

## **2-Port Impedance Measurement using the P2102A Probe and E5061B 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. Considering the PDN is the transmission line between the Voltage Regulator Module (VRM) and the load, it is then important to make the starting point for a good PDN design at 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 without direct SMA connections to 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 measurement 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, add additional SMA connections, 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 output capacitor. 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 as well as a DC Block option. 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 Keysight E5061B 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.

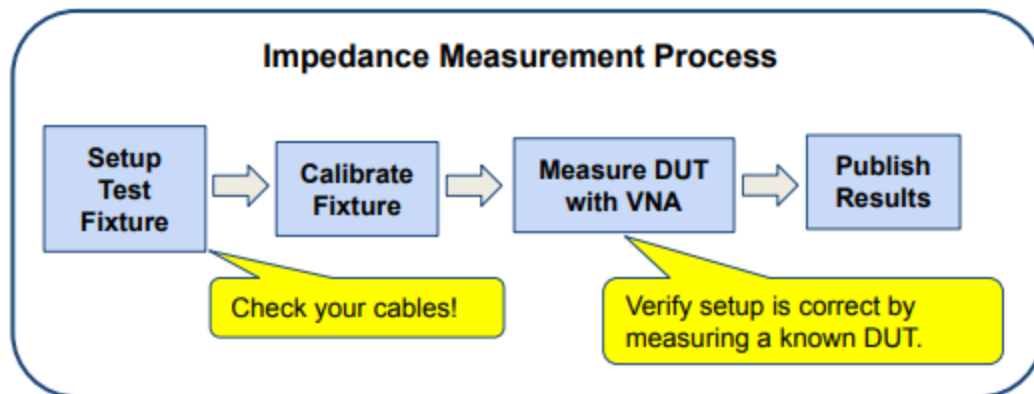


Fig. 1 - Impedance Measurement Process.

### 1.0 Test Equipment List

| <b>Description</b>                           | <b>Model</b>                    | <b>QTY</b> |
|--|---------------------------------|------------|
| Vector Network Analyzer                      | Keysight E5061B [3]             | 1          |
| 2-port PDN Transmission Line Probe Kit       | Picotest P2102A-1X [4]          | 1          |
| Common Mode Transformer                      | Picotest J2102B-N [5]           | 1          |
| 2-Port Probe Adapter Panel                   | Picotest J2160A [6]             | 1          |
| Picotest PDN Cable®, BNC-BNC, 0.25 meter     | BNCJ/BNCJ-250 [7]               | 1          |
| N Male to BNC Female Adapter                 | Pasternack PE9002 [8]           | 2          |
| 3D Probe Positioner                          | Keysight N2787A [9]             | 1          |
| VRM Demo Boards (Flat and Varying Impedance) | LM20143B [10]                   | 1          |
| VRM - Infineon PS5401 Eval (DUT)             | EVAL_PS5401-INT [11]            | 1          |
| Calibration Board/Substrate                  | Included in Picotest P2102A kit | 1          |



**Fig. 2 - Picotest P2102A probe, P2102A probe tips, Picotest PDN Cable, J2102B ground isolator, adapters, calibration substrate, and probe holder for measurement (for use with the Port 1-Port-2, N-conductor S-parameter ports).**



**Fig. 3 - Picotest P2102A probe, P2102A probe tips, J2160A, calibration substrate, and probe holder for measurement (for use with the low frequency-RF(T/R) BNC-conductor ports).**

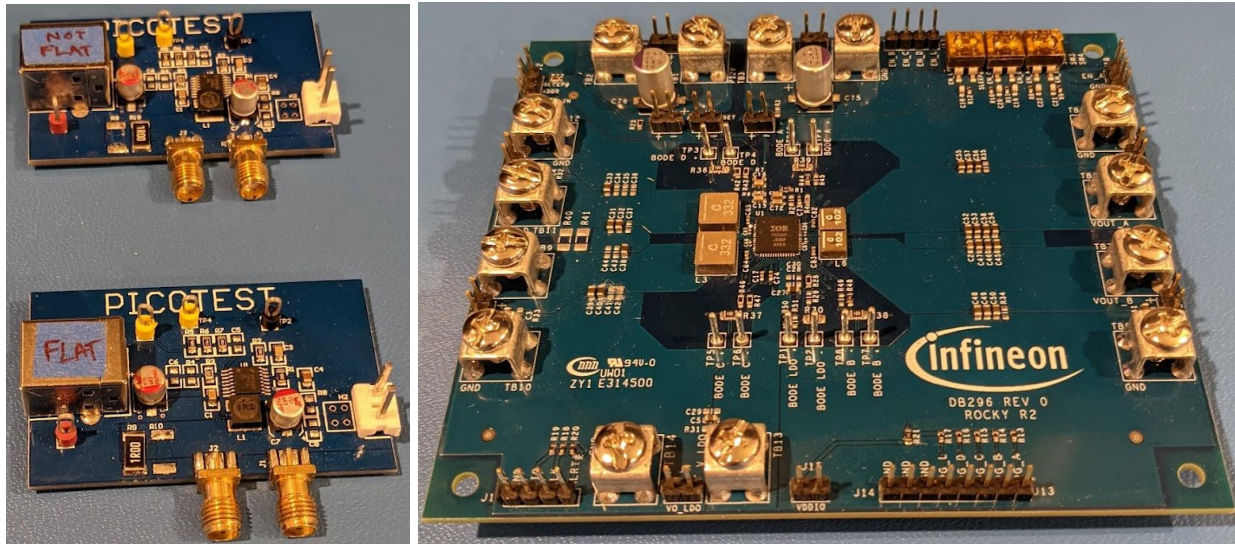


Fig. 4 - Picotest LM20143 DUTs\* (left) and Infineon PS5401 Eval DUT (right).

**\*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  $\Omega$  series resistors ( $R_s$ ), which can be set up/accounted for in the E5061B Calibration menu. Figures 5 and 6 provide a depiction of how the DUT is connected to the 2-port P2102A probe with the E5061B S-parameter ports.

For the other P2102A-#X probe tip models, set  $R_s$  as defined below in the E5061B VNAs:

P2102A-1X -  $R_s = 0\Omega$

P2102A-5X -  $R_s = 200\Omega$

P2102A-10X -  $R_s = 450\Omega$

With the Keysight E5061B VNA, there are two possible 2-Port Shunt-Through measurement setups with the P2102A.

One setup includes the Picotest J2102B common mode transformer, connected to ports 1 and 2 on the E5061B S-parameter ports as shown in Figure 5. The necessary test equipment for this setup is shown in Figure 2.

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 between 10 kHz to 100 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 [12].

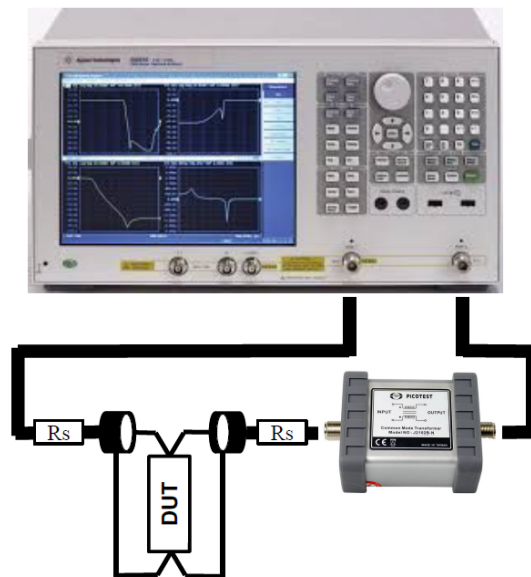
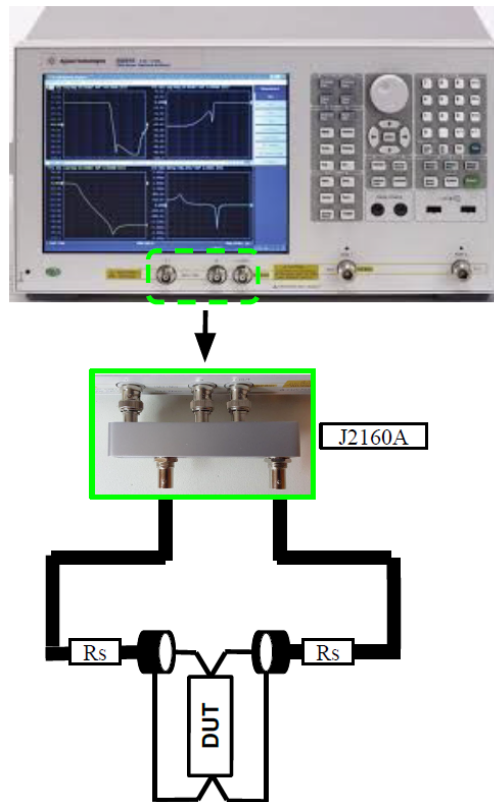


Fig. 5 - 2-port Shunt-Thru with series resistance impedance measurement setup using E5061B and Picotest ground isolator J2102B.

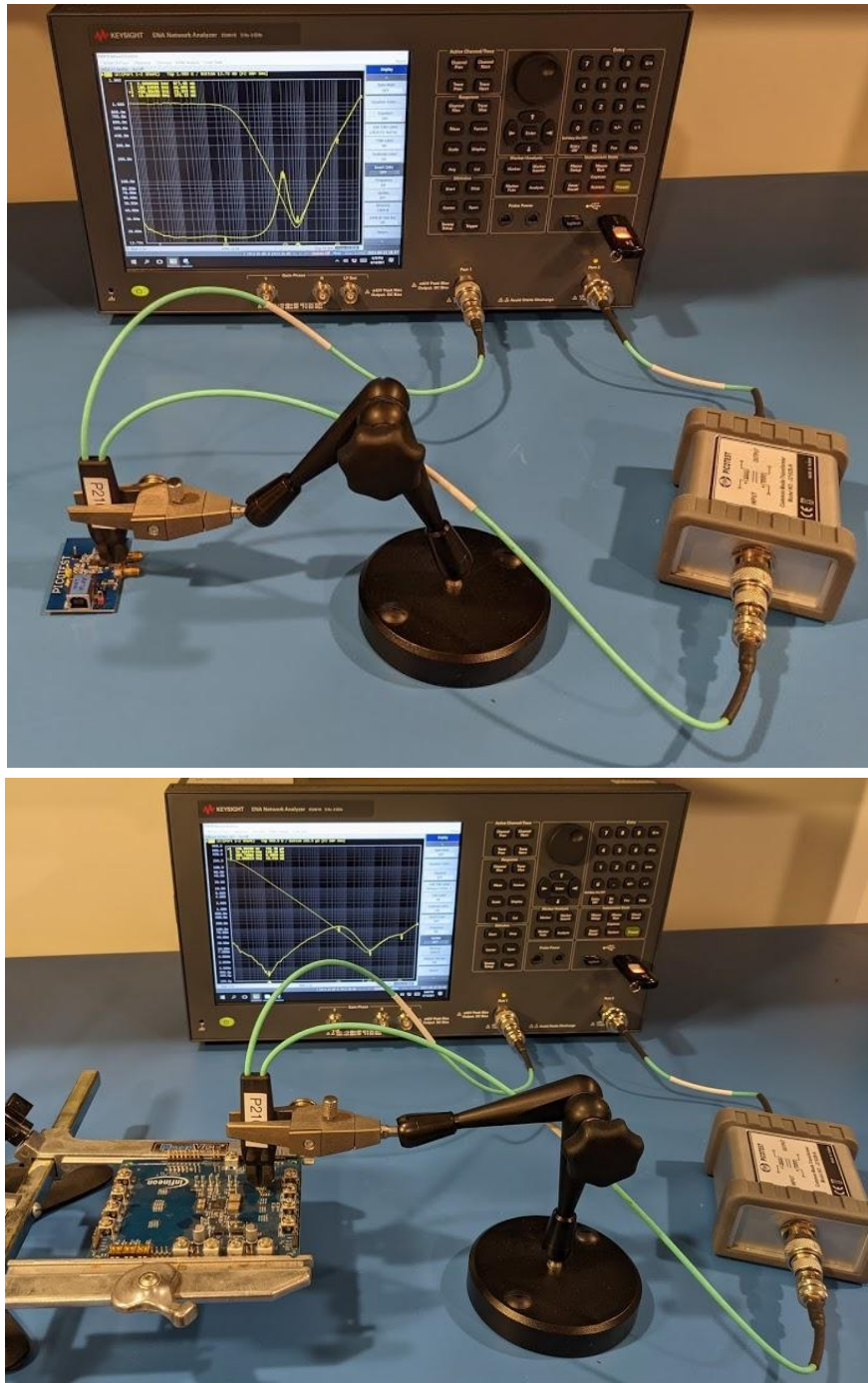
The other measurement setup includes the Picotest J2160A 2-port probe adapter, connected to the T/R ports' low frequency VNA BNC ports on the E5061B, as shown in Figure 6. The necessary test equipment for this setup is shown in Figure 3.

The Picotest J2160A Probe Adapter provides a low noise, compact solution when using the E5061B T/R ports in a 2-port shunt-through measurement. It converts the instrument's three GP ports to the 2 ports necessary to perform a 2-port shunt-through measurement. The T/R ports are desirable for low frequency 2-port measurements, since the receiver port is semi-floating, allowing low impedance measurements **without** the use of a coaxial common mode transformer such as the J2102B. The floating ports allow milliohm measurements even at very low frequency and up to the 30 MHz range of the T/R ports.



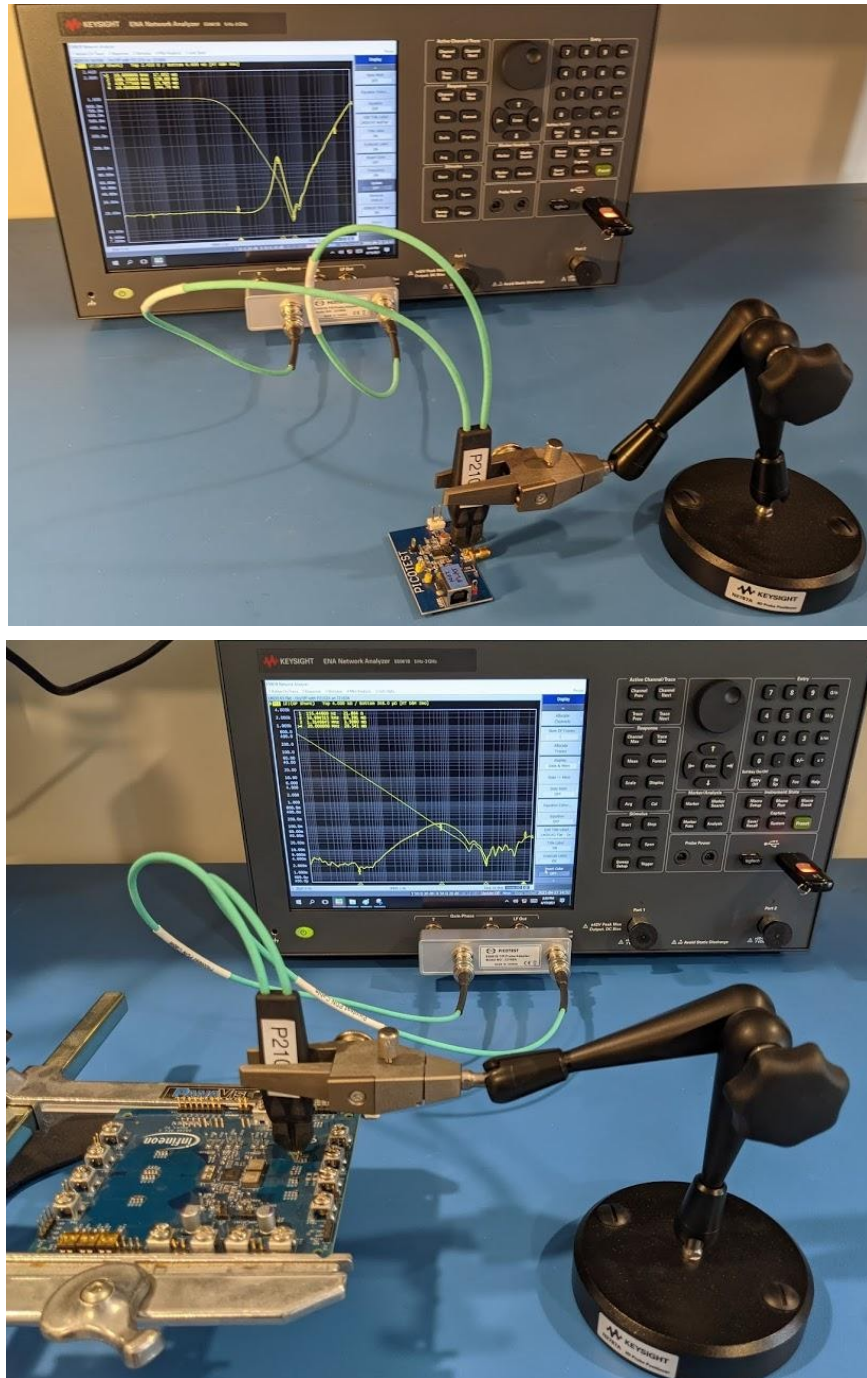
**Fig. 6- 2-Port Shunt-Thru with series resistance impedance measurement setup using E5061B and Picotest J2160A 2-port probe adapter.**

2-port probe users generally own a probe 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 Figures 7 and 8.



**Fig. 7 - Measurement Setup after calibration with DUTs, the P2102A probe and the J2102B Common Mode Transformer.**

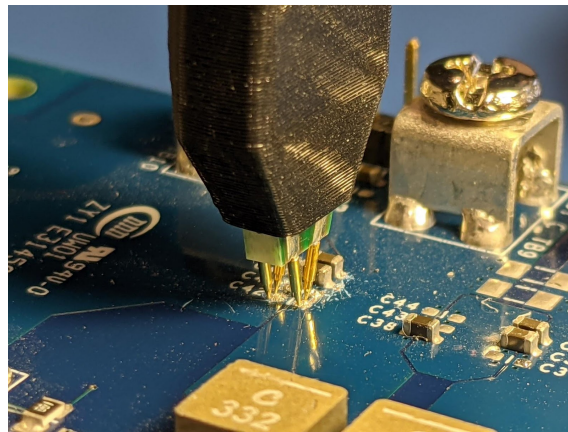




**Fig. 8 - Measurement Setup after calibration with DUTs, the P2102A probe and the J2160A 2-Port Probe Adapter.**

Prior to making any measurements, you should ensure calibration of the setup is performed by using the proper calibration method. The E5061B VNA has multiple calibration options shown in Table 4-1 of the E5061B user manual. Proper calibration is critical since it corrects for contact resistance, tip inductance, coupling, and thermocouple effects. For the highest accuracy measurements, Picotest's recommendation is to use the Full 2-Port Calibration which includes SHORT-OPEN-LOAD-THRU-ISOLATION calibration method with the E5061B. This ensures high accuracy with a 12-term error correction model by requiring 8 standard measurements shown by Figure 18. An example of why this is important is shown later in this document. In addition, to ensure consistent contact resistance, it is recommended that a probe holder be used during calibration and measurement. There are other calibration options available on the E5061B such as Enhanced Response Calibration which includes an OPEN-SHORT-LOAD-THRU calibration method to provide a 5-term error correction model, as well as a Response Calibration to provide a 2-term error correction model which includes either an OPEN-SHORT-LOAD or THRU-LOAD calibration.

Figures 9 and 10 provide a depiction of the probe tip location on each DUT. For Figure 9, 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. 9 - Probe location on DUT - Infineon PS5401 Eval at C42.**

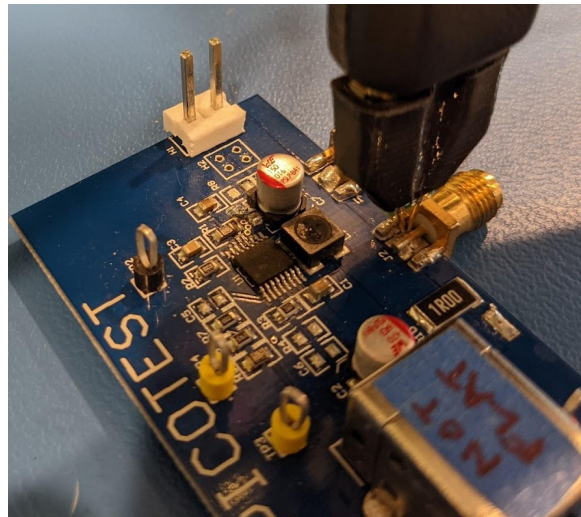


Fig. 10 - Probe location on DUT - LM20143 at J2.

### 3.0 Measurement Results

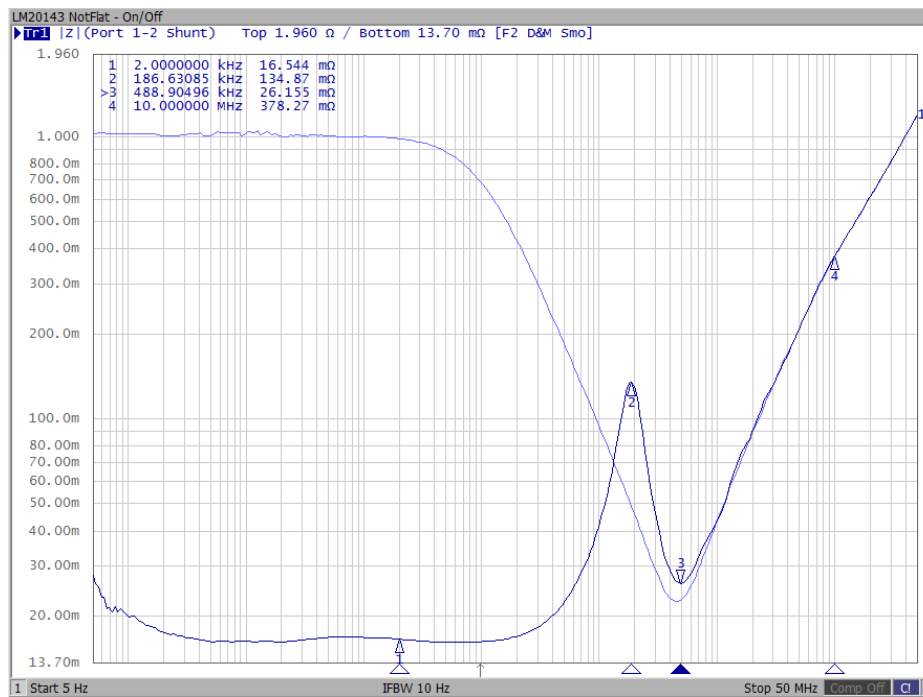
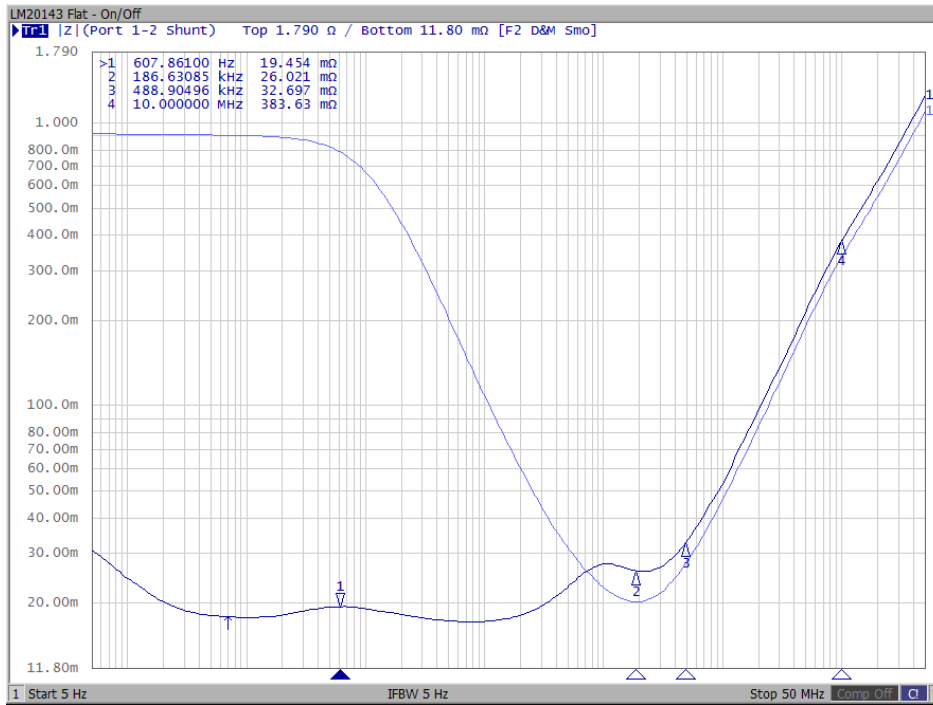
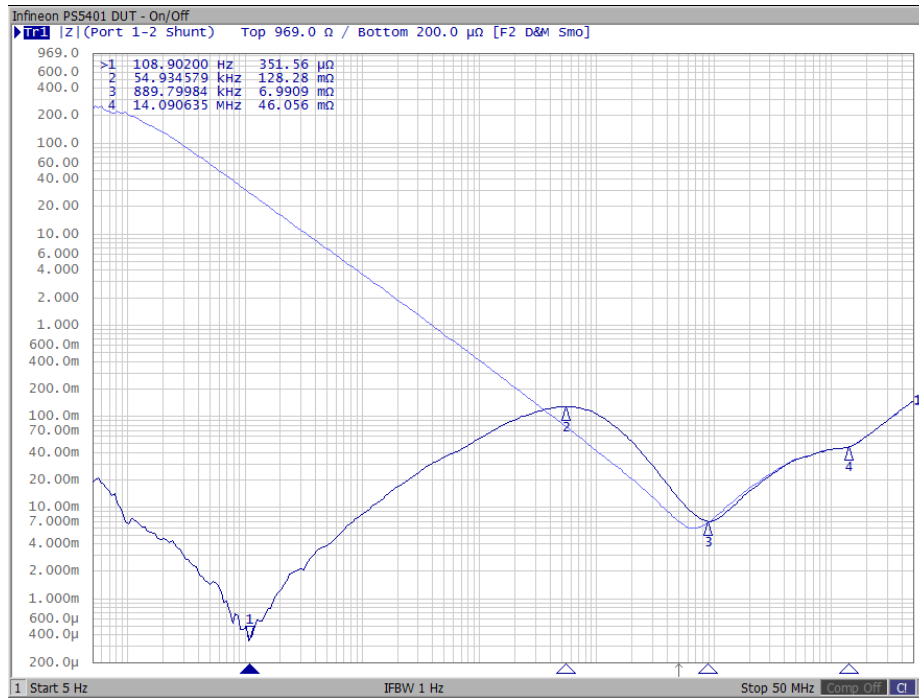


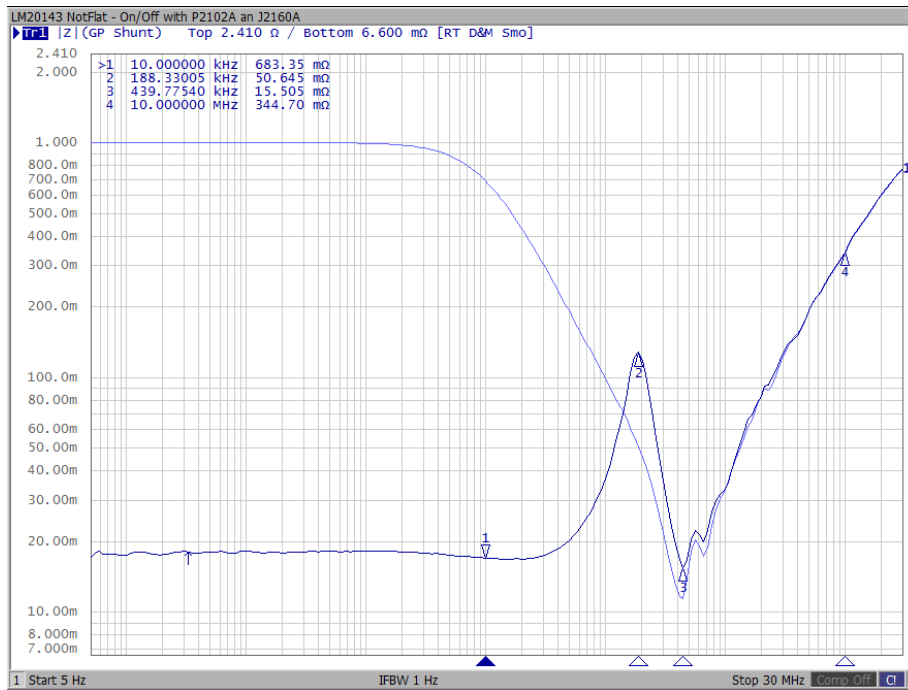
Fig. 11 - LM20143 NF VRM Output Impedance results OFF and ON (Full 2-port calibration method) with J2102B.



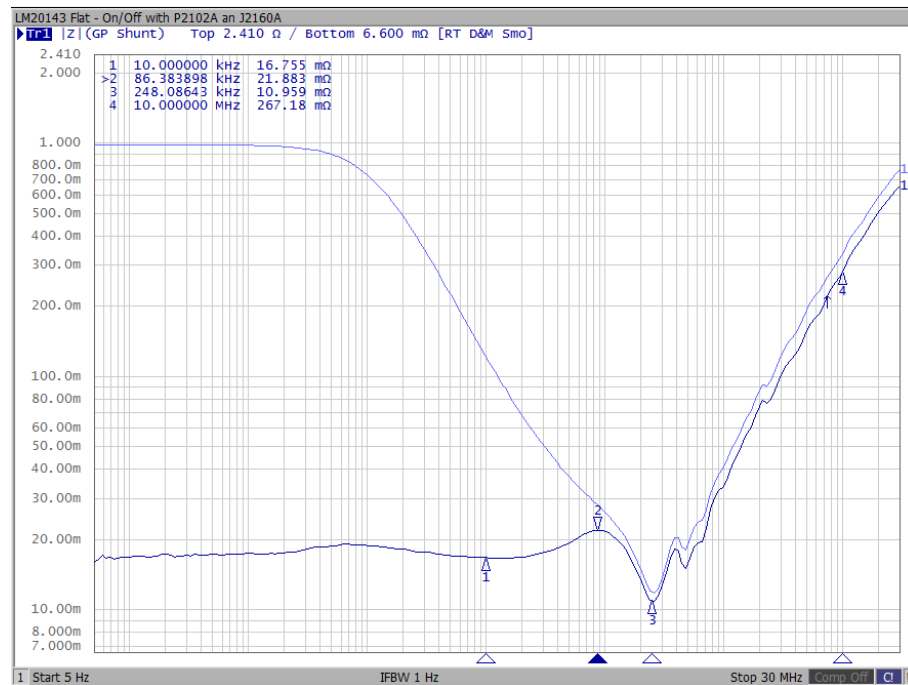
**Fig. 12 - LM20143 FLAT VRM Output Impedance results OFF and ON (Full 2-port calibration method) with J2102B.**



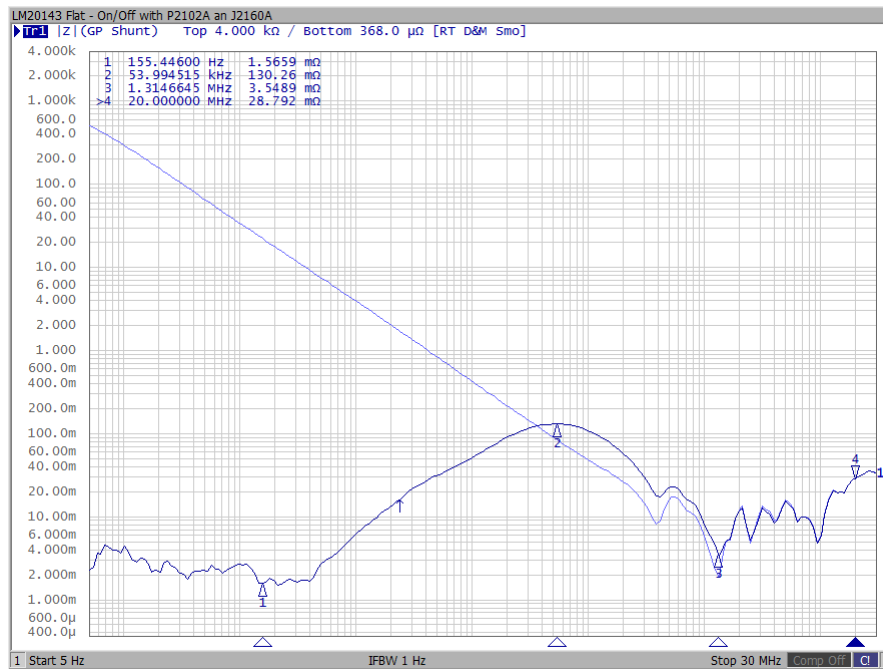
**Fig. 13 - PS5401 VRM Output Impedance results OFF and ON (Full 2-port calibration method) with J2102B.**



**Fig. 14 - LM20143 NF VRM Output Impedance results OFF and ON (Full 2-port calibration method) with J2160A.**



**Fig. 15 - LM20143 FLAT VRM Output Impedance results OFF and ON (Full 2-port calibration method) with J2160A.**



**Fig. 16 - PS4501 VRM Output Impedance results OFF and ON (Full 2-port calibration method) with J2160A.**

As shown by the results in Figures 13 and 16, it is possible to accurately measure below 1 mΩ with the P2102A browser probe, using either measurement setup.

### 4.0 P2102A Calibration and Setup Checklist with E5061B

**Calibration of the testing setup for the shunt-through impedance with series resistance measurement with both the J2102B common mode transformer and the J2160A 2-port probe adapter.**

#### 4.1 2-Port Calibration Method with the E5061B and J2102B Common Mode Transformer

After powering on the E5061B, with cables connected for calibration as shown in Figure 7, follow the steps below to calibrate your measurement setup prior to making measurements on your DUT.

Step 1: (On the E5061B) Press > **Cal** button

Step 2: Set > **Rs**, by specifying under  $Z_0$  (as shown by Figure 17)

**\*Note: Rs only needs to be specified for P2102A-2X, 5X, 10X probes. For 1X probes this step can be ignored. For DC Block use 1X settings.**

Step 3: Select > **Calibrate**

Step 4: Select > **2-Port Cal\***

Step 5: Select > **Reflection**

Step 6: *Place Probe on calibration substrate as appropriate*

Step 7: Select > **Port1 Open**

✓ *will appear next to the 'Port1 Open' LSK*

Step 8: Select > **Port2 Open**

✓ *will appear next to the 'Port2 Open' LSK*

Step 9: *Repeat for all 6 Reflection calibration steps until ✓ are reflected, as shown in Figure 19. Reference Figure 18 to complete all Full 2-port calibration steps.*

Step 10: Select > **Return**

Step 11: Select > **Transmission**

Step 12: Select > **Port 1-2 Thru**

✓ *will appear next to the 'Port 1-2 Thru' LSK*

Step 13: Select > **Return**

Step 14: Select > **Isolation (Optional)**

Step 15: Select > **Port 1-2 Isol**

✓ *will appear next to the 'Port 1-2 Isol' LSK*

Step 16: Select > **Return**

**\*Note: Full 2-port calibration is completed when ✓ is shown for Reflection, Transmission, Isolation, as depicted by figure 20.**

Step 17: Select > **Done**

Step 18: Select > **Return**

#### **4.2 2-Port Calibration Method with the E5061B and J2160A 2-Port Probe Adapter**

After powering on the E5061B, with cables connected for calibration as shown in Figure 8, follow the steps below to calibrate your measurement setup prior to making measurements on your DUT.

Step 1: (On the E5061B) Press > **Meas** button

Step 2: Select > **Impedance Analysis Menu**

Step 3: Select > **Method Port 1 Refl**

Step 4: Select > **GP Shunt T 50Ω, R 50Ω**

Step 5: Select > **|Z|**

Step 6: Select > **Gain-Phase Setup**

Step 7: Set > **T input Z = 50 Ω**

Step 8: Set > **R Input Z = 50 Ω**

Set the attenuation for *T Attenuator* & *R Attenuator* as needed

Step 9: Press > **Cal** button

Step 10: Set > **Rs**, by specifying under  $Z_0$  (as shown by Figure 17)

**\*Note: Rs only needs to be specified for P2102A-2X, 5X, 10X probes. For 1X probes this step can be ignored.**

Step 11: Select > **Calibrate**

Step 12: Select > **Response (Open)**

Step 13: Ensure **Select Port > GP Port\***

Step 14: *Place Probe on calibration substrate as appropriate*

Step 15: Select > **Open(f)**

Step 16: *Place Probe on calibration substrate as appropriate*

Step 17: Select > **Load (Optional)**

Step 18: Select > **Done**

Step 19: Select > **Return**

Step 20: *Repeat for **Response (Short)** and **Response (Thru)** calibration steps until ✓ are reflected. Reference Figure 18 to complete all Full 2-port calibration steps.*



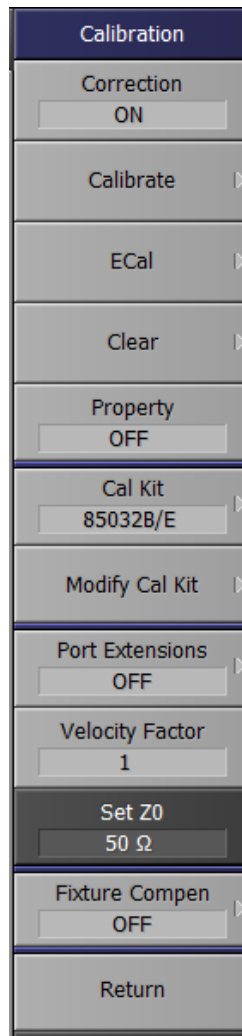


Fig. 17 - E5061B Calibration menu, where  $Z_0$  is highlighted.

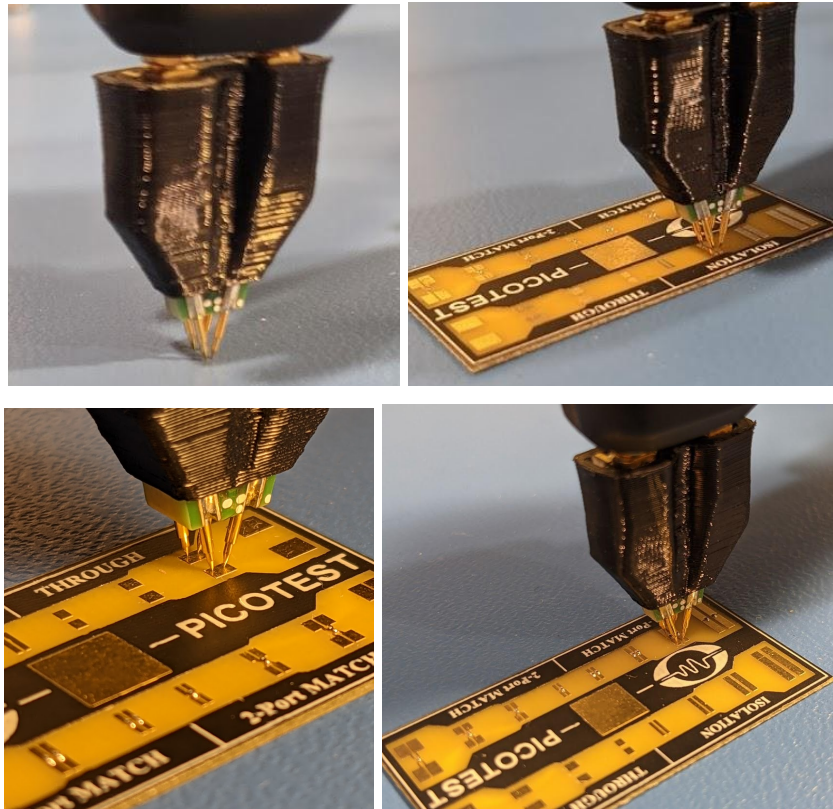


Fig. 18 - P2102A 2-port Calibration Open (top left), Short and Isolation (top right), through (bottom left) and Match/Load (bottom right).

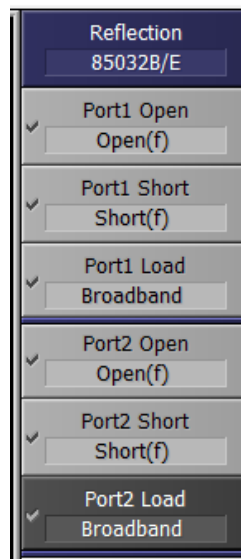


Fig. 19 - Full 2-port Calibration - Reflection Calibration Steps Completed.

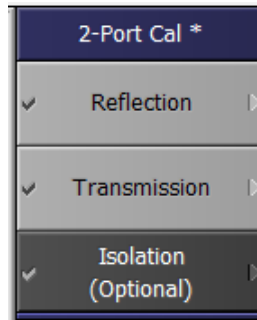


Fig. 20 - Full 2-port Calibration Steps Completed.

### 4.3 Checklist for Shunt-Through Measurement of the DUT with J2102B Common Mode Transformer

With the DUT connected to the E5061B to make a shunt-through measurement as shown in Figure 7.

Step 1: (On the E5061B) Press > **Meas** button

Step 2: Select > **Impedance Analysis Menu**

Step 3: Select > **Method Port 1 Repl**

Step 4: Select > **Port 1-2 Shunt**

Step 5: Select > **|Z|**

Step 6: Press > **Scale** button

*Set scale or select 'Auto Scale' as appropriate*

Step 7: Select > **Y-axis Log**

Step 8: Select > **Log**

Step 9: Press > **Display** button

*Set title labels and display colors as appropriate*

Step 10: Press > **Ave** button

Step 11: Set > *IF Bandwidth*

**Note: The lower the bandwidth  $\Rightarrow$  higher resolution, but also the slower the measurement. Typically, a good starting point is 1 kHz.**

Step 12: Press > **Start** button

Step 13: Set *Start* frequency for measurement

Step 14: Press > **Stop** button

- Step 15: Set *Stop* frequency for measurement
- Step 16: Press > **Sweep Setup** button
- Step 17: Select > **Power**
- Step 18: Set *Power* dBm level
- Step 19: Select > **Return**
- Step 20: Select > **Sweep Type**
- Step 21: Select > **Log Freq**
- Step 22: Select > **Return**
- Step 23: Select > **Return** (to return to E5061B Menu)

Begin capturing measurements of the DUT...

#### 4.4 Checklist for Shunt-Through Measurement of the DUT with J2160A

With the DUT connected to the E5061B to make a shunt-through measurement as shown in Figure 8...

- Step 1: (On the E5061B) Press > **Meas** button
- Step 2: Select > **Impedance Analysis Menu**
- Step 3: Select > **Method Port 1 Refl**
- Step 4: Select > **GP Shunt T 50Ω, R 50Ω**
- Step 5: Select > **|Z|**
- Step 6: Select > **Gain-Phase Setup**
- Step 7: Set > **T input Z = 50 Ω**
- Step 8: Set > **R Input Z = 50 Ω**

**Note: If the signal being measured is noisy, decrease the attenuation (T Attenuator & R Attenuator) from 20dB as needed.**

- Step 9: Select > **Return**
- Step 10: Press > **Scale** button
- Set scale or select '**Auto Scale**' as appropriate
- Step 11: Select > **Y-axis Log**
- Step 12: Select > **Log**
- Step 13: Press > **Display** button
- Set title labels and display colors as appropriate*

Step 14: Press > **Ave** button

Step 15: Set > *IF Bandwidth*

**Note: The lower the bandwidth  $\Rightarrow$  higher resolution, but also the slower the measurement. Typically, a good starting point is 1kHz.**

Step 16: Press > **Start** button

Step 17: Set *Start* frequency for measurement

Step 18: Press > **Stop** button

Step 19: Set *Stop* frequency for measurement

Step 20: Press > **Sweep Setup** button

Step 21: Select > **Power**

Step 22: Set > *Power* dBm level

**Note: In Gain-Phase Setup Menu, adjust attenuation levels as needed to prevent overload. This can be done in combination with the Power level.**

Step 23: Select > **Return**

Step 24: Select > **Sweep Type**

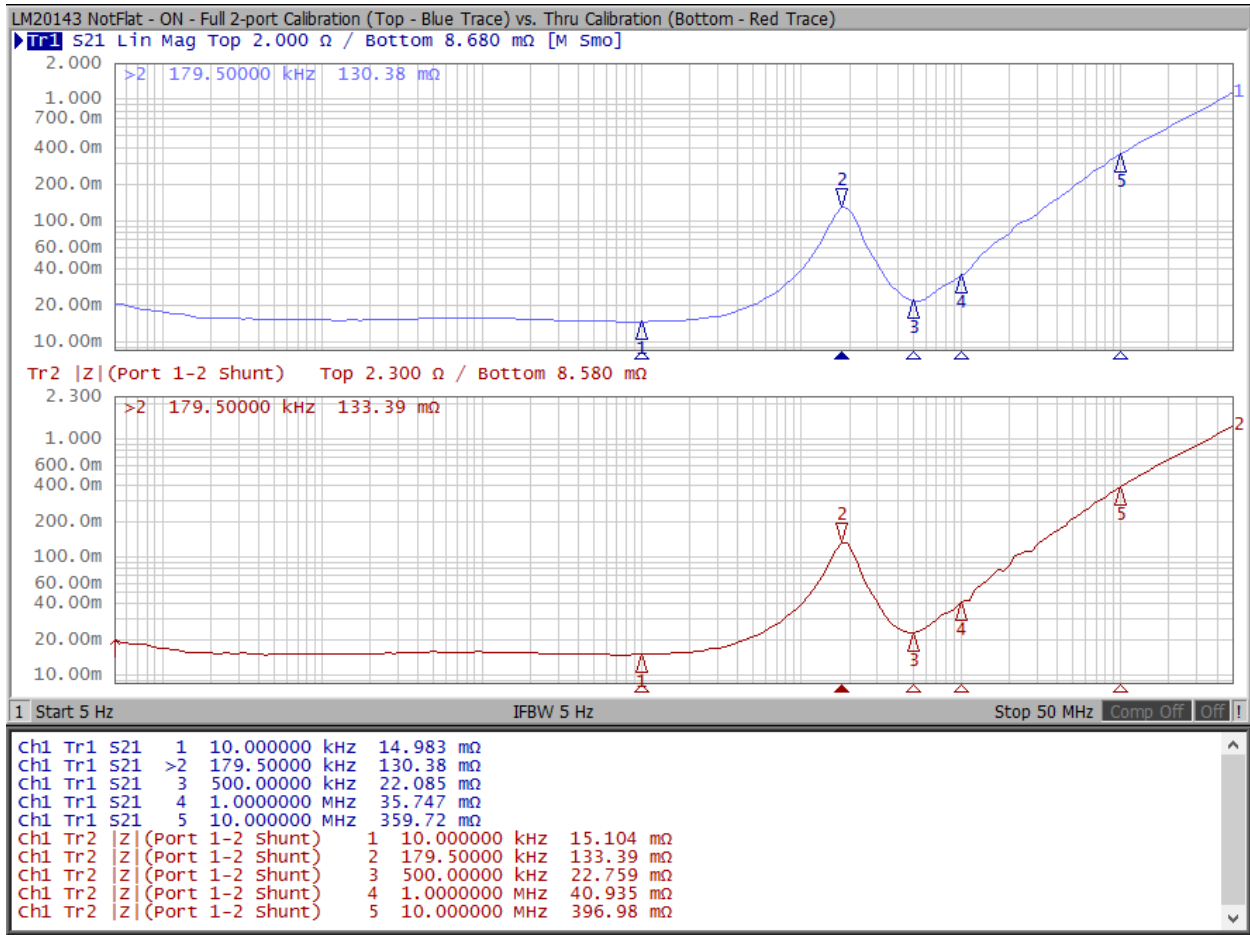
Step 25: Select > **Log Freq**

Step 26: Select > **Return**

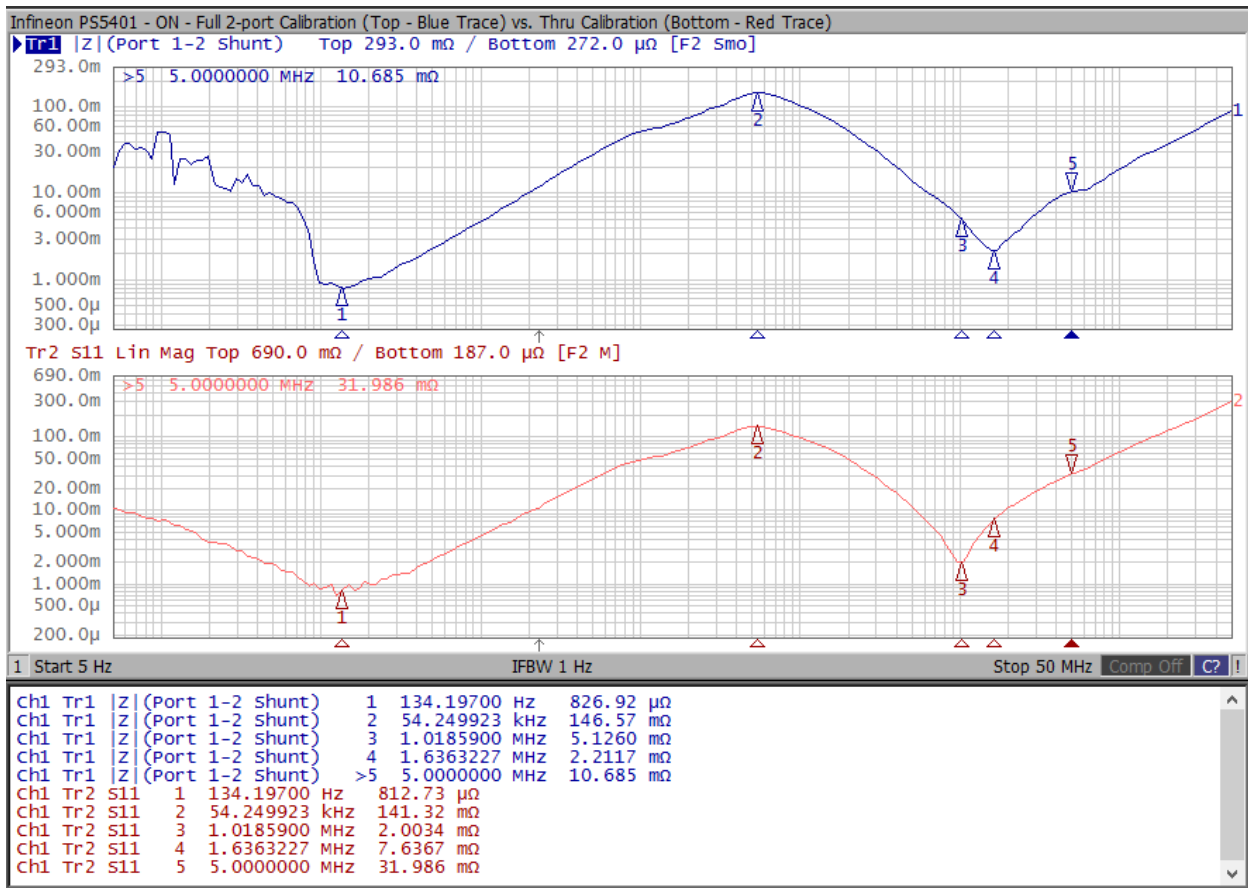
Step 27: Select > **Return** (to return to E5061B Menu)

Begin capturing measurements of the DUT...

Measurement accuracy can be further improved by using the full 2-port calibration method versus only the Thru calibration method. The Thru calibration method does not account for inductive coupling errors. Figures 21 and 22 provide two examples comparing the measurement error due to inductive coupling when using the full 2-port calibration method versus Thru method.



**Fig. 21 - LM20143 NF - Measurement Results using Full 2-port calibration (BLUE) vs. Thru calibration method (RED) with the E5061B, P2102A, and J2102B Common Mode Transformer.**



**Fig. 22 - Infineon PS5401 ON - Measurement Results using Full 2-port calibration (BLUE) vs. Thru calibration method (RED) with the E5061B, P2102A, and J2102B Common Mode Transformer.**

As shown by Figure 21, a 37 mΩ decrease is observed at 10 MHz with the full 2-port calibrated measurement versus with the Thru calibrated measurement on the LM20143 Not Flat DUT. A similar result is also seen by Figure 22, where a 21 mΩ decrease at 5 MHz is observed by using the full 2-port calibration method in comparison to the Thru calibration method.

### 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. With good calibration, as demonstrated by the results in Figure 22, it is possible to achieve an impedance measurement below  $1\text{m}\Omega$  with the P2102A probe and the E5061B VNA.

If you really want to measure planes or high frequency impedance, the P2104A 1-Port Probes [13] can be an even better option.

As shown in this document, to make low impedance measurements with a E5061B 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 [14], or one of the probe holders from PacketMicro.



## 6.0 References

1. Ultra-low Impedance (20 micro ohm) Measurement using 2-Port Shunt-Through - <https://www.picotest.com/images/download/Ultra-low.pdf>
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4. Picotest P2102A - 2 Port PDN Transmission Line Probe - [https://www.picotest.com/products\\_PDN\\_Probe.html](https://www.picotest.com/products_PDN_Probe.html)
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6. Picotest J2160A 2-Port Probe Adapter Panel for E5061B - [https://www.picotest.com/products\\_J2160A.html](https://www.picotest.com/products_J2160A.html)
7. Picotest PDN Cable® - <https://www.picotest.com/pdn-cable.html>
8. Pasternack PE9002 - N Male to BNC Female Adapter - <https://www.pasternack.com/n-male-bnc-female-straight-adapter-pe9002-p.aspx>
9. Keysight 3D Probe Positioner - N2787A - <https://www.keysight.com/en/pd-1643963-pn-N2787A/3d-probe-positioner?cc=US&lc=en>
10. DUT - Picotest LM20143 - [https://www.picotest.com/products\\_LM20143.html](https://www.picotest.com/products_LM20143.html)
11. DUT - Infineon PS5401 Eval - [https://www.infineon.com/cms/en/product/evaluation-boards/eval\\_ps5401-int/](https://www.infineon.com/cms/en/product/evaluation-boards/eval_ps5401-int/)
12. J2113A Semi-Floating Differential Amplifier - [https://www.picotest.com/products\\_J2113A.html](https://www.picotest.com/products_J2113A.html)
13. Picotest P2104A 1-Port Probe - coming 2021 to [https://www.picotest.com/products\\_PDN\\_Probe.html](https://www.picotest.com/products_PDN_Probe.html)
14. ClampMan PCB Holder and Clamping Solution - [https://www.picotest.com/products\\_clampman.html](https://www.picotest.com/products_clampman.html)
15. PacketMicro TP150 Precision Positioner - [https://www.picotest.com/products\\_TP150\\_Precision\\_Positioner.html](https://www.picotest.com/products_TP150_Precision_Positioner.html)