7. Experiment K: Wave Propagation

This laboratory will be based upon observing standing waves in three different ways, through coaxial cables, in free space and in a waveguide. You will also observe some other aspects of wave propagation and by the end of the lab you should have successfully learnt about standing wave and transmission theory, in particular the reflection coefficient, $\Gamma$ and the voltage standing wave ratio, VSWR.

You may commence with any part, A, B, or C, but must only spend two hours on each, recording results and performing calculations as you go along. There is preparation work which must be carried out in advance of coming to the laboratory class, failure to do so will have consequences. Useful references to use are by J. D Kraus, “Electromagnetics with Applications” and D. M. Pozar, “Microwave Engineering”.

7.1. Preparation - General

1. Go to the webpage http://info.ee.surrey.ac.uk/Teaching/Courses/WPLab/standing_waves.html to have a look at the animations and see how standing waves operate in the three different scenarios that the experiment will cover.

2. Using the standing wave animations and background reading, explain in one or two sentences how the reflection coefficient, $\Gamma$, can be used. This is a voltage ratio, what are the two voltages it compares?

3. Write down the equation that relates $\Gamma$ to the source impedance, $Z_0$ and the load impedance, $Z_L$ of a transmission line.

4. Using the standing wave animations and background reading, explain in one or two sentences how the voltage standing wave ratio, VSWR, can be used to define the standing wave. This is also a voltage ratio, what are the two voltages it compares?

5. Write down the equation that relates VSWR to $\Gamma$.

6. With these equations write down a table like the one below that compares the reflection coefficients and VSWR for different values of load impedance if $Z_0$ is 50Ω. Comment also on how standing waves are formed.

<table>
<thead>
<tr>
<th>$Z_L$</th>
<th>$\Gamma$</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short Circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50Ω matched load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(100 + j100) Ω</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. Write down the expression relating $c$, the velocity of propagation of an electromagnetic wave in free space, to the permittivity $\varepsilon_0$ and the permeability $\mu_0$, of free space.

8. Write down expression relating the intrinsic impedance $\eta_0$ of free space to $\varepsilon_0$ and $\mu_0$ and state the value of $\eta_0$. 
9. Read about and make a sketch showing how $\Gamma$ is applied in a Smith Chart. But DO NOT spend a long time on this question, it will be painful!

7.2. Preparation: Part A - Coax Cables
1. Write down the expression relating the relative phase velocity of propagation $v$ of an electromagnetic down a cable to $c$, the relative permittivity $\varepsilon_r$ and relative permeability $\mu_r$, of a dielectric. Simplify the expression for the case when $\mu_r = 1$. Assuming $\varepsilon_r = 2.25$, calculate $v$.

2. Hence calculate the lowest frequency $f_{\text{min}}$ which will set up a standing wave in a 10m cable, which has a short-circuit load, using the values given in question 1 above.

3. Calculate the approximate reflection time for a pulse to travel to a load and back, in a cable of about 100m length, which has a dielectric of $\varepsilon_r = 2.25$.

4. If a pulse is sent down a transmission line, why may there be multiple pulses that reflect back?

5. Explain what is meant by the term characteristic impedance $Z_0$ of a lossless transmission line (assume $Z_0$ purely resistive). Find an equation that relates $Z_0$ to the inductance, $L$ and the capacitance, $C$, of a transmission line.

7.3. Preparation: Part B - Waveguides
Because of the way in which waves propagate along a waveguide, the guide wavelength $\lambda_g$ will be different from the free space value $\lambda_0$. The relationship is given by the formula:

$$\frac{1}{\lambda_0^2} = \frac{1}{\lambda_g^2} + \left(\frac{m}{2a}\right)^2 + \left(\frac{n}{2b}\right)^2$$

where $m$ and $n$ relate to the order of the mode and $a$ and $b$ are the lengths of the sides of the guide.

In the experiment you will only be interested in the TE$_{10}$ mode for which $m = 1$ and $n = 0$. The guide has dimensions $a = 2.28\text{cm}$, $b = 1.02\text{cm}$.

1. Take a look at the animation of a TE$_{10}$ waveguide on webpage [http://info.ee.surrey.ac.uk/Teaching/Courses/WPLab/standing_waves.html](http://info.ee.surrey.ac.uk/Teaching/Courses/WPLab/standing_waves.html). Take a copy of the image and indicate which fields are electric and magnetic. Show clearly their direction and give reasoning as to how they are orientated. Sketch the electric and magnetic field patterns for the TE$_{10}$ mode in a waveguide.

2. For the above equation, for a TE$_{10}$ mode with the dimensions specified above, re-arrange the equation to define $\lambda_g$ in terms of $\lambda_0$. Sketch a rough curve for this equation for values of $\lambda_0$ from 0mm to 50mm.

3. Change the equation in the previous equation to define $\lambda_g$ in terms of frequency, $f$. Sketch another rough curve for this equation for frequency values of 4GHz to 10GHz. On this graph you should be able to indicate a cut off frequency, where an asymptote occurs in the graph. Draw this also on the graph and calculate the cut off frequency, $f_c$ which is derived to be $f_c = c/2a$. 

34
4. Have a think and write a few ideas about what the difference between $\lambda_0$ and $\lambda_g$ means for waves travelling down a waveguide.

5. Read through the experiment notes to gain some idea and thought as to what you will have to do in the experiment. Drawing your own diagrams may help here.

### 7.4. Preparation: Part C - Free Space Propagation

1. Take a look at the animation on [http://info.ee.surrey.ac.uk/Teaching/Courses/WPLab/antennas.html](http://info.ee.surrey.ac.uk/Teaching/Courses/WPLab/antennas.html). Write some comment in your own words as to how you would understand the difference between a near field and far field of an antenna. Consider in particular how the near field and far field differ when thinking about voltage received from the transmitter to the receiver versus distance.

2. Calculate the minimum distance $d$ to the far field, known as the Rayleigh distance, for an antenna of maximum dimension $D = 65$ mm, at a frequency of 1.2 GHz, using the formula:

   $$ d = \frac{2D^2}{\lambda_0} $$

3. Read up on some notes such as linear polarisation, front to back ratio and the free space path loss of antennas and wave propagation.

### 7.5. Experiment: Part A - Coaxial Cables (2 Hours)

1. You are provided with a 10m length of coaxial cable with a short circuit on one end and a BNC connector on the other. Using the signal generator set up as below and measuring with an oscilloscope, find the lowest frequency, $f_{\text{min}}$, at which a minimum occurs at the generator. Think carefully about where you should position the oscilloscope and what you are looking to measure. The value for $f_{\text{min}}$ should be close to what you calculated in your preparation.

2. Hence calculate the velocity of propagation $v$, of the electromagnetic wave in the cable. Deduce the value of $\varepsilon_r$ of the cable dielectric, assuming $\mu_r = 1$. What are the values of $\Gamma$ and VSWR under these conditions and why?

3. Now connect the source to the large drum of cable which contains about 100m of identical cable to that in the previous question but has a variable resistor $R_L$ as a load. Using a pulse generator and setting an appropriate pulse width, frequency, apply short pulses to the input end of the cable and by observing reflections at the generator end. Determine the length of the cable and sketch the pulse response that you get and explain why it looks like it does. (Hint put $R_L$ to a max or a min value to get full reflections, you should realise by now what value should it be!)

4. Adjust $R_L$ so that the reflections disappear. Now by measuring $R_L$ with an AVO meter (remember you may need to ensure you are NOT also measuring the dc resistance of the cable!), you can easily determine $Z_0$ for the cable. Your preparation will help you with this.
5. Adjust $R_L$ to its maximum value of 470Ω. Calculate $\Gamma$ and the VSWR. Assuming a lossless line, measure the incident and reflected pulse at the load (it’s not that hard!), hence determine $\Gamma$ and compare with your calculated value.

7.6. **Experiment: Part B - Waveguides (2 Hours)**

The equipment consists of a Gunn diode microwave source and a PIN diode acting as a modulator as set up in the diagrams below. A square wave signal is applied to the modulator. The microwaves are fed into a cavity wave meter which contains a directional coupler whereby a small percentage of the power is tapped off to measure the frequency. This deflected energy is then passed through to a crystal detector which can be seen from a CRO. The bulk of the energy passes to a variable attenuator and then to a second crystal detector. In the experiment this detector is later replaced by a standing wave detector, which is a section of slotted line, which enables a probe to be inserted into the beam to measure the electric field. A short (or metal plate) or load is used at the end of the detector in the experiment.

**ON NO ACCOUNT SHOULD YOU LOOK INTO THE OPEN END OF A WORKING WAVEGUIDE AS MICROWAVES CAN CAUSE PERMANENT DAMAGE TO YOUR EYESIGHT!**
ASK THE SUPERVISOR TO CHECK THE SETUP BEFORE SWITCHING ON AND STARTING THE EXPERIMENT

ALSO DO NOT GO PLAYING WITH IT AS YOU MAY BREAK IT AND YOU’LL LOSE MARKS FOR IT!

1. Your first task is to measure the frequency of the microwaves by adjusting the cavity wave meter until the output from the crystal detector connected to it drops its output value by a few percent. You will need to adjust the micrometer carefully — i.e. don’t just turn it fast, do it slowly. You can then take the micrometer reading and look in the calibration folder to see what frequency this corresponds to. Check the frequency you have read with your supervisor to see if you have done it right.

2. Adjust the variable attenuator until both detectors give the same output and hence find the number of dB of power that the directional coupler diverts into the side limb. You need to do this because you want to make the voltage output of the two crystal detectors the same. Some of it will have been attenuated in the cavity wave meter.

SWITCH OFF THE SOURCE BEFORE PROCEEDING TO THE NEXT TASK
3. Using the tools provided, remove the crystal detector marked with an asterisk (*) in the diagram and replace it by the standing wave detector (as shown in the photograph) followed by a short circuit load (i.e. a metal plate!).

GET THE SUPERVISOR TO CHECK THE SETUP BEFORE PROCEEDING.

4. Connect the line to the VSWR meter to measure A-B as follows.

5. Adjust the probe on top of the standing wave detector and adjust the VSWR meter as necessary in order to obtain a maximum output.

6. Taking readings as you go along, move the probe along the guide about 40mm in small steps to determine the location of maxima and minima. Record and plot the readings, from which you can determine $\lambda_g$. Having also measured the frequency you are using, you can compare this to the theoretical wavelength using the equations derived in your preparation. Furthermore, using the equation, $v = \beta \lambda_g$, you can find the velocity. How different is this to what you would get in free space?

7. From the graph or from the readings made you can determine the VSWR of the wave. What value would you expect?

SWITCH OFF THE SOURCE AND REPLACE THE SHORT CIRCUIT LOAD WITH A MATCHED LOAD.

GET THE SUPERVISOR TO CHECK THE SETUP BEFORE SWITCHING ON AND PROCEEDING.

8. Repeat the readings done in task 6 and determine the VSWR this time. What would you expect?

9. For the frequency being used, determine the characteristic impedance $Z_o$ of the guide using the equation:

$$Z_0 = \frac{|E|}{|H|} = \eta_0 \left( \frac{\lambda_g}{\lambda_0} \right)$$
10. Looking at the above equation as a ratio of electric to magnetic field, how might the changes in these fields explain the difference in wavelength (and hence velocity) of waves going down a waveguide?

### 7.7. Experiment: Part C - Free Space Propagation (2 Hours)

The setup for this experiment is shown in the diagram on the next page looking from the top view. The transmit (Tx) antenna is a Yagi-Uda antenna connected to a source with unknown frequency. The receive antenna (Rx) is a folded dipole antenna with a light aluminium shield that can be placed behind it. The antenna can then be moved up and down a sliding line for doing measurements. A microwave amplifier helps with measurement to read a received square wave on the CRO.

1. First of all ensure that you have aligned the Tx and Rx antenna to the same height and that they are both horizontal. This is essential in terms of making good readings for the first part of the experiment.

2. Your first task is to make a standing wave in free space. With the shield behind the Rx, ensure you have set the slider to move back and forth over a range of around 4-10cm. Thinking about the principles of standing waves, determine the minimum distance at which a standing wave minima has occurred. Take care with this as it takes patience to detect and there are spurious responses when the antennas are very close. From this you will then be able to determine the wavelength of that standing wave and hence the frequency of operation. Check the result with your supervisor before you move on.

3. For the transmit antenna find the Rayleigh distance with this frequency as you did in your preparation.

4. The remainder of the experiment involves measuring some simple antenna parameters. The first is to measure the front to back ratio (F/B) of the Tx antenna. Remove the reflecting plate and place the Rx about 6cm away from the Tx and then you can rotate the Tx antenna so that the smaller elements of the Yagi-Uda structure are facing forward or backwards. Take a measurement with the antenna facing either way around. From the measurement you will be able to determine which way the antenna is radiating most energy and you can also calculate F/B as follows:
5. Another simple parameter is to measure the cross polarisation ratio, XPR, of the Rx antenna. Again place the RX about 6cm away from the TX radiating in the right direction. Adjust the preamplifier to obtain a reasonable trace. With both antennas horizontal, you can measure voltage $V_1$ on the CRO. After this you can tilt the Rx antenna $90^\circ$ around the vertical axis easily on the sliding line. This will then measure the cross polarised voltage, $V_2$ but make sure you keep the Rx the same distance apart from the Tx.

$$XPR = 20 \log \left( \frac{V_1}{V_2} \right)$$

6. With the receiving antenna horizontal again, vary the distance RX from TX and plot the voltage reading as a function of distance over the range 50mm to 200mm. Vary the gain of the preamplifier as required.

7. Using a calculator, convert your voltage readings to dB by using $20 \log(V)$ in a table. You can then plot results of dB versus distance in mm. Is there any difference in the results beyond the far field?

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