EE3P11 - EM Practicum, 2024-2025 Q3

I. Introduction

1. General Comments

Lab Organization:

The EM Practicum includes a few laboratory experiments organized in two Sessions. The first session involves basic microwave measurement techniques related to electromagnetic wave propagation in transmission lines. The second session includes experiments and simulations related to electromagnetic wave propagation in free space and near the Earth's surface.

The current arrangement of the sessions periods and timeslots, which depends on the number of enrolled students and availability of the Tellegen Hall's laboratory spaces, can be found on the practicum pages of the EE3P11 course Brightspace directory. During a session period, every student has to do measurements within a group of students during a pre-allocated time slot (2 academic hours duration). Every practicum session has a specific equipment setup that is assembled and exists only during that session's period. As a result, it will not be possible to make or repeat experiments at other times.

Be sure to completely read the description of each experiment before beginning the experiment. This will help you to see the overall plan of action and should decrease the likelihood that you will do the procedure incorrectly, or forget to do part of the procedure.

Some of the laboratory experiments will involve material that is out of sequence with the lectures, and you will be covering topics that have not yet been discussed in class. You will need to read some text material (provided for your convenience via Practicum pages on brightspace.tudelft.nl) ahead of the lecture schedule so that you have a better understanding of the experiments you are performing. These materials can also include some MATLAB codes for the demonstration wave concepts, involved in the Practicum. You have to read and study all these materials before coming into the laboratory to be able to do all planned activities correctly.

Lab Reports:

Lab reports are required of every group of students, and have to be completed and submitted to http://brightspace.tudelft.nl before specified deadline. Students are encouraged to keep a lab notebook + usb stick to record original data, equipment layout, and notes about the experiment. Reports should be neat and clearly organized, and should include original data sheets. Graphs should be neatly drawn. Each graph axis of a graph must include a title and units. Organization of the lab report is left to the student, but a suggested report outline follows:

1. Introduction (purpose of experiment)
2. Procedure (equipment used, configuration, unexpected problems)
3. Results (measured data, relevant calculations)
4. Discussion (interpretation of results)
5. Conclusions (what was learned, recommendations)

In some of the experiments topics for optional work are suggested - you should consider these options, if time permits. Students are also encouraged to try out their own "what if. . . " ideas.

Important comment: Lab Reports Authorship and Grading Procedure

The group report is a formal document that is used for grading. By default teachers assume that all students group members, which are included in the report's authors list that has to be included in every report, participated equally in measurements, data and results processing and analysis, report preparation.

If you simply did not receive an **expected** support or input from any member of the group, you can issue and submit report without his/her name on it.

The list of submitted report's authors is more important for grading than the list of group members.

If you have an alternative vision/opinion about results analysis/interpretation and could not reach the agreement with other members of your group/team, you can simply issue and submit your personal report (BS site gives such a possibility. In case of problems with submission - contact the responsible teacher by e-mail).

You also can update your submitted report -via submission of a new version – the last submitted version will be used for evaluation.

Care of Equipment:

Please be very careful with the microwave test equipment, as it is very delicate, and expensive to repair or replace. Microwave measurement devices can cost up to a few tens thousand euros; microwave connectors and adapters range in cost from 35 to 90 euro each. If you suspect something is not operating correctly, report it to the lab technician or Teaching Assistant. Be especially careful when using connectors to avoid breaking pins and cross-threading. If at any time you are uncertain about lab safety, please ask the Teaching Assistant before proceeding.

Lab Support:

There will be a Teaching Assistant assigned to each of the Lab Session to help with questions about experiment setup and measurements. Any problems with basic measurement equipment should be reported.

2. Microwave Radiation Hazards

Excessive exposure to electromagnetic fields, including microwave radiation, can be harmful. Although the power levels used in our EM Practicum are very low and should not present a health risk, it is still prudent to,

- be aware of the recommended safe power limits
- be aware of the power densities with which you will be working
- use good work habits to minimize exposure to radiated fields

The question of what is a "safe" radiation level is controversial; like highway speed limits, all we can say with total certainty is that less is safer. Microwave radiation is nonionizing, so the main biological effect is induced heating, which may occur relatively deep inside the body to affect sensitive organs. Health risks increase according to the power density and the duration of the exposure. The eye is the most sensitive organ, and studies have shown that cataracts can develop from exposures as short as 1.5 hours to power densities of 150 mW/cm^2. Thus, using a safety factor of more than 10, the current safety standard recommends a maximum exposure power density of 10 mW/cm^2, at frequencies above 10 GHz, with lower levels at lower frequencies. By comparison, the power density from the sun on a clear day is about 100 mW/cm^2, but most of this power is beyond the microwave spectrum, and so does not enter deeply into the body.

The sources used in the EM Practicum, have power outputs in the 10 - 15 mW range. In most cases, there is negligible danger of being exposed to radiation at these power levels because our experiments use coaxial lines or waveguide, which provide a high degree of shielding. It is possible, however, to encounter power densities near the recommended limit at the end of an open-ended coaxial cable or waveguide. Such power densities exist only right at the open end of the coax line or waveguide, due to the 1/r^2 decrease of radiated power with distance. For example, at a distance of 10 cm from a waveguide flange with an input power of 20 mW, the Friis formula gives the power density as,

$$S = \frac{PG}{4\pi R^2} = \frac{(20)(2.5)}{4\pi(10)^2} = 0.04 \left[\mathrm{mW/cm^2}\right]$$

which is seen to be far below the recommend safety limits.

Even though there should be little danger from microwave radiation hazards in the lab, the following work habits are recommended whenever working with RF or microwave equipment:

- ***Never look into the open end of a waveguide or transmission line that is connected to other equipment.***
- ***Do not place any part of your body against the open end of a waveguide or transmission line.***

EE3P11 - EM Practicum, 2024-2025 Q3

Session I TRANSMISSION LINES

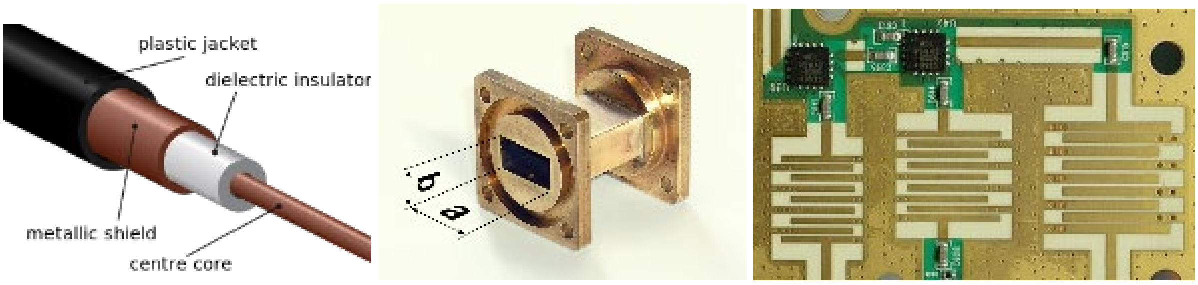
Reports: One report per group. Deadline for report submission**: Check the BS site**

Introduction

Any wave is an oscillating process that simultaneously oscillates in time and in space. The oscillation process in time is characterized by the wave period in time (which is inversely proportional to the wave frequency f) while the oscillation process in space is characterized by the wavelength. Relating these two characteristics one can define the wavelength as the distance which wave propagates during one period of oscillation in time. From this definition follows a very simple but important equation $v_p = \lambda \cdot f$, which says that the wavelength times the frequency equals to the propagation velocity of the electromagnetic wave.

The main task of the EM Practicum Session I is to measure the ***propagation velocity of electromagnetic waves***. In free space, electromagnetic waves propagate in all directions within three-dimensional space as spherical waves. In many practical cases, it is desirable however to canalize propagation of electromagnetic waves into one direction (say, from a generator to receiver). Devices, which are used for such canalization, are called ***transmission lines***.

From an engineering point of view, the transmission lines are components of radio-electronic devices designed for guiding electromagnetic waves to specific block/location with minimum energy spreading and losses. There are different types of transmission lines: coaxial cables, waveguides, (micro)strip lines.



(a) (b) (c)

Fig.1. Transmission lines: (a) coaxial cable, (b) waveguide, (c) micro-strip lines

Within the EM Practicum Session 1 we are going to investigate two cases - the wave propagation in coaxial cables and waveguides, concentrating on a few issues related to the difference between these two transmission lines in terms of their characteristics and capabilities.

The major type of wave, which propagates in a coaxial cable, is the so-called TEM wave (transverse electromagnetic wave) with the same mutually orthogonal orientation of its electric field, magnetic field, and propagation vector as in free space. Very important is that in a coaxial cable waves with such structure can exist and propagate starting from very low frequency, theoretically from the DC, and their propagation velocity does not depend on frequency. This frequency-independence of the transmission line characteristics results in the capability of coaxial cable to transfer signals with complex waveform and modulation without distortion of the waveform - the amplitude and phase relations between different frequency components of the signal do not change during the propagation. The EM waves propagation velocity in coaxial cable is less than propagation velocity in free-space and depends on the relative dielectric permittivity of internal insulator material ε (usually it is a plastic material like Teflon or similar): $v_p = c/\sqrt{\varepsilon}$.

A hollow metal waveguide supports propagation of a wide spectrum of waves, which can belong to either so-called TE or TM waves (*transverse electric* or *transverse magnetic* waves - this means that either the electric (for TE-) or magnetic (for TM-) field vector is orthogonal to the direction of propagation). These waves propagate in a waveguide starting only from some minimal frequency (*cut-off frequency*), and that is why different-sized waveguides are used for different frequency bands. Most efficient for practical needs single-mode wave propagation in a waveguide is also possible only until some higher frequency when waves with more complex multiple modes structure start forming (actually, it is also valid for coaxial cable but on much higher frequencies). The propagation velocity of waves in a waveguide is strongly frequency-dependent, which makes this transmission line *dispersive*. ("*Dispersive*" means that wave propagation velocity depends on frequency). For example, the transmission of short pulses (the bandwidth is inversely proportional to the pulse duration) via waveguide will result in a very strong distortion of the shape of the pulses. As result, being a very useful type of transmission line for canalization of high power with small losses, waveguides have to be specifically designed for every specific frequency band and even then they have limited bandwidth, much less than coaxial cables.

The first Session of the EE3P11 EM Practicum includes two assignments, related to effects and phenomena, which take place during the propagation of the EM waves (microwaves) in two types of standard transmission lines – coaxial cables and waveguides. These assignments are designed to stress an additional learning objective - to show that microwave measurements can be done in time and frequency domains.

The **time domain** refers to the analysis of mathematical functions or physical signals concerning time dependency. In the time domain, the signal or function's value is known for all real values in the case of continuous-time or all sample instances in the case of discrete-time. An oscilloscope is a tool that is commonly used to visualize real-world signals in the time domain. In the microwave frequency bands (300 MHz – 300 GHz) the measurements of signals in the time domain can be done only if the sampling frequency is high enough to resolve investigated time-dependency. To provide the equipment with such a high sampling rate can be quite difficult and costly even with modern progress in technology.

The **frequency-domain** refers to the analysis of mathematical functions or signals concerning frequency, rather than time, dependency.

A time-domain graph shows how a signal changes over time, whereas a frequency-domain graph shows how much of the signal lies within each given frequency band over a range of frequencies. A frequency-domain representation also includes information on the phase shift that must be applied to each sinusoid in order to be able to recombine the frequency components to recover the original time signal.

A given function or signal can be converted between the *time* and *frequency domains* with a pair of mathematical operators called a *transform*. The most popular example is the Fourier transform, which converts the time function into a sum of sine waves of different frequencies, each of which represents a frequency component. The *'spectrum'* of frequency components is the *frequency domain representation* of the signal. The inverse Fourier transform converts the frequency domain function back to a time function. A *spectrum analyser* is a device commonly used to visualize real-world signals in the frequency domain. A *network analyser* can work in both domains.

Short theoretical overview

Chapters 2, 3, 6.1 and 7.1-7.7 of A.L. Lance *Introduction to Microwave Theory and Measurements*. McGraw-Hill Co. (scanned book chapters on the bright space’s practicum page)

Assignment 1. Transmission Lines in Frequency Domain.
45 min for experiments

For this assignment, we do not use any equipment that can resolve the temporal structure of the EM waves. Instead, we will use an equipment setup that measures a standing-wave pattern – the spatial dependence of the amplitude of the standing electromagnetic wave with one specific frequency. Such measurements can be done only with a monochromatic wave.

The main goal of this assignment is to measure the propagation velocity of an electromagnetic wave in a waveguide. As the constant frequency of the monochromatic electromagnetic wave is determined by the generator and known (measured), propagation velocity can be found from the measurement of the wavelength in the waveguide. As the wavelength of a traveling wave is difficult to determine, the wavelength measurements are often done for the *standing wave* that is the result of interference of two components of the same wave that are traveling in opposite directions - one travels from the generator to the load, then it reflects from the load and travels to the generator. The relation between the spatial period of the standing wave amplitude pattern and the wavelength of a traveling wave should be known from the lectures and provided reading materials.

The second goal of this assignment is to characterize different loads of the waveguide by studying the standing wave characteristics. The minimum of the standing wave amplitude (see Fig. 1.1) is defined by the amplitude of the wave reflection coefficient on the load; the positions of standing wave's nodes and antinodes inside the slotted line - by the phase of that reflection coefficient. The reflection coefficient itself is defined by the matching impedances of the transmission line and the load. The process of standing wave formation can be studied using the MATLAB script "StandingWave.m" from the Brightspace practicum page.

The typical standing-wave pattern in case of strong reflection from the load shown in Fig. 1.1.

Note: According to the theory, the wavelength of the EM wave in a rectangular waveguide, which is used in this experiment, can be computed as

$$\lambda_w = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{2a}\right)^2}}$$

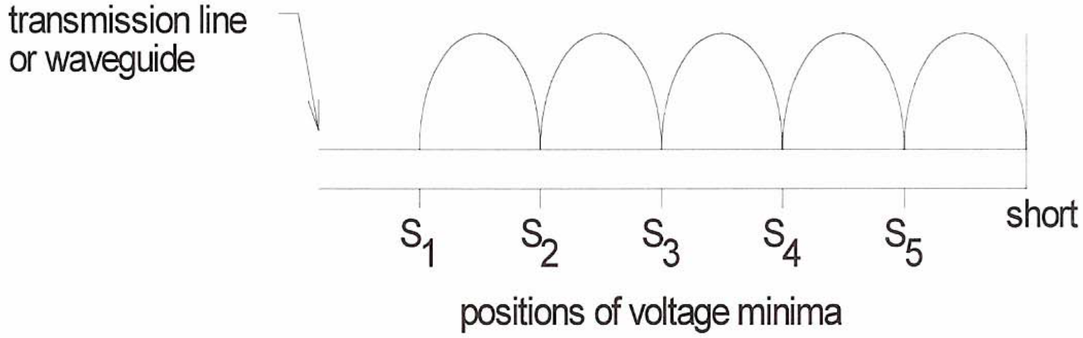


Fig.1.1. Typical standing-wave pattern in case of strong reflection from the load.

where λ_0 - wavelength in free space, $\lambda_0 = c/f$, c - speed of light in free space, f - frequency, a - size of long side of waveguide (22.86 mm in our case)). The phase velocity of wave in a waveguide equals to

$$v_p = \lambda_w f$$

The voltage-standing-wave ratio (VSWR) is defined as

$$VSWR = \frac{E_{\max}}{E_{\min}} = \frac{1+|\Gamma|}{1-|\Gamma|}$$

Then the absolute value of the reflection coefficient from the load equals to

$$|\Gamma| = \frac{VSWR-1}{VSWR+1}$$

The positions of the standing wave pattern maxima and minima relatively to that for calibration load can be used to define the phase of the reflection coefficient. More detailed description of the standing wave theory and practical use can be found in provided chapters of the book *Introduction to Microwave Theory and Measurements* by A.L. Lance

Experimental Setup

This experiment uses an RF signal source (klystron) that operates within the X-band of frequency (8-12 GHz), waveguide signal isolator (it prevents the reflected from following blocks signal to propagate back to generator), the Frequency Wave Meter, tuneable attenuator, a ***waveguide slotted line*** and various loads and cables. The indication of the standing wave nodes and antinodes in the slotted line and the measurement of the standing wave ratio can be done with the analogue VSWR meter. The experiment setup is presented in Fig.1.2.

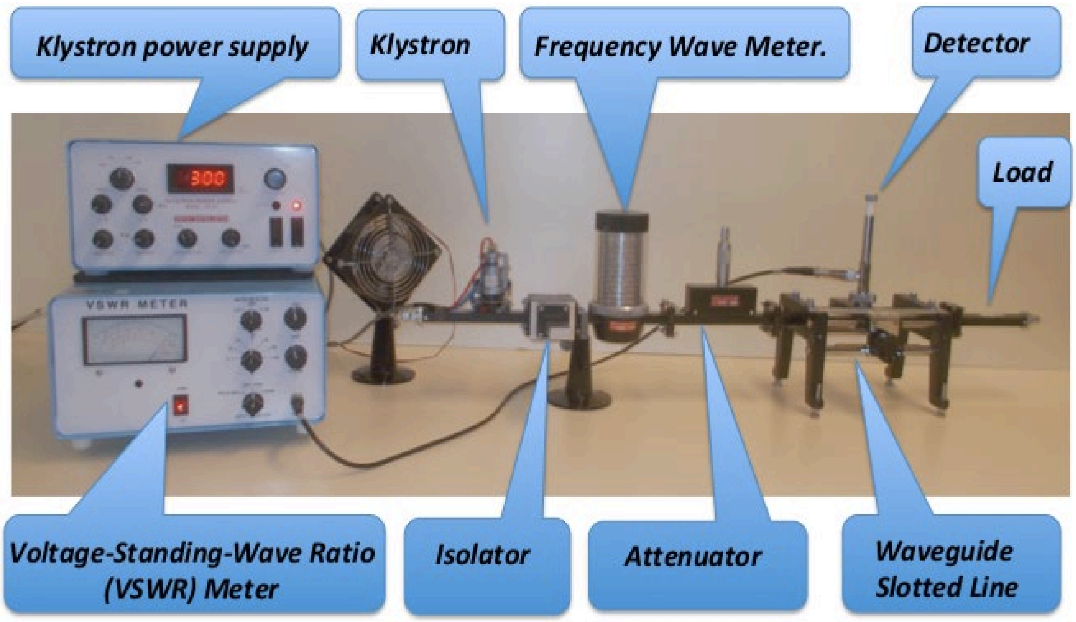


Fig. 1.2. Experimental set-up

Slotted lines can be made with any type of transmission line (waveguide, coax, micro-strip line, etc.), but in all cases the electric field magnitude is measured along the line with a small probe antenna and diode detector. The diode is assumed to operate in the square-law region, so its *output voltage is proportional to the power* on the line. This signal can be measured with a voltmeter, with an ***oscilloscope***, or with special VSWR meter. In case of measurements with oscilloscope or with SWR meter, for the sensitivity improvement the amplitude of RF signal can be modulated with a 1 kHz frequency square waves for better visualization and measurement precision.

Fig.1.3. The Frequency Wave Meter

For the experiments it is necessary to set the source (klystron) to a continuous wave with amplitude modulation (AM) transmission of the wave with specific for this source frequency in the X-band frequency range, and measure the frequency with the Frequency Wave Meter (*in case of the on-line practicum in 2021-2022Q3 the value of the frequency for your group will be given together with other measurement results*).

The Frequency Wave Meter (Fig.1.3) is a tuneable resonant cavity, and is used by tuning it until a dip is registered on the SWR meter/oscilloscope; the frequency is then read from the scale of the Frequency Wave Meter. Be sure to detune the Frequency Wave Meter after frequency measurement to avoid amplitude fluctuations that may occur when the Frequency Wave Meter is set to the operating frequency.

The ***slotted line*** consists of a piece of metal tubing (which in our case is a WR-90 rectangular waveguide with the operational frequency band from 8.2 to 12.4 GHz, internal size 22.86 x 10.16 mm), a probe, and a detector. The probe measures the electric field present in the line and uses a detector to convert the measured field to a voltage. The probe and the detector are housed on a mount, which can slide down the line. On the side of the mount is a ***vernier scale*** (check Wikipedia how to read high precision measurements https://en.wikipedia.org/wiki/Vernier_scale) that can be used to measure the position of the probe with precision about 0.01-0.02mm (check the Appendix 1 to see examples). The slotted waveguide section is show in Fig. 1.4.

For the search of minima and maxima of the standing wave pattern and for the measurement of the voltage-standing-wave ratio (VSWR) in this experiment the analogue VSWR meter will be used. The full instruction of this device usage is presented in the Appendix 2, but in this experiment we will use a bit simplified procedure: you can assume that procedures *a-g* from instruction have been done during the preparation of the equipment for experiment, the measurements will include the repetition steps *h-i,* using for the VSWR reading the top rule on indicator panel only. So, the procedure for the measurement of the VSWR of the specific load include following steps:

- moving the probe along the slotted line looking for the maximum of the standing wave;
- at the maximum point set the indication into the SWR=1 position using SWR meter controls;
- moving the probe along the slotted line looking for the minimum of standing wave;
- at the minimum point the indicator will show actual value of the VSWR for current load;
- for all these measurements has to be used upper scale on the indicator panel (see Fig.1.5).

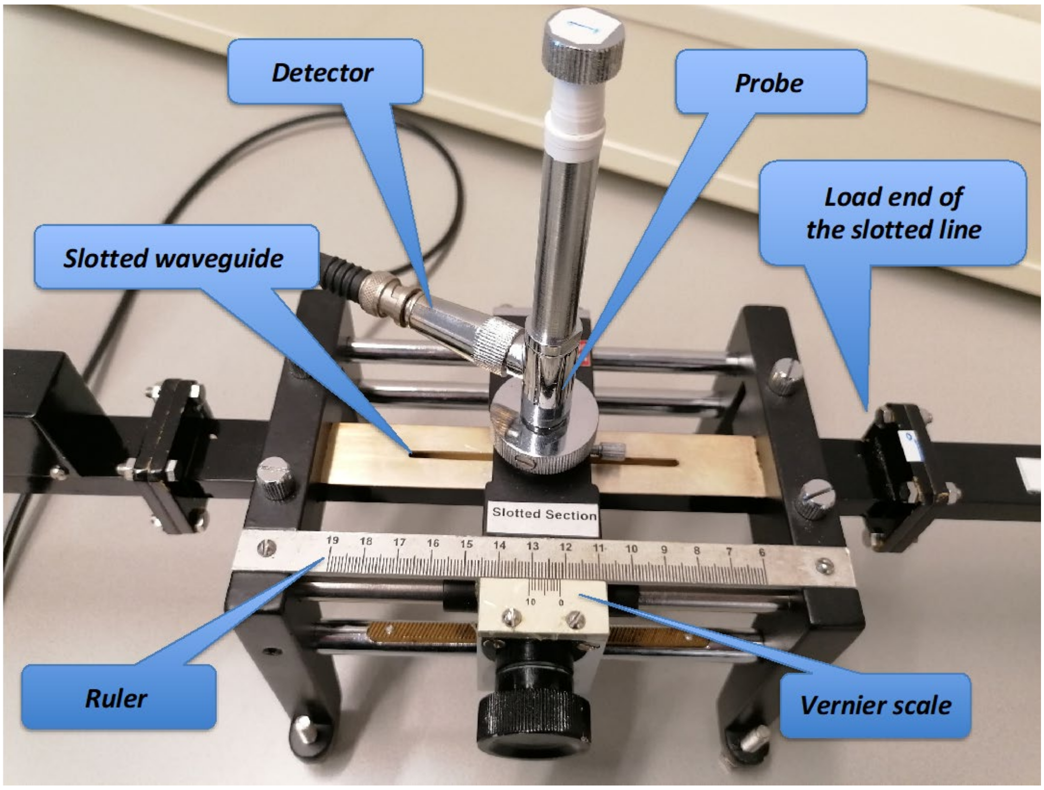


Figure 1.4: The slotted line

This experiment setup is initially un-calibrated. In order to correct for this, the first step is to measure the standing-wave pattern for a known load and to use it as a reference. The short termination with known expected standing wave pattern can be used as the reference load. The characteristics of various loads can be precisely estimated by the comparison of their measurements results with the measurements results for the reference load.
During the experiment you have to place the investigating load's flange on the load end of the slotted line; use two or more screws to get a good contact. Only if needed adjust the attenuator to prevent excessive signal strength for SWR meter (rotate attenuator ‘knob’ -right-handed- down to increase attenuation) else only adjust the SWR sensitivity for a reading near midscale, then adjust the carriage position to locate several minima, and record these positions from the scale on the slotted line. Note

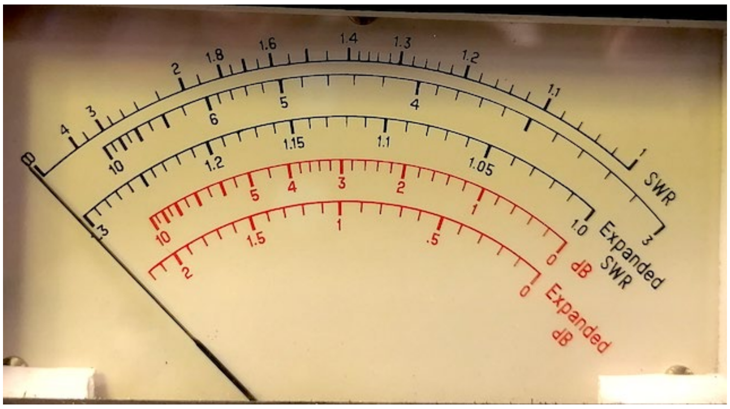
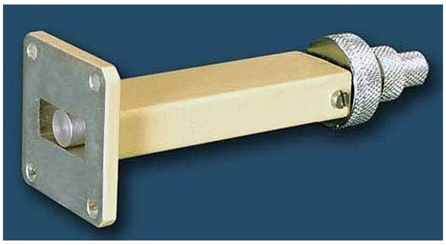


Figure 1.5: The indicator panel of the VSWR meter. We will use the top SWR scale only.

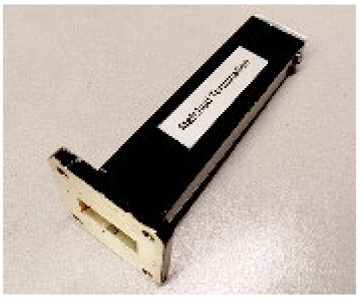
that voltage minima are more sharply defined than voltage maxima, so the minima positions lead to more accurate results.

Experiments to be done and questions to answer in report

1. Determine the phase velocity of the EM wave in the given waveguide within the frequency band from 8GHz till 12GHz theoretically (using provided equations) and on one fixed frequency at this band experimentally, using the measurements of standing wave. Make measurements a few times to improve the accuracy of your estimation and to estimate the measurement error. Analyse the frequency dependence of the EM waves propagation velocity in waveguide and compare experimental result with theoretical prediction, estimate the accuracy of your measurements.
2. Compare the measured velocities with that in free space and explain your observations.
3. Determine the ***absolute value of the reflection coefficients*** for different loads (see below) and the ***fraction of power***, which is delivered into this load from the transmission line (waveguide). To this end, measure the ***voltage-standing-wave ratio (VSWR)*** for:
    a. Movable short circuit – the piece of the waveguide that has a variable depth that changes using a metal piston with contacting fingers riding against the sides of the waveguide. Check the reflection coefficients for a few positions of the piston. Combine these measurements with measurements for the task 4 (below).

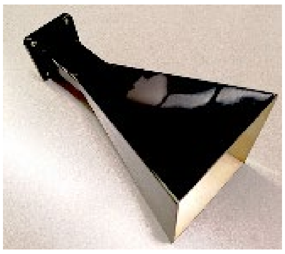



    b. Matched load



    c. Open waveguide

d. Horn antenna (Antenna is a device that have not only a function to direct electromagnetic waves in free space in specific direction but also to match impedances of the transmission line and free space, preventing wave reflections and energy losses)



Note: The given waveguide loads can look differently than presented in picture above.

4. Compare patterns of standing waves (nodes-antinodes location) for a few positions of the piston of the movable short circuit (see task 3a, the standing wave patterns looks like in Fig.1.6). Use the first position as a reference, measure all other relatively to it. Use the normalization of the depth of the short to the wavelength of the EMW in the waveguide. Explain the shift of standing waves antinodes.

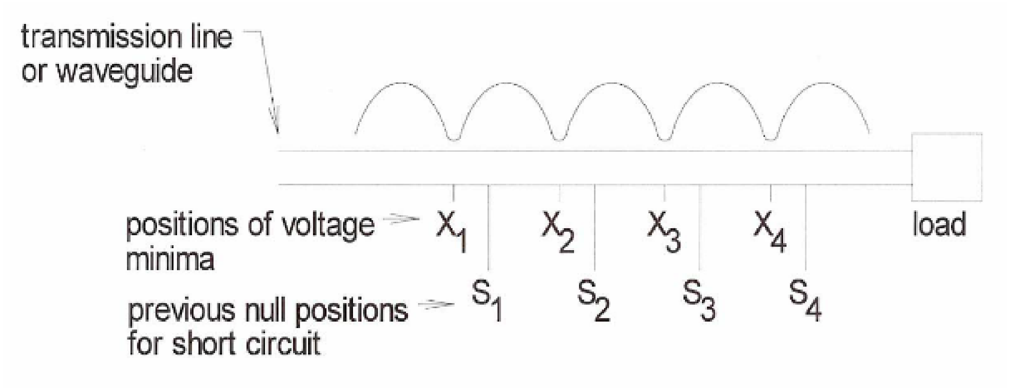


Figure 1.6. Shift of standing wave pattern for different loads

Additional tasks for the report:

- What other parameters of waveguide and loads can be estimated from your measurements?

On-line version of the assignment

If it will not be possible to visit laboratory and make real measurements due to anti-covid limitations, every group will receive an individual set of materials for processing:

- the text file with the value of electromagnetic wave frequency that has been used during measurements.
- the gallery of photos that show the vernier scale position together with the VSWR meter indicator at specific points (max and min of standing wave pattern) for all types of loads (2 short circuits with different length, matched load, open waveguide and horn antenna that directed on the RF absorber to prevent the influence of the external reflections).

You will have to study and analyse these materials, make necessary estimations and answer formulated above questions, present all this results in the group report.

Appendix 1.

Examples of the vernier scale usage

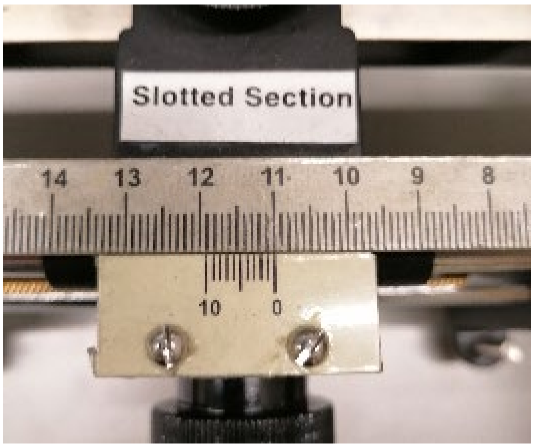


Fig A1.1. The vernier scale position 11.00 cm

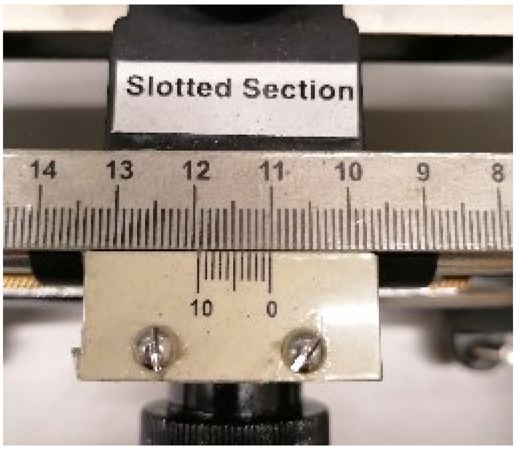


Fig A1.2. The vernier scale position 11.02 cm

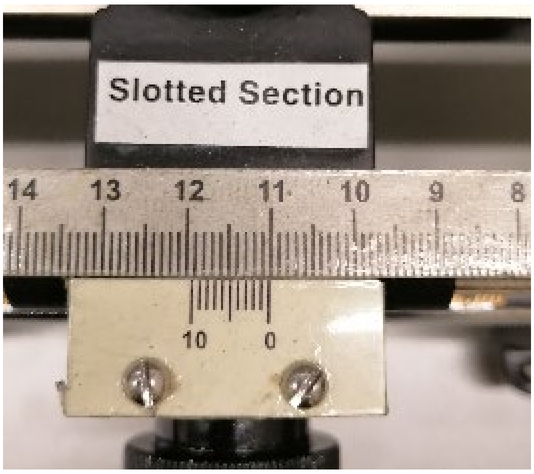


Fig A1.3. The vernier scale position 11.03 cm

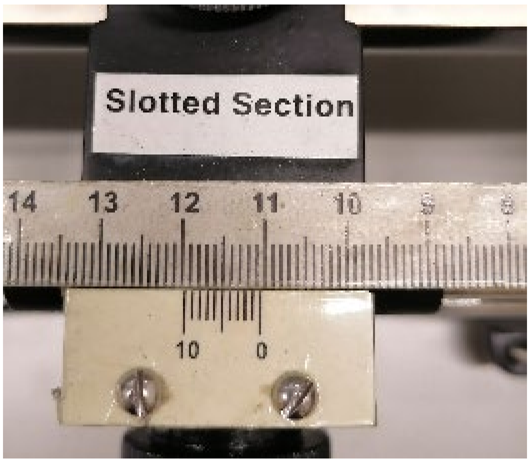


Fig A1.4. The vernier scale position 11.06 cm

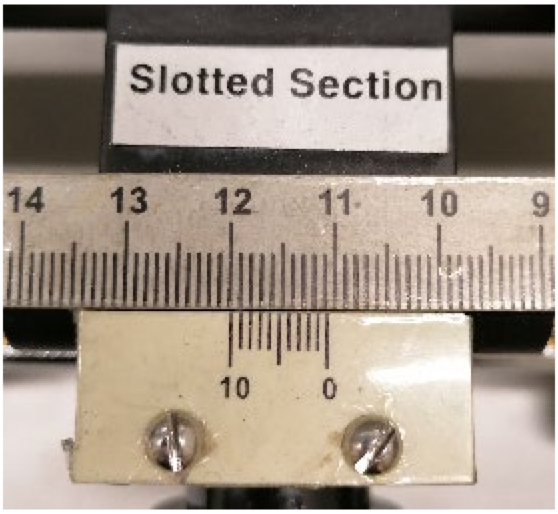


Fig A1.5. The vernier scale position 11.08 cm

Fig A1.6. The vernier scale position 11.10 cm

Appendix 2

The SWR Measurement Procedure.

The VSWR meter may be used to measure a standing wave ratio as a direct reading or as a decibel reading to be converted to SWR. Normally the measurement of SWR will lie in a range from 1:1 to 10:1 (low). However, measurements greater than 10:1 (high) may be made. The expand Switch of the VSWR meter allows full scale presentation of any 2.5 dB segment of the 10 dB steps. Figures A2.1 and A2.2 permit conversion of dB to SWR.

LOW SWR (1:1 to 10:1) : When measuring SWR in the low range, proceed as follows:

Turn VSWR Meter POWER switch to AC.

a- Set INPUT SELECTOR for type detector being used. The XTAL (crystal) 200K position gives the proper load on crystal detectors for optimum square law detection.
b- Connect detector cable to INPUT.
c- Set GAIN and VERNIER controls to about 1/2 maximum.
d- Set RANGE switch to 40 dB or 50 dB, EXPAND switch to NORM (normal) position. Adjust probe penetration to obtain an on-scale reading.
e- Peak the VSWR Meter (i.e. move needle to right) by adjusting the modulation frequency of the signal source, if adjustable. Frequency peaking is also achieved by adjusting the FREQ (frequency) control on the front panel of the VSWR meter. Reduce probe penetration to keep needle on scale.
f- Peak the VSWR meter by tuning the probe detector, if tuneable. Reduce probe penetration to keep needle on scale.
g- Peak the VSWR meter by moving the probe along the line, reducing probe penetration to keep needle on scale.
h- Adjust GAIN and VERNIER of VSWR meter and/or output power from signal source to obtain a SWR reading of exactly 1.0.
i- Move the probe along the line to a voltage minimum (needle moves to left). Do not retune probe or detector.
j- If the indicated SWR is between 1 and 3.2, greater accuracy in a reading is possible if the EXPAND function is used. For a SWR between 1 and 1.3, a SWR scale is provided for a direct reading when the EXPAND switch is changed to the 0.0 position. If the SWR is between 1.3 and 3.2, the EXPAND dB scale may be used to obtain an accurate dB reading for conversion to SWR using Figure A2.1. For SWR between 3.2 and 10, a scale on the meter provides the reading. Refer to Figure 6 and obtain the SWR reading as follows:
    1- For a reading between 1 and 1.3 on the 1 to 4 SWR scale after step 10 above, change the EXPAND switch to 0.0. This SWR segment is then expanded to full scale and the reading is taken from the 1 to 1.3 dB scale.
    2- If needle is between 1.3 and 3.2 after step j, note the reading on the 0 to 10 dB scale and change EXPAND switch to a position which normalizes the beginning of the proper 2.5 dB segment. For example, if the reading is approximately 8.4

dB, then change EXPAND switch to 7.5. The reading is then the sum of the needle indication on the 0 to 2.5 dB scale and the EXPAND switch setting (for example, 0.95 + 7.5 = 8.45 dB). Locate this dB reading on Figure 4 and note the corresponding SWR value (8.45 dB is read as SWR of 2.66).

3- After step j, if the needle is to the left of 3.2 (possibly to the left, off- scale) on the 1 to 4 SWR scale, change the RANGE switch to the next 10 DB position above the initial setting. The SWR is then indicated directly on the 3.2 to 10 dB scale.

High SWR (Above 10:1): A reading is possible on the VSWR meter for SWR greater than 10. If the indication is more than 10 after step j (3), change the RANGE switch to the next 10 dB position (now two steps, or 20 dB, above the initial setting). Read the SWR on the 1 to 4 SWR scale and multiply the reading by ten. Here, again, a dB reading may be converted to SWR using Figure 5. The reading used for converting is the amount of dB above the initial RANGE switch setting in step 3.

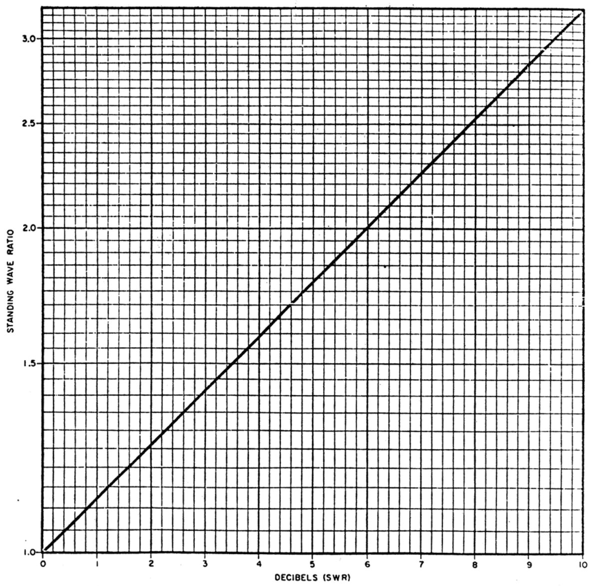


Figure A2.1

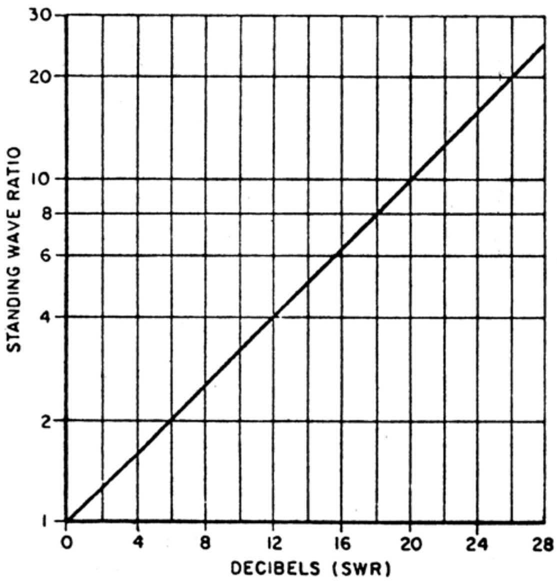


Figure A2.2.

Assignment 2. Transmission Lines in Time Domain. (45 min in lab)

The goals of this assignment are to measure the propagation velocity of electromagnetic wave in a coaxial cable and estimate the load impedance via the load reflection coefficient over a large frequency band using time domain technique.

Tellegen Hall equipment:

- Tektronix TDS 2022B oscilloscope.
- Tektronix AFG 3021C arbitrary function generator.

Extra parts for this assignment:

- 2x 50 cm BNC cables (blue).
- 1x 10 m BNC cable (green).
- 1x BNC tees (colours can differ from setup to setup).
- 1x BNC female-female adapter.
- 1x 50Ω BNC load (green).
- 2 x unknown resistors from 10 Ω to 180 Ω (black and grey).
- 1x short BNC.

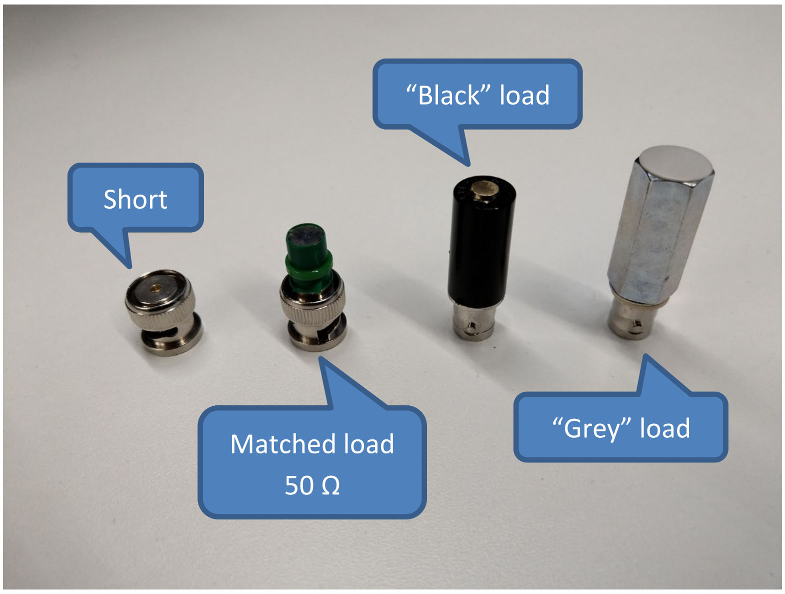


Figure 2. 1 Terminations

Experimental Setup

For the time domain we will use the Tektronix AFG 3021C arbitrary function generator and Tektronix TDS 2022B oscilloscope. This setup gives a possibility to sample, measure and visualise short pulses in time domain. Propagation effects can be measured directly from the comparison of transmitted and propagating pulses amplitudes and time delays.

Function generator settings:

- Pulse waveform
- Frequency 1 MHz
- Amplitude 5 Vpp
- Offset 2.5 V

A tee is connected to the scope's CH1 input, one port is terminated with a 50 Ω load and the other one is connected to the function generator's output with a "blue" cable.

The arbitrary function generator (AFG) TTL output is connected to the scope's CH2 input

On the oscilloscope:

- Probe attenuation is set to 1X.
- CH1 coupling is set to DC.
- Measurements are triggered on CH2.

Experiments to be done and questions to answer in report

Part 1. Dielectric in Coaxial Cable: the Estimation of the Propagation Speed and Relative Permittivity

The goal is to compute the relative permittivity of the coaxial cable's dielectric filling based on the measured propagation delay and the cable's physical length.

Two waveforms are acquired, the "reference", with the short "blue" cable connected to the scope (Figure 2. 2), and the "delayed" waveform, with a 10 m "green" cable inserted between the "blue" cable and the scope (Figure 2. 3). The length of "blue" signal and trigger cables are equal - that gives a possibility to directly estimate the time delay for the propagation of signal through the additional "green" cable comparing time delays of signal fronts for both cases recorded with different length of "signal" cables.

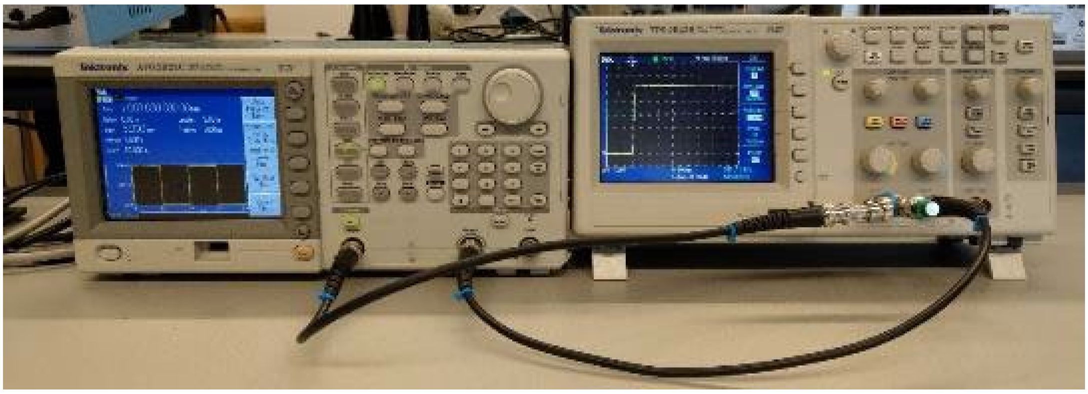


Figure 2. 2 Reference waveform

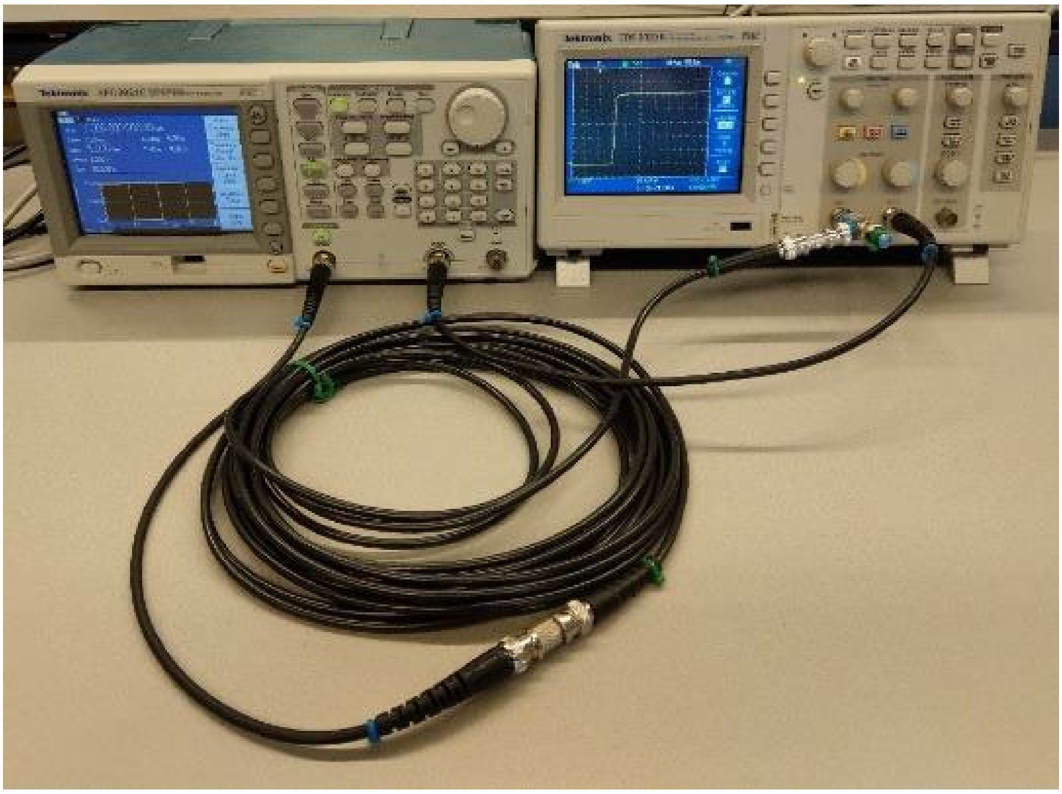


Figure 2. 3 Delayed waveform due to insertion of "green" cable

Use the *TDR_USB_SCOPE.m* Matlab script located in the TDR folder on the desktop to save your data for postprocessing. The variables *t* and *y*, are the time vector in seconds and the amplitude vector in Volts, respectively.

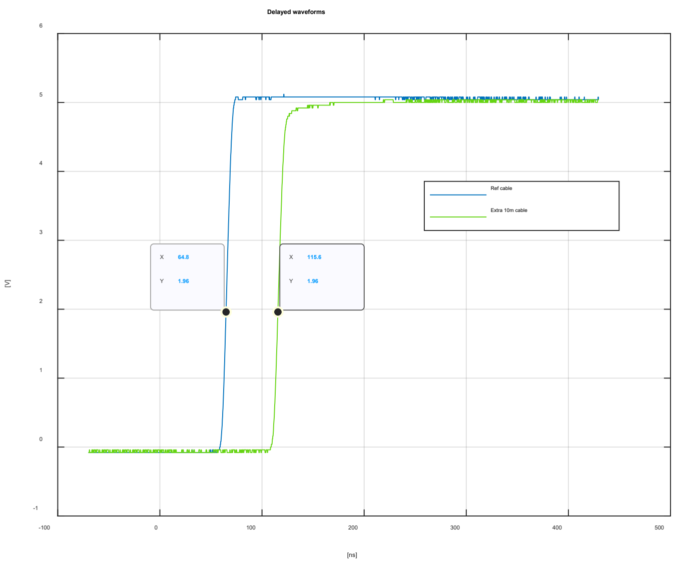


Figure 2. 4 Example plot of waveforms that propagated through the cables of different length

You can also read the delays directly on the oscilloscope following the steps below.

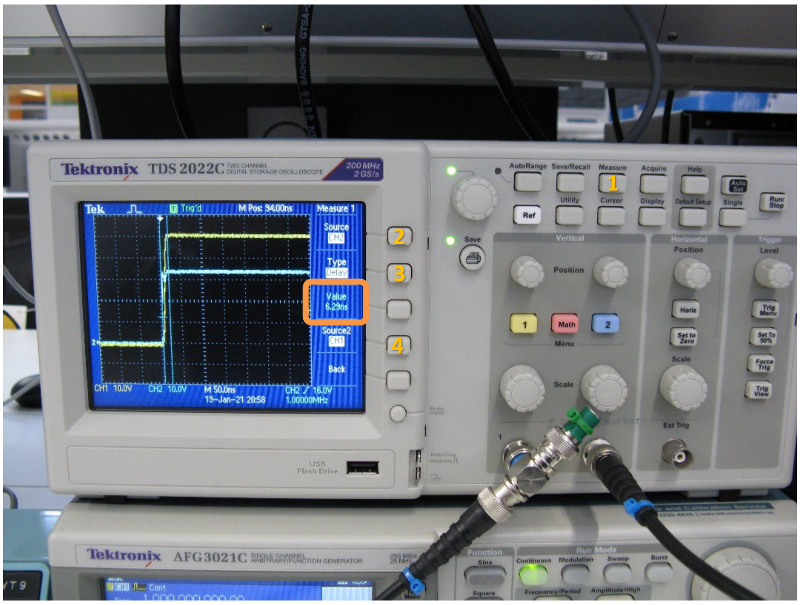


Figure 2. 5 Measuring delays

- Measure the delay between the 2 channels (use softkeys 1 to 4 as shown in Figure 2. 5), this is your time reference.
- Insert the green cable (10 m) between the tee and the blue cable using a female-female adapter, as in the Figure 2. 3.
- Measure the new delay between the two channels (see Figure 2. 6).

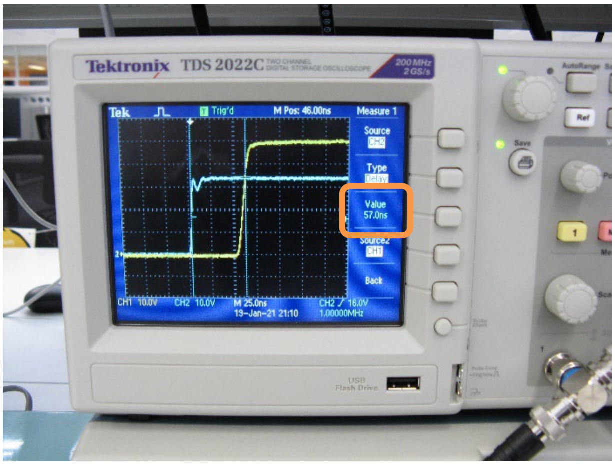


Figure 2. 6 Delay caused by extra cable.

Knowing the propagation time through the cable as well as its physical length, you can calculate the propagation velocity inside the coaxial cable and deduce the relative permittivity of its dielectric filling.

Part 2. Time Domain Reflectometry: estimate the load's impedance

The goal of this assignment is to compute the impedance of the loads using the measured reflection coefficients. Compared with frequency domain techniques, time domain reflectometry (TDR) provides a more intuitive and direct look at the *device under test* (DUT) characteristics. A step pulse is transmitted through the line under investigation and the incident and reflected voltage waves are measured with an oscilloscope. Interpret the recorder time dependency of the signals when the oscilloscope measures initially only the incident signal and then - the sum of incident and reflected from the load signals. See ***Agilent's TDR theory application note*** for more details about your measurements interpretation.

Measurement procedure

Channel 2 can be switched off on the oscilloscope.

A tee is connected to the oscilloscope CH 1 input. One tee port is connected to the function generator via a 50 cm cable (blue) and the other port is connected to a 10 m cable (green) terminated with the load under test.

With the termination open (max reflection coefficient of 1, see Figure 2. 7), set the vertical scale so that the you can see the complete waveform to prevent clipping.

NB: if clipping occurs, the Matlab data will also be erroneous (Figure 2. 8).

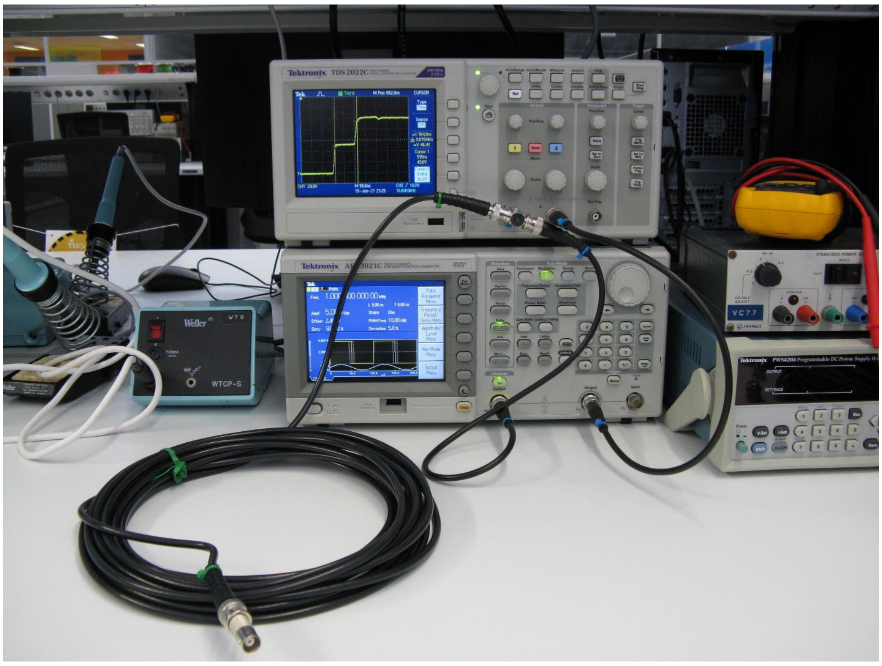


Figure 2. 7 Open termination for vertical scaling

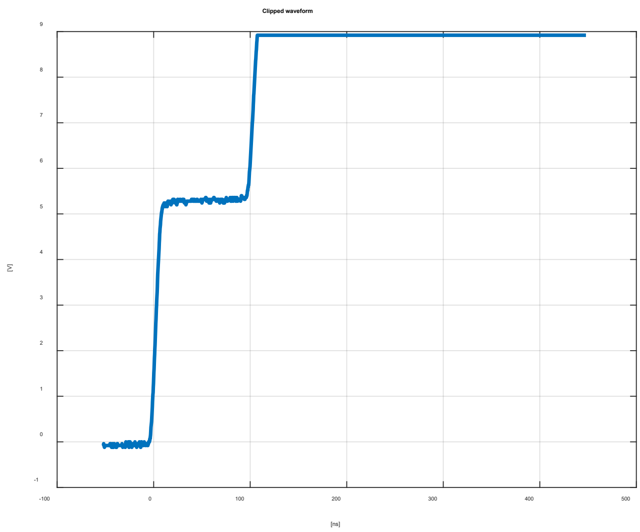


Figure 2. 8 Example of a clipped waveform

Calibration

We measure two known loads to calibrate the system.

Connect the matched load (green) at the end of the green cable and measure the amplitude of the reflection with the cursor as shown below.

Save the data using the Matlab script.

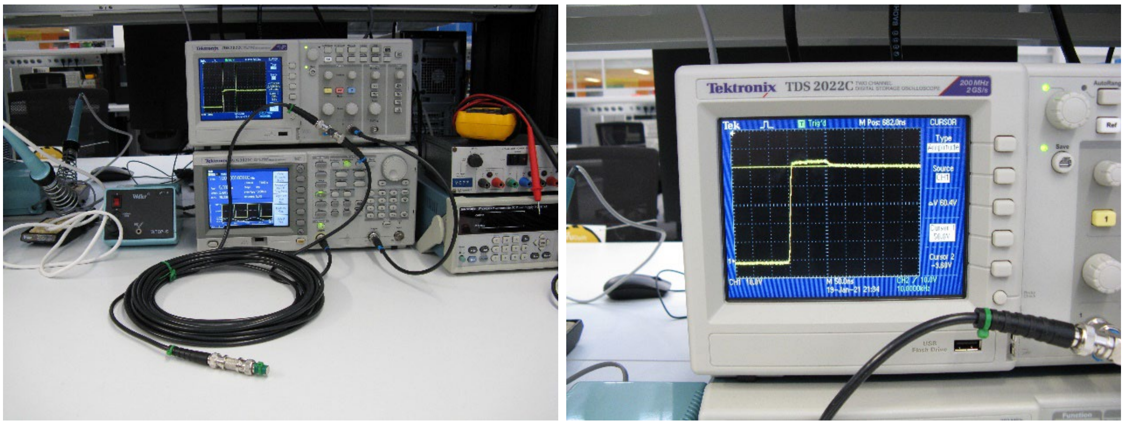


Figure 2. 9 Matched load measurement

Since the reflection coefficient of a matched load is equal to zero, this value will be your zero reference for the amplitude of the reflected signal (E_r). Keep cursor 1 as is and use ΔV with cursor 2 to directly measure the amplitude of the reflected signal.

Connect the short at the end of the green cable and save the data with Matlab. The magnitude of the reflected signal give you the value of the incident voltage E_i, since the reflection of a short is equal to -1 (here E_i = 4.96 V).

<u>NB:</u> The ΔV values given by the oscilloscope are always positive. Change sign if below the reference value (cursor 1). See Figure 2. 11.

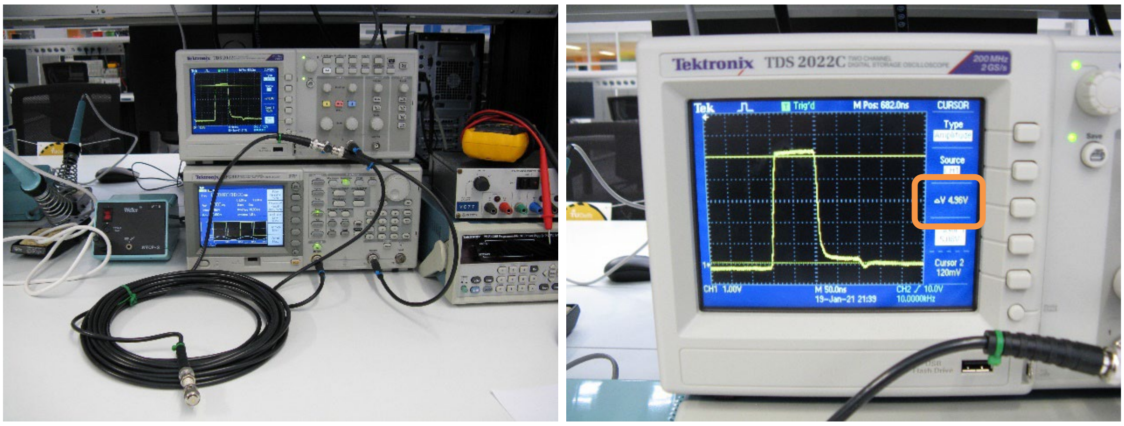


Figure 2.9 Short measurement

Loads characterization

Connect the “black” load at the end of the green cable and measure the amplitude of the reflected signal. Save the data and repeat for the “grey” load.

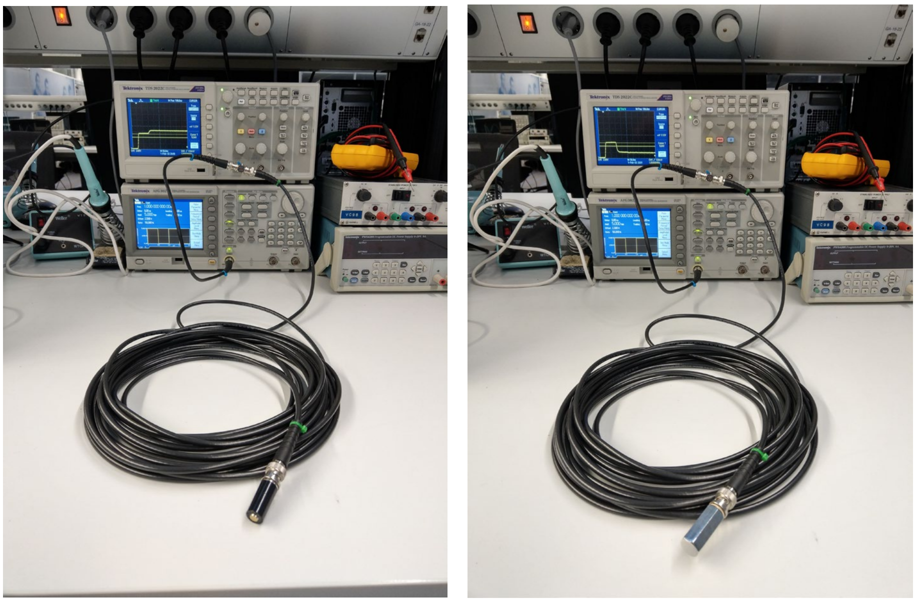


Figure 2. 10 Unknown loads measurements

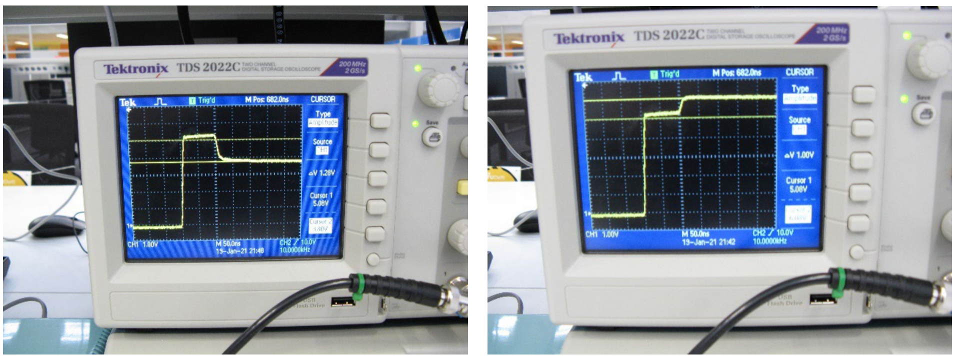


Figure 2. 11 ΔV is negative on the left!!

An example of measured and recorded data is presented in Figure 2. 12. Based on the analysis of this data your report has to include the following:

- Using the measured signals, for each unknown load compute the reflection coefficient and determine the impedance Z_l knowing that $Z_0 = 50\Omega$.
- Explain the difference between measurements of load's impedance in time and frequency domains.

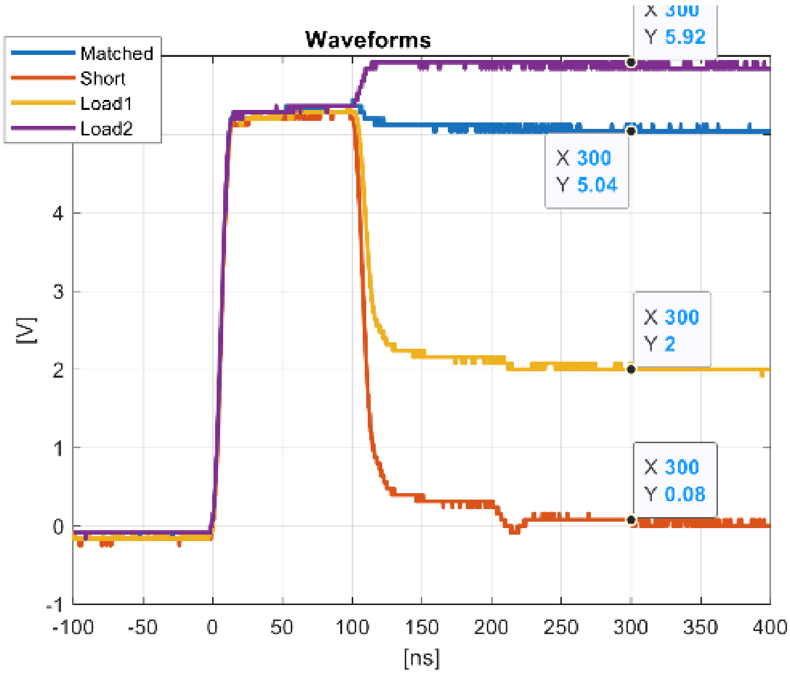


Figure 2. 12 An example of waveforms recorded for all loads