EE3P11 - Electromagnetism Practical

Session 1 Report - Group 03.1
Transmission Lines

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Introduction

In the first practical session, an investigation was made into two types of transmission lines: wave guides and coaxial cables. The waves guides were analysed in the frequency domain, and the voltage-standing-wave ration (VSWR) was determined for different loads, or terminations. The coaxial cables were measured in the time domain, placing emphasis on reflections and propagation speeds, which are effected by the type of load and cable parameters.

Assignment 1: Frequency Domain Transmission Lines

The first experiment was set-up as show below in figure 1 and figure 2. From left to right, it consisted of a RF signal source, a signal generator, and an amplifier to modulate a 1 kHz square wave onto the RF signal source with a frequency of 9.4756 GHz, which is then transmitted down the wave guide, past the slotted line detector, and to the load under investigation. The detector can then measure the amplitude variations over it's adjustable distance of the standing wave inside the wave guide, and display the signal on an oscilloscope (for qualitative representation) and a digital multimeter (for quantitative results). The oscilloscope show the 1 kHz modulated wave, with the amplitude representing that of the RF signal amplitude.

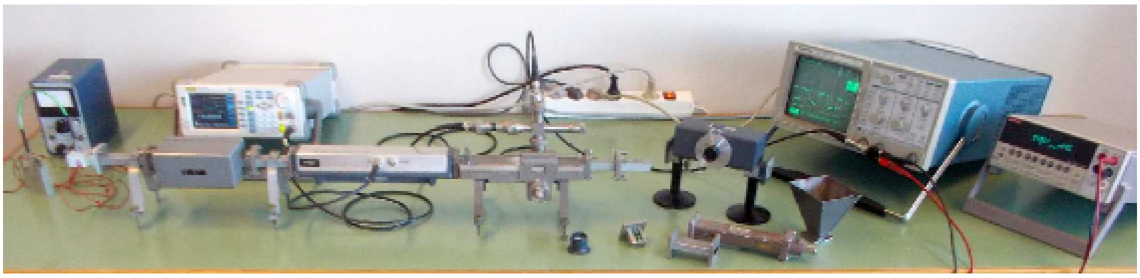

Figure 1: Experimental set-up for assignment 1 [1, p.3]

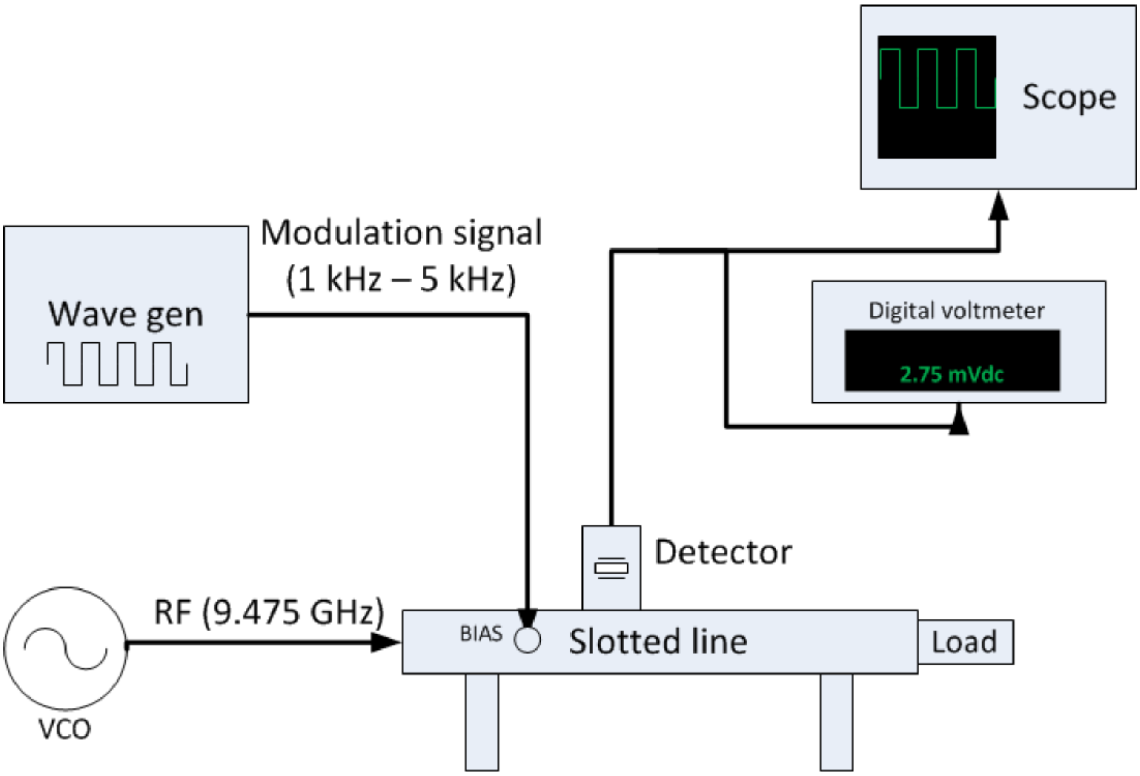

Figure 2: Diagram of experimental set-up for assignment 1

The following questions were answered for the experimental set-up:

Wavelength

The wavelength of the standing wave was determined by measuring the distance between the amplitude peaks on the slotted detector. By averaging three measurements, the final distance was 2.2 cm, which is half the wavelength, giving a total wavelength of 4.39 cm. The phase velocity is given by $v_p = \lambda \cdot f = 416 \cdot 10^6\ \mathrm{m\,s^{-1}}$ (1.39c).

The phase velocity represents the propagation speed of a single frequency component of the wave between to points. However, this information has little actual benefit, as it does not represent the propagation delay of the wave in the time domain. Instead, the value represents the distance and time between two consecutive phase occurrences in the standing wave. As two identical interference patterns can happen independent of each other, the interpreted speed of this occurrence (phase velocity) can be higher than the speed of light. As no information can be transmitted between these two points as this speed, this observation gives little usable information on the compound waveform.

Voltage-standing-wave ration (VSWR)

Five different loads were compared, where the amplitudes of the maxima and minima of the standing wave were measured, and compared below in table 1. For each load, the VSWR, the reflection coefficient Γ, and the delivered power to the load were calculated. Below are the formulas used for each value.

Load	$E_{min}(mV)$	$E_{max}(mV)$	VSWR	$\|\Gamma\|$	$P_{Load}(W)$
a) Open Waveguide	26.5	56.9	2.15	0.37	$1.20 \cdot 10^{-3}/Z_0$
b) Short Circuit 33 mm	0	76.6	∞	1.00	0
b) Short Circuit 55 mm	0	79.6	∞	1.00	0
c) Matched Load	41.7	46.5	1.12	0.057	$1.27 \cdot 10^{-3}/Z_0$
d) Horn Antenna	39.3	49.0	1.25	0.11	$1.31 \cdot 10^{-3}/Z_0$

Table 1: Results for different loads

The VSWR is:

$$VSWR = \frac{|V_{max}|}{|V_{min}|} \tag{1}$$

The reflection coefficient:

$$|\Gamma| = \frac{VSWR - 1}{VSWR + 1} \tag{2}$$

The power delivered to the load is:

$$P_{abs} = \frac{(V_0^+)^2}{2Z_0}(1 - |\Gamma|^2) \tag{3}$$

Standing wave pattern comparison

There is not measurable shift in the position of the nodes and anti-node between the 55mm and 33mm wave guide short circuits. The reason behind this is that the difference in the shorts is 22mm, which is have the calculated wavelength of the standing wave. Due to this, the observed standing wave in the detector has identical positions of the nodes and anti nodes.

X-band phase velocity

For an electromagnetic wave in a wave guide, the wavelength is not the same as it would be in free space. The equation for the phase velocity is given below in equation 4, where c is the speed of light, λ is the wavelength, and a is the length of the wave guide

$$v = \lambda f = \frac{c}{\sqrt{1 - (\frac{\lambda}{2a})^2}} \tag{4}$$

The wavelength of the EM wave must fit within the length of the wave guide, as it forms a standing wave between the two edges of the wave guide (as the body of the wave guide must be the same potential). Using the data from the experiment, we can plot the phase velocity for different frequencies in the X-band (8 GHz - 12 GHz), as show below in figure 3

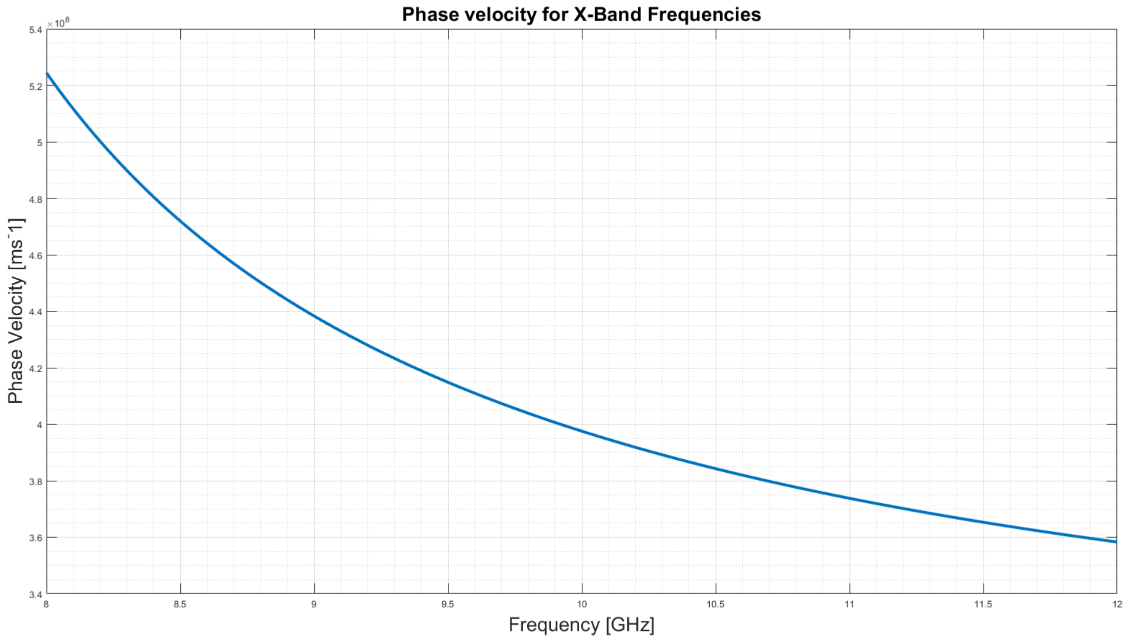

Figure 3: X-Band phase velocities

Other parameters

As the impedance of the loads can be calculated, using the measured values, the impedance of the wave guide can also be estimated.

Assignment 2: Time Domain Transmission Lines

During this assignment, the setup in figure 4 was used. It consisted of a pulse generator which sends a square pulse to a DUT (device under test) via a coax cable (with $Z_0 = 50\Omega$), a sampling unit, which samples the electric field in the coax cable, and an oscilloscope, which measures the sampled electric field strength.

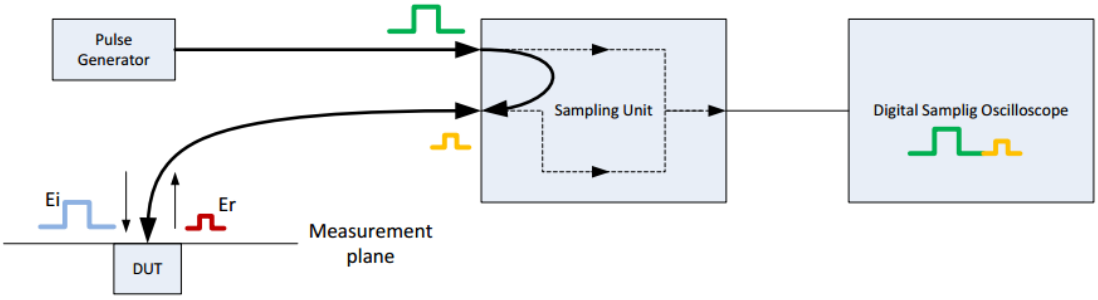

Figure 4: Experimental set-up for Assignment 2

Time Domain Reflectometry

In this part, the reflection of an incident square pulse was investigated. As the oscilloscope measured the total electric field in the coax cable, it also registered the reflection of the pulse, from which the reflection coefficient was be derived. Three loads were used: a short circuit, a matched load, and an unknown load. The three measurements were plotted together an shown below in figure 5.

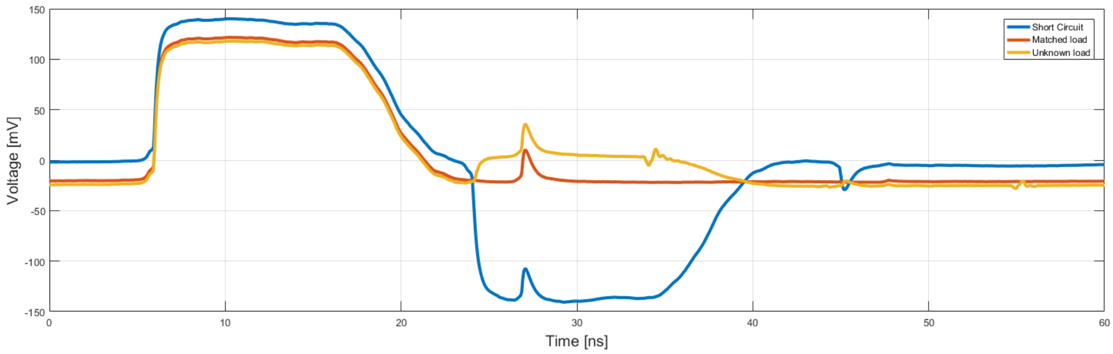

Figure 5: Experimental set-up for Assignment 2

From transmission line theory [2], we know that the reflection coefficient can be written as shown below in equation 5.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{5}$$

From this, equation 6 follows:

$$V^r = \Gamma \cdot V^i \tag{6}$$

Using the equations, we can evaluate the two known loads, and determine the unknown load as well/

1. Short Circuit: With a short circuit, $Z_L = 0$, which gives a reflection coëficient of $\Gamma = -1$. From figure 5 we see that the peak of V^i is 140mV, and that V^r is -140mV, which is also to be expected.
2. Matched Load: For the matched load, we see that $Z_L = Z_0$, which gives a reflection coëficient of $\Gamma = 0$. Figure 5 also shows that the matched load has no reflection, which agrees with the above reflection coëficient.
3. Unknown Load: Figure 5 gives V^i as 140mV, and V^r as 28mV. This gives a reflection coëficient of approximately 0.2. Know that $Z_0 = 50\ \Omega$ from the experiment, we calculate that the unknown load is $Z_L = 75\ \Omega$.

Is the cases above, only the real parts of the reflection coëficient and load impedance are calculated, as only the amplitude of the signals were looked at. By investigating the phase shift of the signals, we could also calculated the imaginary parts. Looking at the results in figure 5, we can see very little phase shift in the reflected signals, which is also to be expected, as imaginary loads are typically dominated by the cable length and construction, as discussed in the next section.

Propagation speed and relative permittivity

The experimental set-up was adjusted so that the delay in a coaxial cable can be measured. The results of the measurements can be see below in figure 6.

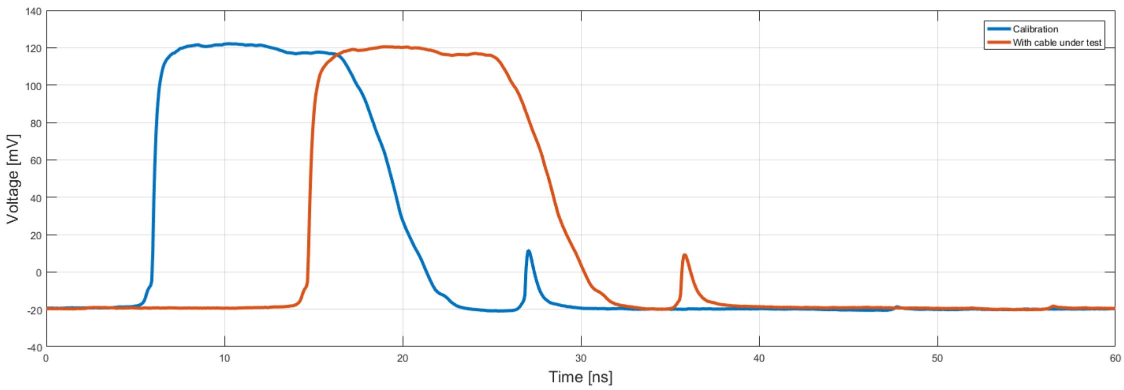

Figure 6: Experimental set-up for Assignment 2

For the results, we see the expected phase shift due to the varying cable lengths. The cable construction forms a capacitance between the outer shield and core, which is dependant of the diameter, the cable length, and the di-electric of the insulator. We can calculate the difference in the relative permittivity of the di-electric insulators between the two cables.

Looking at the graph, we can see that the delay between the two rising edges is approximately 8.8 ns. Given that the cable was 2 m long, we calculate the propagation speed in the cable to be $2.2 \cdot 10^8\ \mathrm{m\,s^{-1}}$. From transmission line theory [2] we get equation 7 below, where μ_r is the relative permeability, and ϵ_r is the relative permittivity.

$$c = (\mu\epsilon)^{-1} = c_0(\mu_r\epsilon_r)^{-1} \tag{7}$$

Assuming the relative permeability to be 1, we can compare the speeds of the EM waves in the two cables, and determine the relative permittivity of the cable dielectric, as shown below in equation 8.

$$\sqrt{\epsilon_r \mu_r} = \frac{c_0}{c} \Leftrightarrow \epsilon_r = \left(\frac{c_0}{c}\right)^2 = \left(\frac{3 \cdot 10^8 \text{ m/s}}{2.2 \cdot 10^8 \text{ m/s}}\right)^2 \approx 1.86 \tag{8}$$

References

[1] Blackboard Lab Manual. (2017). EE3P11 - EM Practicum, 2016-2017 Q3.

[2] A.L. Lance, *Introduction To Microwave Theory And Measurements*, New York: McGraw-Hill, 1964.