go, as depicted by Figure 5.

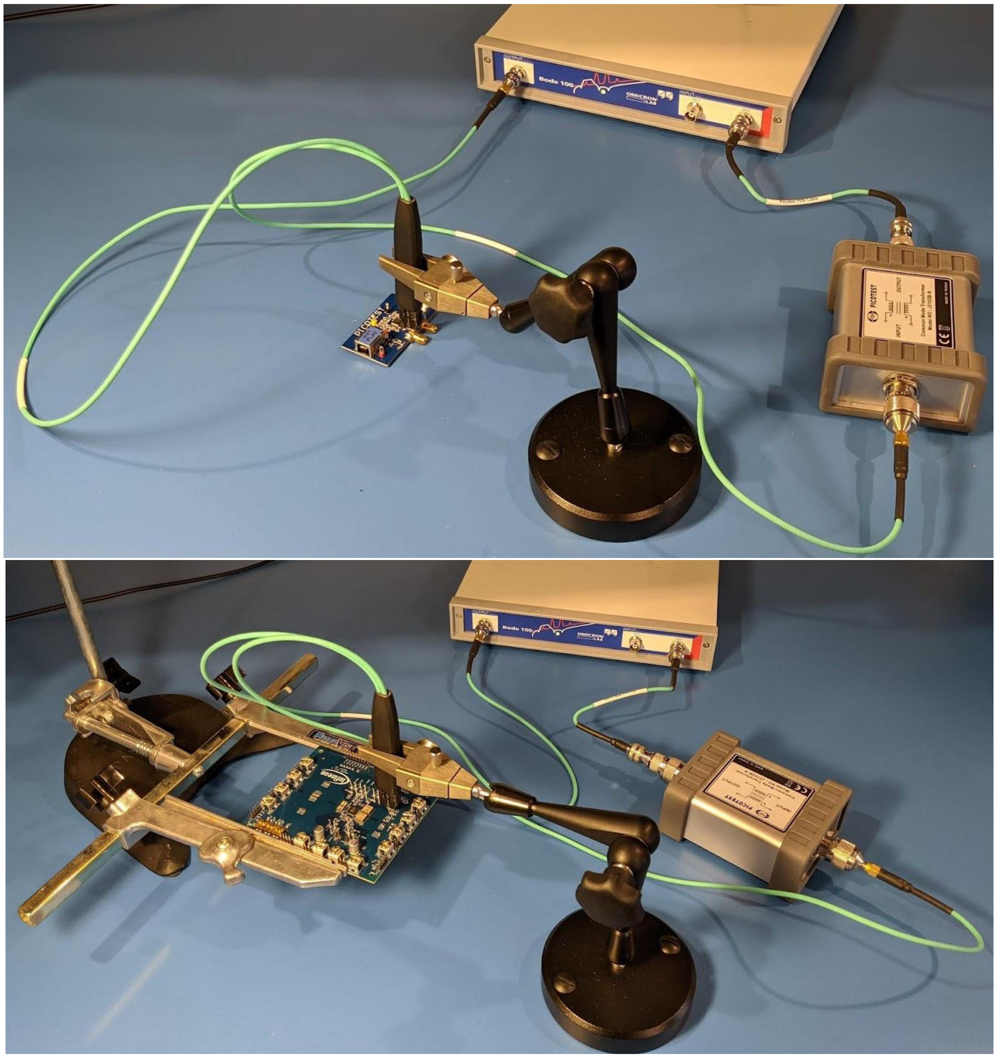


Fig. 5 - Measurement Setup after Calibration with DUTs.

The Shunt-Thru configuration inherently suffers a ground-loop error at low frequencies. The current flowing through the cable shield of the connection to channel 2 ground introduces a measurement error that can become significant at frequencies below a few MHz when measuring very low impedance values. To reduce the ground loop error at low frequencies, use a ground isolator or common mode transformer (e.g., J2102B) or an active isolation device such as the J2113A [13].

Prior to making any measurements you should ensure calibration of the setup is performed by using either the thru-calibration or the Short-Open-Load (SOL) calibration method. Proper calibration is critical since it corrects for contact resistance, tip inductance, coupling, and thermocouple effects. Picotest's recommendation is to use the SOL calibration method with the Bode 100. An example of why this is important is shown later in this document. In addition, to ensure consistent contact resistance, optimum accuracy as well as repeatability, a probe holder can be used during calibration and measurement.

Figures 6 and 7 provide a depiction of the probe tip location on each DUT. For Figure 6, an 0603 capacitor (C42) was removed prior to measurement and the 0603 probe tip is then used as shown. However, it is not necessary to remove the capacitor to make this measurement. For identification purposes, the probe head side with a label indicates the positive signal side.

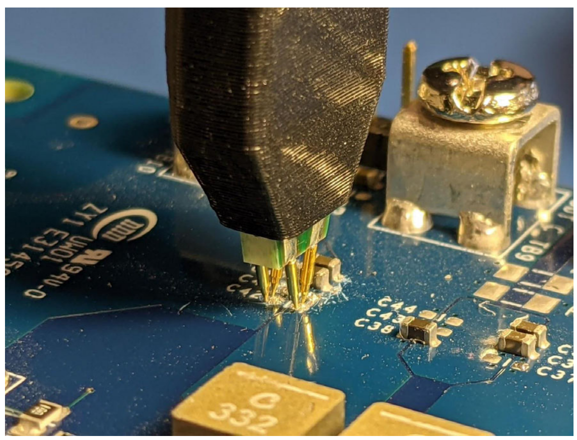


Fig. 6 - Probe location on DUT - Infineon PS5401 Eval at C42.

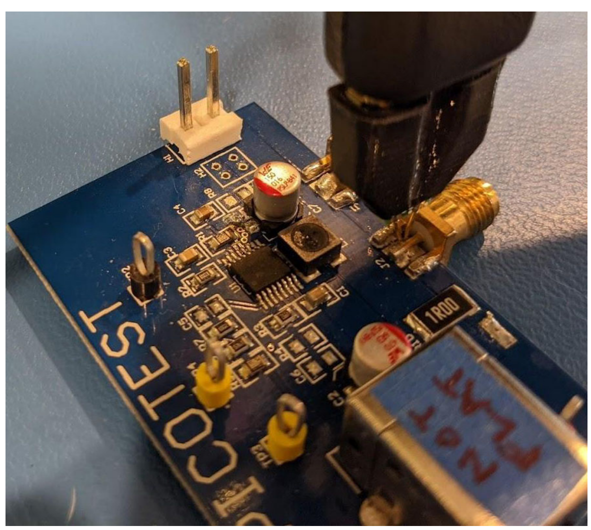


Fig. 7 - Probe location on DUT - LM20143 at J2.

3.0 Measurement Results

The results shown in Figure 8 depict the LM20143 DUTs both ON and OFF using the P2102A browser probe. Where Table 1 provides a summary of the impedances at three cursor locations.

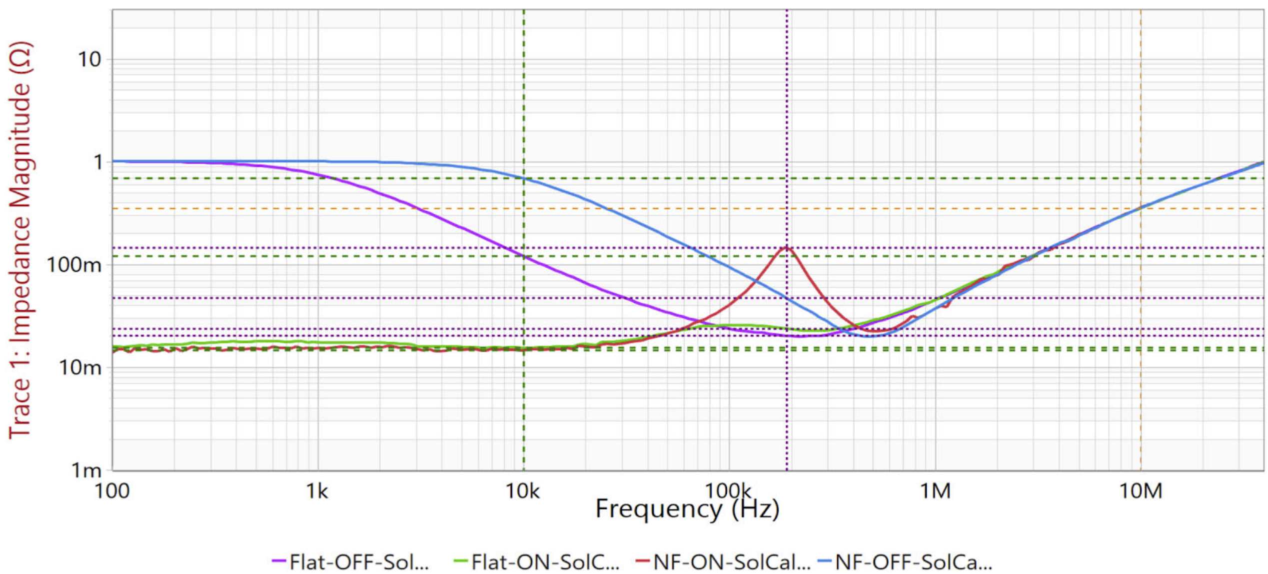


Fig. 8 - LM20143 VRM Output Impedance results OFF and ON (SOL calibration method).

Table 1 - Results of the LM20143 Flat vs. Not Flat DUT boards at J2.

	Cursor 1	Cursor 2	Cursor 3
Frequency	10 kHz	190.708 kHz	10 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
Flat-OFF-Sol...	120.101 mΩ	20.188 mΩ	352.353 mΩ
Flat-ON-SolC...	15.444 mΩ	23.607 mΩ	350.559 mΩ
NF-ON-SolCal...	14.569 mΩ	144.882 mΩ	353.724 mΩ
NF-OFF-SolCa...	686.32 mΩ	46.963 mΩ	352.433 mΩ

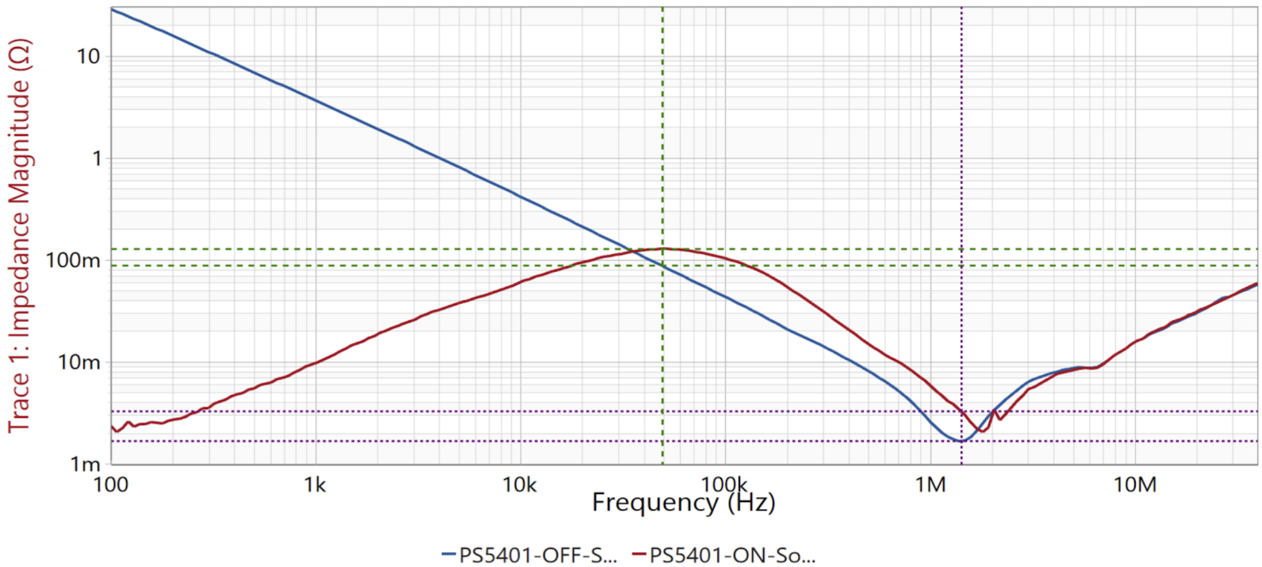


Fig. 9 - Infineon PS5401 Eval - VRM Output Impedance Results OFF and ON at C42 (SOL calibration method).

Table 2 - Results of Infineon PS5401 Eval DUT OFF and ON at C42.

	Cursor 1	**Cursor 2**	
Frequency	49.119 kHz	1.426 MHz	
Trace 1	**Magnitude**	**Magnitude**	
PS5401-OFF-S...	87.704 mΩ	1.669 mΩ	
PS5401-ON-So...	127.674 mΩ	3.272 mΩ	

As shown by the results in Figure 9 and Table 2, it is possible to accurately measure below 10 mΩ with the P2102A browser probe.

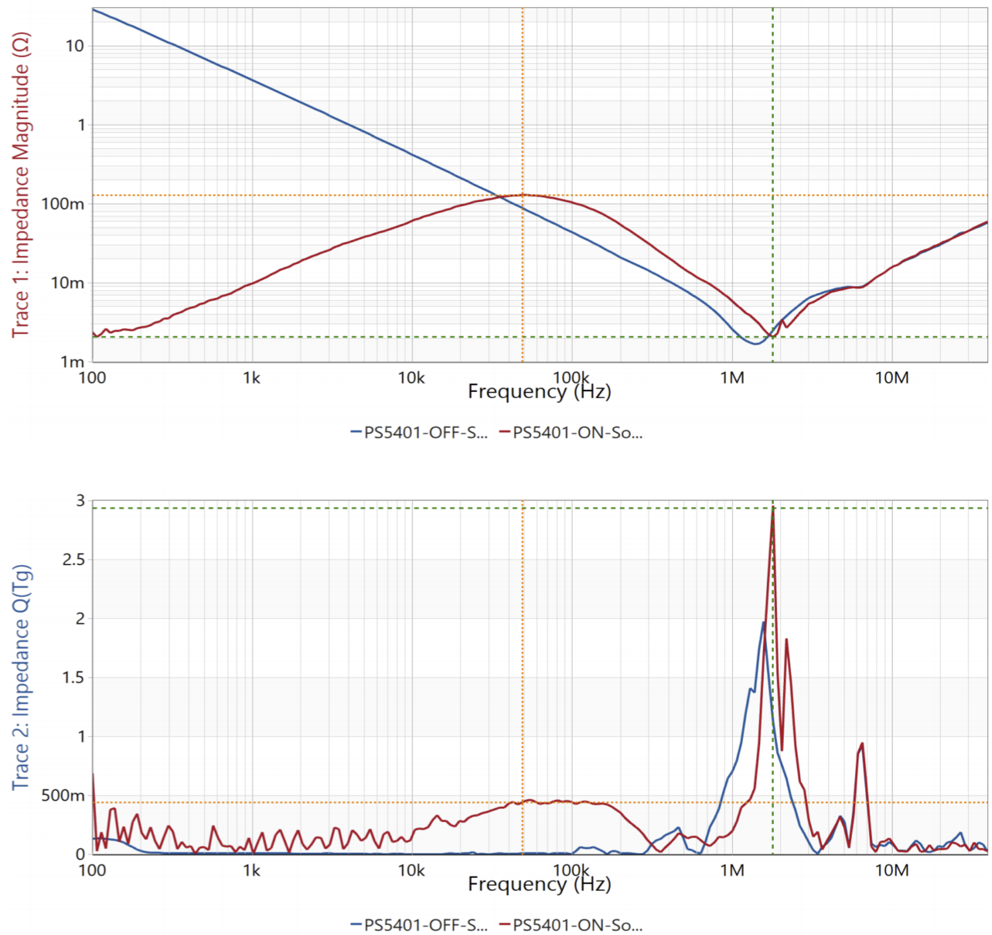


Fig. 10 - NISM Method of Infineon PS5401 at C42 (SOL calibration method).

Table 3 - NISM Method Results of Infineon PS5401 Eval DUT ON at C42.

	Cursor 1	**Cursor 2**	
Frequency	1.805 MHz	48.874 kHz	
Trace 1	**Magnitude**	**Magnitude**	
PS5401-ON-So...	2.058 mΩ	127.677 mΩ	
Trace 2	**Q(Tg)**	**Q(Tg)**	
PS5401-ON-So...	2.935	438.715 m	

NISM Measurement Result for Infineon PS5401 DUT:

Phase margin Cursor 1-Cursor 2: >71° of PS5401-ON-So...

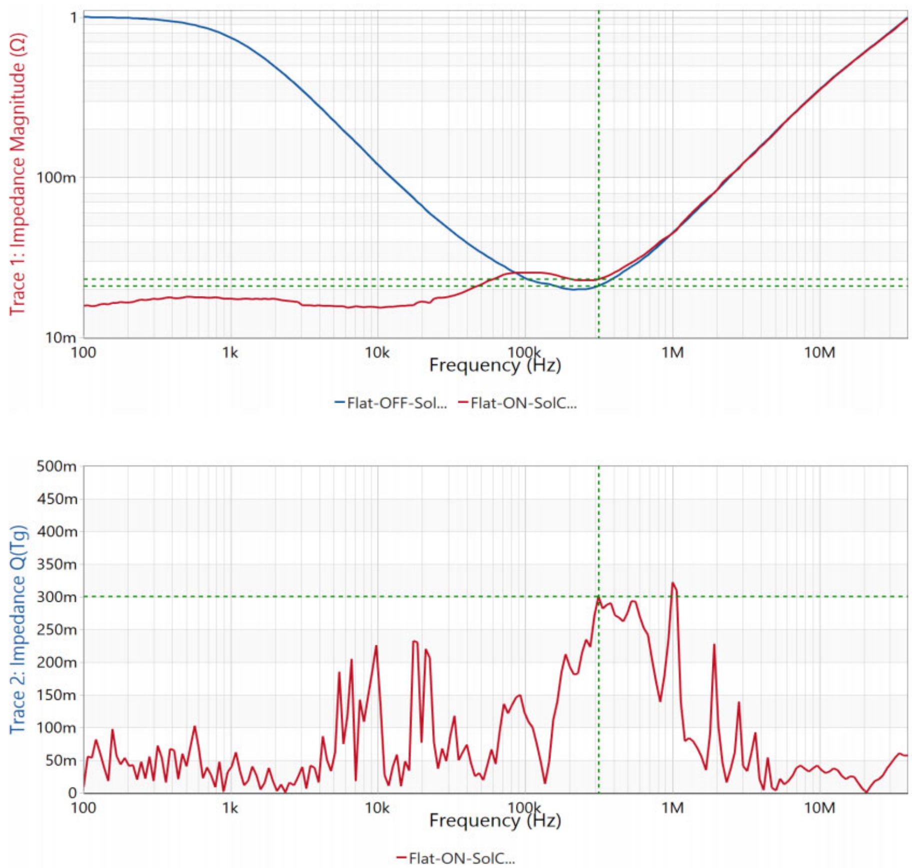


Fig. 11 - NISM Method of LM20143 Flat at J2 (SOL calibration method).

Table 4 - NISM Method Results of LM20142 Flat DUT ON at J2.

	Cursor 1
Frequency	317.167 kHz
Trace 1	**Magnitude**
Flat-OFF-Sol...	20.976 mΩ
Flat-ON-SolC...	23.159 mΩ
Trace 2	**Q(Tg)**
Flat-ON-SolC...	300.47 m

NISM Measurement Result for LM20143 Flat DUT:

Phase margin of Cursor 1:	>71° of Flat-ON-SolC...

By using NISM, we can determine a VRM's stability. As shown by Figure 10 and 11 the calculated result from the Bode Analyzer Suite allows a quick determination that these two VRMs have a stable control loop by analysis of the Phase Margin (PM) showing greater than 71°.

4.0 P2102A Calibration Checklist with Bode 100

Calibration of Testing Setup for Shunt-Through Impedance with Series Resistance Measurement

After powering on the Bode 100, with cables connected for calibration as shown in Figure 5, follow the steps below to calibrate your measurement setup prior to making measurements on your DUT.

4.1 Thru Calibration Method with Bode 100

Step 1: (In Bode Analyzer Suite) Select **File** > **New Measurement**
Step 2: Select "Impedance Analysis" tab
Step 3: Select **Shunt-Thru with Series Resistance** drop down > select **Start measurement**
Step 4: On menu ribbon > select [Hz → MHz Ω Full-Range] drop-down > select ▶ **Perform new calibration**
Step 5: Set Serial resistor Rs = **50 Ω**
Step 6: Ensure cables and probe are connected as shown in Figures 5 and 12 for **Thru calibration**
Step 7: Under Thru calibration > select **Start**
Step 8: Ensure the arrow points to the left, **Thru calibration** is applied

Thru calibration ◀ Open/Short/Load calibration

Step 9: Select **Close**

Begin capturing measurements of the DUT…

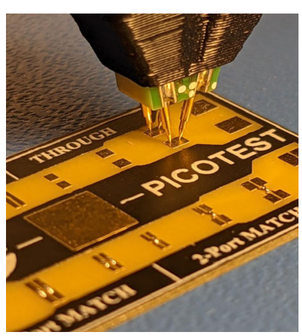


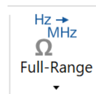
Fig. 12 - P2102A 2-port Thru-Calibration with Bode 100.

4.2 Short-Open-Load (SOL) Calibration Method with Bode 100

Step 1: (In Bode Analyzer Suite) Select **File** > **New Measurement**

Step 2: Select "Impedance Analysis" tab

Step 3: Select **Shunt-Thru with Series Resistance** drop down > select **Start measurement**

Step 4: On menu ribbon > select 

drop-down > select ▶ **Perform new calibration**

Step 5: Set Serial resistor Rs = **50 Ω**

Note: For 1X, 5X, or 10X probe tips Rs needs to be set accordingly.

Step 6: Ensure cables and probe are connected as shown in Figures 5 and 13 for **Open** calibration

Step 7: Under **Open** calibration > select **Start**

Step 8: Ensure cables and probe are connected as shown in Figures 5 and 13 for **Short** calibration

Step 9: Under **Short** calibration > select **Start**

Step 10: Ensure cables and probe are connected as shown in Figures 5 and 13 for **Load** calibration

Step 11: Under **Load** calibration > select **Start**

Step 12: Ensure the arrow points to the right, **Open/Short/Load calibration** is applied

Step 12: Select **Close**

Begin capturing measurements of the DUT…..

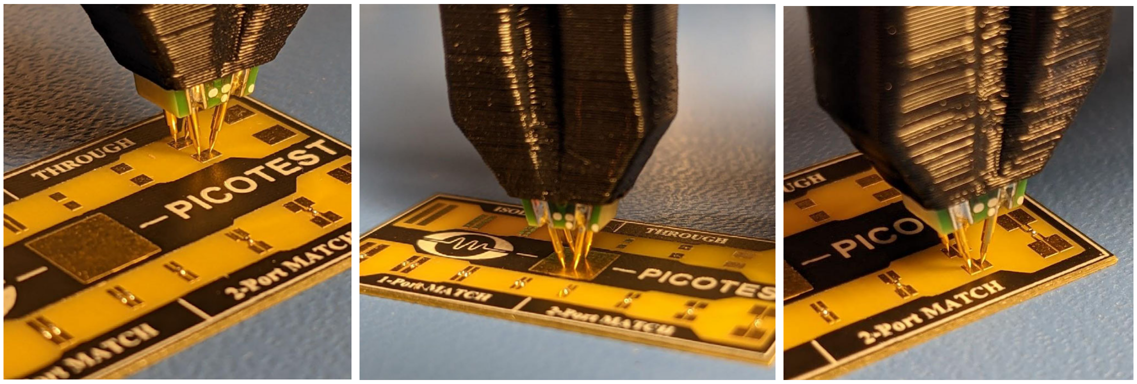


Fig. 13 - P2102A 2-port Calibration Open (left), Short (center), and Load (right) with Bode 100.

Measurement accuracy can be further improved by instead using the SOL calibration method versus the Thru-calibration method. The Thru-calibration method does not account for inductive coupling errors. Figures 14 and 15 provide two examples comparing the measurement error due to inductive coupling when using the Thru-calibration method versus SOL calibration method.

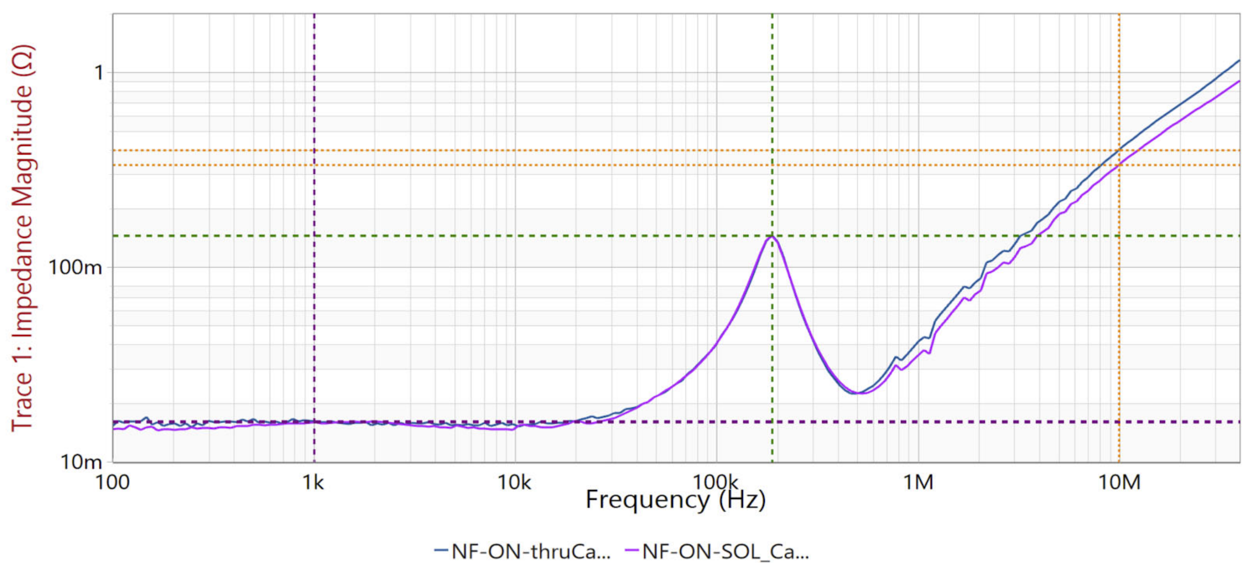


Fig. 14 - LM20143 Not Flat- Measurement Results using Thru-cal method (blue) vs. SOL method (violet) with Bode 100 and P2102A.

Table 5 - Thru-Cal Method vs. SOL Method Results for the LM20143 Not Flat DUT at J2.

	Cursor 1	Cursor 2	Cursor 3
Frequency	188.808 kHz	10 MHz	1 kHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
NF-ON-thruCa...	145.238 mΩ	398.314 mΩ	16.129 mΩ
NF-ON-SOL_Ca...	144.409 mΩ	334.099 mΩ	15.898 mΩ

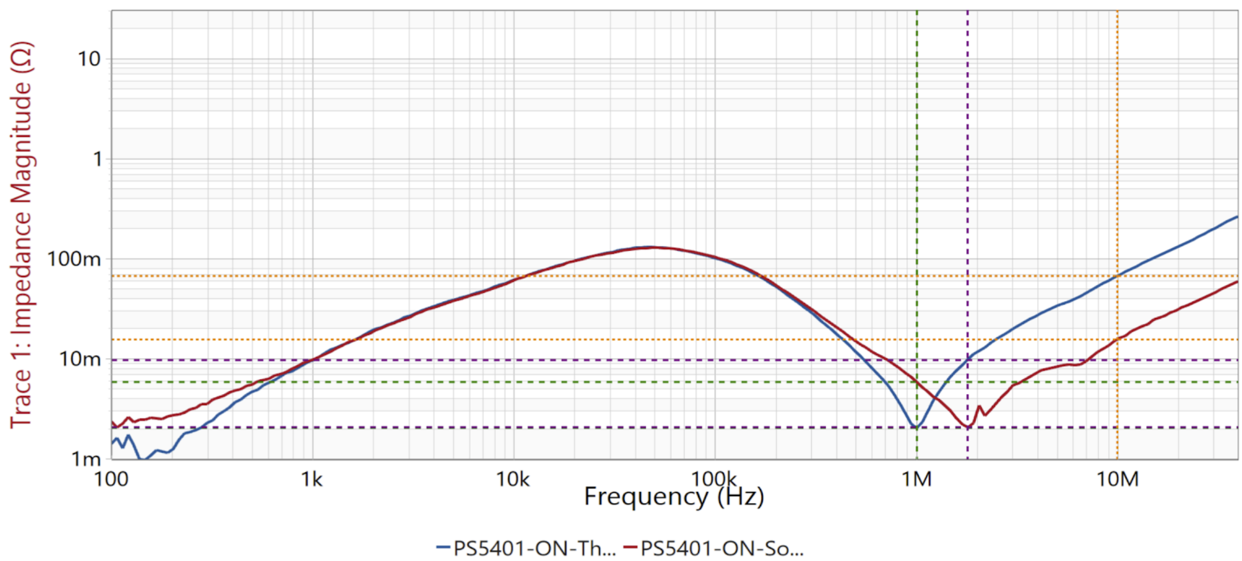


Fig. 15 - Infineon PS5401 ON - Measurement Results using Thru-cal method (blue) vs. SOL method (red) with Bode 100 and P2102A.

Table 6 - Thru-cal Method vs. SOL Method Results on Infineon PS5401 DUT at C42.

	Cursor 1	Cursor 2	Cursor 3
Frequency	1 MHz	1.8 MHz	10 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
PS5401-ON-Th...	2.068 mΩ	9.667 mΩ	66.742 mΩ
PS5401-ON-So...	5.927 mΩ	2.063 mΩ	15.501 mΩ

As shown by Figure 14 and Table 5, a 64 mΩ decrease is observed at 10 MHz (Cursor 2) with the SOL calibrated measurement versus with the Thru-calibrated measurement on the LM20143 Not Flat DUT. A similar result is also seen by Figure 15 and Table 6 where a 40 mΩ decease at 10 MHz (Cursor 3) is observed by using the SOL calibration method in comparison to the Thru-calibration method. Lastly, as observed earlier there is a resonance in the impedance of the Infineon PS5401 DUT. What is important to note is that during measurement if the inductive coupling is not accounted for during calibration this resonant peak can shift (due to inductance). Specifically, the resonant peak for a Thru-cal method occurs at 1MHz whereas when the inductive coupling is accounted for during calibration by using the SOL calibration method, the resonant peak occurs at 1.8 MHz, an 800 kHz change in frequency. This additional residual inductance from the Thru-cal can be seen post-calibration by measuring a short.

5.0 Conclusion

The 2-port shunt-through impedance testing method shown here is the gold standard for measuring a VRM's output impedance and the control loop gain (phase) stability performance.

The P2102A browser probe allows you to very simply, quickly, and accurately make 2-port impedance measurements that help better design your PDN and provide quick GO/NO-GO testing. When impedances are measured, not only can we determine a VRM's stability, but we can also determine what the power supply distribution network is composed of. We can even create a highly accurate model of the VRM from the impedance measurement that includes time domain, frequency domain and even EMI related data. We can tell which parts of the impedance are based on control loop performance and which parts are based on printed circuit board and/or decoupling performance.

If you want to measure planes or high frequency impedance, the P2104A 1-port probes [14] can be an even better option.

As shown in this document, to make low impedance measurements with a Bode 100 VNA with the P2102A browser probe:

- It is essential to have the correct (low inductance) probes, high quality cables, and the common mode transformer (J2102B).
- You must properly calibrate your setup as this is essential to achieve high fidelity measurement and eliminate sources of test setup errors.
- A consistent repeatable contact resistance that applies consistent tip pressure is necessary. This can be done with a probe holder like the N2787A shown, ClampMan [15], or one of the probe holders from PacketMicro.

6.0 References

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6. Picotest PDN Cable® - https://www.picotest.com/pdn-cable.html
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