Diffraction of Light Waves

Objectives

After going through this module, the learner will be able to :

- Understand the term Diffraction
- Explain diffraction as a case of interference.
- Know and explain fringes produced by a single slit
- Mathematically derive an expression for width of the central maxima
- Distinguish between fringes obtained in young's experiment and those in diffraction from a single slit

Content Outline

- Unit syllabus
- Module wise distribution of unit syllabus
- Words you must know
- Introduction
- Diffraction
- Diffraction at a single slit
- Difference between interference and diffraction
- Seeing the single slit diffraction pattern
- Summary

Unit Syllabus

UNIT 6: Optics

Chapter–9: Ray Optics and Optical Instruments

Ray optics: Reflection of light; spherical mirrors; mirror formula; refraction of light; total internal reflection and its applications; optical fibres; refraction at spherical surfaces; lenses; thin lens formula; lens maker's formula; magnification, power of a lens; combination of thin lenses in contact; refraction and dispersion of light through a prism.

Scattering of light – blue color of sky and reddish appearance of the sun at sunrise and sunset

Optical instruments – microscopes and astronomical telescopes (refracting and reflecting) and their magnifying powers

Chapter 10 Wave Optics

Wave optics: wavefront and Huygens's principle, reflection and refraction of plane wave at a plane surface using wavefronts. proof of laws of reflection and refraction using Huygens's principle. Interference, Young's double slit experiment and expression for fringe width, coherent sources and sustained interference of light; diffraction due to a single slit width of central maximum; resolving power of microscope and astronomical telescope. Polarisation, plane polarised light, Malus's law, Brewster's law, uses of plane polarised light and polaroid.

Module Wise Distribution Of Unit Syllabus - 15 Modules

Module 1	• Introduction • How we will study optics • Light facts • Ray optics, beams • Light falling on surfaces of any shape texture • Peculiar observations
Module 2	• Reflection of light • Laws of reflection • Reflection of light by plane and spherical surfaces • Spherical Mirrors aperture, radius of curvature, pole principal axis • Focus, Focal length, focal plane • Image – real and virtual • Sign convention • The mirror equation, magnification • To find the value of image distance v for different values of object distance u and find the focal length of a concave mirror • Application of mirror formula
Module 3	• Refraction of light • Optical density and mass density • Incident ray, refracted ray emergent ray • Angle of incidence, angle of refraction angle of emergence To study the effect on intensity of light emerging through different coloured transparent sheets using an LDR

	• Refractive index • Oblique incidence of light, Snell's law • Refraction through a parallel sided slab • Lateral displacement, factors affecting lateral displacement • To observe refraction and lateral displacement of a beam of light incident obliquely on a glass slab • Formation of image in a glass slab
Module 4	• Special effects due to refraction • Real and apparent depth • To determine the refractive index of a liquid using travelling microscope • Total internal reflection • Optical fibres and other applications
Module 5	• Refraction through a prism • Deviation of light -angle of deviation • Angle of minimum deviation • Expression relating refractive index for material of the prism and angle of minimum deviation • To determine the angle of minimum deviation for given prism by plotting a graph between angle of incidence and angle of deviation • Dispersion, spectrum
Module 6	• Refraction at spherical surfaces • Radius of curvature • Refraction by a lens • Foci, focal plane, focal length, optical center, principal axis • Formation of images real and virtual • Lens maker's formula • Lens formula and magnification • Sign convention • Application of lens formula • Power of lens • Combination of thin lenses in contact

Module 7	• To study the nature and size of image formed by a ii) convex lens ii) concave mirror using a candle and a screen • To determine the focal length of convex lens by plotting graphs between u and v, between 1/u and 1/v • To determine the focal length of a convex mirror using a convex lens • To find the focal length of a concave lens using a convex lens • To find the refractive index of a liquid by using a convex lens and a plane mirror
Module 8	• Scattering of light – • Blue color of sky • Reddish appearance of the sun at sunrise and sunset • Dust haze
Module 9	• Optical instruments • Human eye • Microscope • Astronomical telescopes reflecting and refracting • Magnification • Making your own telescope
Module 10	• Wave optics • Wavefront • Huygens's principle shapes of wavefront • Plane wavefront • Refraction and reflection of plane wavefront using Huygens's principle • Verification of Laws of refraction and reflection of light using Huygens's principle
Module 11	• Superposition of waves • Coherent and incoherent addition of waves
Module 12	• Interference of light • Young's double slit experiment

	● Expression for fringe width ● Graphical representation of intensity of fringes ● Effect on interference fringes in double slit experiment ● Black and white or coloured fringes
Module 13	● Diffraction ● Diffraction at a single slit ● Width of the central maxima ● Comparison of fringes in young's experiment and those in diffraction from a single slit
Module 14	● Diffraction in real life ● Seeing the single slit diffraction pattern ● Resolving power of optical instruments ● Validity of ray optics ● Fresnel distance
Module 15	● Polarisation ● To observe polarization of light using two polaroid ● Plane polarised light ● Polariser analyser Malus law ● Brewster/s law ● Polarisation due to scattering ● Uses of plane polarised light and polaroids

Module 13

Words You Must Know

Let us remember the words we have been using in our study of this physics course.

Converging and diverging rays; rays of light may converge to or seem to diverge from a point after reflection or refraction such rays are called converging or diverging rays.

Laws of reflection: Laws followed by light rays whenever reflection takes place

- The incident ray, reflected ray and the normal at the point of incidence all lie in the same plane
- The angle of reflection is equal to the angle of incidence

Snell's law: For oblique incidence of light on a transparent medium surface

$$refractive\ index = \frac{\sin i}{\sin r}$$

- The incident ray, refracted ray and the normal at the point of incidence all lie in the same plane
- The angle of refraction is not equal to the angle of incidence.
- A ray of light propagating from a rarer to a denser medium moves towards the normal. This can be observed for obliquely incident rays.

Plane mirror: A polished surface with infinite radius of curvature.

Spherical mirror- concave and convex: spherical mirrors are part of spherical surfaces. The polished surface makes them concave or convex.

Spherical lens-convex and concave: transparent medium bounded by spherical surfaces, if a thin block of medium has two surfaces bulge out, they form a convex lens

Prism: a rectangular block cut along its diagonal gives two prisms. Each piece has two refracting surfaces, a base and the angle between the refracting surfaces (in this case $=90^0$) is called angle of prism.

Light Wave. Light is part of the electromagnetic spectrum. They are transverse waves, origin of light is from electromagnetic transitions of electrons inside the atoms giving out the radiation. The frequency depends upon the source. Wavelength depends upon the medium in which light is travelling.

Wavefront: Defined as a surface of constant phase.

Huygens's principle

- Each point of the wavefront is a source of a secondary disturbance and the wavelets emanating from these points spread out in all directions with the speed of the wave. These wavelets emanating from the wavefront are usually referred to as secondary wavelets
- If we draw a common tangent (in the forward direction) to all these spheres, we obtain the new position of the wavefront at a later time.

Huygens's construction; Wavefronts drawn on the basis of Huygens principle

Superposition of waves: if two (or more) waves travelling through the same medium at the same time meet, the net displacement of the medium at any time becomes equal to the algebraic sum of the individual displacements.

Coherent sources of light

Two sources are said to be coherent if they obey the following properties:

(a) Two sources must be emitting waves of the same wavelength or frequency.

(b) The amplitude of the waves produced by the two sources must be either equal or approximately equal.

(c) The waves produced by the two sources must have either the same phase or a constant phase difference

Coherent sources of light

Two sources are said to be incoherent if they obey the following properties:

(a) Two sources may be emitting waves of the same wavelength or frequency.

(b) The amplitude of the waves produced by the two sources may not be either equal or approximately equal.

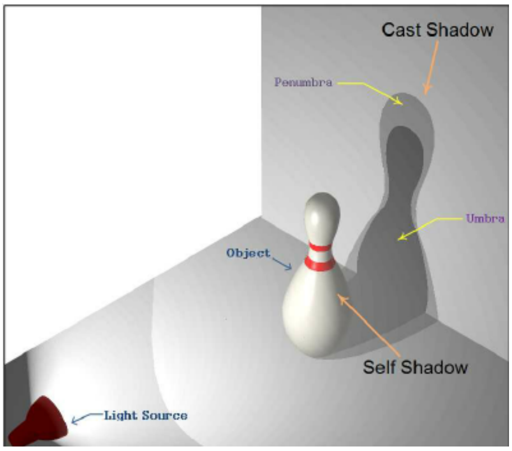
(c) The waves produced by the two sources do not have either the same phase or a constant phase difference.

Fringes: The bright and dark line pattern obtained due to interference of light

Fringe width: The separation between two consecutive bright or dark fringes. It depends upon the wavelength of light

Introduction

If we look clearly at the shadow cast by an opaque object, close to the region of geometrical shadow, there are alternate dark and bright regions just like in interference.



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When we hold our hand between a light source and a screen, the light and dark shadow depends upon the size of the light source, its distance from our hand, orientation of our hand and the distance the hand from the screen

Try This

Loosen your hand,Close your fingers not too tight small gaps between fingers will be good.Hold the gap in the fingers against any light source.Observe the thin collection of dark lines in the gap.Explain the existence of dark lines.

This happens due to the phenomenon of diffraction.

Diffraction is a general characteristic exhibited by all types of waves, be it sound waves, light waves, water waves or matter waves.

We will now discuss the phenomenon of diffraction of light.

Diffraction

The bending of light at corners is called diffraction, so instead of geometrical shadow of objects the bending creates a hazy outline of a dark shadow patch. But this is not observable as the wavelength of light is small.

Since the wavelength of light is much smaller than the dimensions of most obstacles; we do not encounter diffraction effects of light in everyday observations. However, the finite resolution (to see close objects distinctly) of our eye or of optical instruments such as telescopes or microscopes is limited due to the phenomenon of diffraction.

To understand the meaning of resolution

On a plane sheet of paper draw two parallel lines about 1 mm apart. Stick the paper on a door, now move away from the door seeing and finding a place where the two lines reduce to one. The resolution ability of the eye stops here; it cannot distinctly see the two close lines at that distance. This distance may not be the same for another person.

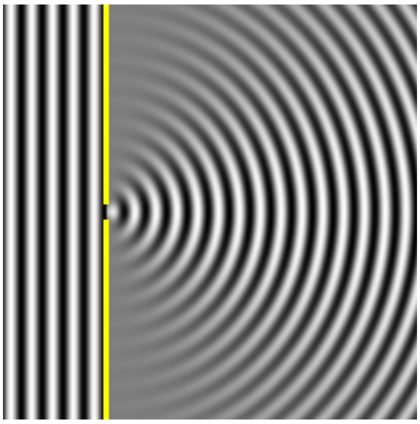
Indeed, the colours that you see when a CD is viewed is due to diffraction effects

https://upload.wikimedia.org/wikipedia/commons/thumb/c/ca/CD-ROM.png/480px-CD-ROM.png

In the discussion of Young's experiment, we stated that a single narrow slit acts as a new source from which light spreads out. Even before Young, early experimenters – including Newton – had noticed that light spreads out from narrow holes and slits.
It seems to turn around corners and enter regions where we would expect a shadow.
These effects, known as diffraction, can only be properly understood using wave ideas.
After all, you are hardly surprised to hear sound waves from someone talking around a corner!

Diffraction At Single Slit

When the double slit in Young's experiment is replaced by a single narrow slit (illuminated by a monochromatic source), a broad pattern with a central bright region is seen.



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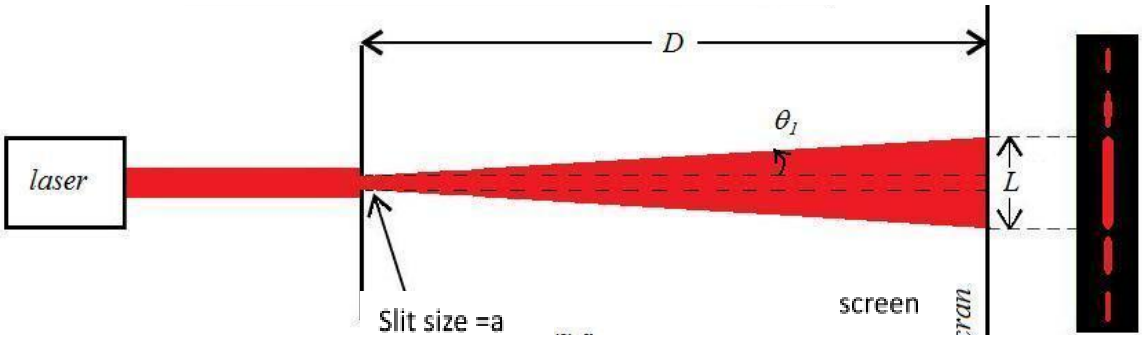

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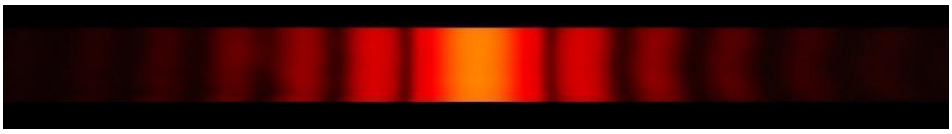
At a distance from the slit in a plane parallel to the slit plane a fringe-like pattern can be observed.

On both sides, there are alternate dark and bright regions, the intensity becoming weaker away from the centre. This is similar to what you would observe in the gap between the fringes.The pattern is observed with a red laser pointer.



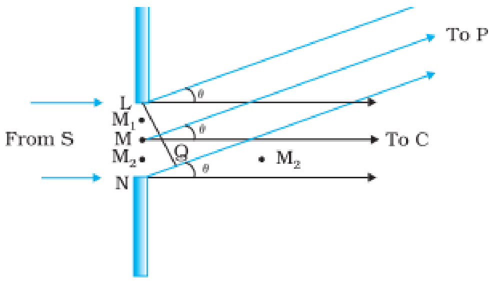
https://upload.wikimedia.org/wikipedia/commons/7/75/Diffraction_sunlight_0.02mm.jpg

- In the above pattern the central part is bright and large.
- The intensity of fringes on either side of the central bright fringe is far less.
- The fringes other than the central and few others are not distinctly visible.
- The pattern is different from that obtained in young's double slit experiment as described in module 12 of this unit.

Explanation In Support Of The Observation

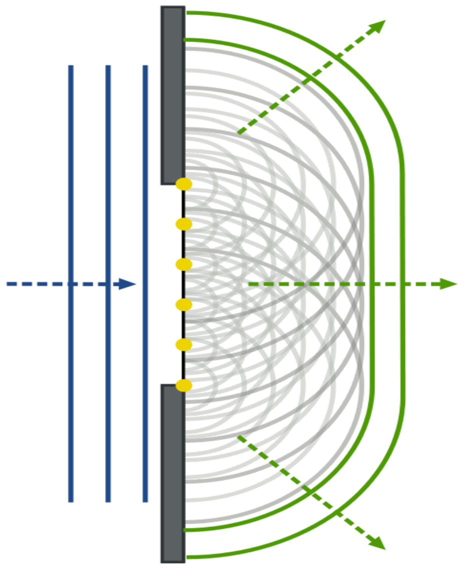
Question is; why do we get a dark space when there is one opening. There should only be a light patch

To understand this, observe the following figure.



It shows a parallel beam of light, from S, falling normally on a single slit LN of width a.

Keep in mind Huygens principle and imagine a plane wavefront reaching LN, so infinite number of secondary sources lie in LN, giving secondary wavelets.



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These secondary wavelets interfere and create a diffraction pattern on the screen.The diffracted light goes on to meet a screen.

Three features are important

- the central patch is wider than ‘a’ (the slit opening).
- A dark region is seen symmetrically on sides of the central bright patch.
- Bright patches are seen beyond the dark ones with much lower intensity as compared to the central bright space.

Say the midpoint of the slit is M.A straight line through M perpendicular to the slit plane meets the screen at C.

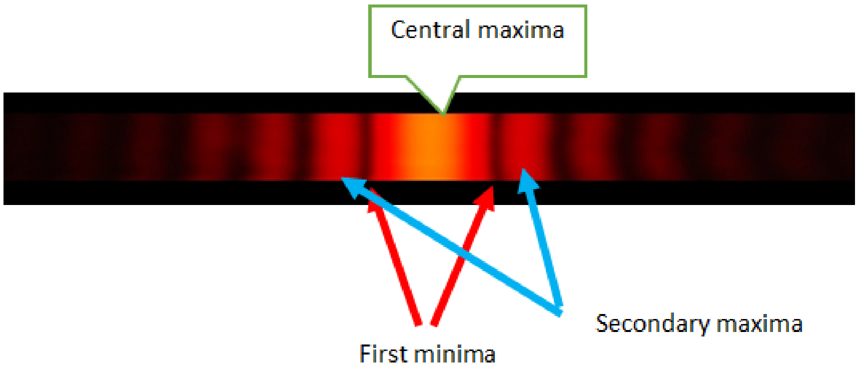
Let us say P is the boundary of the central bright patch, or it is the dark point.We want the intensity at any point P on the screen to be zero. As before, straight lines joining P to the different points L, M, N, etc., can be treated as parallel, making an angle θ with the normal MC.

The basic idea is to divide the slit into much smaller parts, and add their contributions at P with the proper phase differences.

We are treating different parts of the incident plane wavefront at the slit as secondary sources. Because the incoming wavefront is parallel to the plane of the slit, these sources are in phase.

All wavelets reaching the central part would be in phase from the infinite secondary sources in 'a'

The central bright patch is called the central maxima

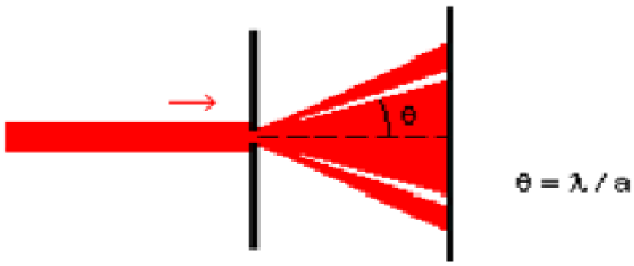


Why should there be a dark fringe?

If the secondary wavelets are divided into pairs, such that one wavelet cancels the effect of the other wavelet or due to destructive interference the intensity is zero.

This condition will arise if the path difference is λ/2 or odd multiple of λ/2.

If we divide the secondary sources into half such that, half the secondary wavelets cancel the effect of the other half we will get a **minima'**



Why should bright fringes appear on the two sides other than the central bright fringe?

In order to explain this we can divide the secondary wavelets into three equal parts, two parts have a pair of secondary wavelets that reach a point on the screen causing destructive interference (path difference = λ/2) , however the wavelets from one third offer constructive interference. The intensity is much less than that of the central maxima.

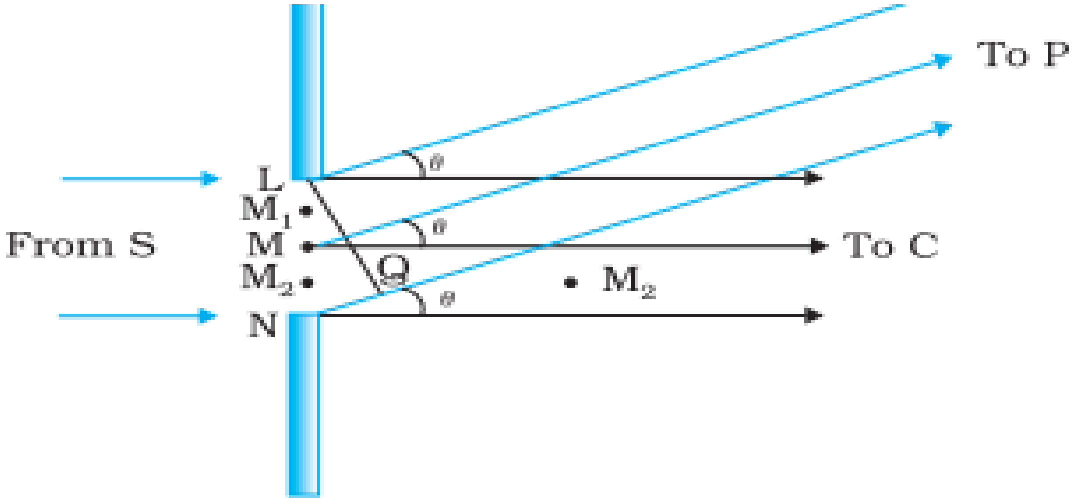
The reduced intensity may be explained in this way. We cannot explain why the intensity of the secondary maxima is not reduced to 1/3 but far less than that.

Mathematically

The path difference NP – LP between the two edges of the slit can be calculated exactly as for Young's experiment.

The basic idea is to divide the slit into much smaller parts and add their contributions at P with proper phase differences.

For central and other maxima



The geometry of path differences for diffraction by a single slit

$NP - LP = NQ$

$= a\sin\theta$

a is the slit width LN,θ is the angle MP makes with MC.

if θ is small, sin θ may be taken = θ

Similarly, if two points M_1 and M_2 in the slit plane are separated by y,

The path difference

$$M_2P - M_1P \approx y\,\theta$$

We now have to sum up equal, coherent contributions from a large number of sources, each with a different phase. This calculation was made by Fresnel using integral calculus, so we omit it here.

The main features of the diffraction pattern can be understood by simple arguments. At the central point C on the screen, the angle θ is zero. All path differences are zero and hence all the parts of the slit contribute in phase. This gives maximum intensity at C due to constructive interference Experimental observation shown in the above figure.

The central bright patch is called the central maxima

Other secondary maxima at

$$\theta = (2n+1)\,\lambda/a, \quad n = \pm1, \pm2, \pm3....$$

and has minima (zero intensity) at

$$\theta = n\,\lambda/a, \quad n = \pm1, \pm2, \pm3....$$

It is easy to see why it has minima at these values of angle.

Consider first the angle θ where the path difference a θ is λ.

Then,

$$\theta = \lambda / a$$

Angular width of the maxima = 2θ = 2λ/a

Linear width of central maxima depends upon how far away the screen is from the slit

tan θ = CP/D (distance of screen from the slit)

or 2CP =2D tan θ **or 2D** θ or **2 D λ /a**

The secondary maximas are much smaller in width about half the size of the central maxima.

Position of minima

Now choose an angle θ such that the path difference between L and N at P is (λ/2+λ/2= λ)

For this divide the split into two equal halves LM and MN each of size a/2.

For every point M_1 in LM, there is a point M_2 in MN such that $M_1 M_2 = a/2$.

The path difference between M_1 and M_2 at

$$P = M_2\,P - M_1\,P = \theta\, a/2 = \lambda/2$$

for the angle chosen.

This means that the contributions from M_1 and M_2 are out of phase and cancel in the direction θ = λ/a. or there is destructive interference.

Contributions from the two halves of the slit LM and MN, therefore cancel each other.

Equation

θ = λ/a gives the angle at which the intensity falls to zero.

One can similarly show that the intensity is zero for θ = n λ/a, with n being any integer (except zero!).

Notice that the angular size of the central maximum increases when the slit width decreases.

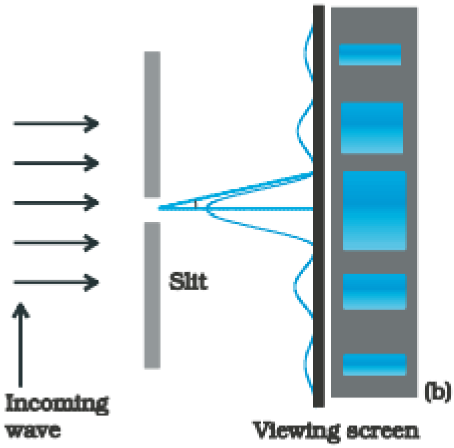
It is also easy to see why there are maxima at $\theta = (n + 1/2)\,\lambda/a$ and why they go on becoming weaker and weaker with increasing n.

Consider an angle θ = 3λ/2a which is midway between two of the dark fringes. Divide the slit into three equal parts. If we take the first two thirds of the slit, the path difference between the two ends would be

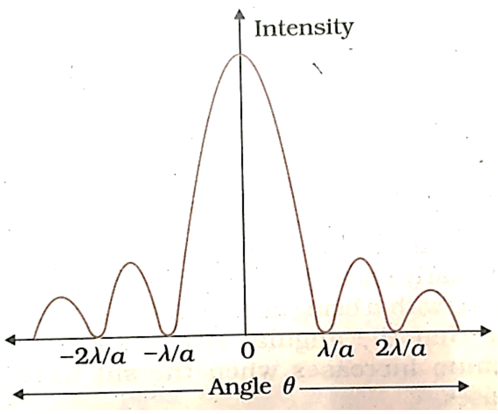
$$\frac{2}{3}a\times\theta = \frac{2a}{3} \times \frac{3\lambda}{2a} = \lambda$$

The first two-thirds of the slit can therefore be divided into two halves which have a λ/2 path difference. The contributions of these two halves cancel in the same manner as described earlier. Only the remaining one-third of the slit contributes to the intensity at a point between the two minima. Clearly, this will be much weaker than the central maximum (where the entire slit contributes in phase). One can similarly show that there are maxima at $(2n + 1) \lambda/a$ with n = 2, 3, etc.

These become weaker with increasing n, since only one-fifth, one-seventh, etc., of the slit contributes in these cases. The photograph and intensity pattern corresponding to it is shown in Figure

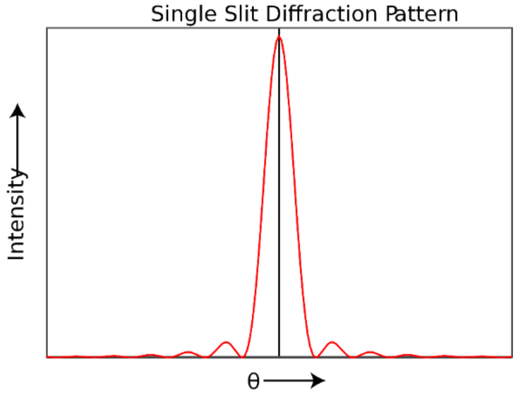


Intensity distribution and photograph of fringes due to diffraction at single slit.



The above graph shows variation in intensity with angle in single slit diffraction.

Actually the intensity in the first secondary maxima drops to 4 % of the central maxima intensity and the graph may be as below, but to show clarity drawn both



Variation of intensity with angle θ in a single slit diffraction pattern

The **minimas occur at θ = n λ/a,** or at n =1, 2, 3, 4…

So

$\theta = \pm\frac{\lambda}{a}, \frac{2\lambda}{a}, \frac{3\lambda}{a}$

The **maximas at θ = (2n+1) λ/2a** at n =1,2,3,4…

For this

$\theta = \pm\frac{3\lambda}{2a}, \frac{5\lambda}{2a}, \frac{7\lambda}{2a},$

The experimental observations, intensities of secondary maxima relating to the intensity of central maxima are in the ratio

$1 : \frac{1}{21} : \frac{1}{61} : \frac{1}{121} \ldots$

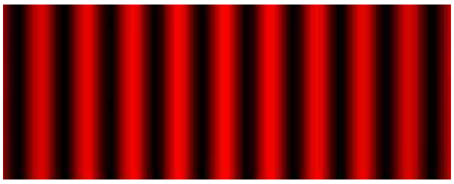
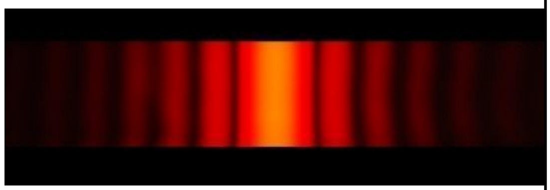
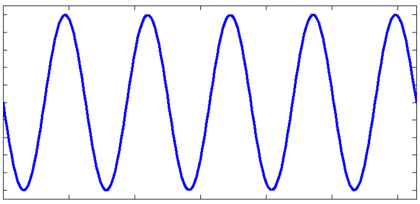
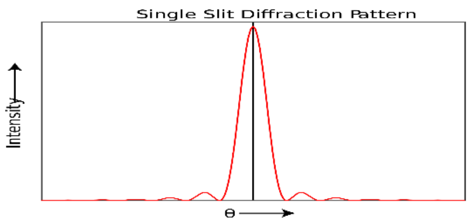
Thus intensity of the first secondary maxima is just 4 % of that of the central maxima.

Difference Between Interference And Diffraction Pattern

There has been prolonged discussion about the difference between interference and diffraction among scientists since the discovery of these phenomena.

In this context, it is interesting to note what Richard Feynman* has said in his famous Feynman Lectures on Physics:

No one has ever been able to define the difference between interference and diffraction satisfactorily. It is just a question of usage, and there is no specific, important physical difference between them. The best we can do is, roughly speaking, is to say that when there are only a few sources, say two interfering sources, then the result is usually called interference, but if there is a large number of them, it seems that the word diffraction is more often used.

	Interference	Diffraction
1	Interference is the result of superposition of secondary wavelets from two coherent sources	Diffraction is the result of superposition of a large number of waves emanating from the same wavefront
2	All bright and dark fringes are of equal width	The width of the central bright fringe is much larger than the other maximas
3	All bright fringes are of nearly same intensity	Intensity decreases sharply as we move away from the central maxima
4	Good contrast between bright and dark fringes	The dark regions are not perfectly dark and the contrast is not strong
5	At an angle of λ/a we obtain a bright fringe where a is the separation between the two slits	At an angle of λ/a we obtain the first dark fringe where a is the width of the slit
6	Fringe pattern 	Fringe pattern 
7	Graphical Intensity distribution 	Graphical Intensity distribution 

Example

Answer the following questions:

(a) In a single slit diffraction experiment, the width of the slit is made double the original width. How does this affect the size and intensity of the central diffraction band?

(b) In what way is diffraction from each slit related to the interference pattern in a double-slit experiment?

(c) When a tiny circular obstacle is placed in the path of light from a distant source, a bright spot is seen at the centre of the shadow of the obstacle. Explain why?

(d) Two students are separated by a 7 m partition wall in a room 10 m high. If both light and sound waves can bend around obstacles, how is it that the students are unable to see each other even though they can converse easily?

(e) Ray optics is based on the assumption that light travels in a straight line. Diffraction effects (observed when light propagates through small apertures/slits or around small obstacles) disprove this assumption. Yet the ray optics assumption is so commonly used in understanding location and several other properties of images in optical instruments. What is the justification?

Solution

(a) When the width of a single slit is made double, the angular width of the central maxima reduces to half. The intensity of the central maxima will become 4 times. This is because the area of the central diffraction band would become $1/4^{th}$.

(b) If the width of each slit is of the order of λ, then the interference pattern in the double slit experiment is modified by the diffraction from each of the two slits.

(c) This is because waves diffracted from the edges of circular obstacles interfere constructively at the centre of the shadow resulting in the formation of a bright spot.

(d) For diffraction of waves by obstacle, through a large angle, the size of obstacle / aperture should be comparable to wavelength. This follows $\theta = \frac{\lambda}{a}$.

(e) The ray optics assumption is used in understanding location and several other properties of images in optical instruments. This is because typical sizes of aperture involved in ordinary optical instruments are much larger than the wavelength of light. Therefore, diffraction on bending of waves is of no significance.

Example

A parallel beam of light of wavelength 500 nm falls on a narrow slit and the resulting diffraction pattern is observed on a screen 1 m away. It is observed that the first minimum is at a distance of 2.5 mm from the centre of the screen. Find the width of the slit.

Solution: $\lambda = 500\, nm = 500\times10^{-9} m = 5\times10^{-7} m$

$D = 1$

$m = 1$

$x = 2.5\, mm = 2.5\times10^{-3} m$

$a = ?$

We know $a\frac{x}{D} = n\lambda$

$a = \frac{n\lambda D}{x} = \frac{1\times5\times10^{-7}\times1}{2.5\times10^{-3}} = 2\times10^{-4} m$

$a = 0.2\, mm$

Example

In deriving the single slit diffraction pattern, it was stated that the intensity is zero at angles of n λ/a. Justify this by suitably dividing the slit to bring out the cancellation.

Solution: let the slit be divided into n smaller slits each of width $a' = \frac{a}{n}$

The angle

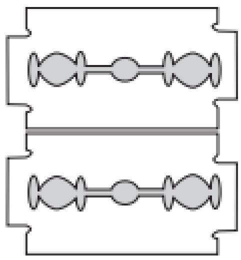
$\theta = \frac{n\lambda}{a} = \frac{n\lambda}{a'n} = \frac{\lambda}{a'}$

Therefore, each of the smaller slits would send zero intensity in the direction of **θ**. Hence for the entire single slit, intensity at angle $\frac{n\lambda}{a}$ would be zero.

Seeing The Single Slit Diffraction Pattern

It is surprisingly easy to see the single-slit diffraction pattern for oneself.

The equipment needed can be found in most homes — **two razor blades and one clear glass electric bulb preferably with a straight filament.** One has to hold the two blades so that the edges are parallel and have a narrow slit in between.



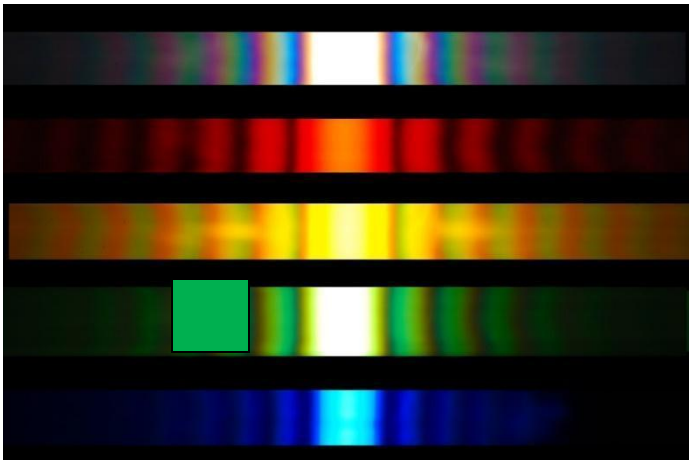
Holding two blades to form a single slit, a bulb filament viewed through this shows clear diffraction bands.This is easily done with the thumb and forefingers. Keep the slit parallel to the filament, right in front of the eye. Use spectacles if you normally do. With slight adjustment of the width of the slit and the parallelism of the edges, the pattern should be seen with its bright and dark bands.

Since the position of all the bands (except the central one) depends on wavelength, they will show some colours. Using a filter for red or blue will make the fringes clearer. With both filters available, the wider fringes for red compared to blue can be seen.

In this experiment, the filament plays the role of the first slit S. The lens of the eye focuses the pattern on the screen (the retina of the eye). With some effort, one can cut a double slit in an aluminium foil with a blade. The bulb filament can be viewed as before to repeat Young's experiment. In daytime, there is another suitable bright source subtending a small angle at the eye. This is the reflection of the Sun in any shiny convex surface (e.g., a cycle bell). Do not try direct sunlight – it can damage the eye and will not give fringes anyway as the Sun subtends an angle of $(1/2)^o$. In interference and diffraction, light energy is redistributed. If it reduces in one region, producing a dark fringe, it increases in another region, producing a bright fringe. There is no gain or loss of energy, which is consistent with the principle of conservation of energy.

Example

Observe the diffraction pattern obtained when a single slit is exposed to light of different colour



a) Why is the central maxima for red is broader than that for blue?
b) What can you say about the light source in the top most diffraction pattern?

Solution

a) Angular width of central maxima

$2\,\theta = 2\lambda/a$

wavelength of red is greater than wavelength of blue

b) White light pattern

Summary

- The principle of superposition of waves applies whenever two or more sources of light illuminate the same point. When we consider the intensity of light due to these sources at the given point, there is an interference term in addition to the sum of the individual intensities.
- Interference is a result of superposition of two waves.
- the sources for interference pattern, must have the same frequency and a stable phase difference or be arising from coherent sources
- A single slit of width gives a diffraction pattern with a central maximum.
- A fringe pattern is obtained due to interference of waves emanating from different portions of the single slit.
- The dark fringes can be explained as destructive interference due to most of the wavelets.
- The contrast between bright and dark fringes and fringe width is not equal as in the interference pattern produced in Young's double slit experiment.
- The intensity falls to zero at angles of 2 λ/a, 3 λ/a etc., with successively weaker secondary maxima in between.
- The intensity of secondary maximas falls sharply.