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Why S11 VNA Measurements Don't Work for PDN Measurements

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At the beginning of the previous column we compared the one-port and two-port Vector Network Analyzer (VNA) measurement setups for PDN measurements and said that one-port VNA measurements don't work well for PDN applications. Our argument was that the one-port scheme (shown in Figure 1), unless the DUT is connectorized, requires an extra connection beyond the calibration plane to reach the DUT.

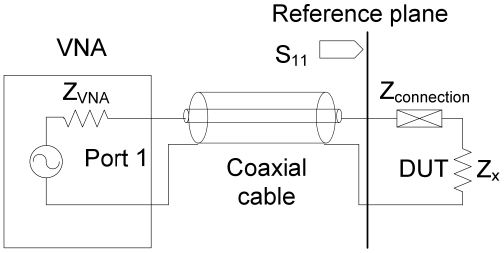


Figure 1: Connection discontinuity in one-port VNA PDN measurements.

If we want to measure very small impedances, this extra discontinuity, $Z_{connection}$, usually a small series resistance and inductance, becomes detrimental even at very low frequencies. By hand soldering, we may be able to get the extra connection as short as 1 mm (40 mils), which may represent say 1 nH inductance and 1 milliohm resistance. If we need to measure PDN impedances at or below 5 milliohms values, we will be limited by the inductive reactance of $Z_{connection}$ above 1 MHz and by the resistance of $Z_{connection}$ below 100 kHz. This is illustrated in Figure 2, where we also show on the same plot the 50-ohm reference impedance value and our 5 milliohm target impedance. In the usual high-frequency VNA measurements, where we want to measure DUTs with impedances close to 50 Ohms, the same 1 nH series inductance would create minimal error anywhere below 1 GHz.

Note that this error due to the series discontinuity is not the characteristics of the VNA; this limitation is inherent to any measurement setup where only one cable or one pair of wires connects to a low-impedance DUT and we have extra connection beyond the calibration plane.

We can eliminate the series discontinuity, even if the DUT is not connectorized, by using wafer probes calibrated to their tips. This may be the subject of a future column.

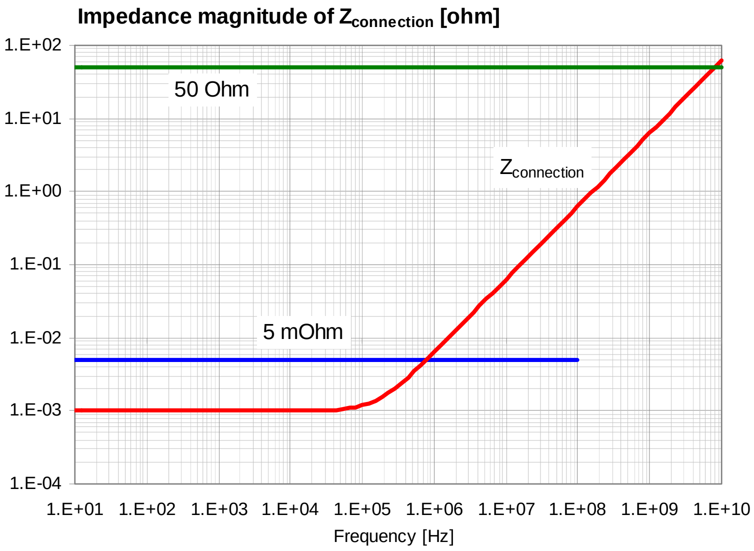


Figure 2: Comparing the 50-ohm VNA impedance and a five milliohm PDN impedance target to the impedance magnitude of a 1-mOhm 1-nH $Z_{\text{connection}}$ discontinuity.

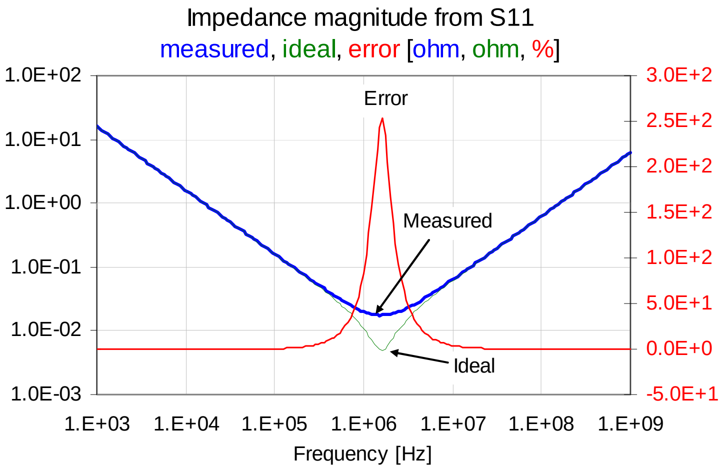
However, there is yet another, even bigger problem when we measure low impedances with a one-port VNA setup. To understand this, we need to look at how the VNA works. In one-port connections the VNA measures the outgoing wave, called incident wave, because this is the wave entering the DUT and the backward-travelling wave, called reflected wave. The complex ratio of these waves is called the Voltage Reflection Coefficient, commonly denoted by capital gamma (Γ). Γ has a direct relationship to the impedance connected to the VNA port, as shown in Equation (1). If we invert the voltage reflection coefficient formula, we get the complex unknown impedance:

$$\Gamma = \frac{\text{Reflected wave}}{\text{Incident wave}} = \frac{Z - Z_0}{Z + Z_0}; \qquad Z = Z_0 \frac{1+\Gamma}{1-\Gamma} \tag{1}$$

In these expressions Z_0 is the nominal connection impedance of the VNA, usually 50 Ohms. Γ becomes identically -1 when the unknown impedance is zero. Since the reference is the 50-ohm VNA impedance, Γ becomes close to -1 for any impedance much smaller than 50 ohms. For instance, if the impedance is 5 milliohms, Γ = -0.9998. And here comes the problem: VNAs are not prepared to measure Γ with this accuracy; they are optimized to measure accurately G for impedances close to 50 Ohms. When |Γ| approaches one, VNAs will have an error in the order of a percent, which will prevent us from measuring impedances lower than a few hundred milliohms.

We have to note that this is not an issue when we simulate the circuit, because in a simulator we can afford to have much higher precision of calculations.

The above problem can be illustrated by Figure 3. The figure shows measurement results generated by simulations, when we can accurately control the errors. We assume a single capacitor to be measured: a 10 uF capacitor with 5 mOhm ESR and 1 nH ESL. The top graph shows the result assuming we measure with 1-port setup, where the VNA has a 0.05% scaling error and a noise floor approximately 10^{-5} times below the full scale. The thin green line is the ideal result, the thick blue line shows what the instrument would report and the red line shows the percentage error between the two. The error at the series resonance frequency is 250%. In contrast, when we assume the same scaling error and noise floor, but instead use two-port shunt through connection, the error stays below 5% over the entire frequency range.



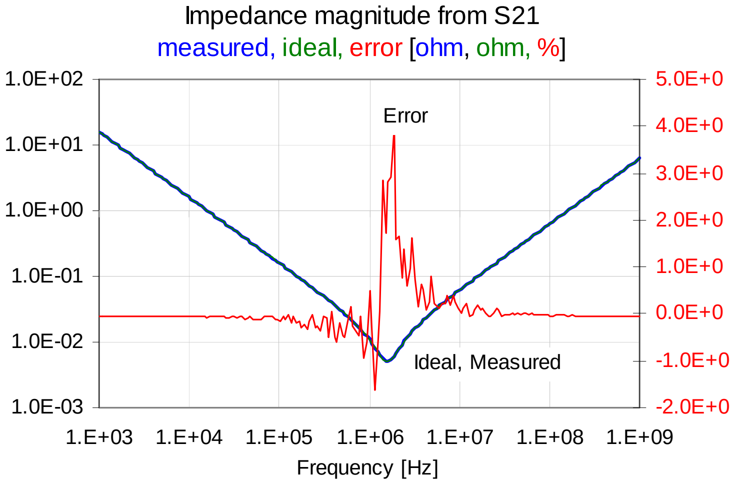


Figure 3: Comparing one-port and two-port VNA setups when we assume to measure a 10 uF 5 mOhm 1 nH capacitor.