EE 133: Intro to RF Systems Laboratory

Lab 1: The Secret Life of Passive Components
And
We meet a new friend, the VNA

Instructor:
Steven Clark
Lecturer
Electrical Engineering Department
David Packard Building, Room 112
350 Jane Stanford Way
Stanford, CA, 94305-9505
+1 650 723 1660
steven.clark@stanford.edu

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DELIVERABLES:

- A lab report in the style described on the Github containing
  - Picture of schematic and plot of capacitor impedance from LTSpice simulation
  - Picture of schematic and plot of inductor impedance from LTSpice simulation
  - Descriptions and pictures of real measurements taken with the VNA

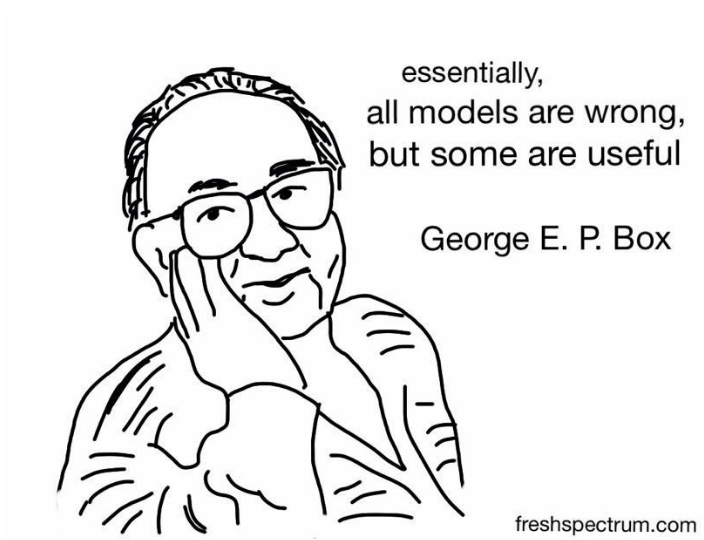
SUBMISSION:

Push your files to a fork of the lab repo. Place this in a folder called Lab 1 to make sure the files stay organized.

Objective

The objectives of this lab are:

- to learn how to use a VNA
  - how not to abuse your VNA
  - calibration (SOLT)
  - different display modes
  - and recording / displaying data on your laptop, and
- to understand the properties of passive components.



(not an endorsement, they just had a nice line drawing)

Introduction

Passive components are such a good deal! We *always* get three for the price of one. That is to say that all components have "parasitic" properties that may influence circuit performance in some frequency regime. To be clear, the term "parasitic" is somewhat of a misnomer; devices and circuits don't have "parasitics", they simply obey Maxwell's equations. It is only when we attempt to use "lumped" circuit elements to facilitate calculations that we are forced to add extra "components" to make the model correspond well enough to measurement to be useful.

Resistors -

For example, resistors can have lead inductance and capacitance associated with their construction. Figure 1 shows several aspects of a leaded (through-hole) resistor.

R is the nominal resistance while C_p is the "parasitic" capacitance of the resistor. The R_{lead1}, R_{lead2}, L_{lead1}, and L_{lead2} are the resistances and inductances associated with the lead wires. L_{self} is any inductance due to the physical construction of the resistor; so L_{self} is the inductance left if we imagine a resistor without leads (like an SMT style resistor).

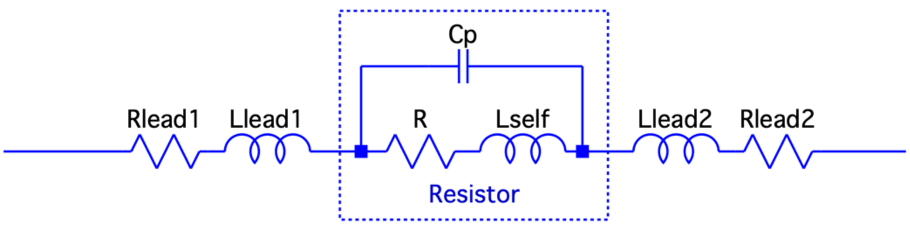


Figure 1a. – Schematic of a more realistic resistor model

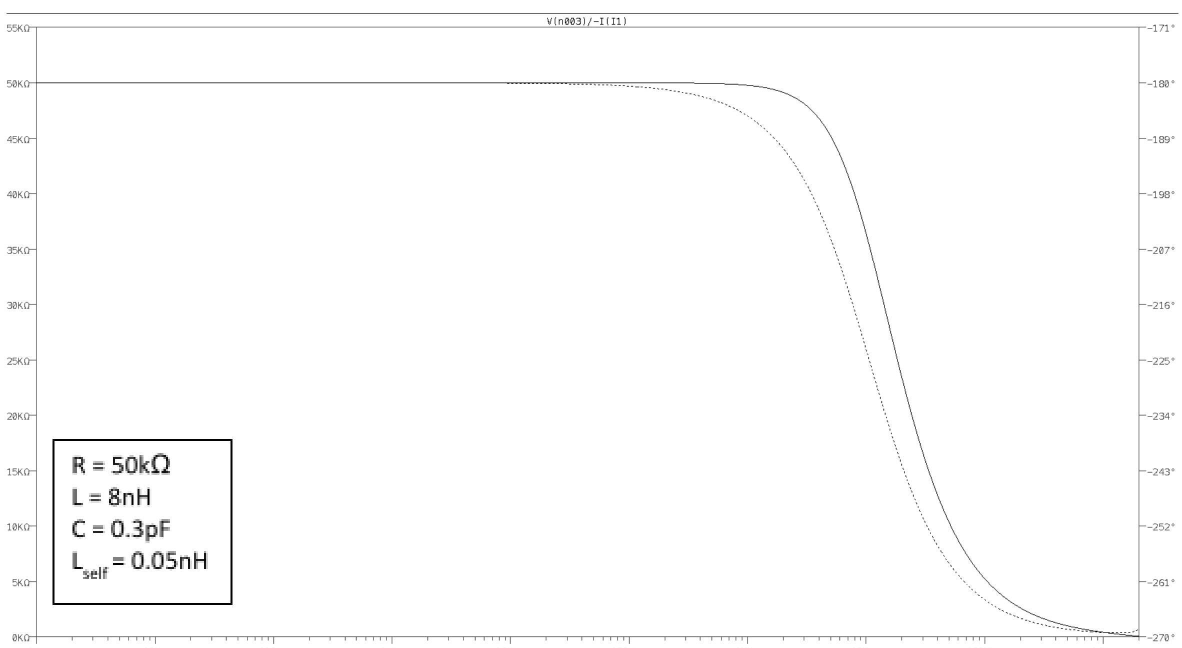


Figure 1b. – Impedance plot when R = 50kΩ

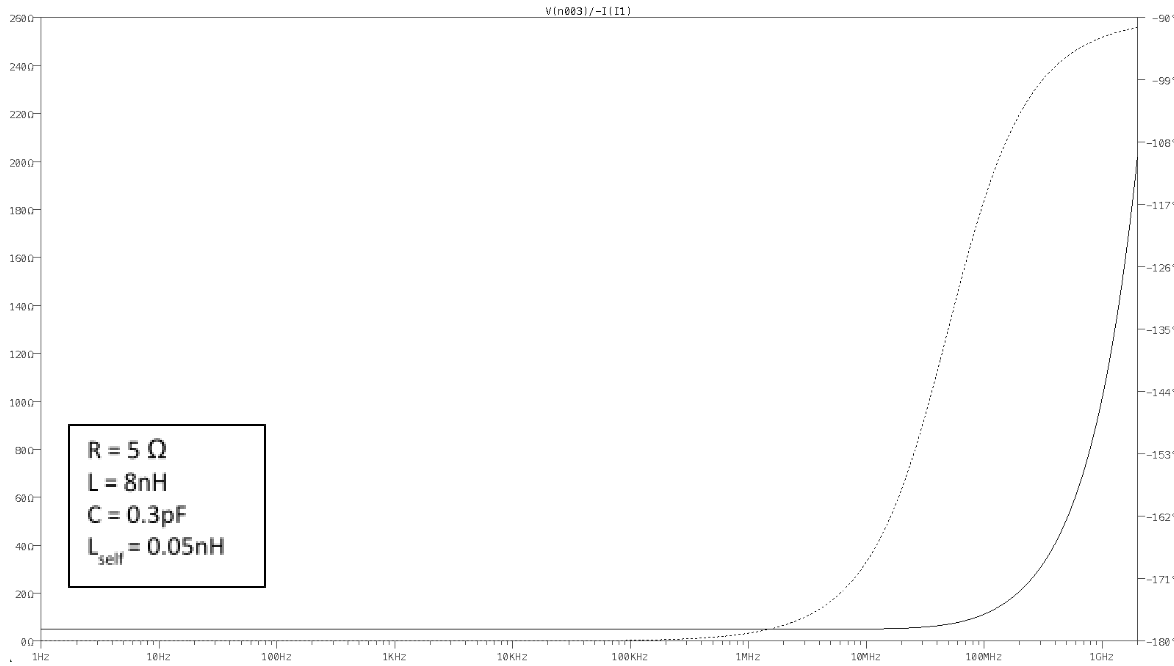


Figure 1c. – Impedance plot when R = 5 Ohms

Figure 1. - A more realistic model of a resistor and the frequency dependence of its impedance.

References 1 and 2 provide more information on resistors and their properties.

Let's also think about models for capacitors and inductors while we're at it.

Capacitors-

Capacitors are ubiquitous devices, are available in many different "technologies", and have values that span 12 orders of magnitude! A nice overview of various types of capacitors and their properties can be found, as usual, in H&H 3 §1.4 and H&H X § 1.3. For those folks that find videos easier, you might enjoy [this one].

A more realistic model for capacitors is shown in Figure 2.

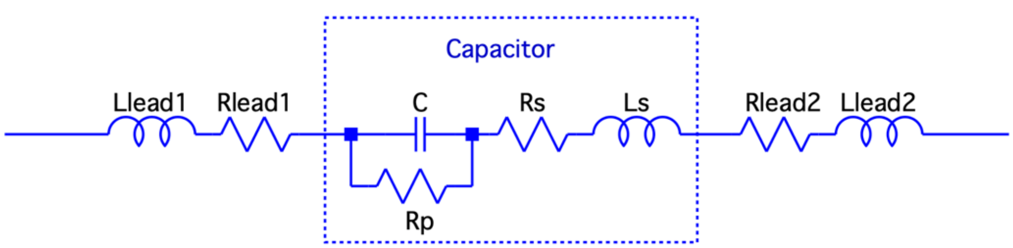


Figure 2. – Schematic of a more realistic capacitor model

One feature that might be puzzling is the presence of resistors R_p and R_s. These can be understood by observing that current flows even when a DC voltage (f = 0) is applied across a capacitor. To account for this "leakage" current we introduce the resistance R_p. R_p is typically very large. In fact, without R_p the model capacitor would hold charge forever and we know this is not the case with self-discharge time constants τ (= R_pC) ranging from thousands of seconds to a few years for VERY good capacitors.

Urban legend - Capacitors can suck charge from the environment. Is this true?

While we're discussing capacitors it is worth noting that there is a persistent urban myth that capacitors "suck" charge from their surroundings and this is why large value capacitors should be stored "shorted". Capacitors do *not* suck charge from thin air; they can have large dielectric absorption effects which give rise to residual charge storage and this, in turn, appears across the terminals and can give a nasty shock. So large value capacitors ***should*** be stored with a wire shorting the two terminals for safety but not because they are violating the laws of thermodynamics. A demonstration of dielectric absorption may be found HERE.

But then what about R_s? This is also known as equivalent series resistance (ESR) and is frequency dependent because it is composed of differing components. At low frequencies the dominant contributor to ESR is the dissipative loss from dielectric polarization changes; at higher frequencies the ESR is primarily due to losses from metallic resistivity and skin effect.

Similarly, L_s, the equivalent series inductance (ESL), arises from inductance attributable to metallization structures in the device. ESL is typically in the range of a few nH but may be reduced to ~ 1 nH by using special geometries inside the capacitor.

What is the consequence of all this? To see, let's plot impedance at various frequencies.

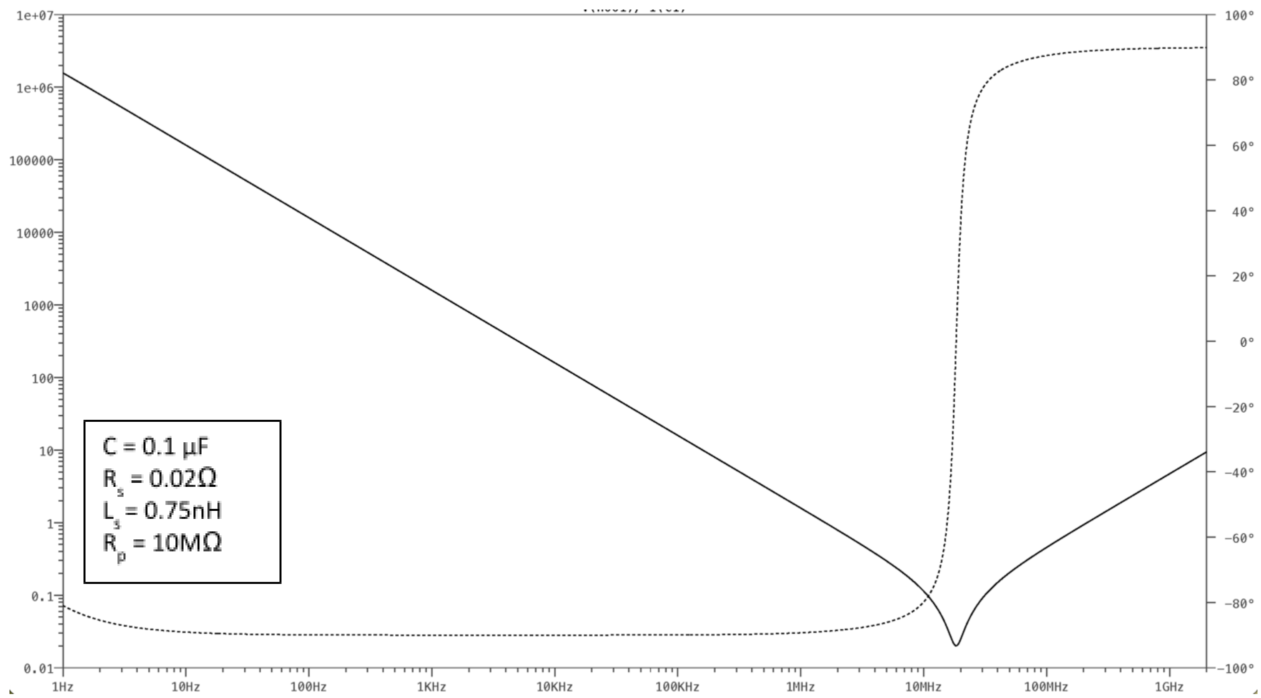


Figure 3. – Impedance plot for “realistic” capacitor (model in Figure 2.).
Note the “self-resonance” at approximately 19MHz. The lowest point is where C and L_s are in resonance and so R_s is limiting. Plot generated using LTSpice.

It can be quite helpful to consider ESR in relation to the capacitive reactance of the device and the ratio ESR/X_c is known as the dissipation factor, DF (DF = ESR/X_c). DF is inversely related to the quality factor, Q (i.e., DF = 1/Q). If we are thinking in terms of complex numbers (phasors), the dissipation factor may be written as DF = tan(δ) where the angle δ is called the loss tangent. For small DF, the loss tangent in radians is approximately equal to DF ($\delta \approx$ DF, for $\delta \ll 1$). Datasheets will often specify a loss tangent for a capacitor series and may well give a self-resonant frequency.

For SMT capacitors the R_{lead} and L_{lead} values are quite small and may usually be neglected except at high frequencies.

While one may be tempted to think this is all one needs to know about capacitors, this would be a mistake. Capacitors exhibit many “interesting” properties such as temperature and voltage dependence, microphonics, etc. For a more detailed discussion of these and other interesting things visit Ch. 1x of Ref. 1, while Refs. 3 and 4 contain additional information on high frequency applications of ceramic capacitors.

Inductors-
Inductors present a more complicated situation, and we won’t go into much detail in this lab, however Figure 3. shows a more realistic inductor model (lead parasitics not shown).

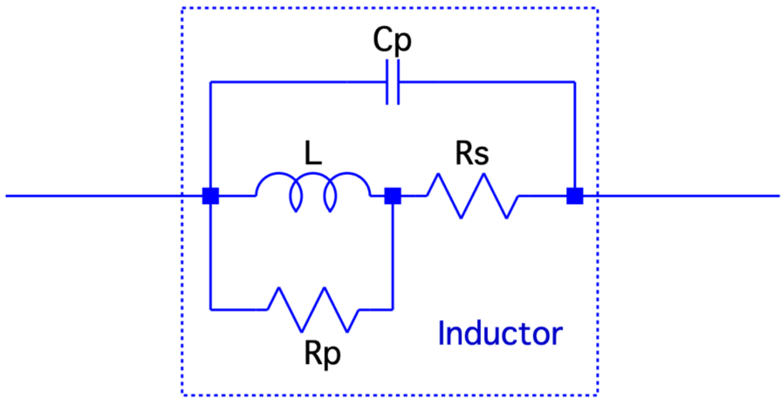


Figure 4. – Schematic of a more realistic inductor model

In this model R_s is the resistance of the inductor at DC (f = 0). R_p can be quite complicated because we are lumping together core losses, eddy current losses, hysteresis losses and so forth. Dr. Greig Scott of the Stanford Magnetic Resonance Systems Research Laboratory (MRSRL) points out that R_p is a "big deal" for folks working in MRI – for them **R_p is the patient!** C_p is the interwinding or shunt capacitance. At high enough frequencies, C_p will dominate the total impedance and the inductor will "turn capacitive". This being the case, it might be expected that there will be a "self-resonant" frequency for an inductor. Figure 5. shows an impedance plot for a simulated 100 nH SMT inductor.

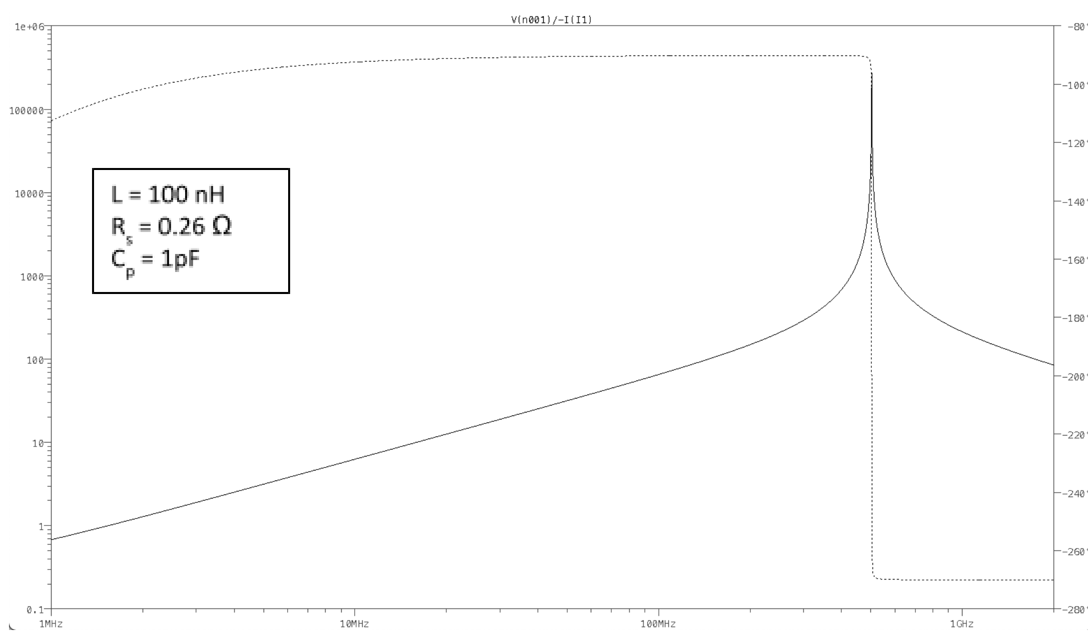


Figure 5. – Impedance plot for simulated 100nH SMT inductor.

One can check their understanding of things by answering the questions:

- what is the self-resonant frequency for this inductor?
- what limits the magnitude of the response (the height of the peak)?
- the peak looks narrow, is this correct?

Great! We're ready to move on to the lab part!

In this lab, you'll learn how to use a vector network analyzer (VNA) to measure the values of the various "parasitic" components associated with the thing you think you have (resistor, capacitor, or inductor). The goal of this exercise is to develop at least a nascent intuition for when "parasitics" can be ignored and when they must be taken into consideration. In addition, you may gain enough confidence to be able to measure component properties and assign values for the relevant "parasitics".

Meeting our new friend, the Vector Network Analyzer (VNA)

What does a VNA do?

A VNA is: *an instrument that measures the frequency dependent magnitude and phase of the reflection and transmission properties of a network*.

To discuss how this is done, a simplified block diagram of the VNA we will be using is shown in Figure 6.

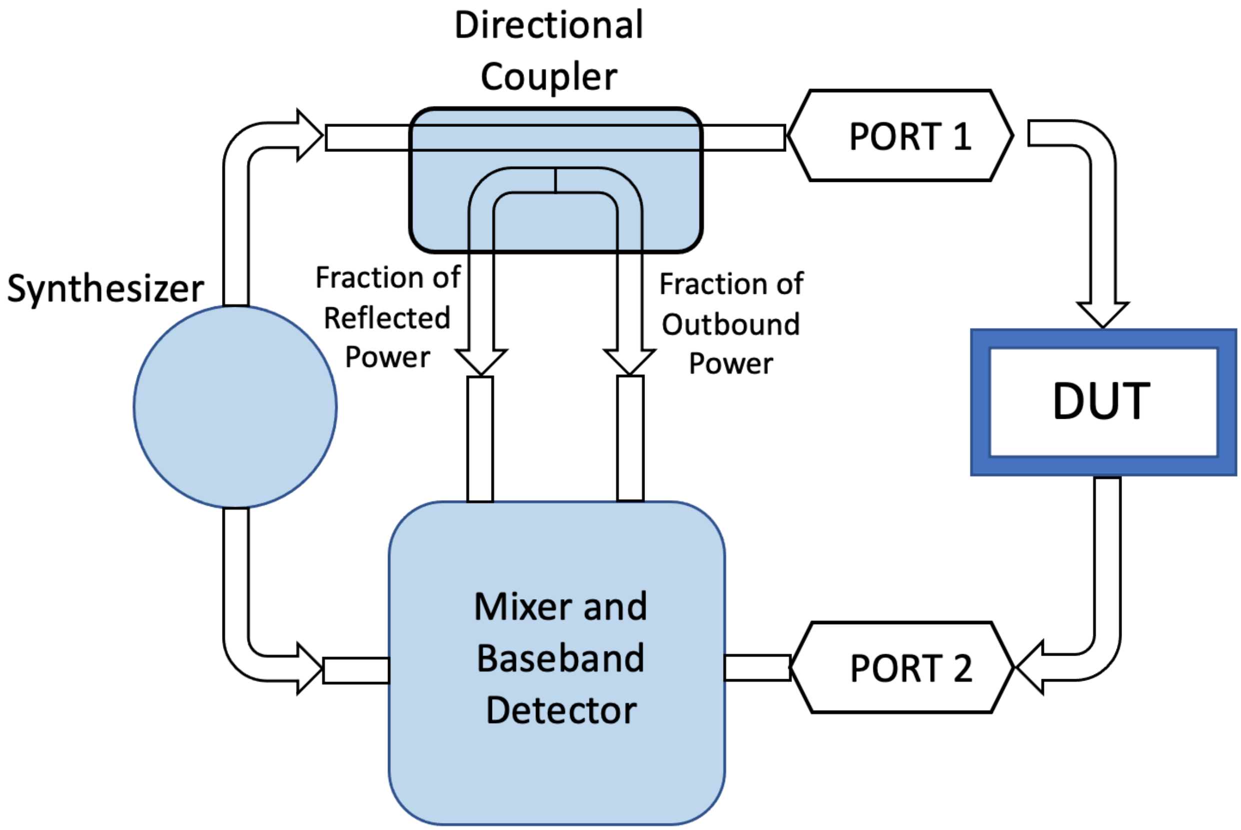


Figure 6. – An extremely simplified block diagram of the nanoVNA v2 Plus4.
The VNA measures both the incident power and the power reflected by the Device Under Test (DUT) via Port 1. Power transmitted by the DUT is measured via Port 2.

The VNA measures the S-parameters of a system (device under test or DUT) over some frequency range. It does this by sending a signal out of a port and simultaneously measuring the signal reflected from the system back toward the same port. By comparing the outbound signal with the reflected signal (both magnitude and phase) S_{11} can be calculated.

Often there is a second path that allows the measurement of the signal transmitted through the DUT. This allows S_{21} to be calculated. This is the case with the VNA we will be using.
In more advanced VNAs the entire first port path is replicated facilitating measurement of S_{12} and S_{22}. This is typical of the (much) more expensive instruments.

For more information on VNA basics you may wish to read Reference 6. or watch Reference 7. These provide much more detail on how these instruments work.

The VNA we will use – the NanoVNA2 PLUS4
In keeping with the goal of accessibility, we will be using the NanoVNA V2 Plus4 which is an inexpensive open-source vector network analyzer. The NanoVNA V2 Plus4 is an active project and it is helpful to refer to the most current information (found at https://nanorfe.com/).

Please take some time to review the material presented on this site since it will help you save time in the lab.

Although the NanoVNA2 PLUS4 can be used in “standalone” mode, we will want to use the additional functionality provided by the associated computer software. There are several programs available for the nanoVNA V2 Plus4: NanoVNA-QT, NanoVNA Saver, and NanoVNA_Software. The website says-

“NanoVNA-QT is the native V2 software and allows adjustable sweep points and firmware updating. NanoVNA-Saver was originally developed for the V1 NanoVNA but now also has support for V2.”

What it actually does
How the results are displayed

How to avoid abusing your VNA
Using connector savers (aka - sacrificial connectors)
One of the first things to understand about the VNA is how to connect it to the things to be tested. A lot of the equipment we’ll be using has connectors called SMA connectors.

What about BNCs?
How to avoid overloading the front end

Setting up your VNA
First power-up
Checking the configuration
Upgrading the firmware
Loading software on your computer
Storing files / keeping things tidy

Calibration is the key!
The SOLT calibration process
How good do the “standards” need to be

Let’s measure stuff!
Does your thru look like a thru?
Let’s measure a few resistors.
Now let’s try some caps!
And how about some inductors?

Now let’s plot things to see if they look as expected!

VNA’s can do a LOT more!
Measuring VSWR / antenna tuning
Characteristic impedance of a cable

References

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2. Vishay Technical Note 60107, “Frequency Response of Thin Film Chip Resistors.”
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5. Reference 5.
6. Lee, Thomas H. *Planar Microwave Engineering*, Cambridge University Press, 2004.
7. https://www.youtube.com/watch?v=Sb3q8f0NBZc&list=PL4ZSD4omd_AylEyNCQYR3RcEb0olukPEJ&index=4
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