ECE 451

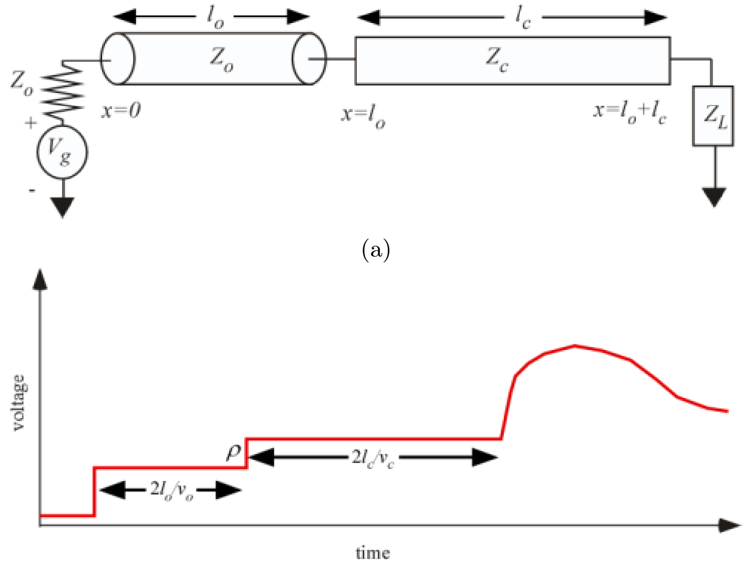
Automated Microwave Measurements Laboratory

Experiment 4 - Time-domain Reflectometry

1 Introduction

In this laboratory session, we will be using a modern network analyzer to perform microwave measurements, **just as an engineer would in a real work environment**. You will learn how well sophisticated RF/microwave measurement systems are hidden from the users by just some simple button presses. It provides simple procedures and elegant ways to save time and effort when a measurement is needed. But it also takes away the insights and could leave a lot of troubles for the users when something malfunctions or when the users fail to interpret mere tabulated numeric values obtained by the machine.

Time domain reflectometry is a procedure in which the step response of an unknown device connected at the end of a known lossless transmission line is used to determine the characteristics of said device. The device can be a reactive element such as a capacitor or an inductor. In particular, if the unknown device is another lossless transmission line, the TDR method allows to fully characterize it by extracting its characteristic impedance and propagation velocity. Consider the test setup in Figure 1a. A step generator V_g with internal impedance Z_0 is connected to a reference transmission line with characteristic impedance Z_0, length lo and propagation velocity V_0. The reference line is then connected to an arbitrary transmission line of unknown characteristic impedance Z_c, unknown propagation velocity V_c and known length l_c.



(a)

(b)

Figure 1: Time-domain reflectometry; application to transmission-line characterization. (a) Experimental setup. (b) Voltage readings at point x=0. The time axis can also be used as position axis, which allows location of discontinuities along the test line.

A step excitation will produce the response shown in Figure 1b in which a reflection with respect to the reference line ρ and the propagation delay τ_c in the test line can be easily measured. The characteristic impedance of the line and its propagation velocity can be extracted using the relations:

$$Z_c = Z_o \left(\frac{1+\rho}{1-\rho} \right) \tag{1}$$

And the propagation velocity of the unknown line is found using:

$$v_c = \frac{2l_c}{\tau_c} \tag{2}$$

For more information refer to the **Keysight TDR Application Note**.

This lab will take two weeks to finish. We strongly suggest you to read through the entire lab before the class, so you have a better understanding on the lab structure. If you finish the work for week 1 early, feel free to work on week 2 materials.

In week 1, You will walk through the necessary procedure to perform 2-port measurements and learn to interpret the data with 4-port device exercise. Then You will be introduced to perform time-domain reflectometry (TDR) analysis on NanoVNA. In week 2, you will learn the important correlation between frequency- and time-domain characterizations by re-producing TDR results with ADS transient simulation. Last but not least, you will use various TDR tools to characterize the SMA cables.

2 Background

Time-domain reflectometry (TDR) using VNA

The measurement technique of TDR was introduced in the early 1960's and works on the same principle as radar. A pulse of energy is transmitted down a cable. When that pulse reaches the end of the cable, or a fault along the cable, part or all of the pulse energy is reflected back to the instrument. TDR measurements are made by launching an impulse or a step into the test device and observing the response in time. By measuring the ratio of the input voltage to the reflected voltage, the impedance of simple discontinuities can be calculated. The position of the discontinuity can also be calculated as a function of time by applying the velocity of propagation along the transmission line. The type of discontinuity (capacitive or inductive) can be identified by its response.

Then, in the 70's, it was shown that the relationship between the frequency domain and the time domain could be described using the Fourier Transform. The Fourier Transform of the network reflection coefficient as a function of frequency is the reflection coefficient as a function of time; i.e., the distance along a transmission line. It was possible to measure the response of a DUT in the frequency domain and then mathematically calculate the inverse Fourier Transform of the data to give the time domain response.

Even though some VNAs provide a TDR-like display, there are differences between traditional TDR and VNA time domain techniques. The transform used by the VNA resembles time domain reflectometry, however, the analyzer makes swept frequency response measurements and mathematically transforms the data into a TDR-like display. In low-pass mode, which supports both impulse and step TDR response, thus, is used in this experiment, the VNA measures discrete positive frequency points, extrapolates DC, and assumes that the negative frequency response is the conjugate of the positive, i.e., that the response is Hermitian[1]. Band-pass mode, which only supports impulse TDR response, is beyond the scope of this course, thus, will not be discussed here. For the complete theory behind calculating TDR responses on the VNA, please refer to [1] .

NanoVNA TDR Measurement Instructions

After doing 1 port SOL calibration from 50kHz to 3GHz on NanoVNA, you can use port 0 for TDR measurement. Disable all other traces and leave only Trace 0 on display. Select *DISPLAY→TRANSFORM→TRANSFORM ON* to convert measured data to the time domain. Under the same menu, you can choose excitation sources (low pass impulse/step) for the TDR simulation based on your need. There are two format the trace can be displayed: REAL (in terms of voltage vs time) and RESISTANCE (in terms of trace resistance vs time). You can find measurement examples of OPEN and SHORT standers in NanoVNA user manuals [2].

In order to obtain a more accurate TDR measurement, you are encouraged to set the *VELOCITY FACTOR* under the *TRANSFORM* menu. This is the speed reduction for electromagnetic waves travelling in medium compared to in vacuum. For now, you can set this value to 59 (wavelength reduction rate of 59%). The calculation detail for this constant will be introduced in Lab 6 Advance Technique.

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[1] A complex-valued function $H(s) : \mathbb{C} \mapsto \mathbb{C}^m$ is Hermitian iff $H(s^*) = H^*(s)$

Scattering Parameters for TDR

Scattering parameter of one-port network can be measured over a wide frequency range. Since incident and reflected voltage waves on a transmission line are related through the measured scattering parameters, the total voltage can be determined as a function of frequency. In this lab we propose to reproduce the TDR response of a DUT from its measured scattering parameters. For this purpose, we need to simulate the time-domain response associated with frequency-domain measurements using a step function as the excitation (see Figure 2). The main motivation or advantage for taking this approach stems from the fact that fast rise time pulse and steps are difficult to design; but high-frequency signals are available. A fast step will produce higher spatial resolution in characterizing the unknown device.

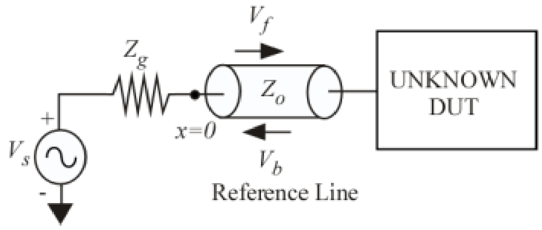


Figure 2: S-parameter setup for TDR simulation

Since the system is linear, its response in the time domain is the superposition of the responses due to all frequencies $S_{11}(\omega)$ is measured experimentally. Assume $V_s(t)$ to be an arbitrary time-domain signal (unit step, pulse, impulse). $V_s(\omega)$ is its transform. We also have:

$$V_f(x=0,\omega) = \frac{V_s(\omega)}{2} \tag{3}$$

$$V_b(x=0,\omega) = \frac{V_s(\omega)}{2} S_{11}(\omega) \tag{4}$$

$$V(x=0,\omega) = V_o(\omega) = \frac{V_s(\omega)}{2}\left[1+S_{11}(\omega)\right] \tag{5}$$

where

$$V_s(\omega) = \int_{-\infty}^{\infty} v_s(t) e^{-j2\pi f t} dt \tag{6}$$

$$v_o(t) = \int_{-\infty}^{\infty} \frac{V_s(\omega)}{2}\left[1+S_{11}(\omega)\right] e^{+j2\pi f t} df \tag{7}$$

Consequently, the time-domain response measured at x = 0 can be obtained from the inverse Fourier transform of the frequency-domain response at x=0. If the excitation corresponding to $V_s(t)$ is a step function, then the time-domain response will correspond to the TDR response of the DUT.

Summary of Steps

1. Measure $S_1 1(f)$
2. Calculate $V_s(\omega)$ analytically
3. Evaluate $V_o(\omega) = V_s(\omega)\left[1+S_{11}(\omega)\right]/2$
4. Feed $V_0(\omega)$ into inverse Fourier transform to get $V_0(t)$

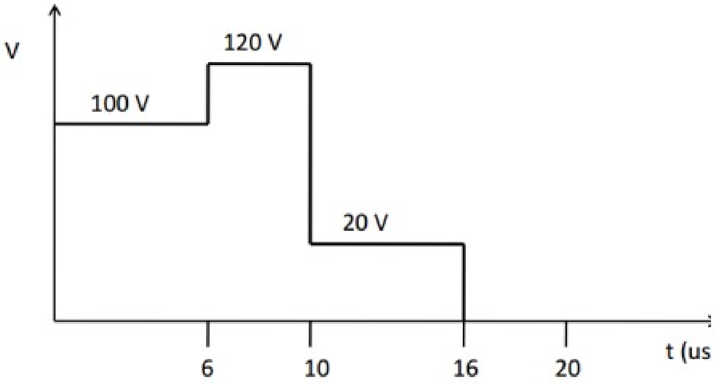
Special Considerations

- For negative frequencies use conjugate relation $V(-\omega) = V^*(\omega)$
- DC value: use lower frequency measurement
- Rise time is determined by frequency range or bandwidth

- Time step is determined by frequency range
- Duration of simulation is determined by frequency step

3 Pre-lab

1. Suppose a TDR having a source impedance of 50Ω is attached to a 50Ω coaxial cable having some unknown length and load resistance. The dielectric of the cable is Teflon ($\epsilon_r = 2.1$) and the open circuit voltage of the TDR is a pulse of duration $10\mu s$. The recorded voltage at the input to the line is shown below:

   (a) Determine length of the line.

   (b) Determine the unknown load resistance.

2. You are given a 4-port device that is reciprocal and has obvious symmetry depicted in Figure 3. Explain how you would use the following 2-port measurements to obtain all 16 S-parameters of device (numbers in the table are corresponding to that denoted in Figure 3).

	Port 1	Port 2
Measurement 1	1	2
Measurement 2	1	3
Measurement 3	1	4

Figure 3: Reciprocal 4-port device

3. The rise time of a signal is 100ps, what is the highest frequency content in this signal? If a signal is fed through an LTI system, we know from Fourier theory that the output spectrum is given by the product of the input spectrum with the transfer function of the system. If the 100ps rise time signal is fed through an LTI system that is represented by S-parameter, what is the required frequency range of the S-parameter file to correctly calculate the output signal?

4. By inspecting the **hardware architecture** of NanoVNA, which port/ports have source? which port/ports have receiver? If only port 1 has source, which one/ones of measurements (S_{11}, S_{21}, S_{12}, S_{22}) are meaningful?

4 Equipment

- Advanced Design System (ADS)
- JupyterLab
- S-A-A-2 NanoVNA
- 3.5mm SOLT calibration kit
- Student board: DUT 4 & DUT 5

5 Procedure

Part 1 (week 1) - 1 Port & 2 Port S-parameter Measurement

Note: For future measurement, unless otherwise noted, use 201 points for accuracy concern.

1. Perform a **1 Port SOL** calibration on NanoVNA from 1GHz to 3GHz with 401 points. Measure DUT 4. Capture and Save the file as 'dut4.s1p'.

2. Import your DUT 4 measurement to ADS, compare it with the TA data for DUT 4. Overlay their S_{11} on smith chart and also dB/phase plots. Does your measurement match with ours? If not, re-do the calibration and then repeat the measurement.

3. Perform a **2 Port SOLT** calibration on NanoVNA from 100kHz to 3GHz with 201 points and then measure DUT 5. Note that NanoVNA only supports up to 6-terms error model (SOLT(T/R)) that correct for S11 and S21 response. Hence, for a full 2 port calibration, you will need to calibrate and measure the device twice by physically swapping the DUT's ports to get all 4 s-parameters (S11, S21, S12, S22) corrected. You will then manually combine matrix of S11 & S21 (from port 1 calibration) and S22 & S12 (from port 2 calibration) in Jupyter Notebook. You may now save the post-processed s-parameter as 'dut5.s2p'.

4. Compare your DUT 5 measurement with the TA data for DUT 5. Plot the following items:

   - S_{21} (dB & phase)
   - S_{12} (dB & phase)
   - S_{11} (smith chart)
   - S_{22} (smith chart)

   Re-do calibration and measurement if needed. The reason you have to swap ports during measurement is that NanoVNA only has a single source on CH0. It creates a full s2p file by duplicating S11 & S21 as S22 & S12 based on reciprocal property. However, as you may now see on the plots above, there indeed exists small variation between S11 & S22 (same for S21 & S12). Therefore, for all future 2-port measurements, you will need to measure the item twice and manually combine the matrix in Jupyter Notebook.

Part 2 (week 1) - 4 Port Device

1. For a 4-port device as shown in Figure 4, What is the least number of 2-port measurement should you do to create a full s4p file (assuming both VNA ports have source)? List out the measurements (use the table format from pre-lab) and explain how you plan to combine them.

2. For a 4-port device as shown in Figure 5, What is the least number of 2-port measurement should you do to create a full s4p file (assuming both VNA ports have source)? Again, list out the measurements and explain how you plan to combine them. Compared to device I (Figure 4), why does device II take less steps?

3. For a 4-port device as shown in Figure 6, What is the least number of 2-port measurement should you do to create a full s4p file (assuming both VNA ports have source)? List out the measurements and explain how you plan to combine them. Compared to device I (Figure 4),why device III take less steps?

Figure 4: 4-port device I

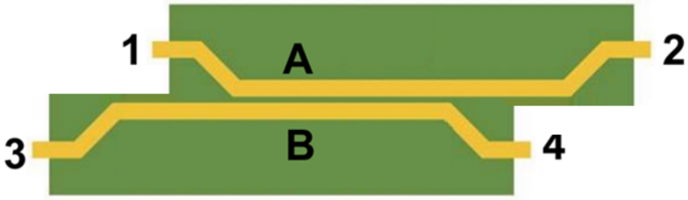


Figure 5: 4-port device II

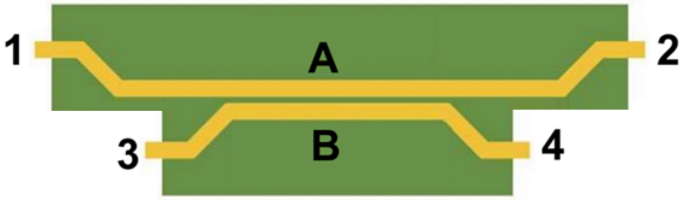


Figure 6: 4-port device III

Part 3 (week 1) - TDR using NanoVNA (Low-pass Mode)

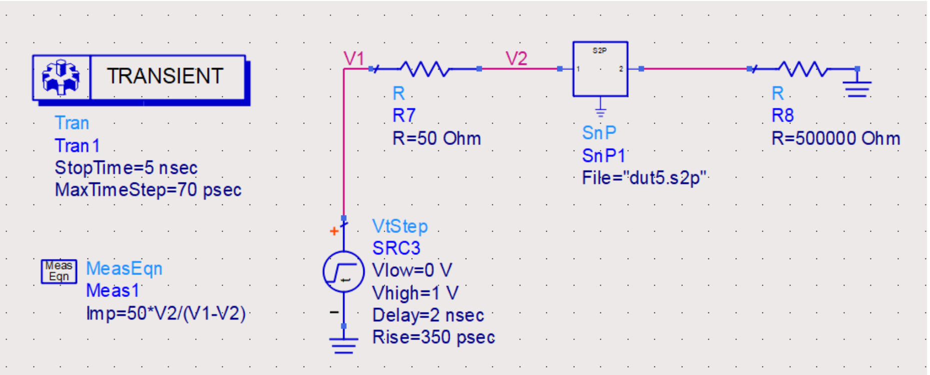
After 1 port SOL calibration of 50KHz to 3GHz, connect one side of DUT 5 to NanoVNA port 1 and the other side with terminations listed below. Obtain the following TDR measurements (you may refer to Background section):

1. TDR impulse response of DUT 4.
2. TDR impulse response when DUT 5 is terminated with an open, short and matched load (3 plots).
3. TDR step response of DUT 4.
4. TDR step response when DUT 5 is terminated with an open, short and matched load (3 plots).

Comment on what you observe for each TDR response (number of segments, impedance of each section, etc). Add as many markers as needed to support your claim. Also, take photos of your NanoVNA display for the report.

Part 4 (week 2) - TDR using Transient Simulation in ADS

1. In ADS, draw the schematic as shown in Figure 7. The measurement equation (*MeasEqn*) takes the voltage readings and calculates the (time-varying) impedance looking-toward-the-load at "v2" node. The load resembles an open termination.
2. Run the simulation and plot the TDR impedance of DUT5. Does it match with the expected impedance profile in your Prelab question? Does it match with the TDR step response shown on VNA (put your photo of VNA display here for proof)? Identify as many segments as you can on the impedance profile compared to the physical board, for example, identify which part in the impedance profile is the longest piece (the middle segment) on DUT5, can you identify other segments?



Tran
Tran1
StopTime=5 nsec
MaxTimeStep=70 psec

MeasEqn
Meas1
Imp=50*V2/(V1-V2)

R
R7
R=50 Ohm

SnP
SnP1
File="dut5.s2p"

R
R8
R=500000 Ohm

VtStep
SRC3
Vlow=0 V
Vhigh=1 V
Delay=2 nsec
Rise=350 psec

Figure 7: TDR analysis using ADS (slow rise time)

3. Now, decrease the rise time to 30ps. Comment on any changes in the impedance profile now. It would be more convenient for comparison if you set up a parametric sweep for the rise time so that you can plot the response for both cases on the same plot. What was the required bandwidth corresponding to a 30ps rise time signal? Does your measurement provide requested data? If not, explain how the simulation is feasible? Hint: Go to tab *Options* in the Transient solver palette, change "Status level" from 2 to 4 so that ADS would provide more information about the simulation in the *"Simulation Messages"* window.

4. You can download the TDR response of 30ps rise time step excitation measured by an oscilloscope HERE. Note that in this TDR measurement, a short SMA cable was included as a reference line (Z_0 in Figure 1a). Plot it on top of the simulation response above, comment on the discrepancies you observe between this measurement and your simulation.

Part 5 (week 2) - Measurement of SMA Cable

1. Calibrate VNA from 1MHz to 2.8GHz with 301 points (1 port SOL). Connect the blue SMA cable (terminated with open) to port 1 and perform TDR measurement. Put markers on where the cable starts and ends. What is the impedance of the cable? What is the length of the cable (given the wavelength reduction is 70)? Take a ruler and measure the cable's physical length, does it match with your calculation?

2. Save the 1-port s-parameter and import it to ADS. Perform TDR using transient simulation with appropriate rise time. Does your results match with previous observations? Place markers in data display to verify.

3. Download the IFFT code HERE. It is a simple program that calculates cable length from s-parameter files. Create a new python 3 file in to your Jupyter Notebook and copy over the text. Under the same folder, upload the 1-port measurement and name it as 'cable.s1p'.

4. Run the code you just created and screen capture the result. Is the length of the cable expected?

6 Conclusion

1. Explain how the *MeasEqn* in Figure 7 gives the TDR impedance profile. Prove the formula.

2. For the most accurate result, what is the theoretical bandwidth we need for the measurement (Hint: use ruler to measure the shortest segment of DUT 4 & DUT 5)? What is the theoretical rise-time setup?

3. If we are to measure TDR step response of a inductor in series with a 50 Ω resistor, what do you expected to see on the display? Answer this question with ADS screenshot (HINT: help yourself HERE).

References

[1] Keysight Technologies, Inc. *Time Domain Analysis Using a Network Analyzer.*

[2] `https://nanorfe.com/nanovna-v2-user-manual.html`.