EXPERIMENT 3
TO STUDY THE DIFFRACTION PATTERN OF A THIN WIRE

Structure

3.1 INTRODUCTION

In the previous experiment you learnt to investigate one of the various manifestations of wave nature of light in the form of interference. You may recall that interference has genesis in superposition principle for waves. Physically, it corresponds to redistribution of energy in the visible region. In the historical perspective, Fresnel's biprism experiment set at rest all speculations on the validity of wave theory of light. Another phenomenon which gave support to wave model was diffraction – the bending of waves around corners. You have learnt about it in Block 3 of our PHE-09 course on Optics. As we now know, the ease with which a wave bends strongly depends upon the size of the obstacle relative to its wavelength. The objects used in every day life are about 10^5 times bigger than the wavelength of light. And light appears to follow a rectilinear path. It, however, only means that to observe bending of light, we have to make careful observations under suitable conditions. If you closely examine shadows cast by objects, you will observe that the edges of shadows are not sharp. This is due to diffraction. Similarly, if you look at a distant street lamp at night and squint, you will realise that light appear to streak out. This is because light has bent around the corners of your eyelids. Alternatively, by holding a fine handkerchief close to your eye, you will observe an enlarged disc surrounded by a regular pattern of coloured spots. This pattern is formed by the diffraction of light from the distant lamp. The brilliant halos seen while going by a car whose fogged windows are illuminated by a motor cycle at the back are also due to diffraction of light. The green on the neck of a male mallard duck, blue appearance of wings of Morpho butterflies and the beautiful colours of the 'eye' of the peacock's feathers are other effects of diffraction of light.

The phenomenon of diffraction was first observed by Grimaldi. But a systematic explanation of diffraction was given by Fresnel on the basis of Huygens' principle. From Block 3 of PHE-09 course on Optics you may recall that diffraction is classified in Fraunhofer and Fresnel classes. In the former the source of light and the observation screen (or human eye) are effectively at infinite distances from the obstacle. This is ensured very conveniently by using suitable lenses. The phenomenon of diffraction is of particular practical importance in respect of the working of optical instruments. In Fresnel class of diffraction, either the source or the observation screen or both are at finite distances from the obstacle and the experimental arrangement is fairly simple. Moreover, the diffraction pattern depends on the type of obstacle. While diffraction pattern of a circular aperture consists of Airy's pattern (a disc surrounded by circular rings), the diffraction pattern of a thin wire is in the form of straight bands. You will get an opportunity to appreciate these aspects while performing this experiment.

The phenomenon of diffraction restricts our ability to obtain (perfect) point images of point objects. Similarly, it constrains optical instruments, including human eye, to resolve objects with small angular resolution. You will learn to compare theoretical and practical resolving powers of a telescope in the next experiment.

Resolving power of a telescope is defined as the inverse of the minimum angle for which two close objects can be seen distinctly.

A question that must have come to your mind is: What physical parameter are we to measure? The answer is: We can determine the diameter of wire giving rise to diffraction. Then you may ask: Why use such a sophisticated arrangement for a trivial exercise like measurement of diameter? It can readily be measured using a micrometer screw. Well, you may not be wrong. But our actual purpose is to exhibit how light can be made to diffract even by macroscopic objects. The detailed objectives of this experiment are, however, listed below.

Objectives

After performing this experiment, you will be able to

- appreciate how two extremities of a wire act as ends of a straight edge
- observe interference and diffraction patterns simultaneously
- measure interference fringe width, and
- determine diameter of the given thin wire.

3.2 DIFFRACTION PATTERN OF A THIN WIRE: THEORETICAL ANALYSIS

To study diffraction effects due to a thin wire, refer to Fig. 3.1. Monochromatic light from a sodium lamp is made to fall on slit S. (A convex lens of short focal length can be used, if necessary, to focus light on S.) It then acts as a source and sends cylindrical wavefronts towards the diffracting aperture. (Plane wavefronts originate from a point source.) When a cylindrical wavefront propagating from the source reaches the (thin) wire (EF), the extremities of the wire (E and F) serve as two straight edges and diffract light. That is, the diffracting aperture is a straight edge.

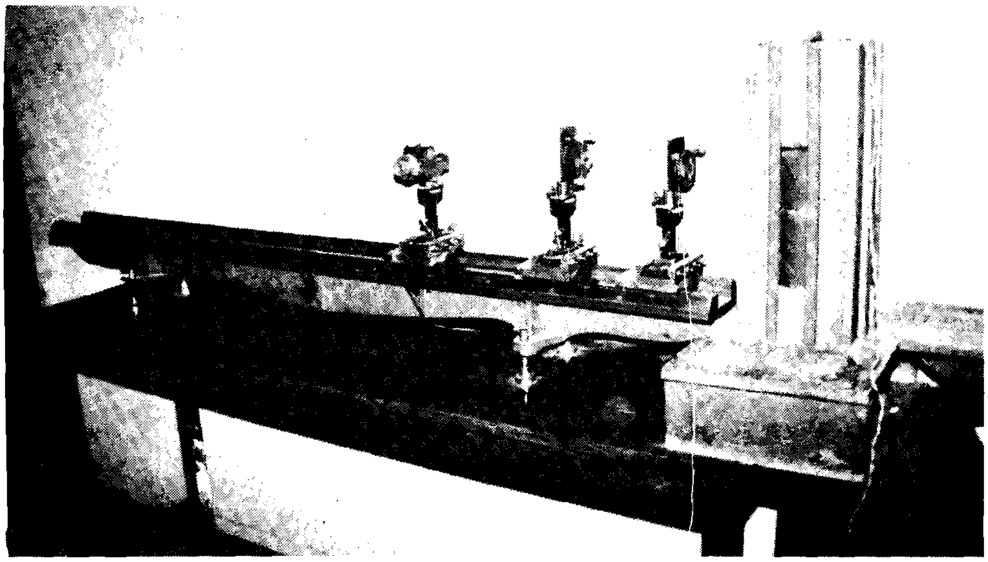


Fig.3.1: Observing diffraction due to a thin wire

We expect that:

i) The shadow on the screen P_1P_2 placed at O is bound by straight, unequally spaced diffraction fringes.

ii) The shadow region $E'F'$ on the screen displays interference fringes characterised by sharp contrast and equal spacing.

To understand how these two fringe patterns appear, Ref. to Fig. 3.2.

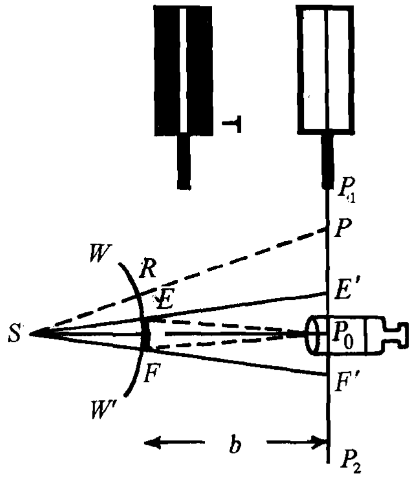


Fig.3.2: Ray diagram for diffraction due to a straight edge

The lines joining S with E and F when produced meet the screen at E' and F'. Obviously, $E'F'$ marks the geometrical boundary of the shadow on the screen. Let us consider a point P **outside** the geometrical shadow. A line joining it to S cuts the wavefront at R. From Unit 8, Block 3 of PHE-09 course, you may recall that when a plane wave is obstructed by an obstacle with axial symmetry, the half period elements are circular (in 2-D). However, for a cylindrical wavefront, these elements are somewhat complicated, particularly when the obstacle does not have an axial symmetry. Before we proceed further, it may be worthwhile for you to think for a while and answer the following SAQ.

The half-period elements for a straight edge are constructed by dividing the cylindrical wavefront into strips so that the amplitudes of the wavelets from these strips arrive at P out of phase by π. That is, the successive strips should be one-half wavelengths apart. This is achieved by drawing a set of circles with Q as centre and radii $b, b+\frac{\lambda}{2}, b+2\frac{\lambda}{2}$, .. etc. cutting the circular section of the cylindrical wave at points O, AA', BB', CC', ... (Fig. 3.3). If lines are drawn through A, A', B, B' etc. normal to the plane of the paper, the upper as well as the lower half of the wavefront gets divided into a set of **half- period strips.** These half period strips stretch along the wavefront perpendicular to the plane of the paper and have widths OA, AB, BC ... in the upper half and OA', $A'B'$, $B'C'$, ... in the lower half. The half-period strips are not necessarily of equal area. The areas of half-period strips are proportional to their widths and these decrease rapidly as we go out along the wavefront from O. It may be emphasized here that the amplitudes due to these strips are alternately positive and negative.

SAQ 1

Why do we use a slit source rather than a point source in this experimental arrangement?

Proceeding further we note that the wavefront is divided in two parts when we join P and S. The intensity of light at P is due to the portion WE of the wavefront. The part **above** R is completely unaffected by the straight edge; in fact, light from it reaches P uninterrupted. The portion RE also contributes light at P depending on the number of half-period strips in it. If RE contains an odd number of half-period strips, the intensity at P is maximum. (This will happen if the path difference $EP - RP = (2n+1)\lambda/2$.) Physically, it means that there is at least one half period zone **whose contribution is not cancelled by neighbouring** zones. When $EP - RP = n\lambda$, the portion RE will contain even number of strips, which cancel out in pairs, and no light reaches P from RE. The intensity at P will be minimum. Therefore, as point P moves away from O, the illumination on the screen should pass alternately through maxima and minima depending on the number of half period strips in RE (1,2,3,4,...).

In the eye piece you should observe dark and bright bands parallel to the edge. But the question arises: Are the dark bands completely dark? We expect these not to be completely dark because the upper part of the wavefront (RW) always contributes light to the screen. The same is also true for the lower portion FW' of the wavefront.

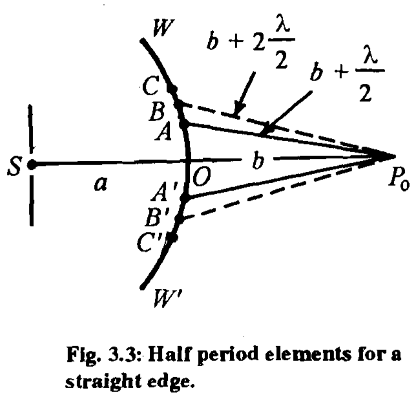
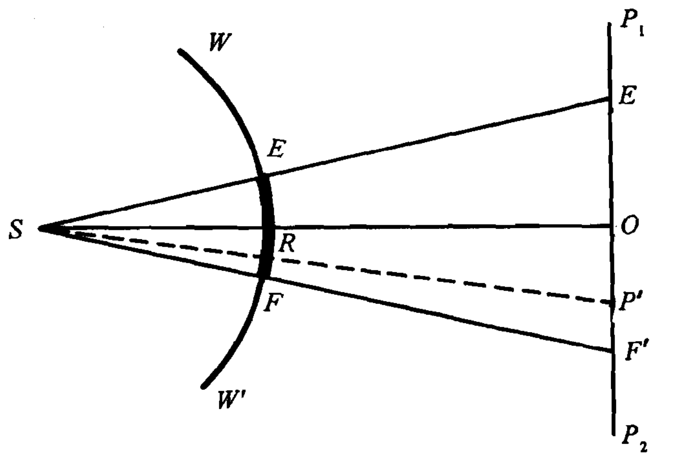


Fig. 3.3: Half period elements for a straight edge.

Let us now consider a point P' inside the geometrical shadow $E'F'$. Refer to Fig. 3.4. You will note that the point corresponding to R is shifted below the edge E. The illumination at P' will then be due entirely to the wavelets from the upper part of the wavefront; the lower portion having been blocked by the edge. Even the upper half is exposed only in part. If the edge cuts off r strips of the upper half of the **wavefront,** the effect at P' will be due to $(r+1)$, $(r+2)$, $(r+3)$ etc. strips which **may be taken** to be equal to one-half of that due to $(r + 1)$th strip. This will rapidly diminish to zero because the effectiveness of higher order strips goes on decreasing.



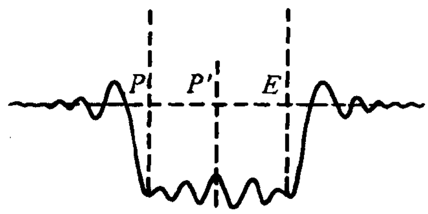


Fig.3.4: Fringe pattern for a point P' in the geometrical shadow of the straight edge

You can regard the portion of the wavefront EW as a luminous source at E. Similarly, the lower portion FW' can also be replaced by a luminous source at F. They behave as a pair of coherent sources and give rise to interference effects in the shadowed region. The point O will be a bright point if $EO - FO = n\lambda$ and dark if $EO - FO = (2n-1)\frac{\lambda}{2}$. Do you expect equally spaced fringes characterized by sharp contrast between maxima and minima? If so, you can be sure that these are interference fringes. Now suppose that light on the side of E is obstructed. Will you observe interference fringes or diffraction fringes or both? You should obtain neither. Then you can say with confidence that fringes in the shadowed region are due to interference of light from EW and FW'.

From the previous experiment you will recall that the width of an interference fringe is given by

$$\beta = \frac{D\lambda}{d} \tag{3.1}$$

where D is the distance of the wire from eye piece, d is the diameter of the wire EF and λ is the wavelength of light used. It shows that as the diameter of the wire increases, the band width tends to decrease. It suggests that no interference bands will be visible if you use a thick wire. The diffraction patterns should, however, persist.

You can rearrange Eq. (3.1) as

$$d = \frac{D\lambda}{\beta} \tag{3.2}$$

For a given source (fixed λ), you can easily determine the diameter of the wire once you measure the width of interference fringes, β.

Before we outline the procedure to set up the apparatus and measure β, we list the required apparatus.

Apparatus

An Optical bench, three uprights for holding the wire, the slit and the micrometer eye piece, metre rod, sodium lamp, a reading lens, a screw gauge and a lens for focussing light on the slit.

3.3 SETTING UP THE APPARATUS

To be able to measure the width of interference fringes, you should set up the apparatus using following steps:

1. Mount the slit, the wire (fixed) vertically and the micrometer eye piece capable of horizontal movement on the optical bench, as shown in Fig. 3.1.
2. You must ensure that the slit, the wire and the eye-piece are in the same horizontal line.
3. Make the slit S parallel to the wire.
4. Move the upright carrying the wire along the optical bench and fix its position about 15 cm from the slit. Next fix the micrometer eyepiece at about 50 cm from the wire.
5. Illuminate the slit with sodium light. If required, you can use a convex lens of short focal length.
6. With the light focussed on the slit, look through the micrometer eyepiece. Do you observe equally spaced bright and dark interference fringes? If not, move the eyepiece along the optical bench to obtain the patch of light corresponding to the region $E'F'$ (Fig. 3.2) in the focal plane of the eyepiece. Move the upright carrying the wire in its own plane till you observe interference fringes with good contrast in the field of view. This can happen only when the slit and the wire are parallel.
7. Remove the lateral shift as discussed in the previous experiment.

Now your apparatus is set for making measurement of the width of interference fringes. However, before you do so, we would like you to determine the diameter of the given wire by measuring it at a number of positions in two mutually perpendicular directions using a screw gauge and record your observations below. Compare this value with the value you obtain after doing the experiment.

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3.4 MEASUREMENT OF FRINGE WIDTH

1. Move the eyepiece so that the cross-wire is focussed in the centre of a dark fringe. Note the scale reading and record it in Observation Table 3.1. You must ensure that the fringes are visible without parallax (with the cross-wires) in the eyepiece.

Observation Table 3.1: Measurement of the width of fringes

Least count of the micrometer = ... cm

Distance between the wire and the eyepiece = ... cm

Wavelength of light used (given) = ... cm

S. No.	No. of fringes passed	Position of cross wire (cm)			β (cm)
		Initial	Final	Difference	
1.					
2.					
3.					
4.					
5.					

2. Now focus the eyepiece on the next fringe and note the micrometer scale. If you cannot do so because of the closeness of fringes, you should allow a few fringes to pass. Divide the difference by the number of fringes passed to obtain β.
3. Repeat the above step at least five times. Are the fringes equally spaced?
4. Calculate the average fringe width.
5. Calculate d using Eq. (3.2). Compare it with the value measured using a screw gauge and comment on your result.

Result: The diameter of the given wire is .... cm.

6. Next you should change the distance between the wire and the eyepiece. Repeat steps 1 to 5 given above. Make your own Observation Table.

Calculate d again. Does it show dependence on D? We do not expect any change in the value of d. If your measurements suggest any such dependence, you have certainly made some error. You should discuss your results with your counsellor.

7. If time permits, you should repeat steps 1 to 6 given above for another somewhat thicker wire and summarise your observations in the space given below

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8. Can you perform this experiment with a white light source? If yes, do explore the possibility and observe the diffraction pattern. How does it differ from the pattern obtained earlier?

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