ELEC0019 Interference, Diffraction and Polarization of Electromagnetic Waves

Note: This tutorial originates from and older Laboratory experiment on "Interference and Diffraction" and can be completed without attending to the lab. Results of experiments are given instead in order to perform the calculations, analyse results and plot graphs. Completion of the tasks requires the student to study the topics in more detail using the references and other material and the use of Matlab for the calculations and plots.
Assessment will be based on the answers to the questions marked in this script and background material.
Complete this tutorial, answer all the questions and keep the answers, plots and programs requested in the script safely in your records. ***You will need these to answer the Coursework test close to the end of term***.

Wave Propagation

Wave propagation is a central concept in physics and engineering. It is at the heart of most systems and devices in electronic engineering. Examples are ubiquitous and include among others, long, medium and short wave radio and microwave links, optical fibre systems, sonar, audio (acoustic) systems, optics and electron waves in semiconductor devices.

Interference and diffraction of waves in water. Picture from: http://www.afhalifax.ca/magazine/zero/3164-2/en-sequence-physique-sp02

In this tutorial we will be concerned with electromagnetic waves, nevertheless many (but not all) of the results and conclusions will apply to other kinds of wave such as acoustic or electron waves. This tutorial has two main parts that deal with important aspects of wave propagation: The first part is "Interference of waves", that will investigate the superposition effect of two waves and includes a section on Antenna Arrays. The second part, "Diffraction of waves" concerns the effect of superposition of an infinite number of waves, which is commonly manifested by the *bending of wave paths at the edges of obstacles*. Diffraction is just another form of interference. Usually, when two or a few waves interfere, the phenomenon is called interference and when it is a large or infinite number it is called diffraction. The final section briefly examines the polarisation of waves in connection to the experiments. You will be asked to explain aspects of the theory and to show your theoretical calculations as part of the answers to the questions indicated in this script.

Part 1 Interference of waves

In this section we will be concerned with monochromatic waves, that is, waves of the same, single frequency, not made up of a superposition of multiple components of different frequency – like for example, a beam of sunlight, which is composed by multiple waves of different frequency.

Two waves at the same frequency will give rise to interference effects when they overlap. This effect appears in numerous practical applications. It is the basis of interference fringes in, for example, optical interferometers and in the design and use of gratings and antenna arrays. The figure above illustrates the phenomenon with water in the sea where waves and their reflections from the coastline interfere and diffract in obstacles. You can also see Fig. 3.5 in the course lecture notes where an interference pattern is generated by the superposition of two plane waves propagating in different directions.

In this experiment we investigate a particularly simple case of interference of waves emitted from two small aperture sources. The experiment is essentially the microwave counterpart of Young's two-slit experiment in optics. Microwaves are convenient for us because their wavelength is much longer than those of optical waves, and the interference pattern can therefore be measured with reasonable accuracy using a simple apparatus.

Consider the situation shown in Fig.1.

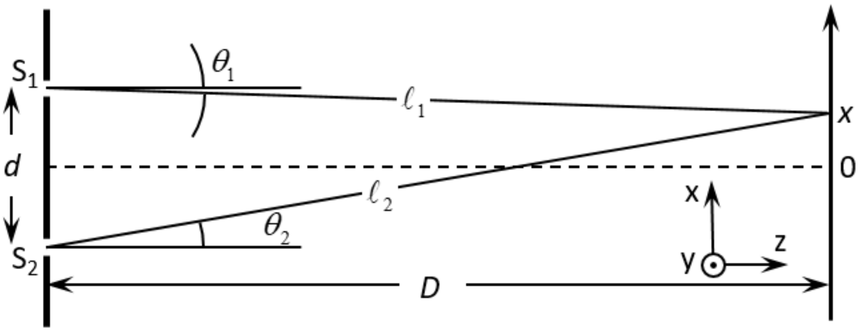

Fig. 1 Two in-phase sources, S_1 and S_2, illuminating an observation plane.

Two sources, S_1 and S_2, with equal amplitude and in phase illuminate an observation plane where we consider an arbitrary point at a distance x from the central point denoted by 0. The sources could be 'line sources' (along z) or 'point sources' generating cylindrical or spherical waves, respectively. In either case waves propagating away from a source will suffer some reduction in intensity ($|E|^2$)[1] with $1/r$ or $1/r^2$, respectively. If D is much larger than d, the distance from the sources to the point x, ℓ_1 and ℓ_2, are nearly equal ($(\ell_1 - \ell_2)/D << 1$) and we can approximate and neglect the difference in amplitudes at the observation plane. However, we cannot neglect the difference in phase. Hence, we can see that there will be constructive interference at some position x when the path lengths ℓ_1 and ℓ_2 differ by zero or an integer number of wavelengths *i.e.* when $\ell_1 - \ell_2 = n\lambda$. Similarly, there will be destructive interference at some position x when the path lengths ℓ_1 and ℓ_2 differ by an odd integer number of half wavelengths *i.e.* when $\ell_1 - \ell_2 = (2n+1)\lambda/2$. Thus, along the x-axis there will be a series of maxima and minima of intensity.

We can easily calculate a general expression for the intensity along the x-axis (far field). The total field at x on the observation plane, without the approximation described above is given by[2]:

$$E_T = \frac{e^{-jk\ell_1}}{\ell_1} + \frac{e^{-jk\ell_2}}{\ell_2} \tag{1}$$

Here we have considered a $1/r$-fall off of field (*i.e.* a $1/r^2$ fall-off of intensity), corresponding to a point source radiating in 3D space (spherical wave).

From Fig. 1 we have:

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[1] Here we define "Intensity" as the square of the amplitude of the wave. Notice that in some other contexts intensity is the amplitude.

[2] This expression is an approximation for the "*far-field*", and is only valid at large distances from the source. Also, here we assume that the fields originated by both sources are parallel at the point of observation (x) so we can use a scalar sum. This will be the case if their polarisation is along the y-axis. Otherwise, it can be approximated if the distances from the sources are long enough so the paths are close to being parallel ($\ell_1 \approx \ell_2 \approx D$).

$$\sin\theta_1 = (d/2 - x)/\ell_1 \qquad \text{and} \qquad \cos\theta_1 = D/\ell_1$$

also: $$\sin\theta_2 = (d/2 + x)/\ell_2 \qquad \text{and} \qquad \cos\theta_2 = D/\ell_2$$

Then, since $\sin^2\theta + \cos^2\theta = 1$ we can write:

$$\begin{aligned}\ell_1 &= D\cos\theta_1 + (d/2 - x)\sin\theta_1 \\ \ell_2 &= D\cos\theta_2 + (d/2 + x)\sin\theta_2\end{aligned} \tag{2}$$

Now if $\ell_1 \approx \ell_2 \approx D$, we can approximate E_T in (1) by:

$$E_T \approx \frac{1}{D}\left(e^{-jk\ell_1} + e^{-jk\ell_2}\right) \tag{3}$$

and substituting (2):

$$E_T \approx \frac{1}{D}\left(e^{-jk\left[(d/2-x)\sin\theta_1 + D\cos\theta_1\right]} + e^{-jk\left[(d/2+x)\sin\theta_2 + D\cos\theta_2\right]}\right)$$

Since θ_1 and θ_2 are small, we can make the following approximations:

$$\sin\theta_1 \approx \theta_1 \approx (d/2 - x)/D \text{ and similarly, } \sin\theta_2 \approx \theta_2 \approx (d/2 + x)/D\,.$$

Then, for the cosine terms (using the first 2 terms of the Taylor series), we have:

$$\cos\theta_1 \approx 1 - \theta_1^2/2 \text{ and } \cos\theta_2 \approx 1 - \theta_2^2/2\,.$$ taylor series centered x = 0

Q1. The square of the magnitude of the electric field is known as the intensity. Show that the approximations above lead to:

$$|E_T|^2 \approx \frac{4}{D^2}\cos^2\frac{kdx}{2D} \tag{4}$$

From this expression, what is the distance between consecutive maxima or minima?

Q2. Download and run the Matlab script Interference.m that calculates the intensity versus position x using eqn. (1) directly instead of using the approximate expression (4). Modify the script to include a calculation of the intensity as it varies with the displacement x of the observation point on the screen using eqn. (4) as well and plot this in the same figure as the results from eqn. (1). Comment on the approximations used in (1)-(4), compare the results and discuss and explain the differences

Experiment 1.1: Interference of waves

For this part of the experiment, you are given experimental data obtained using the set-up described schematically in Fig. 2.

Two in-phase equi-amplitude 'point' sources are provided by the rectangular waveguide T-junction feeding two open-ended waveguides of equal lengths. The signals from both sources are received by the horn at the right and fed to a microwave detector and amplifier. The horn is moved along a ruler on the x-axis and the measured output is observed as the horn is moved. The whole excursion along the x-axis is ±36 cm and the horn is kept aligned along the y-axis throughout this experiment. The input is provided by a microwave generator connected through a coaxial cable to the waveguide T-junction. It generates a microwave signal of 10 GHz modulated in amplitude with a 5 KHz square wave signal. We need to measure the intensity of the total field received by the horn and this is done using the setup indicated in the figure. The dimensions in Fig. 2 are: D = 255 cm and d = 63 cm.

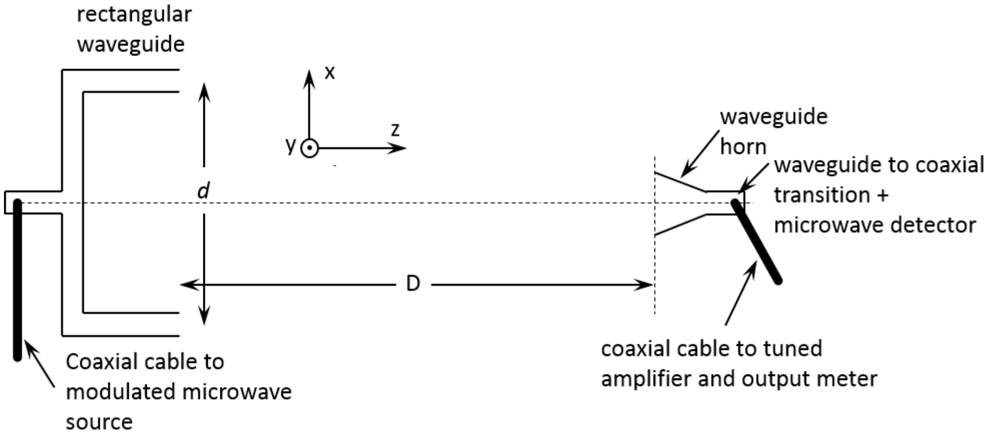

Fig. 2 Experimental arrangement for the interference experiment. Note that the picture is not at scale. In the practical situation $D >> d$.

At the receiver end there is a horn followed by a "detector", which is a piece of waveguide with a probe or a small antenna inside, connected through a microwave diode to the output coaxial cable. The signal received by the horn is very low and needs to be amplified before is sent to the meter. This is done by an amplifier circuit connected between the detector and the meter.

<u>Q3.</u> Explain the function of the detector diode. What is the frequency of the signal carried by the coaxial cable to the meter in the setup described in the figure above?

What is the relation between the electric field intensity received by the horn and the magnitude of the signal (current) coming from the detector through the coaxial cable? It happens that the output of the detector is proportional to $|E|^2$ *i.e.*, is proportional to the field intensity; can you explain why?

<u>Q4.</u> From the Moodle site of the course, download the file Int1.txt containing measurements done using the setup shown in Fig. 2. The file has two columns: the first is the displacement x of the receiving horn in cm, where the origin is at the centre; that is, when the horn is aligned to the midpoint between the two sources. The second column is the reading in the meter, in mV. Write a Matlab program that loads the file Int1.txt, and plots the received voltage versus x. Explain the relation between this voltage and the received field intensity by the horn. Name the program: Pattern1.m and keep it in your records. The program should also plot the theoretical curve from eqn. (1) <u>in the same figure</u>. Compare the two curves and comment. **<u>Hint.</u>** In your program, normalise the intensity values calculated from the given readings to maximum value 1 before plotting and comparing with the theoretical results.

Do all the maxima have equal amplitude? Do all the minima have zero amplitude? Which of these, maxima or minima, will give a better, sharper definition of position? Comment on your observations and compare them with the theoretical results obtained for Fig.1 based on two point sources. Are the approximations in the theory justified? The theoretical description and derivations that follow Fig. 1 assume that the electric field is vertical, that is, along the y-axis and that is also the case of the experiment that produced the results in the file Int1.txt from the set-up in Fig. 2.

Would there be any difference if the sources were transmitting waves with their electric fields in the x-z plane instead? If so, why?

At the observation plane the total field is measured using a horn receiver with a finite aperture. Does this introduce any complication?

Experiment 1.2 Measurement of relative permittivity of a dielectric material

Consider now the modified set-up shown in Fig. 3. A dielectric slab is now interposed between one of the waveguide sources and the receiving horn. The dielectric slab will introduce an extra phase difference in one of the paths and this will cause a shift in the interference pattern in the observation plane.

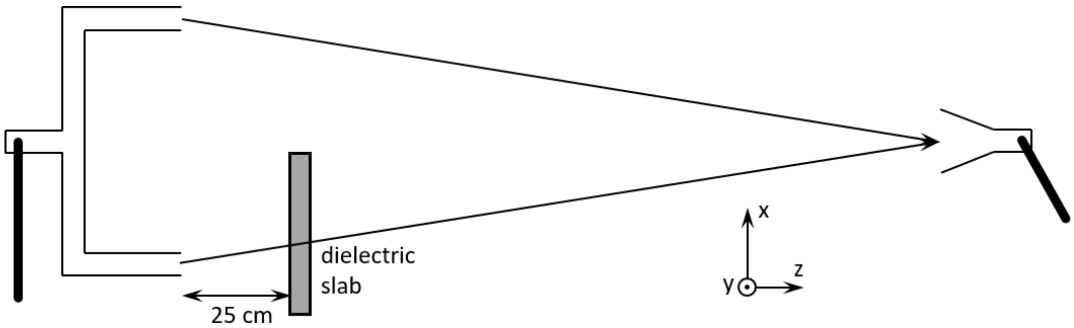

Fig. 3 Experimental arrangement for measurement of relative permittivity of a dielectric sheet.

<u>Q5.</u> Using simple theory, show that the relative permittivity of the sheet is given by:

$$\varepsilon_r = \left[1 + \frac{\Delta s}{\delta}\frac{d}{D}\right]^2 \qquad (5)$$

where Δs is the shift of the central maximum along the x-axis, and δ is the thickness of the dielectric sheet.

<u>Hint</u>. Consider the phase shift introduced by the thickness δ of the dielectric sheet and the corresponding shift in the position of the minima (or maxima). Since you know the phase difference that corresponds to the distance between minima (or maxima) on the screen, you can determine the corresponding value of refractive index.

Fig. 3 is not at scale and the angle between the propagation direction and the normal to the slab is actually very small so it is safe to assume normal incidence on the dielectric slab.

Clearly state any assumptions you make in deriving this expression.

<u>Q6.</u> Download the file Int2.txt that contains the new measurements of intensity versus x. This file has the same format as Int1.txt and the second column lists the readings of the instrument in mV. Create a new Matlab program modifying your Pattern1.m, to read this file and plot both the original and the shifted interference pattern in the same plot. Name this program ShiftedPattern.m and keep it in your records. From the plots and the data files, determine the shift as accurately as you can, explaining your procedure and calculate the relative permittivity of the dielectric slab if its thickness is δ = 1.2 cm.

Would this method be suitable for (a) thick sheets (b) high permittivity sheets? If not, what would be the problem? Is the position of the dielectric sheet between the source and the screen important or relevant? Does it need to be 25 cm as shown in the figure? Discuss.

Exercise 1.3 Antenna Arrays

One important application of the interference of waves is in the design and use of antenna arrays.[3] Antenna arrays are groups of antennas in close proximity and radiating at the same frequency, thus creating an interference pattern around them. This interference pattern can be shaped by varying the position and separation of the individual antennas and the amplitude and phase of their individual excitations.

Consider the arrangement in Fig. 4 that shows two point antennas (isotropic radiators) separated by the distance *d* and excited with currents of value 1 and $e^{j\varphi}$, respectively (phasors of equal magnitude and phase difference = φ).

In general, we are interested in the field radiated by the antennas at a very large distance from the antennas (known as the "far field").

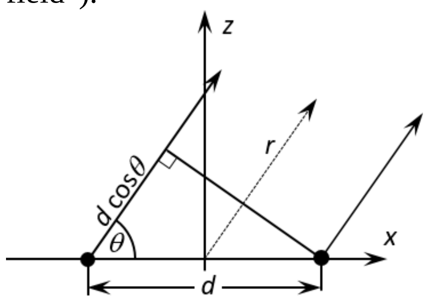

Fig. 4 An array of two point antennas.

Following the same reasoning that leads to eqn. (1) we can write for the field at a very large distance the expression in equation (6). The assumption of a very large distance also allows us to consider the rays from the individual antennas to the observation point as parallel to each other and the corresponding distances as equal to *r* in the amplitude term (denominators in eqn. (1). Note that the path difference cannot be neglected in the calculation of the phase (exponents in (1)) because although the difference ($d\cos\theta$) is very small with respect to *r* it will not be negligible with respect to the wavelength. From this and Fig. 4 we can write:

$$E(r,\theta) = \frac{e^{-jk(r+d\cos\theta/2)}}{r} + \frac{e^{j\varphi}e^{-jk(r-d\cos\theta/2)}}{r} \tag{6}$$

<u>Q7.</u> Starting from equation (6), find an expression for the absolute value of the far field as a function of the angle θ.

The final expression will have the form:

$$\left|E(r,\theta)\right| = \frac{F(\theta)}{r} \tag{7}$$

where the factor $F(\theta)$ is called the radiation pattern of the array, or more properly, the Array Factor.

Write a Matlab program and name it Array.m, to calculate the array factor of this array as a function of the antenna separation *d*, the phase difference between the antennas, φ and the inclination angle θ. Use the Matlab command "polarplot" to plot the <u>normalised</u> array factor versus θ for the cases: (a) $d = \lambda/2$ and $\varphi = 0$, (b) $d = \lambda/2$ and $\varphi = 90$, (c) $d = \lambda/2$ and $\varphi = 180$, (d) $d = \lambda/4$ and $\varphi = 0$, (e) $d = \lambda/4$ and $\varphi = 90$ and (f) $d = \lambda/4$ and $\varphi = 180$. Keep all these plots and the program Array.m in your records.

If we consider now a linear array of *n* sources, equally spaced by the distance *d* and with a

[3] Read the excellent detailed explanation of interference in this case in "The Feynman Lectures of Physics", vol. 1, ch. 29, by R.P. Feynman, R.B. Leighton and M. Sands (https://www.feynmanlectures.caltech.edu/)"

progressive phase difference of ϕ in the form: $0,\ \phi,\ 2\phi,\ 3\phi,\ \cdots,(n-1)\phi$, the corresponding array factor can be written in the form:

$$F(\theta) = e^{j\frac{n-1}{2}\alpha}\,\frac{\sin(n\alpha/2)}{\sin(\alpha/2)} \quad \text{where} \quad \alpha = \phi + d\cos\theta$$

Shifting the phase reference point to the centre of the array and referring the distance *r* to the observation point from there, the array factor will simply be:

$$F(\theta) = \frac{\sin(n\alpha/2)}{\sin(\alpha/2)} \tag{8}$$

Q8. Write down the complete derivation of eqn. (8).

Part 2 Diffraction and Polarisation

For this part you are given data from experiments, that you will have to analyse and explain. You will need to read the script and the references before attempting to complete the answers to the questions in the script.

Many phenomena in electromagnetics can be explained adequately assuming that light will travel along a straight path. This implies the assumption of homogeneous materials and the absence of obstacles. For example, the performance of an optical lens can be studied in great detail using *geometrical optics* by making the assumption that light travels in straight lines. Optical lens design is therefore largely based on geometry and refraction (Snell's Law). The dimensions of a lens in a camera or microscope are very large in terms of optical wavelengths. When the components or space under discussion have dimensions comparable with or smaller than the wavelength then wave theory must be used to describe the situation adequately and explain the way the path bends in the proximity of obstacles. Examples where wave theory is required include optical fibres and optical waveguide components, precise determination of microwave microstrip waveguide components, design of microwave antennas, and modelling of radio propagation over hilly terrain, gratings and holograms.

A full, accurate treatment of the problem solving Maxwell's equations in complicated geometries using numerical methods would lead to the right solution but can be difficult to implement. Approximate solutions that were developed in the past. based on different approximations, which are still in very much use include Fresnel and Fraunhoffer theories. Fraunhoffer diffraction theory deals with the *far field* case, where the distances between the source, the obstacle and the observation point can be considered infinite, the phase fronts incident on the obstacle and arriving at the observation point are planes and the corresponding *rays* are parallel. Fresnel diffraction theory refers to the medium distance regime, when the distances between the source, the obstacle and the observation point are finite. In this case the phase fronts are not planes and the corresponding *rays* are not parallel[4].

To illustrate the problem in a simple way, consider for example, the situation shown diagrammatically in Fig.5.

[4] See for example 'Modern Optics' by Robert D. Guenther, published by John Wiley & Sons or "Introduction to Fourier Optics" by Joseph W. Goodman, (3rd ed. 2005). These books give a very good account of diffraction. Also, for a superb yet simple description of both interference and diffraction, see "The Feynman Lectures of Physics", vol. 1 by R.P. Feynman, R.B. Leighton and M. Sands (https://www.feynmanlectures.caltech.edu/).

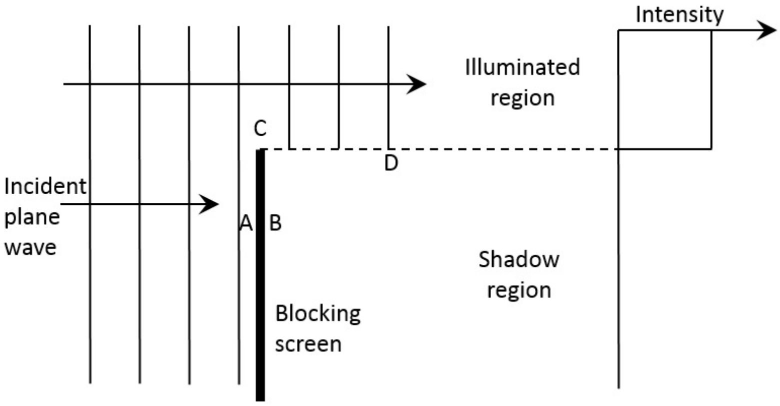

Fig. 5 A simple but incorrect interpretation of the case of a uniform plane wave partially blocked by an opaque screen.

A uniform plane wave is partially blocked by an opaque screen. There is an illuminated region and a region that is in shadow. This simple description seems to fit in well with everyday experience of shadows caused by obstacles to sunlight. But such everyday observation is not that precise. Our eyes can distinguish dimensions of the order of 10^{-4} m. The wavelength of light is less than 10^{-6} m. Suppose we ask what is happening at D in Fig. 5, in the transition between the illuminated region and the shadow region.

How does the intensity suddenly drop to zero there? Even with only a little knowledge of electromagnetic theory we are forced to ask ourselves how the electric field '*ends*' at D. See for example Fig. 6. That would be the case if light followed straight paths but clearly, there cannot be a sharp edge here but there must be a transition region. This is dependent on the wavelength so in the optical range, these effects occur in the order of microns so shadows appear to be sharp. In microwaves, though, with wavelengths in the order of cm and mm these effects are clearer to see.

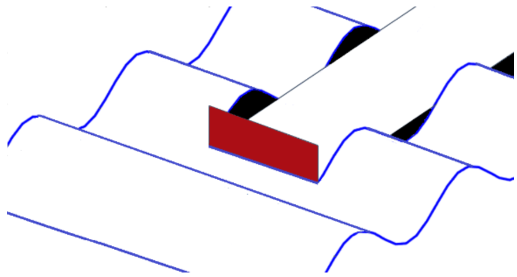

Fig. 6 Detail of Fig. 5 showing unrealistic behaviour for a wave encountering an obstacle.

The nature of the screen is also important. If it is absorbing, then that part of the incident wave arriving at A will be absorbed. However, if the screen is electrically conducting, that part of the incident wave will be reflected. With a conducting screen there might be a current at C. Will this current not radiate into the shadow region? Will there not be some field in the 'shadow' region whatever the screen type?

To understand what happens, we can consider each point in a phase front[5] (infinite number of them and infinitesimally close) as a point source (Huygens's principle[6]), so each of them will produce a spherical (or cylindrical) wave, which will superpose or interfere with each other creating the next wave front.

If the points radiate in phase and are on a plane, the next phase front, which is the superposition of the individual wavelets, will also be a plane: the interference pattern of the infinite array of point sources radiating in phase is just a plane, see Fig. 7a below. If we now consider the phase front passing at position C in Fig. 5, there are no source points on the screen side of C and the wavelets at the edge are not "compensated"; the new phase front will then curve at the edge and there will be propagation into the shadow region due to the interference

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[5] A *phase front* or wavefront in connection to a propagating wave is a surface of constant phase, like the spherical surfaces surrounding a point source, where the phase is the same.

[6] Huygens principle states that: "*Every unobstructed point on a wavefront will act a source of secondary spherical waves. The new wavefront is the surface tangent to all the secondary spherical waves.*"

effect of the infinite number of source points as shown in Fig. 7b. This phenomenon is called diffraction.

Additionally, the nature of the screen will affect the result since for example, in a conductive screen, excited currents will radiate towards the screen, contributing to the total field there.

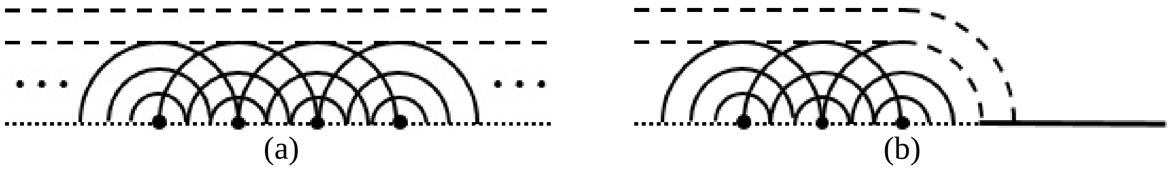

Fig. 7 (a) Each point in a phase front will generate a "wavelet" which will interfere with each other producing the next phase front. (b) At the edge of an obstacle the resultant phase front bends. Schematic diagram; there are infinite point sources, infinitesimally separated.

Strictly speaking, a proper vector theory should be used, involving Maxwell's equations in vector form, boundary conditions, and considerable mathematics. Fortunately, in situations where the observation plane and the sources are many wavelengths away from the diffracting objects, reasonably accurate answers can be obtained using scalar diffraction theory and further approximations lead to those of Fresnel and Fraunhofer.

Q9. Consult the references indicated for the Fresnel and Fraunhofer diffraction theories and/or any other source of information you may find and keep in your records a brief summary description in your own words of the theory of diffraction, in particular concerning the diffraction by a screen as in Experiment 2.1.

Note: When using material taken from a book, journal, webpage or any other source, textual reproduction (or very similar) is not permissible. Read and understand the material and summarise it using your own words and explanations and quote the corresponding source using one of the standard formats to cite references.

Q10. What is the difference between refraction and diffraction? Comment on the effect of diffraction in microwave communications systems. Explain in detail the use of a grating in a device that can separate light with a narrow band of wavelengths from a white source (monochromator).

Experiment 2.1: Diffraction of a wave by a conducting plane

Consider now the set up indicated in Fig. 8. An electromagnetic wave is radiating from a horn antenna and a movable metal screen is placed between this source and the receiver antenna. The receiver is the same described in Part 1 of this script. Both the transmitting and the receiving horns are in fixed positions and only the screen, which can be considered very long in the *x*-direction, will move.

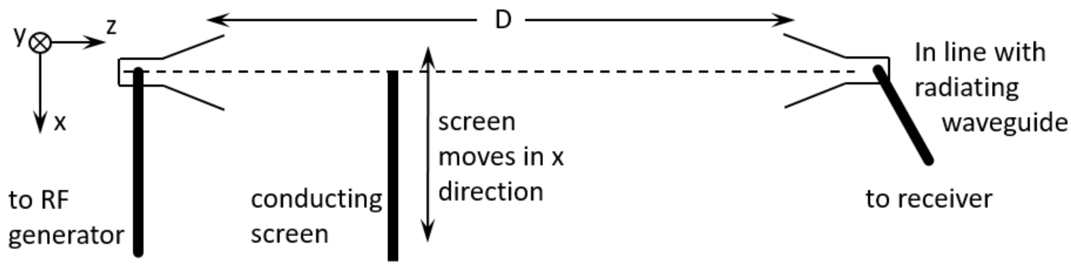

Fig. 8 Experimental setup for diffraction experiment.

Measurements are taken while sliding the screen along the rail in the *x* direction so that the receiving horn is progressively: fully in the shadow region for negative values of *x* (blocked by the screen); partially blocked and then fully illuminated by the source as *x* increases. The figure shows the case when $x = 0$, which corresponds to the edge of the screen being in line with the two horns (dashed line).

The situation is slightly different to the case depicted in Fig.5 where the wave incident at the screen is supposed to be a plane wave. In this experimental set-up the incident wave comes from an antenna at a finite distance from the screen, so the equivalent wavelets (see Fig. 7) from points in the aperture (not obstructed part of the plane of the screen) cannot be considered as having equal amplitude and phase. However, the resultant effect should be fairly similar.

The data obtained from this experiment is in the file *diffraction.xlsx*. This file contains the values of intensity in arbitrary units against the position (in cm) of the edge of the screen taken from a ruler affixed to the experimental setup. The position shown in Fig. 8 ($x = 0$) corresponds to a reading of $x_0^r = 92.3$ cm in the ruler, so a scale conversion must be performed before processing this data. This is $x = x_0^r - x^r$ where x is the position according to the axes in Fig. 8 and the superscript r indicates a reading from the ruler. The data can be read directly from this file into a Matlab script using the command:

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M=xlsread('diffraction.xlsx');
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This will create the array M where the fist column contains the position of the edge of the screen (x values in cm) and the second, the values of intensity at the receiver end. As the values of received intensity are dependent of an arbitrary strength of the source, the plot should be normalised. The best normalisation value in this case is not the maximum intensity, but the steady value that is reached when the screen moves far away from the line of sight (no obstruction). Examine the data file, find this value and use it to normalise your plot.

Q11. Plot the received intensity against the position of the screen edge using the data collected in the file *diffraction.xlsx*. make a special note of the value at x=0 and give a theoretical value and explanation for it. Does the result agree with this? Compare the results with published results for an opaque semi-infinite diffracting screen. Comment on the differences due to the use of an excitation different to a plane wave. How could the set-up be changed to approximate better the case of a plane wave?

Q12. Does this case correspond to a Fresnel or Fraunhofer diffraction? Does a conducting screen really correspond to an opaque screen? Would the experimental results differ if an orthogonal polarisation were incident on the screen? In the experiment the screen was moved. Suppose the screen was fixed and the receiving horn moved instead. Would the results be different? What do the terms 'near field' and 'far field' mean?

Polarisation of Electromagnetic Waves

Electromagnetic waves can be polarised *i.e.* the electric field may be aligned along one particular direction only (linear polarisation case – any other case is simply a superposition of waves with different polarisation states). For example, with respect to the earth we can talk about the E vector being horizontally or vertically polarised – or in general, at any angle. Polarisation is important in radio propagation and antenna design, and in many other applications in microwaves and optics. Antennas for example, can be designed to transmit (or receive) preferentially in one particular polarisation that depends of the antenna geometry and orientation and is then important that if receiving, the antenna's orientation matches the polarisation of the incoming wave.

Q13. Explain briefly what is polarisation of an electromagnetic wave. What is a polariser? Why polarisation is important in anti-glare sun glasses? What effect is used in this case?

Explain what happens when you put a polariser between a source emitting a polarised field and a receiver. How would the intensity of the received wave vary if you rotate the polariser? Derive the expression and draw a graph that relates the intensity with the angle in this case.

Assume that the polarisation orientation of the receiver matches that of the transmitter.

Experiment 2.2: Polarisation

This experiment uses the setup shown in Fig. 9. The *y*-axis corresponds to the vertical and the horizontal plane is the *x*-*z* plane. The horn used as source is emitting a linearly polarised electromagnetic wave and you will need to determine in which direction the field is polarised from the results obtained when a polariser (called an analyser in this case) is placed between the transmitter and receiver.

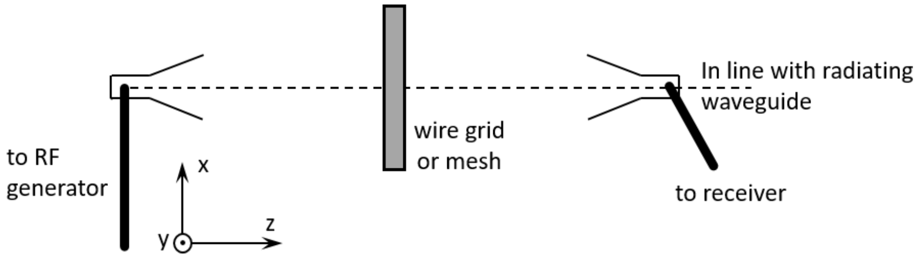

Fig. 9 Showing use of wire grid or mesh to block transmission of a polarised wave.

Two different screens are used in this experiment: a wire grid and a perforated mesh of wires as shown in Fig. 10. The wires can be assumed to be perfectly conducting.

Fig. 10 Screens used in the polarisation experiment. Wire grid (left) and perforated mesh (right).

The screen is placed between the transmitter and receiver and measurements are taken when the screen is in two different orientations. The results are summarized in the following table:

Intensity received (in arbitrary units)			
Wire grid:		Wire mesh:	
wires vertical:	0.015	long diagonal vertical:	0.1
wires horizontal:	0.33	long diagonal horizontal:	0.28

It was also observed that in both cases, when the screen is rotated, the intensity measured varies monotonically but not linearly between the two positions listed above.

To understand better how the perforated mesh works, it can be considered as made of two wire grids positioned at an angle to each other. Notice that the perforations of the mesh, as shown in Fig. 10, are rhombuses and not squares, so the angle of the equivalent wire grids is not 90°.

<u>Q14</u>. Since the excitation comes from a rectangular waveguide and its longer side is horizontal, what do you think the polarisation of the emitted wave should be and why?

From the orientation of the grid and the corresponding received intensity shown in the table above, what is the polarisation of the source: horizontal or vertical and why? Does this coincide with your expectations for this source? Give a full explanation of the blocking mechanism. Which of the two types of screen is more effective as a polariser? Why?

For the case of the wire grid, deduce the expression that relates the intensity received versus the angle that the wires form with the horizontal (wires horizontal: angle = 0 and vertical: angle = 90°).

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Organise your records following the sections of this script and answer the numbered questions in sequence, keeping a clear indication of the question you are answering. Include in your records your explanations, calculations, Matlab programs and plots you have produced, as asked in the script questions. You don't have to submit these records. Instead, there will be a Moodle test based on the material in this script and you will need to use or reproduce material from your own records, possibly including explanations, calculations, programs and plots so you will need to have them at hand and tidy for easy access during the test.

Keep also for each section a description <u>in your own words</u> of the relevant theoretical aspects as instructed in some of the questions. For some of the answers you would need to consult reference material. Use the sources of reference indicated and any other you might find and cite them when and where you are using them.

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