Non-Standard VNA Measurements – LCR Measurement

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Introduction

A Vector Network Analyzer (VNA) is typically used to measure the RF characteristics of filters, amplifiers, antennas and the like. Other measurements are possible though. The VNA can be used like an LCR meter to measure reactance and resistance. Resistances as low as 1 milli-ohm to as high as a meg-ohm can be measured with good accuracy. The built-in trace calculator can be used for interesting processing of measurements. We'll see how circuits may be resolved into "Pi" and "T" networks using the trace calculator to post-process S-Parameter measurements.

LCR Measurement

A resistor, capacitor or inductor can be measured with a VNA. Three connection methods are used. For impedances from 1 milli-ohm to 20 ohms, a 2-Port S_{21} measurement is made with the Device Under Test (DUT) in shunt. For 20 ohms to 100 ohms, a 1-Port, S_{11} measurement is made through the DUT to ground. Finally, for 100 ohms to about 1 megohm, a 2-Port, S_{21} measurement is made through the DUT in series.
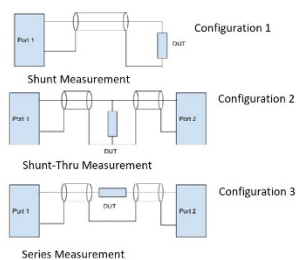

Figure 1 - Measurement Configurations

Measuring complex impedance is difficult. It would be necessary to ensure that the reference plane of calibration is precisely on the leads of the DUT. Port extension might be used to accomplish this, but it usually isn't necessary to go to the trouble. For instance, when measuring an inductor, the impedance *magnitude* will be flat from some low frequency until the reactance of the inductor exceeds its parasitic resistance, then the impedance will rise linearly with frequency as expected. The slope of this linear part

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is the inductance value. The linear magnitude is entirely adequate for this measurement.
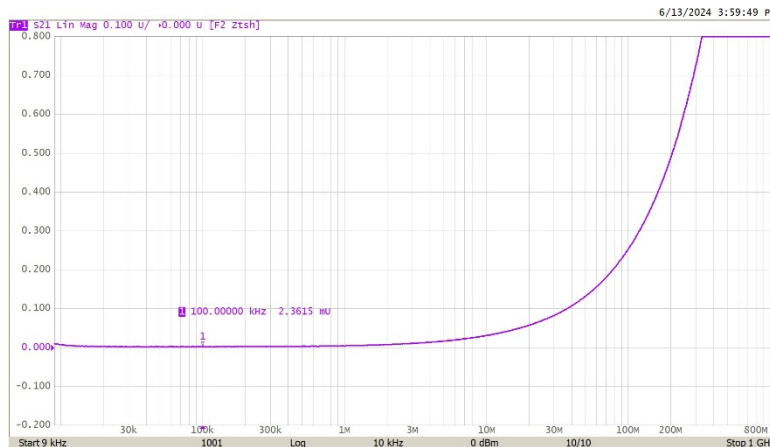

Figure 2 - 2 Milli-Ohm Resistor, Shunt-Thru

Figure 2 above shows the Shunt-Thru measurement of a 2 milli-ohm resistor. The vertical scale is in ohms and a logarithmic frequency range has been chosen. The resistance is flat until about 10 MHz where the lead inductance of the chip resistor begins to dominate, and the impedance rises.

The accuracy for resistance measurement can be kept below a few percent by appropriately choosing the right measurement configuration. Figure 3 shows the accuracy for measurement of resistance for each topology. Note that the accuracy of the shunt measurement doesn't actually reach perfection at 50 ohms, but the error becomes quite small. The accuracy for a complex impedance measurement is much more complicated but this chart may still be used as a guide to choose the appropriate measurement format. See [1]

Keep in mind that a VNA is not an LCR meter per-se but may be effectively used to measure lumped element characteristics. Additionally, LCR meters are generally low frequency devices where the VNA can measure component performance at high enough frequencies to expose the effects of parasitics.
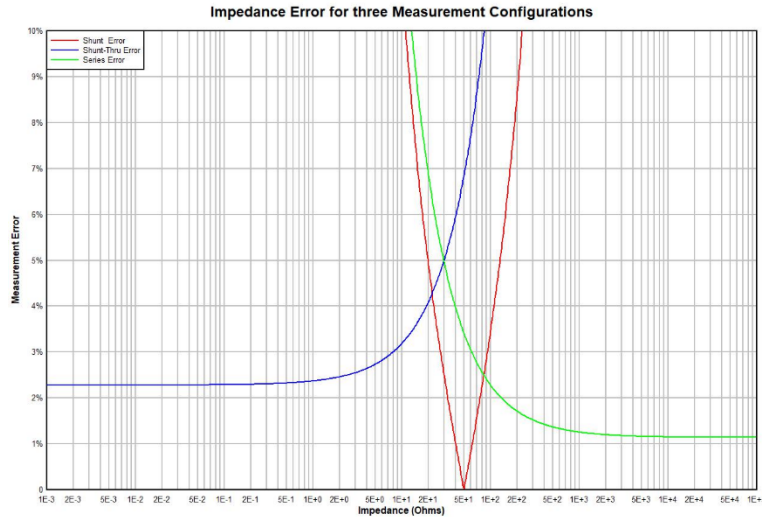
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Figure 3 - Measurement Accuracy

Extracting LCR Elements

It is possible to extract model L, C and R values from an S-Parameter file. We can show how the elements of simple "Pi" and "T" networks may be extracted from S-Parameter measurements [2]. Figure 4 shows two types of networks. The nomenclature here will be used in subsequent formulas where "Y" is an admittance and "Z" an impedance.
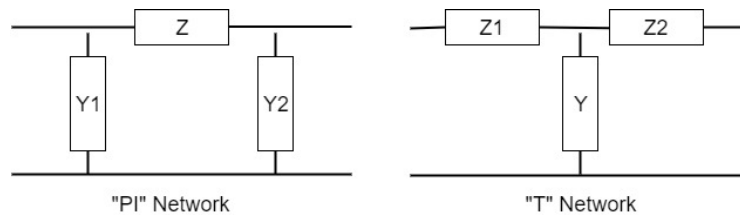

Figure 4 - Pi and T Networks

ABCD parameters will be used for the calculation [3], so it will be necessary to convert to them from S-Parameters. For 50 ohm source and load impedances, those formulas are as follows:

$$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}$$

$$B = \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}$$

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$$C = \frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}}$$

$$D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}}$$

For the Pi network of Figure 4, the ABCD parameters will be:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 + ZY_2 & Z \\ Y_1 + Y_1Y_2Z + Y_2 & 1 + ZY_1 \end{bmatrix}$$

And therefore:

$$Y1 = \frac{D-1}{B}, \ Z = B \ and \ Y2 = \frac{A-1}{B}$$

For the "T" network of Figure 4, the ABCD parameters will be:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 + YZ_1 & Z_1 + Z_1Z_2Y + Z_2 \\ Y & 1 + YZ_2 \end{bmatrix}$$

And therefore:

$$Z1 = \frac{A-1}{C}, \ Y = C \ and \ Z2 = \frac{D-1}{C}$$

A complicated network might have many elements, but it will begin with a series or a shunt element. The "T" extraction could be performed first and Z1 could be evaluated to see if it is proportional or inversely proportional to frequency. If it fits one of these criteria, then it may be modeled as a series inductor or capacitor respectively. If a resonance is seen, then one would have to derive the series L and C values. If no series element is possible, then the "Pi" model should be tried, and the first element will be modeled as a shunt term.

Clearly this method works well for simple, single L, C and R elements. Parallel L, C and R values in a single arm of a Pi or T network will make this process more difficult, but not impossible.

As an example, a 200 MHz, 50 ohm, 3 element Pi type Butterworth filter was analyzed and the S-parameters obtained from 1 kHz to 1 GHz.
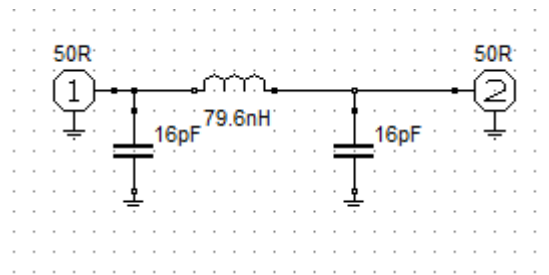
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Figure 5 - 200 MHz Butterworth Filter
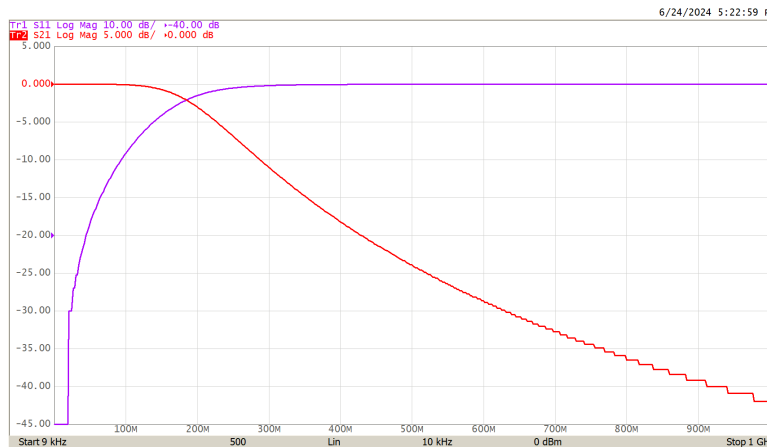
The response is shown in Figure 6.

Figure 6 - 200 MHz Filter Response

Using the Pi network ABCD equations, Y1, Y2 and Z may be extracted from the S-Parameters. In fact, the equations may be entered in the VNAs S-Parameter calculator and the C and L values may be read directly from markers on traces. To do this, click on the S-Parameter in the upper left corner of the screen and choose "more…", then Calculator, then Advanced.
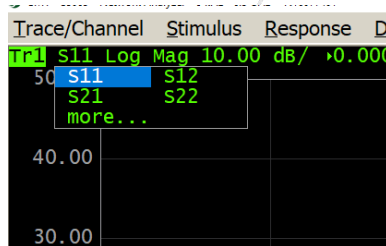

Figure 7 - Calculator menu

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Name the trace C1 and enter:

-0.02*s21*((s12*s21 - (s11 - 1)*(s22 + 1))/s21 - 2)/((s12*s21 - (s11 + 1)*(s22 + 1))*2*PI*frequency)

(You can cut and paste from this document)

Add a new trace to the screen, select it and go to the calculator and enter:

-25*(s12*s21 - (s11 + 1)*(s22 + 1))/(s21*2*PI*frequency)

Name this trace L1.

Add a third trace to the screen, select it and go to the calculator and enter:

-0.02*s21*((s12*s21 - (s11 + 1)*(s22 - 1))/s21 - 2)/((s12*s21 - (s11 + 1)*(s22 + 1))*2*PI*frequency)

Name this trace C2.

In general, for the Pi structure:

Y1 = -s21*((s12*s21 - (s11 - 1)*(s22 + 1))/s21 - 2)/(s12*s21 - (s11 + 1)*(s22 + 1))

Z = -1/2*(s12*s21 - (s11 + 1)*(s22 + 1))/s21

Y2 = -s21*((s12*s21 - (s11 + 1)*(s22 - 1))/s21 - 2)/(s12*s21 - (s11 + 1)*(s22 + 1))

For the T structure:

Z1 = -s21*((s12*s21 - (s11 + 1)*(s22 - 1))/s21 - 2)/(s12*s21 - (s11 - 1)*(s22 - 1))

Y = -1/2*(s12*s21 - (s11 - 1)*(s22 - 1))/s21

Z2 = -s21*((s12*s21 - (s11 - 1)*(s22 + 1))/s21 - 2)/(s12*s21 - (s11 - 1)*(s22 - 1))

These formulas may be pasted directly into the calculator. It is important to note that the example above used a simulation where the reference planes were located directly on the input and output components. For a real measurement, there will be some delay

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between the VNA connection and those components. Port extension must be used to remove this delay.

To characterize an unknown network, determine whether the input has a leading shunt or series term and use the Pi or T model to determine its value. Generate the S-Parameters for this value alone using a linear simulator such as AWR and then use de-embedding on the VNA measurement to virtually remove it. Repeat this process. If the first model component was in series, use the Pi model to find the next shunt term in the de-embedded data. If the first model component was in shunt, use the T model to find the next series element. Now simulate the first and second components with the linear simulator and de-embed the new results from the measurement to get to the third leg. In this way, a ladder network representation of a device may be constructed. Of course, the results will become noisy and ill-conditioned after a limited number of terms.

Fortunately, many devices can be modeled with only three terms. For instance, a surface mount inductor may be modeled as a Pi network. The mounting pads will have shunt capacitance to ground and the inductor itself will have a series resistance, a series inductance and a capacitor in parallel with the inductor due to inter-winding capacitance.

De-embedding a component is accomplished by obtaining the 2-Port S-Parameters of that component and then point the VNA to the file. From the main menu in the S2VNA or S4VNA software, go to Analysis/Fixture Simulator/De-Embedding and point to the file by choosing "S-Parameters File" under Port-1 or Port-2. After selecting the file, Port-1 or Port-2 will indicate "ON" automatically. You must also push the "De-Embedding" button to turn on the function. Finally, navigate up one level in the menu and push the "Fixture Simulator" button. The component represented by the S-Parameter file is now virtually removed from the measurement.

Conclusion

A VNA is a power tool for RF measurement and may be used to characterize lumped elements, resistors, capacitors, and inductors. Copper Mountain Technologies produces world-class metrology grade VNAs suitable for these and other sophisticated measurements. For measurements of lumped elements it is important to use a VNA which can work to very low frequencies.

References

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1. Walker B., Make Accurate Impedance Measurements Using a VNA, Microwaves & RF, 21 June, 2019
2. Walker B., RLC Parameter Extraction Using the Transfer Matrix, Microwave Journal, July, 2020
3. Frickey D., Conversions Between S, Z, Y, h, ABCD and T Parameters which are Valid for Complex Source and Load Impedances, IEEE Transactions on Microwave Theory and Techniques, Vol 42, No 2, Feb 1994