3 TIME DOMAIN REFLECTOMETRY (TDR)

1. Introduction

In this laboratory session we will study a time domain reflectometer (TDR), an instrument providing time domain information for a transmission system under test. In contrast to the instruments essentially operating in the frequency domain (SWR meter, vector network analyser…) which show an aggregate effect of all discontinuities seen at the input of a system, the time domain reflectometer allows determining the position and nature of discontinuities.

2. Operation principle

Fig. 3.1 shows the TDR operation principle [1]. In essence, this instrument can be seen as one-dimensional radar. The (very fast) step generator produces a positive-going incident wave entering into the transmission system under test. The step travels down the system at the velocity of propagation of the line. If the load impedance is equal to the characteristic impedance of the line, nothing is reflected ($E_r = 0$) and only the incident signal is recorded as the wave passes the point on the line monitored by the oscilloscope (Fig. 3.2(a)). If the load is not perfectly matched, part of the incident wave is reflected ($E_r \neq 0$). The reflected voltage will appear on the oscilloscope display algebraically added to the incident wave (Fig. 3.2(b)). The reflected wave is readily identified since it is separated in time from the incident wave. This time is valuable in determining the length D of the transmission system from the monitoring point to the mismatch (discontinuity):

$$D = v_p \cdot \frac{T}{2},$$

where v_p is the velocity of propagation and T is the transit time from the monitoring point to the mismatch (discontinuity) and back, as measured on the oscilloscope (see Fig. 3.2(b)).

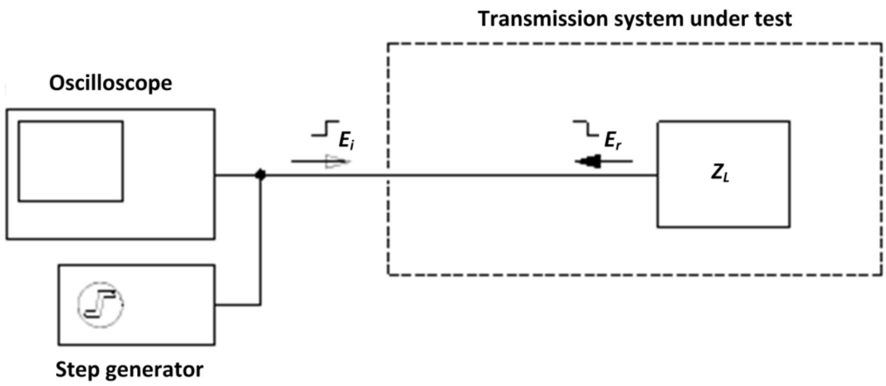


Fig. 3.1 TDR operation principle.

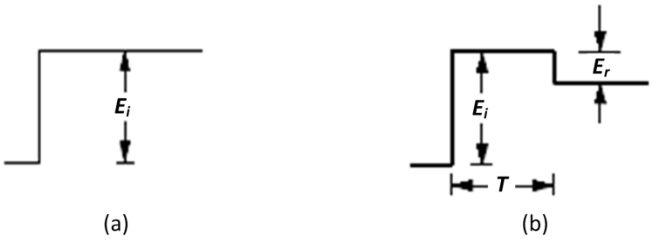


Fig. 3.2 TDR displays: (a) $E_r = 0$; (b) $E_r \neq 0$.

The shape of the reflected wave is also important since it reveals both the nature and the magnitude of the mismatch. Fig. 3.3 shows four typical simple reflections and the (purely resistive) load impedances responsible for each. These displays are easily interpreted by recalling the reflection coefficient ρ, which is the ratio of the reflected wave E_r and the incident wave E_i. In addition, the reflection coefficient is also related to the corresponding load impedance Z_L on a transmission line with the characteristic impedance Z_0:

$$\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_0}{Z_L + Z_0}.$$

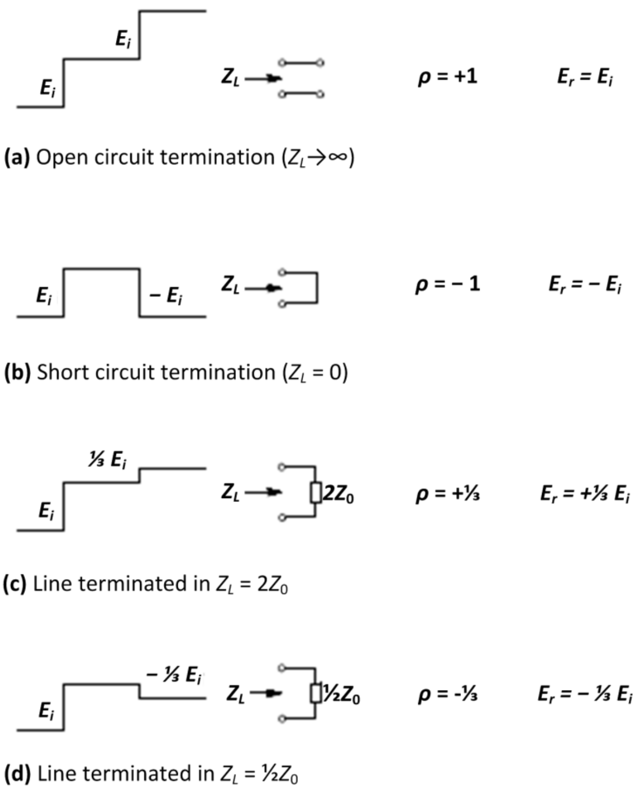


Fig. 3.3 TDR displays for simple resistive load impedances: (a) Open circuit termination; (b) Short circuit termination; (c) $2Z_0$ termination; (d) $½Z_0$ termination.

Also of interest are the reflections produced by complex load impedances. Four basic examples are shown in Fig. 3.4. The equations describing the transients can be derived using Laplace transform. In addition, a simpler and more intuitive approach is possible. First, the reflected voltage $e_r(t)$needs to be evaluated at the beginning of the transient ($t = 0$) and in the stationary state ($t \to \infty$). Any transition between is assumed to be exponential, with a time constant τ that depends on the element values and circuit topology. In the case of the series R-L combination (Fig. 3.4(a)), for example, at $t = 0$ the reflected wave is $+E_i$ because the inductor does not accept any sudden change in current and initially appears as an infinite impedance (as in Fig. 3.3(a)). Then the current through the inductor builds up exponentially and its impedance drops toward zero. At $t \rightarrow \infty$ (practically when $t > 5\tau$) the inductor has no more effect and the reflection is determined solely by the resistor (as in Fig. 3.3(c) or d)).

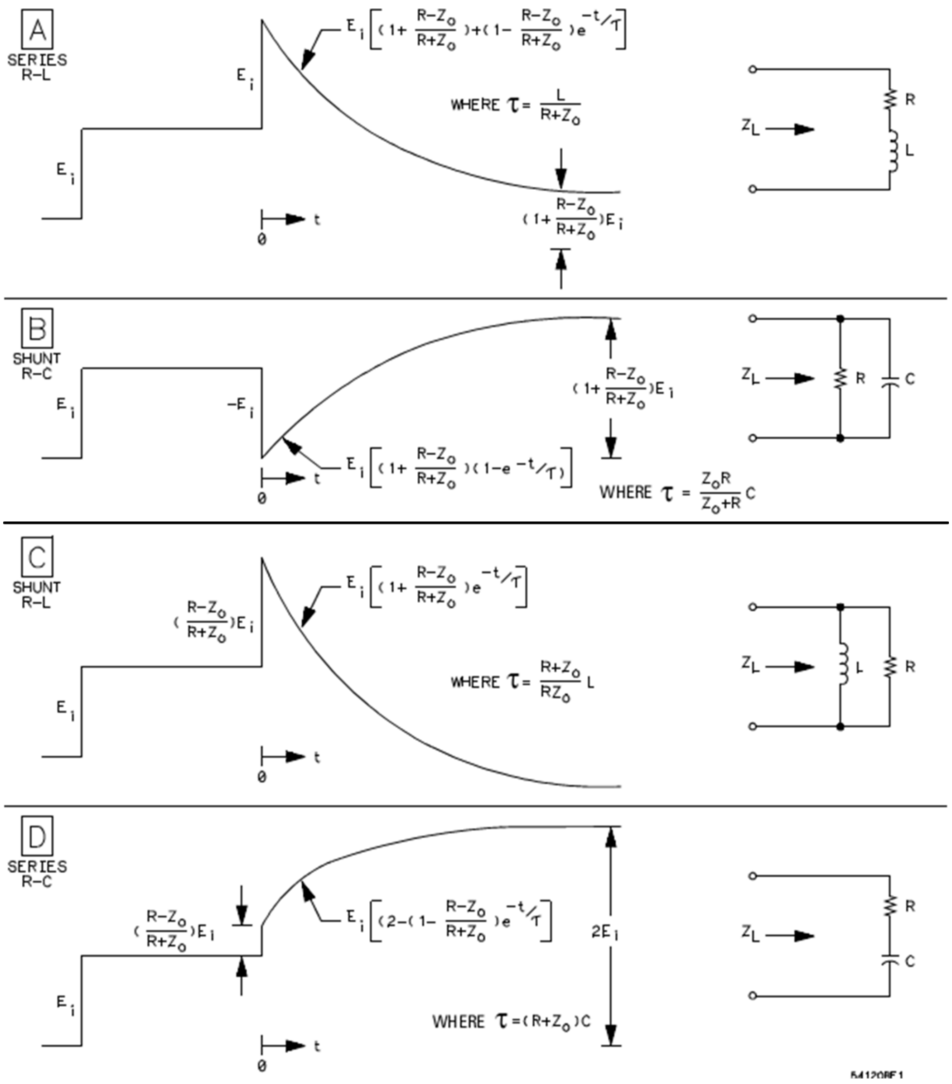


Fig. 3.4 TDR displays for complex load impedances: (a) Series R-L; (b) Shunt R-C; (c) Shunt R-L; (d) Series R-C.

When one encounters a transmission line terminated in a complex impedance, determining the element values comprising Z_L involves measuring the reflected wave levels at the beginning of the transient $e_r(t = 0)$ and at its end $e_r(t > 5\tau)$, and the time constant τ of the exponential transition. Measuring the reflected wave levels is straightforward as amplitude markers are available. Measuring the time constant is most conveniently done my measuring the time elapsed to complete one half (in terms of amplitude) of the exponential transition and knowing that this time corresponds to 0.69 τ. The procedure is illustrated in Fig. 3.5.

It should be noticed that responses of Figs. 3.2-3.5 correspond to ideal circuits excited by ideal (infinitely fast) step signals. In reality, the observed signals will appear somewhat different. The most notable difference will stem from the fact that the real step signal has a finite rise time.

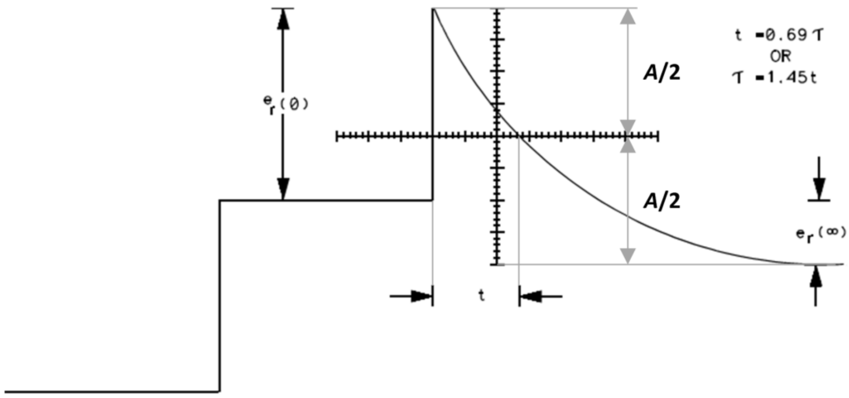


Fig. 3.5 Determining the time constant of a reflected wave returning from a complex load Z_L.

So far, we were considering only the effect of a mismatched load at the end of a transmission line. Often, however, one is not only concerned with what is happening at the load, but also at intermediate points along the line. For instance, the transmission system shown in Fig. 3.6(a) consists of two transmission line sections (both having the characteristic impedance Z_0) terminated in $Z_L = Z_0$ and connected at the point M by a connector of some sort. The connector (e.g. BNC, see Appendix) can act as a small inductor in series with the line. To treat this problem, we can substitute everything to the right of the point M as equivalent impedance and then recall Fig. 3.4(a) since we arrive to the case of the series R-L (where $R = Z_0$). The response, being merely a special case of Fig. 3.4(a), is shown in Fig. 3.6(b).

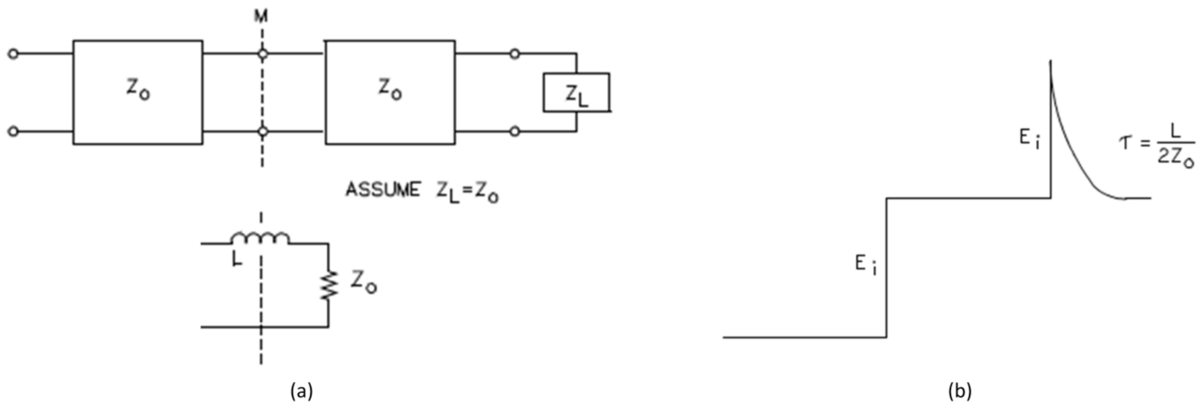


Fig. 3.6 Transmission system with a single discontinuity: (a) Block-scheme and equivalent impedance; (b) TDR display.

An additional advantage of the TDR is its ability to handle several cascaded discontinuities. An example is shown in Fig. 3.7(a). This system has two discontinuities: two line sections having different characteristic impedances, and the load that is not matched to the line. In the TDR display shown in Fig. 3.7(b), the reflections caused by the two discontinuities are clearly observed and can be analysed separately. However, it should be noticed that only the first reflection is truly unaffected by the presence of others: $E_{r1} = \rho_1 E_i$. The reflected field from the second discontinuity (here the load) E_{r2} is not equal to $\rho_2 \cdot E_i$ but to $\rho_2 \cdot (1- \rho_1^2) \cdot E_i$ because a part of the incident wave had been reflected from the first discontinuity (see the details in [1]). The situation gets more complicated for any additional discontinuity. Fortunately, discontinuities in practical systems are not excessive (e.g. $Z_0 \approx Z_0'$, so $\rho_1 \approx 0$ and $E_{r2} \approx \rho_2 E_i$). Nevertheless, it is advisable to clean up a system from discontinuities starting from the generator end. In this way, complications and potential misinterpretations introduced by re-reflections will be avoided.

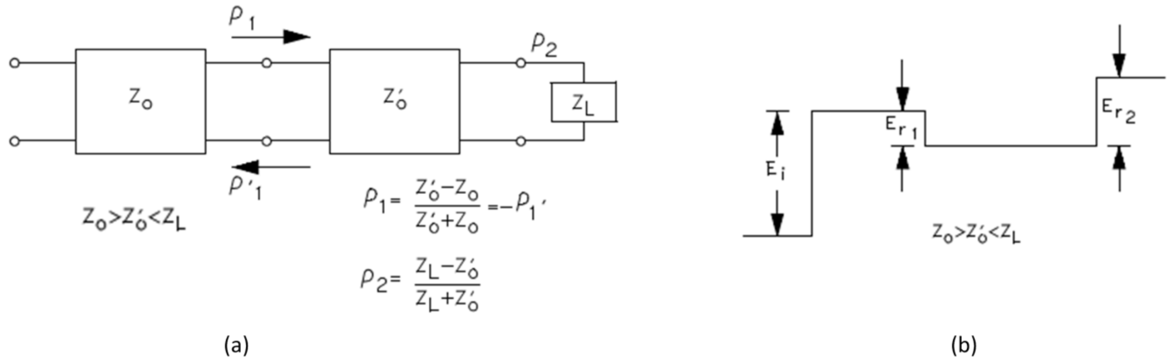


Fig. 3.7 Transmission system with two discontinuities: (a) Block-scheme; (b) TDR display.

3. Experiments

3.1. *Utilised equipment*

- TDR (Oscilloscope *Agilent 86100C* with the TDR plug-in *Agilent TDR 54754A*)
- Broadband matched loads (male and female) from the calibration kit *HP85052*; BNC and SMA matched loads
- High quality male-to-male 3.5 mm adapter from calibration kit *HP85052*
- N, BNC and SMA short circuits
- In-series male-to-male SMA adapter
- Various transitions (in-series and between-series adapters)
- Various coaxial cables: RG214/U, RG58C/U, SR3
- Resistors (overall resistance 22 Ω) soldered in various ways to a SMA connector
- 'Black box' with four ports (complex loads)
- Microstrip line with discontinuities *Agilent 54754-66503*
- Ohm meter
- Meter for measuring distance

3.2. *TDR control*

The TDR is a complex and highly performing instrument, but it is also very delicate. In particular, its input circuits are very sensitive to electrostatic discharge. Therefore:

- Check that the red antistatic mat and wrist-strap are well connected to the instrument

- Always wear the wrist-strap
- Always short-out a cable prior to connecting it to the TDR (to discharge any electrostatic build-up)

Convention in this text: `Hardkey`, *`Softkey`*

Turn on the TDR (the power switch is located on the bottom-left). Operating system (Windows) will start and the measurement application will be loaded automatically (this takes about 1 min). The instrument should be given at least 20 min to warm up. Press `TDR/TDT Mode`. Click on *`Quick TDR`* and select TDR stimulus `Channel 1.` Then go to *`TDR/TDT Setup`* and choose *`Auto Setup`*. A trace with clearly visible voltage step should be displayed. This is the raw signal.

For precise measurements, a normalisation needs to be performed, which will establish the reference plane for a measurement. To perform the normalisation, start by setting the horizontal scale, e.g. to 5 ns (note that a new normalisation is needed each time the horizontal scale is changed). `Press` *`Normalize, Normalize Response 1`*, and follow the instructions from the screen: connect a short circuit followed by the matched load from the calibration kit to the TDR port. A blue trace should appear with its origin corresponding to the plane of the short circuit. This is the normalised signal. Turn off the yellow trace (press the button '1'). Press *`Response, Rise Time`* which enables the adjustment of the step signal rise time; in general, it can be adjusted roughly between 40 ps and 25 ns (according to user's needs but also depending on the chosen horizontal scale and quality of the utilised cable).

Activate two markers (buttons on the bottom of the screen labelled as | and ¦). This will open a window on the bottom of the screen. In this window, click on the *`Markers Setup&Info, TDR/TDT Marker Units`* and choose time or meters (setting meters also requires the relative permittivity of the transmission line to be entered; enter 2.3 for standard cables). For the vertical unit, Ohms are perhaps the most suitable option (note that the voltage level is also available). The two markers can be moved by using the two knobs below the screen, and the corresponding values can be read on the screen.

Take some time to familiarize with the instrument. Some additional practical advices:

- If the horizontal scale is unintentionally altered (by the knob `Horizontal`), the normalisation will be lost. To undo this, press *`Response On`*
- To change the number of averagings: *`Setup, Averaging, Number of Averagings`* and enter the desired number;
- To change the vertical scale: *`Response, Vertical Scaling, Manual`*. It is also possible to use the zoom (define a rectangle using the mouse and click to zoom into its interior)
- To put a title (convenient when printing traces): *`Setup, Display, New Label`*
- To print: *`File, Print`* (use the colour printer located in ELB 027): \\lemasrv1.epfl.ch\HP3525xPCL5

3.3. *Measurements*

As we are working with a real instrument, certain limitations appear. The most significant one is the finite rise time of the step signal, being at least 40 ps For this reason, the appearance on the instrument screen is somewhat different from what is shown in Figs. 3.2-3.7. This rise time also limits the measurement resolution to the order of a centimetre (1 cm corresponds to the round-trip time of 66 ps in the air). Two discontinuities separated by a distance smaller than this cannot be clearly distinguished. Instead, only a combination of reflection contributions of both discontinuities can be observed.

3.3.1. Measuring the characteristic impedance and length of cables

Characteristic impedance and tolerance (for instance, 50 Ω ± 1 Ω) are provided by the manufacturer. A simple reflection coefficient measurement using the SWR meter is often not sufficient to confirm these values as additional error can be introduced by the cable connector discontinuity that can significantly distort the results. By contrast, the TDR ensures separating the reflection caused by the connector from the reflection caused by the cable itself, thereby enabling the reliable verification of the cables.

Perform a normalisation with the reference plane on the level of the TDR connector (PC3.5 female connector). Set the horizontal scale to 5 ns/div. After having this done, connect successively the cables (use a transition if needed). Place marker 1 so that it corresponds to the beginning of the cable (observe the effect of the transition). Place marker 2 to at least two points along the cable (for instance 1/3 and 2/3 of its length) and calculate the mean characteristic impedance. Finally, place marker 2 to the end of the cable and measure its length.

Note: Standard cables typically have polyethylene dielectric whose relative permittivity is 2.3. This default value must be entered into the TDR prior to measuring the distance (cable length).

Verify all the cables at disposition. If there is a cable whose actual length does not correspond to the length measured by the TDR, it means that the dielectric is different. In this case, the relative permittivity setting must be altered.

Table 3.1 Cable measurement results.

Cable	Z_0 **(⅓ length)**, Ω	Z_0 **(⅔ length)**, Ω	Z_0 **(mean)**, Ω	ε_r	***Length***, m
RG213					
Semi-rigid					
BNC 50 Ω					
BNC 75 Ω					
Huber+Suhner					

3.3.2. Measuring the resistors

Connect the male-to-male 3.5 mm adapter (from the calibration kit) to the TDR in order to have the male connector available for this measurement. Perform the normalisation procedure with the horizontal scale of 500 ps/div. During this normalisation use the short circuit from the ‘black box’ (it will ensure the reference plane position exactly at the resistors’ ports.

Use the TDR to measure the four resistors, all with the nominal value of roughly 22 Ω (verify the nominal values using the ohmmeter prior to the TDR measurement):

1.) SMD 22 Ω: chip resistor;
2.) SMD 68||68||68||Ω: three chip resistors in parallel;
3.) Classical 22 Ω; with roughly 1 cm long terminals
4.) Reduced length classical 22 Ω: with terminals having a reduced length.

Explain which effects have caused the measurement results to differ from the ideal case (Fig. 3.3(d) as $R \approx ½Z_0$). Print the traces corresponding to each resistor in a way that the differences between the measurement results are clearly visible.

3.3.3. Measuring the 'black box'

Keep the male-to-male 3.5 mm adapter connected to the TDR. Perform the normalisation procedure with the horizontal scale 5 ns/div. During this normalisation us the short circuit from the 'black box', again to ensure the reference plane position exactly at the edge of the SMA connector where the loads are soldered.

Each connector of the 'black box' (except the reference short) is loaded by two elements (R, L, C) in some combination. Determine the type of each load as well as the value of the elements that it consists of. Refer to Fig. 3.5 for determining the time constant τ. Use markers to measure time and voltage (*`Markers, Setup&Info, TDR/TDT Marker Units`*, choose seconds and volts). Print each trace.

Table 3.2 'Black box' measurement results.

Port	Element types and combination	τ, ns	Element values
1			
2			
3			
4			

3.3.4. Multiple discontinuities

What happens when there are several successive discontinuities present along the transmission line (typical case in reality)? To study this, use the microstrip line with discontinuities (its effective permittivity is 3.945). Perform the normalisation procedure (keep the male-to-male 3.5 mm adapter) with the horizontal scale of 500 ps/div, and connect the microstrip line directly to the TDR. Terminate the end of the microstrip line in a matched load. Print the trace. Comment the obtained trace and measure the characteristic impedance and length of each section. Compare the measured lengths with a geometrical dimensions.

3.3.5. Various transitions

It is often unavoidable to use adapters (in-series, as well as between-series) in a transmission system or when measuring devices. However, each adapter, even of highest quality, inevitably causes a discontinuity (reflection) and influences the measurement/system performance.

Keep the same normalisation as in the previous task. Connect a couple of transitions (for example, APC-7/APC-7, BNC/BNC, SMA/SMA, SMA/N…). Note the quality of the transitions. Print the traces (zoom if necessary in order to clearly display the details around the transition).

4. References

[1] *5473A,4A TDR Plug-in Module Operating Manual*, Agilent, 2000.
http://www.home.agilent.com/agilent/redirector.jspx?action=ref&cname=AGILENT_EDITORIAL&ckey=74760&lc=eng&cc=GB&nfr=-35270.536883050.00

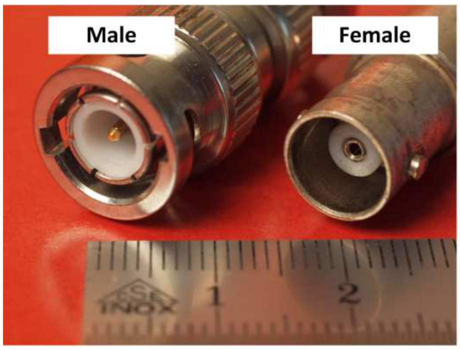
Photography of the experiment setup for Laboratory session 3.

Appendix

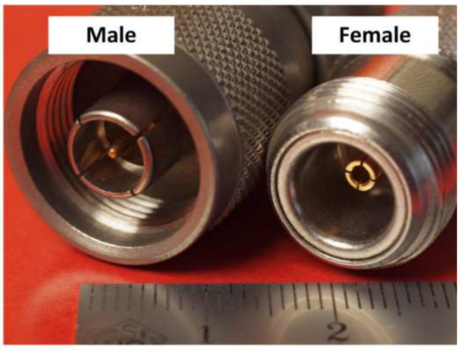
Some common microwave connectors

In general, microwave connectors are used to make low VSWR connections. Their size is typically decreasing as the operating frequency is increasing. High frequency connectors have to be fabricated with exceptional mechanical precision, which of course has impact on their price.

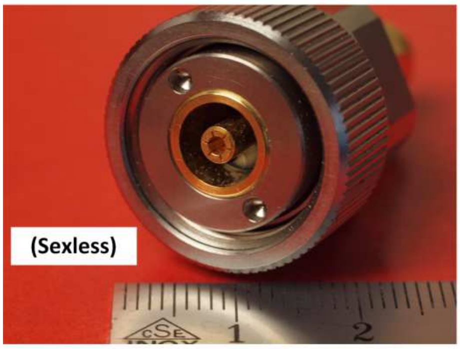
There are many types of connectors (and adapters) available today. Here we only show the most common types used in microwave electronics. More practical information can be found at http://www.microwaves101.com/.



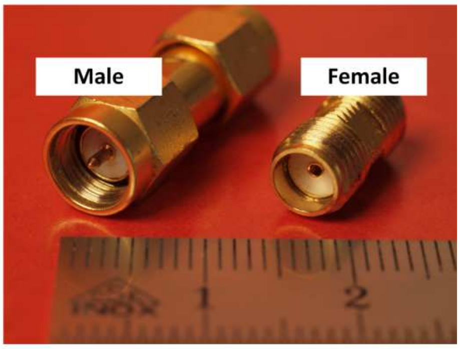
BNC connector
(f_{max} ≈ 2-4 GHz)



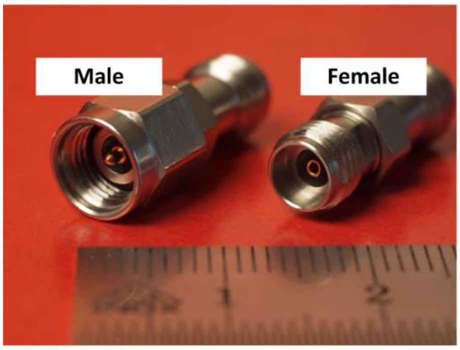
N-type connector
(f_{max} ≈ 12-18 GHz)



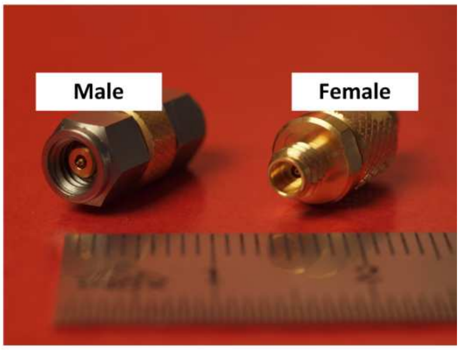
7 mm (APC-7) connector
(f_{max} ≈ 18-20 GHz)



SMA connector
(f_{max} ≈ 18-26 GHz)



2.92 mm (K) connector
(f_{max} ≈ 40 GHz)



1 mm connector
(f_{max} ≈ 110 GHz)