Measuring Ultra Low Impedances and PDNs

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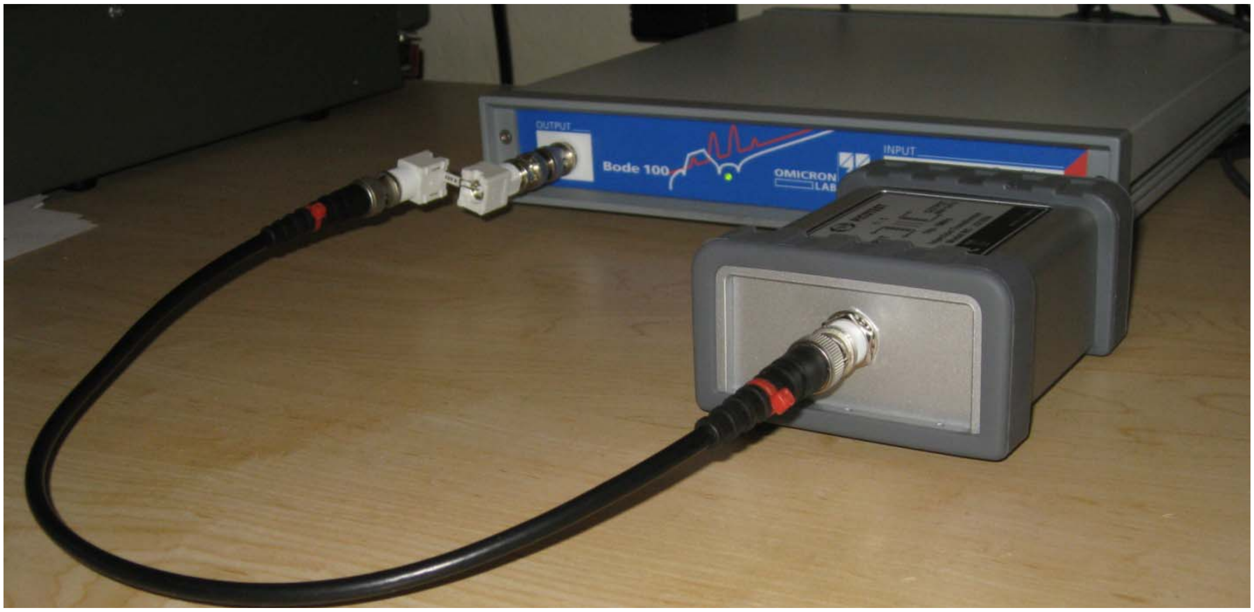

High speed digital circuits are very sensitive to the power supply voltages that they receive. The load demands of high speed FPGAs and processors can also be very dynamic, changing by tens of amps/nSec. Maintaining the voltage regulation within the required limits is the job of the power supply, the design engineer, and the Power Distribution Network ("PDN"). Maintaining the impedance of the PDN requires careful decoupling and circuit board power plane design.

At lower frequencies, the impedance is mostly controlled by the active feedback look of the Voltage Regulator Module ("VRM"). Above the bandwidth of the VRM the impedance is controlled by the circuit board planes and decoupling capacitors.

Measuring the impedance of the power is very simple using a Vector Network Analyzer (VNA) and a high-quality wideband transformer. The complexity and accuracy of the test is not due to the analyzer measurement, but to the probes, or more accurately, the ability to accurately connect the probes and account for parasitics.

The basic measurement for a low impedance is generally performed using the 2 port, shunt thru method. This measurement places the R_DUT in shunt from the two VNA ports to ground. This method is most accurate for impedances less than a few Ohms. This method measures the attenuation of the Device Under Test ("R_DUT") and the impedance of the oscillator port.

A simple schematic of the measurement setup, including the two s-parameter ports is shown in Figure 1.

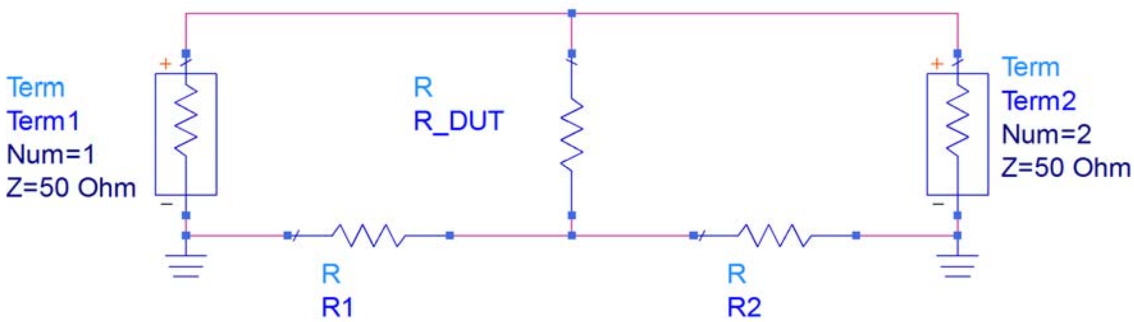

Figure 1, Simple schematic of the 2 port shunt thru method, showing the ground resistances from the interconnect cables, R1 and R2, as well as the device being tested, R_DUT.

Neglecting the finite cable ground resistance elements, R1 and R2, it is seen that Port 2 is in parallel with the R_DUT. It is also seen that R1 and R2 are in parallel since one end is common and the other end of each resistor is grounded. At low frequencies, these ground resistance elements create a ground loop. If unaccounted for the measured result will be R_DUT in series with the parallel combination of the cable ground resistances, R1 and R2. The simplest and most effective method for eliminating the ground loop is to add a wideband common mode transformer to the measurement, such as the Picotest J2102A Common Mode Transformer. The transformer for this measurement must have very wide bandwidth, low loss and tight coupling, otherwise, the results will not be accurate over the measured frequency range. It is also important to maintain the 50 Ohm transmission line impedance through this transformer.

We can easily calculate the magnitude of this s-parameter measurement. We have left out the imaginary terms for all three elements, R_DUT, RS and RL for simplicity:

$$S21 := \frac{2 \cdot \frac{R\_DUT \cdot RL}{R\_DUT + RL}}{\frac{R\_DUT \cdot RL}{R\_DUT + RL} + RS} \qquad \text{Eq 1.}$$

Solving for R_DUT:

$$R\_DUT := \frac{-S21 \cdot RS \cdot RL}{S21 \cdot RL + S21 \cdot RS - 2 \cdot RL} \qquad \text{Eq 2}$$

Since our measurements are in dB, it is helpful to solve this for S21 in dB.

$$S21(S21\_dB) := 10^{\frac{S21\_dB}{20}}$$ EQ3

$$R\_DUT := \frac{-10^{\frac{S21\_dB}{20}} \cdot RS \cdot RL}{10^{\frac{S21\_dB}{20}} \cdot RL + 10^{\frac{S21\_dB}{20}} \cdot RS - 2 \cdot RL}$$ EQ4

We can also evaluate the circuit sensitivity to the three parameters, RS, RL and S21 by evaluating the first derivative of Eq 2 with respect to each variable:

$$dS21 := \left[(-RS) \cdot \frac{RL}{S21 \cdot RL + S21 \cdot RS - 2 \cdot RL} + S21 \cdot RS \cdot \frac{RL}{(S21 \cdot RL + S21 \cdot RS - 2 \cdot RL)^2} \cdot (RL + RS)\right]$$ Eq 5

$$dRL := \left[(-S21) \cdot \frac{RS}{S21 \cdot RL + S21 \cdot RS - 2 \cdot RL} + S21 \cdot RS \cdot \frac{RL}{(S21 \cdot RL + S21 \cdot RS - 2 \cdot RL)^2} \cdot (S21 - 2)\right]$$ Eq 6

$$dRS := \left[(-S21) \cdot \frac{RL}{S21 \cdot RL + S21 \cdot RS - 2 \cdot RL} + S21^2 \cdot RS \cdot \frac{RL}{(S21 \cdot RL + S21 \cdot RS - 2 \cdot RL)^2}\right]$$ Eq 7

$dRL = -4.003 \times 10^{-8}$ $dS21 = 25.02$ $dRS = 2.001 \times 10^{-4}$

Note that S21, in this case, is a magnitude and NOT in dB. The R_DUT impedance is approximately 25*S21 as seen in dS21.

The common mode transformer can either be on the input or output side of the measurement. Note that the sensitivity of the source (dRS) is MUCH greater than the sensitivity of the load (dRL). This means that it is important minimize the impedance between port 1 (the source) and the R_DUT, even at the expense of the connection at port 2, since the port 2 connection is much less sensitive. For that reason it is preferable to locate the common mode transformer on the LOAD side of the measurement.

A simple ADS model of the measurement is shown in Figure 2 with a 2 milliohm resistor as the R_DUT. Arbitrary parasitic resistance, inductance and capacitance are included in the model in order to show the effect of the Common Mode Transformer. The simulation results are shown in Figure 3. They correctly indicate the R_DUT is 2 milliohms with the Common Mode transformer and measure R_DUT in series with the parallel combination of the ground resistance elements without the transformer.

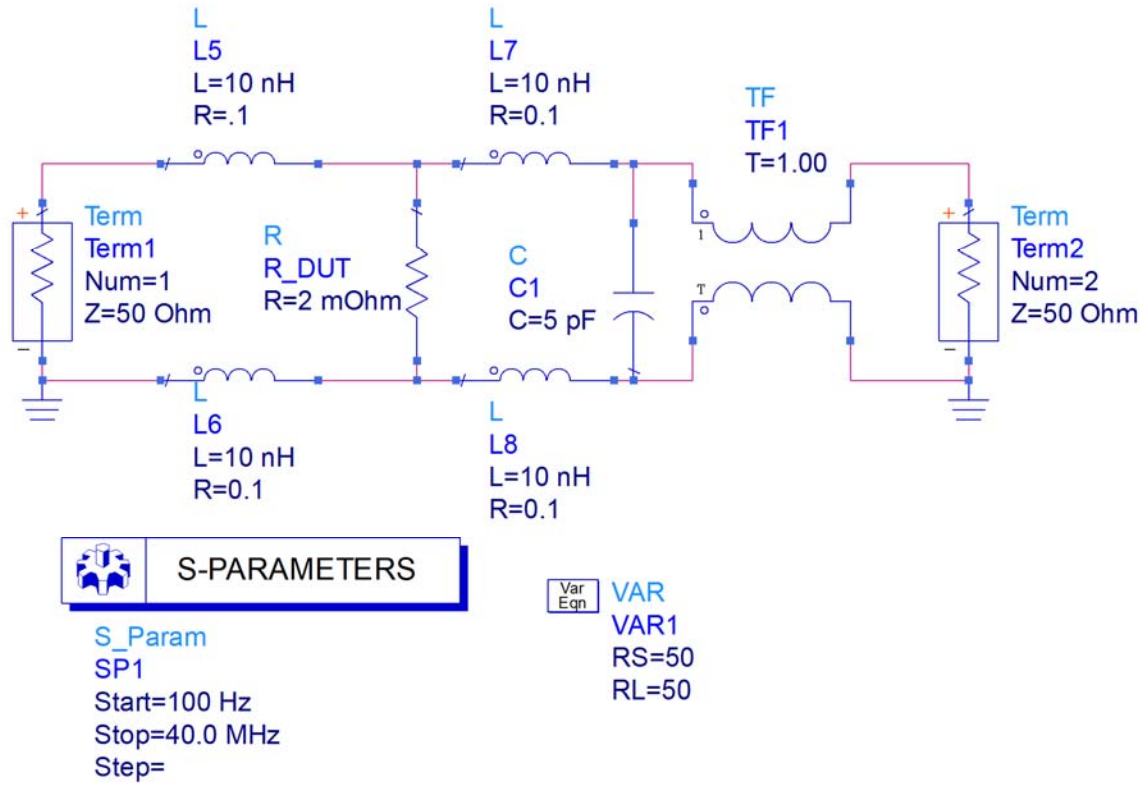

Figure 2, ADS model of the S21 shunt "thru" measurement showing the resistor being tested (R_DUT) and the Picotest J2102A wideband common mode transformer. Term 1 and Term 2 represent the two 50 ohm ports of the VNA. Arbitrary parasitic elements L5, L8 and C1 are added to show their effect and the need for the common mode transformer.

The simulation results show the measured result with and without the common mode transformer. Without the common mode transformer the resistance of L6 and L8 appear in parallel, due to the connection to ground at port 1 and port 2. The parallel combination appears in series with the R_DUT. This can be seen in Figure 4 below, which shows 52 milliOhms, resulting from the parallel resistance of L6 and L8 in series with R_DUT.

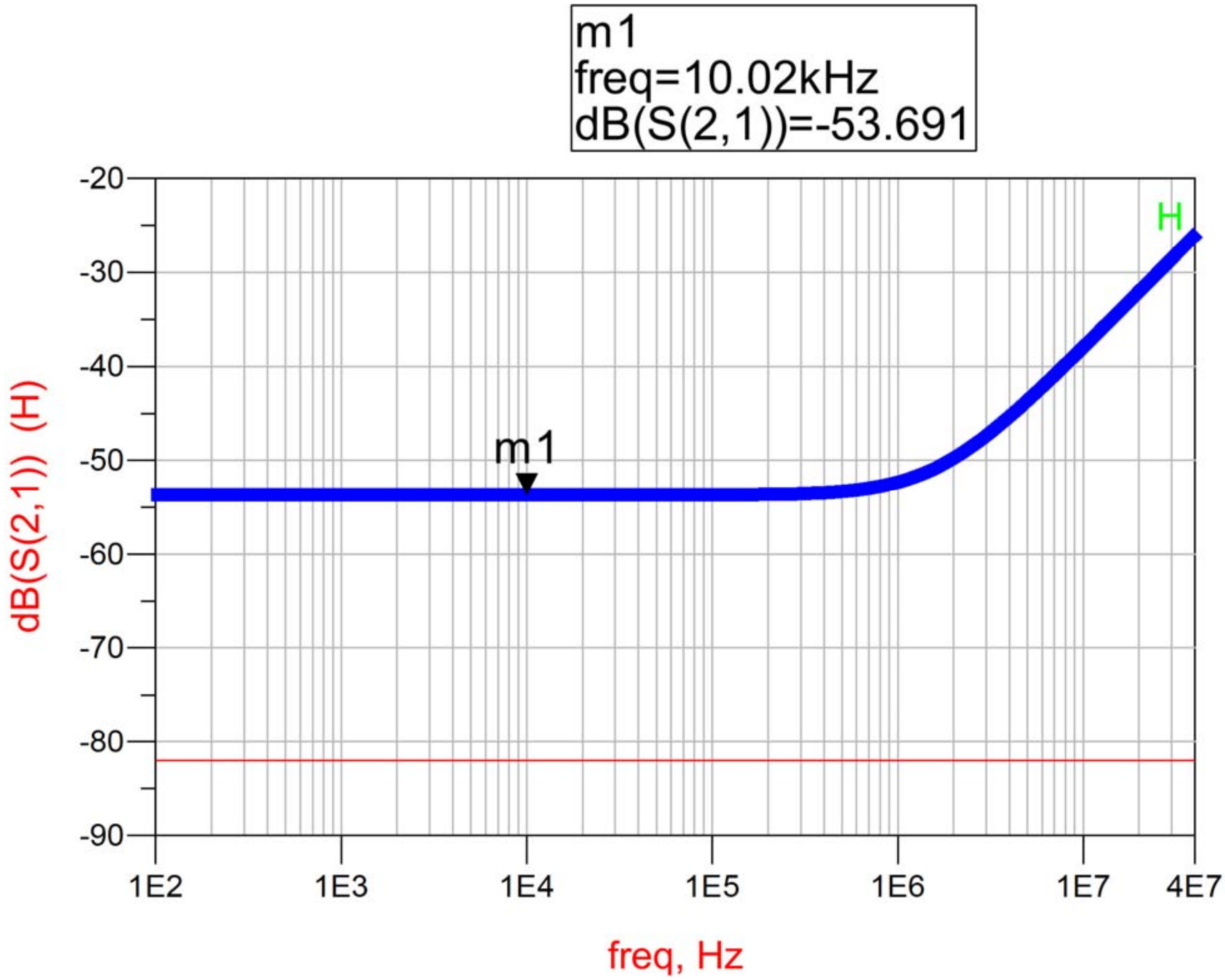

Figure 3, ADS simulation result of the S21 shunt thru measurement for a 2 milliOhm R_DUT with (RED) and without (BLUE) the common mode transformer, displayed as S21.

Equation 2 is implemented in the ADS Data Display file (DDS) in order to convert the S parameters to impedance.

Eqn Z_DUT=-S(2,1)*RS*RL/(S(2,1)*RL+S(2,1)*RS-2*RL)

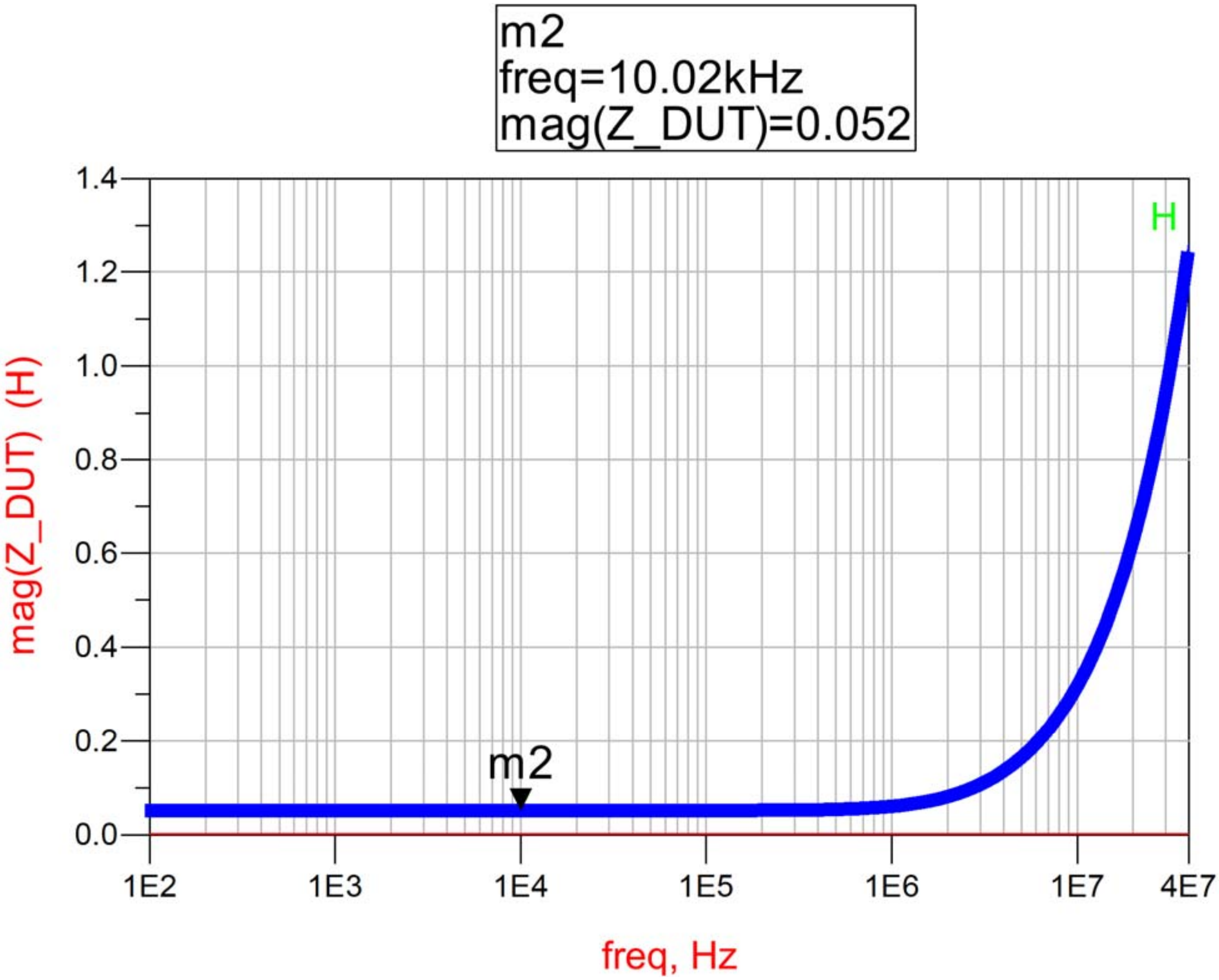

Figure 4, ADS simulation result of the S21 shunt thru measurement for a 2 milliOhm R_DUT with (RED) and without (BLUE) the common mode transformer, converted to ohms.

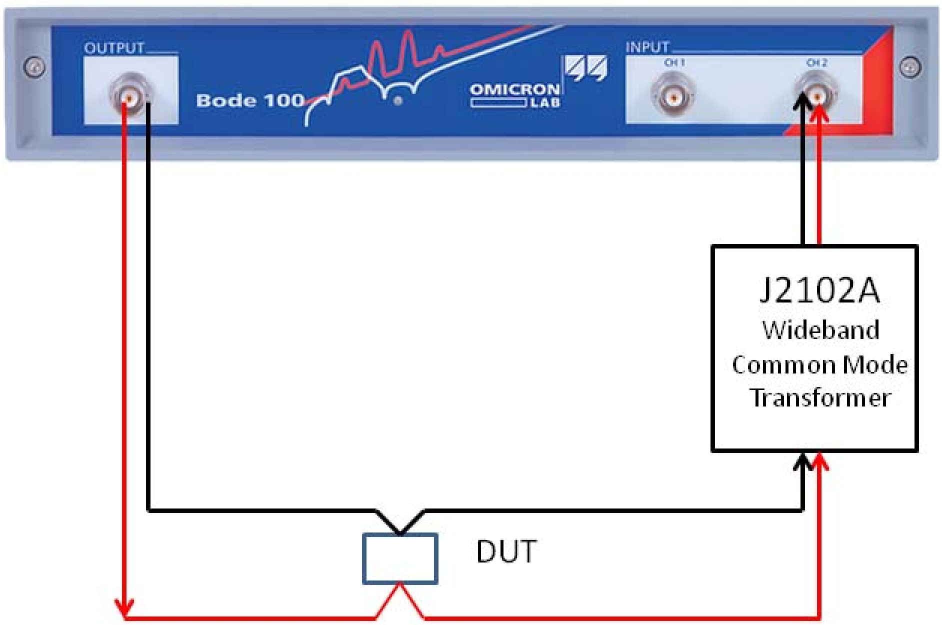

Figure 5, Measurement setup for the 2 port S21 shunt thru method using the OMICRON Lab Bode 100 with the J2102A Common Mode Transformer. The R_DUT is a 10mOhm 0805 surface mount thick film resistor.

Actual bench measurements were also made for comparison. Before making any measurements, it is always good to measure the noise floor of the setup. The noise floor for this setup is shown in Figure 6.

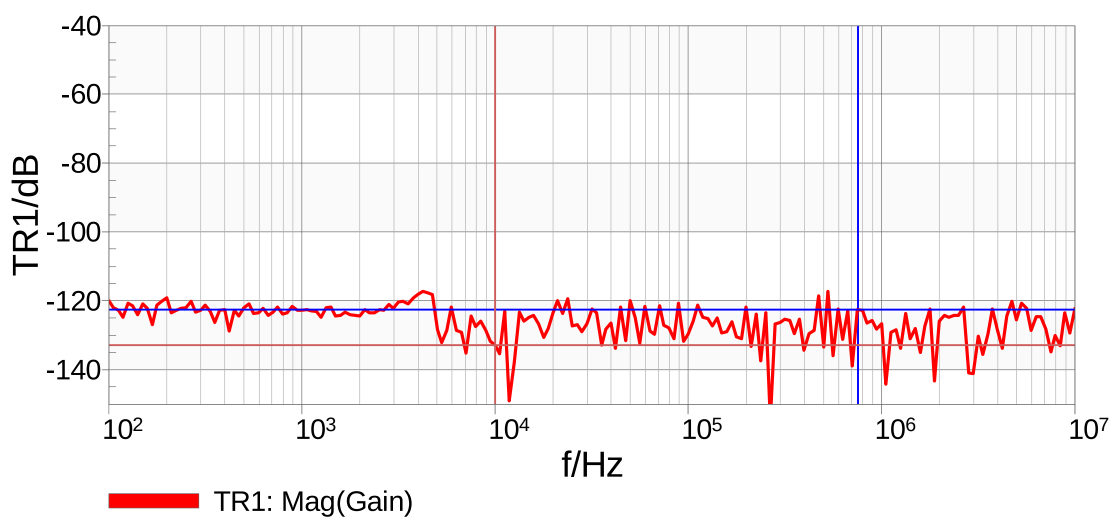

Figure 6, Noise floor measurement of the setup shown in Figure 5.

The -120dB noise floor means that it is theoretically possible to measure impedances as low as 25 uohms as indicated by equation 3. Since we should allow at least 10dB margin from the noise floor, a more practical limit is 80 uohms.

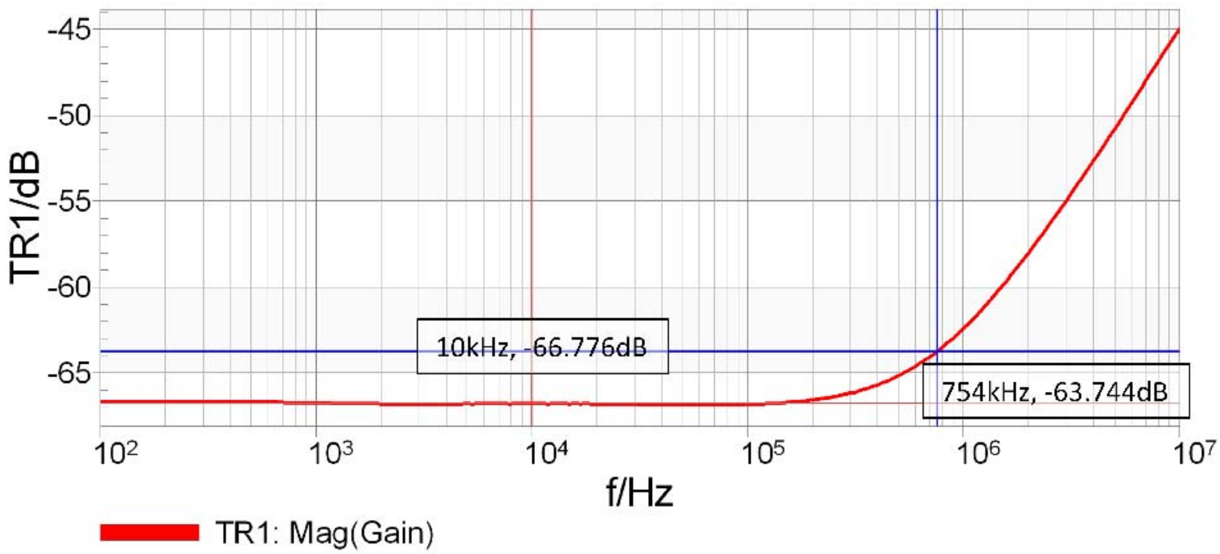

Figure 7, S21 measurement of a 10 milliohm 0805 resistor mounted to PCB. -66.76 dBresults in $R\_DUT(-66.76) = 0.011$**, or 11milliohms.**

The parasitic inductance can be calculated based on the 3dB frequency and the measured resistance, R_DUT.

$$freq := 754 \cdot 10^{3}$$

$$R\_DUT = 2 \cdot \pi \cdot freq \cdot L \qquad \text{Eq 8}$$

$$L := \frac{1}{2} \cdot \frac{R\_DUT}{\pi \cdot freq} \qquad \text{Eq 9}$$

$$L = 2.322 \times 10^{-9}$$

This inductance is due to the device mounting and short traces connecting the resistor to the BNC connector.

Having successfully measured a 10 milliOhm resistor, we can try a smaller value. In this second example, we are measuring a 2 milliOhm low inductance resistor, provided by Ohmite (FCSL76R002GER). We soldered the BNC connectors directly to the resistor pads as shown in Figure 8.

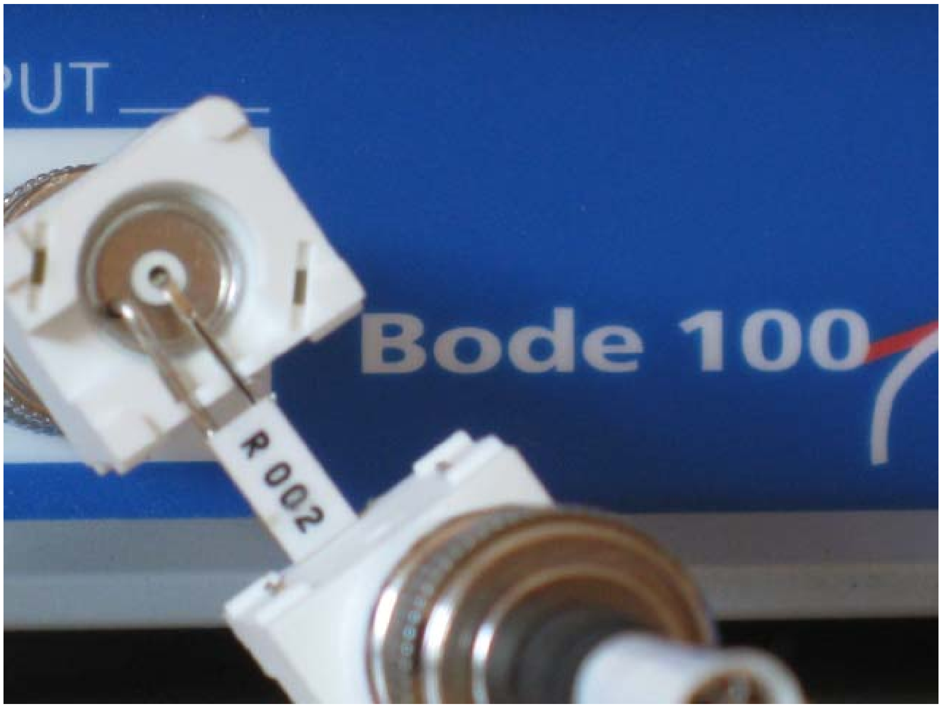

Figure 8, The 2mohm resistor pads of this resistor run the length of the resistor. The BNC leads are soldered over the entire length of the pads.

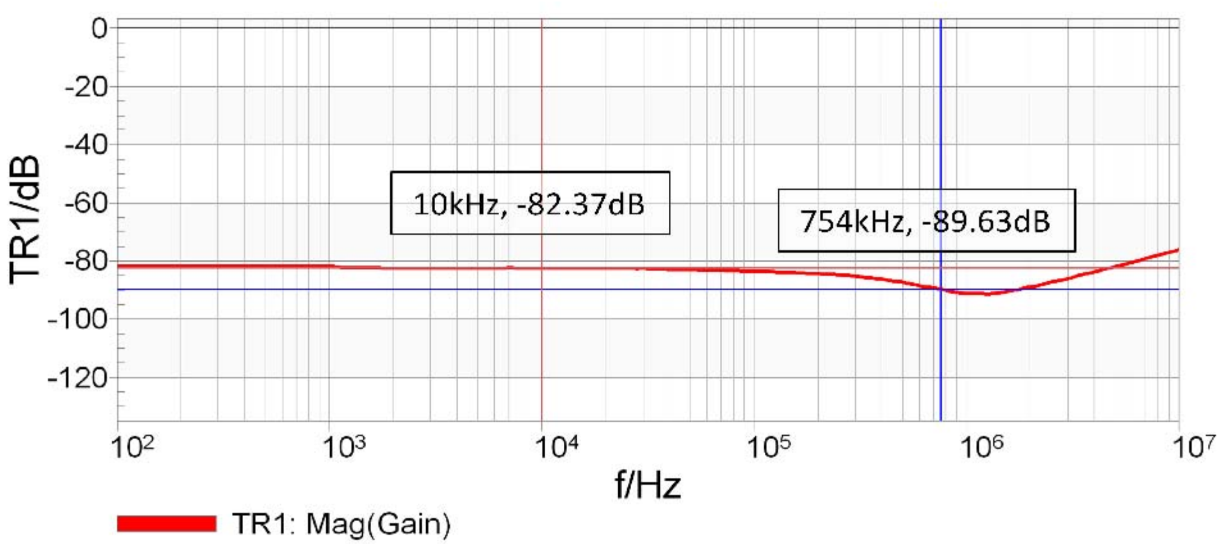

Figure 9, S21 measurement of Ohmite 2 milliohm low inductance resistor mounted to the BNC connector.

The resistance of the device is calculated using equation 3 as:

$$R\_DUT(-82.45) = 1.886\times 10^{-3}$$

The dip in the measurement at 754 kHz is primarily due to the inductance of the BNC leads connected to the resistor and the solder mount of the resistor itself.

We have shown that it is possible to measure very low impedances using the 2 port s-parameter shunt thru method along with the Picotest J2102A Common Mode Transformer. We have successfully measured 2 milliOhms at 10MHz and shown that it is theoretically possible to measure much lower values with careful connection of the probes to the R_DUT.

References

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