1. Details of Module and its structure

Module Detail	
Subject Name	Physics
Course Name	Physics 04 (Physics Part-2, Class XII)
Module Name/Title	Unit-06, Module-14: Effects of Diffraction in daily life Chapter -10: Wave Optics
Module Id	leph_201005_eContent
Pre-requisites	Superposition of waves, ray optics, interference of waves, young's double slit experiment, diffraction, diffraction fringes, interference fringes
Objectives	After going through this module, the learner will be able to : • Appreciate Diffraction in real life • Understand the effect of diffraction on resolving power of optical instruments • Calculate resolving power of optical instruments • Deduce Validity of ray optics • Define Fresnel distance
Keywords	Diffraction, resolving power, limit of resolution, validity of ray optic, Fresnel distance

2. Development Team

Role	Name	Affiliation
National MOOC Coordinator (NMC)	Prof Amarendra P. Bahera	Central Institute of Educational Technology, NCERT, New Delhi
Programme Coordinator	Dr. Mohd Mamur Ali	Central Institute of Educational Technology, NCERT, New Delhi
Course Coordinator / PI	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
Subject Matter Expert (SME)	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
Review Team	Prof. V. B. Bhatia (Retd.) Associate Prof. N.K. Sehgal (Retd.) Prof. B. K. Sharma (Retd.)	Delhi University Delhi University DESM, NCERT, New Delhi

TABLE OF CONTENTS

1. 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 fibers; 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: wave front and Huygens's principle, reflection and refraction of plane wave at a plane surface using wave fronts. 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.

2. 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 colored 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 fibers 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 • Wave front • Huygens's principle shapes of wave front • Plane wave front • Refraction and reflection of plane wave front 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 colored 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 14

3. 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

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

- 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 wave front 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 wave front 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 wave front at a later time.

Huygens's construction; Wave fronts 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 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 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

Diffraction: the shadow cast by an opaque object, close to the region of geometrical shadow, there are alternate dark and bright regions. Due to bending of light waves by corners Diffraction is a general characteristic exhibited by all types of waves, be it sound waves light waves, water waves or matter waves. 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.

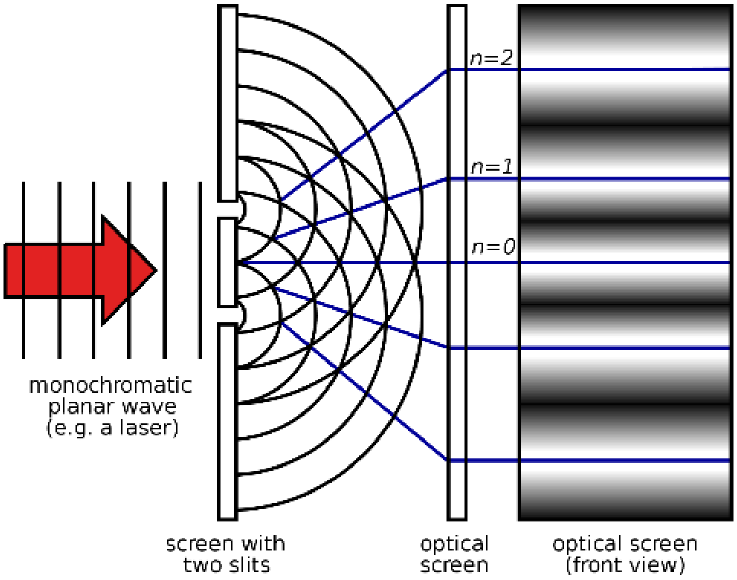
Diffraction fringes: alternate dark and bright regions just like in interference.

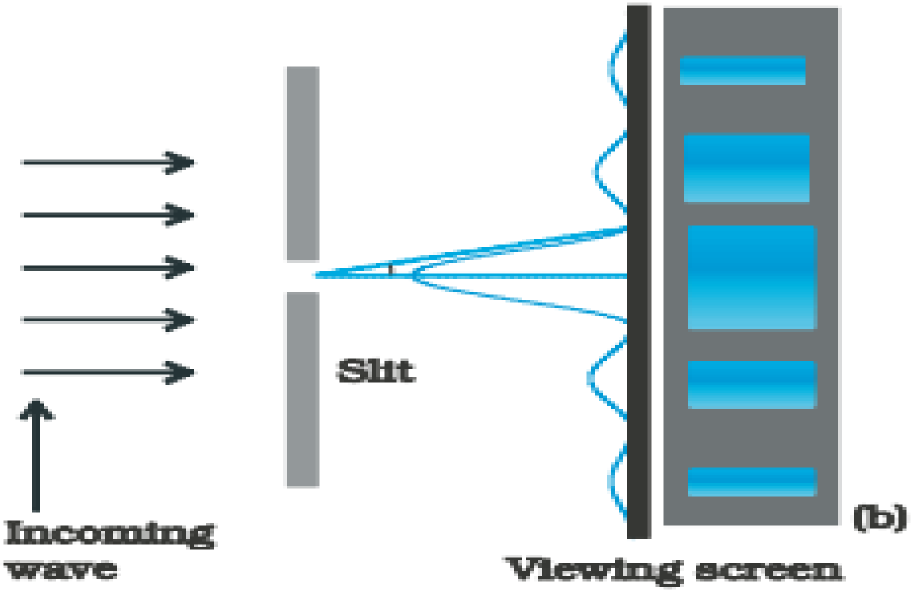
4. INTRODUCTION

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. 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. 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 of our eye or of optical instruments such as telescopes or microscopes is limited due to the phenomenon of diffraction. Indeed, the colors that you see when a CD is viewed are due to diffraction effects.

We are also familiar with the fringe pattern in young's double slit experiment and single slit diffraction pattern.

To recall the above two situations, consider the two figures, the first shows the schematic arrangement for double slit experiment, and the single slit diffraction experiment.



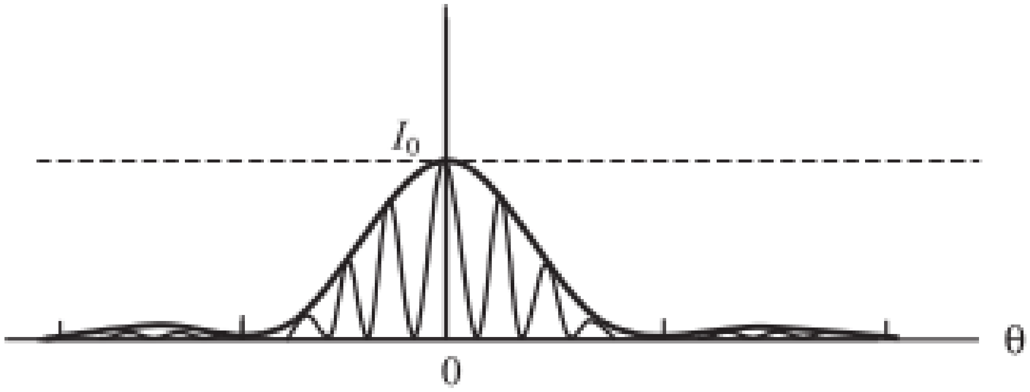


Intensity distribution and photograph of fringes due to diffraction at single slit.

You can now also appreciate that diffraction is a case of interference. The phenomenon is only possible due to wave nature of light.

The size of the slit must be of the same order as the wavelength of light is an important condition for diffraction of light takes place.

Now consider the following graph



The actual double-slit interference pattern. The envelope shows the single slit diffraction.

It shows a broader diffraction peak in which there appear several fringes of smaller width due to double-slit interference.

The number of interference fringes occurring in the broad diffraction peak depends on the ratio $\mathbf{\frac{d}{a}}$

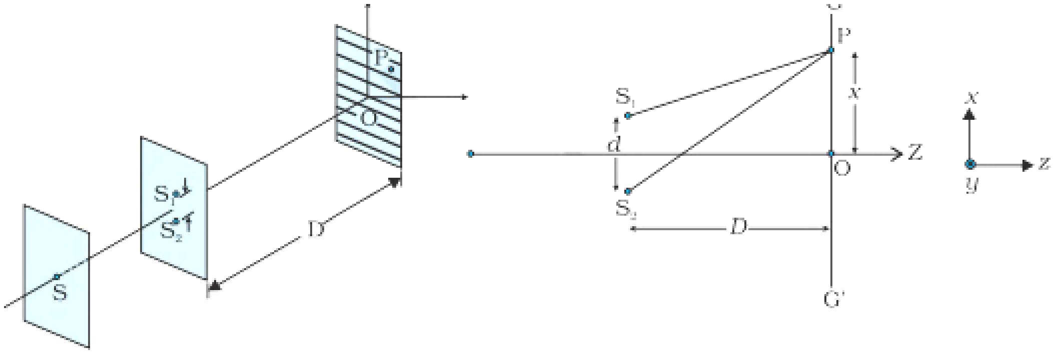
that is **the ratio of 'd' the distance between the two slits to the width 'a' of slit.**

In the limit of '**a**' becoming very small, the diffraction pattern will become very flat and we will observe the two-slit interference pattern

In the double-slit interference experiment, what happens if we close one slit?

You will see that it now amounts to a single slit.

But you will have to take care of some shift in the pattern



(a) (b)

We now have a source at S, and only one hole (or slit) S_1 or S_2.

This will produce a single slit diffraction pattern on the screen.

The center of the central bright fringe will appear at a point which lies on the straight line SS_1 or SS_2, as the case may be.

When we compare and contrast the interference pattern with that seen for an illuminated single slit (usually called the single slit diffraction pattern).

(i) The interference pattern has a number of equally spaced bright and dark bands.

The diffraction pattern has a central bright maximum which is twice as wide as the other maxima. The intensity falls as we go to successive maxima away from the center, on either side.

(ii) We calculate the interference pattern by superposing two waves originating from the two narrow slits.

The diffraction pattern is a superposition of a continuous family of waves originating from each point on a single slit.

(iii) For a single slit of width, a, the first dark of the interference pattern occurs at an angle of λ/a.

At the same angle of λ/a, we get a maximum (not a null) for two narrow slits separated by a distance a.

One must understand that both d and a have to be quite small, to be able to observe good interference and diffraction patterns.

For example, the separation '*d*' between the two slits must be of the order of a millimeter or so.

The width 'a' of each slit must be even smaller, of the order of 0.1mm or 0.2 mm.

In our discussion of Young's experiment and the single-slit diffraction, we have assumed that the screen on which the fringes are formed is at a large distance. The two or more paths from the slits to the screen were treated as parallel.

This situation also occurs when we place a converging lens after the slits and place the screen at the focus. Parallel paths from the slit are combined at a single point on the screen. Note that the lens does not introduce any extra path differences in a parallel beam.

This arrangement is often used since it gives more intensity than placing the screen far away. If f is the focal length of the lens, then we can easily work out the size of the central bright maximum. In terms of angles, the separation of the central maximum from the first null of the diffraction pattern is λ/a. Hence, the size on the screen will be f λ/a.

EXAMPLE

What should the width of each slit be to obtain 10 maxima of the double slit pattern within the central maximum of the single slit pattern?

SOLUTION

We want

$$a\theta = \lambda \qquad \theta = \frac{\lambda}{a}$$

$$10\frac{\lambda}{d} = 2\frac{\lambda}{a} \qquad a = \frac{d}{5} = 0.2\ \text{mm}$$

Notice that the wavelength of light and distance of the screen do not enter in the calculation of a

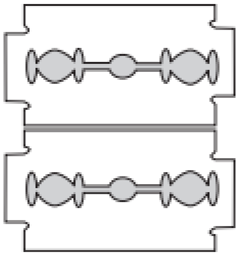
No one has ever been able to define the difference between interference and diffraction satisfactorily.

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 are a large number of them, it seems that the word diffraction is more often used.

5. 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. You can use the small laser pointer available at the toy shop for this. 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 close to the light source, 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 colors in case you are using white light source.

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 light source plays the role of the first slit S.

The lens of the eye focuses the pattern on the screen (the retina of the eye).

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.

You can see the pattern using a kitchen sieve and a laser pointer. Hold the sieve close to the pointer almost touching it, the thin wire making up the sieve will create an easy to see diffraction pattern.

Tea sieve from the kitchen

https://pixabay.com/en/sieve-filter-mesh-kitchen-strainer-2202240/

Green laser light

https://commons.wikimedia.org/wiki/File:Cartoon-love-making.jpg

6. RESOLVING POWER OF OPTICAL INSTRUMENTS

The ability of an optical instrument –

- **eye,**
- **microscopes**
- **telescopes,**

To see distinctly two close objects is called power of resolution

The fitness of the eye depends on the combination of lenses used in the optical instruments. The color of light, wavelength and the distance of viewing become relevant as we will understand the role of diffraction in resolution.

TRY THIS

Hold up the figure with **two** squares drawn on A 4 sheet and

i. **one with close lines**
ii. **the other grey**,

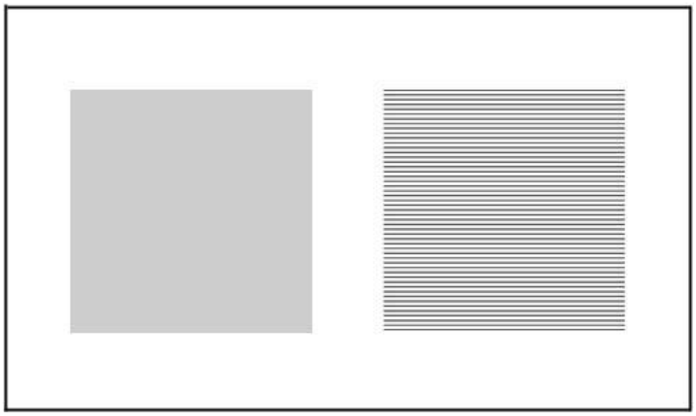
About 4 m away and see the lines in one of the patterns. Usually no one beyond 4 meters can see the lines

Try it with friends and others at home.

ANGULAR RESOLUTION of normal eye = (2 mm)/D

Using the above equation, D = 4 m corresponds to an angular resolution of 0.03 degrees. This means up to 4 m objects that are subtending and angular separation of 0.03^0 can be seen resolved

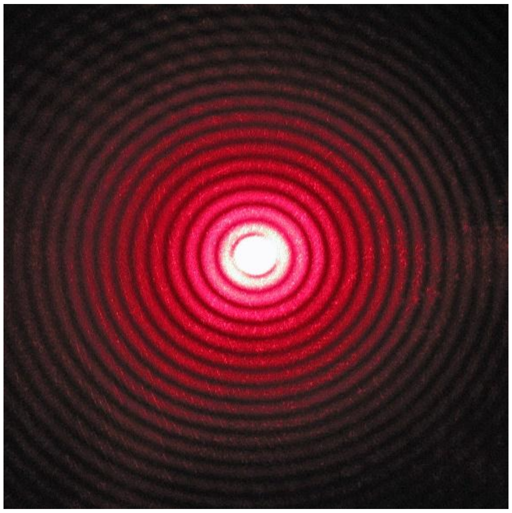
The diffraction limits the ability of the eye to resolve



DIFFRACTION BY A CIRCULAR APERTURE

Before we go any further let us consider diffraction by a circular aperture. This would be for circular lenses, like we use in the laboratories, in microscopes and telescopes, the natural lens in our eye.

So, if the laser pointer (red) is lighting up a lens, the image at focus, is not a point as geometrical ray optics would suggest, but a bright disc surrounded by several progressively fainter rings



https://upload.wikimedia.org/wikipedia/commons/4/42/Laser_Interference.JPG

Calculations show that the **first minima** for the diffraction pattern of a circular aperture of diameter **d** is located by

$$\sin\theta = 1.22\frac{\lambda}{d}$$

The angle θ here is the angle from the central axis to any point on the circular minima

This equation is similar to that for single slit diffraction pattern

$$\sin\theta = \frac{\lambda}{a}$$

The main difference is of 1.22 which is due to circular aperture.

If D is the distance at which the effect is observed, or where a screen is placed to see the diffraction pattern then linear spread

$$x = D\,\sin\theta = D\theta$$

The images formed by lenses are important, whenever we wish to resolve (distinguish) between two point objects whose angular separation is small.

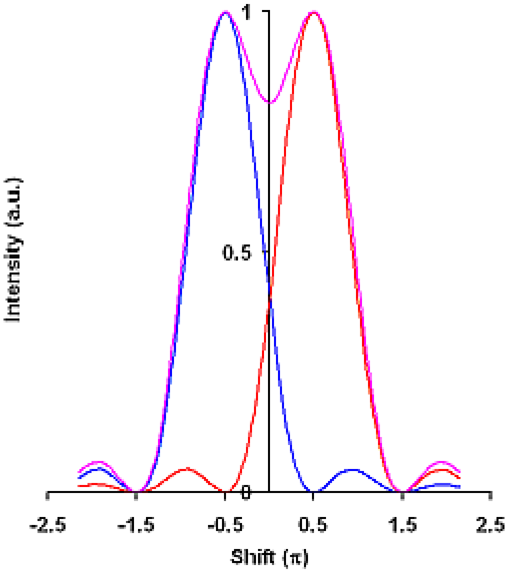
The last picture of the fly has high resolution.

https://upload.wikimedia.org/wikipedia/commons/5/59/Focus_stacking_Tachinid_fly.jpg

For close objects - how clearly and distinctly can we see them with our eyes or any optical instrument, shows the **resolving ability of the instrument**.

RAYLEIGH/S CRITERION FOR RESOLUTION

See the attached power point presentation



The images of two point objects are just resolved, when the central maximum of the diffraction pattern of one falls over the first minima of the diffraction pattern of the other

http://www.thespectroscopynet.eu/images/Pic_rayleigh.png

RESOLVING POWER OF TELESCOPE

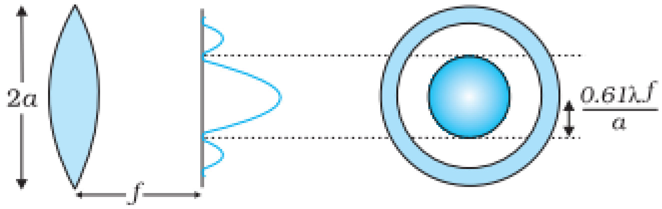
We had discussed about telescopes. The **objective of the telescope determines the angular resolution of the telescope.**

The stars which are not resolved in the image produced by the objective cannot be resolved by any further magnification produced by the eyepiece.

The primary purpose of the eyepiece is to provide magnification of the image produced by the objective.

Consider a parallel beam of light falling on a convex lens. If the lens is well corrected for aberrations, then geometrical optics tells us that the beam will get focused to a point. However, because of diffraction, the beam instead of getting focused to a point gets focused to a spot of finite area.

In this case, the effects due to diffraction can be taken into account by considering a plane wave incident on a circular aperture followed by a convex lens



The analysis of the corresponding diffraction pattern is quite involved; however, in principle, it is similar to the analysis carried out to obtain the single-slit diffraction pattern.

Taking into account the effects due to diffraction,

The pattern on the focal plane would consist of a central bright region surrounded by concentric dark and bright rings

A detailed analysis shows that the radius of the central bright region r_0 is approximately given by

$$r_0 = \frac{1.22\lambda f}{2a} = \frac{0.61\lambda f}{a}$$

A parallel beam of light is incident on a convex lens, because of diffraction effects, the beam gets focused to a spot of radius ≈ 0.61 λ f/a.

Where,

f is the focal length of the lens

2a is the diameter of the circular aperture or the diameter of the lens,

whichever is smaller.

Typically, if

$$\boldsymbol{\lambda = 0.5\mu m \qquad f = 20\ cm \qquad a = 5\ cm}$$

$$\boldsymbol{r_0 = 1.2\mu m}$$

Thus $\Delta\theta$ will be small if the diameter of the objective is large. This implies that the telescope will have better resolving power if 'a' is large.

It is for this reason that for better resolution, a telescope must have a large diameter objective.

EXAMPLE

Assume that light of wavelength 6000Å is coming from a star. What is the limit of resolution of a telescope whose objective has a diameter of 254 cm?

SOLUTION

For the telescope objective 2a = 254 cm.

Thus if, **wavelength 6000Å = 6 x10^{-5} cm**

Then

$$\Delta\theta = \frac{1.22 \times 6 \times 10^{=5}}{2 \times 254} = 2.9 \times 10^{-7}\text{radians}$$

EXAMPLE

What is the angular resolution of a telescope?

If the diameter objective is 10 cm, and wavelength of light is 0.5 µm.

SOLUTION

$$\Delta\theta = \frac{1.22\lambda}{D} = \frac{0.6 \times 10^{-6}}{0.1} = 1.2''$$

In practice optical telescopes do not achieve resolution greater than 1" as the earth's atmosphere disturbs the phase relationship. but telescopes placed above the atmosphere have better resolving power.

RESOLUTION BY MICROSCOPES

We can apply a similar argument to the objective lens of a microscope. In this case, the object is placed slightly beyond f, so that a real image is formed at a distance v

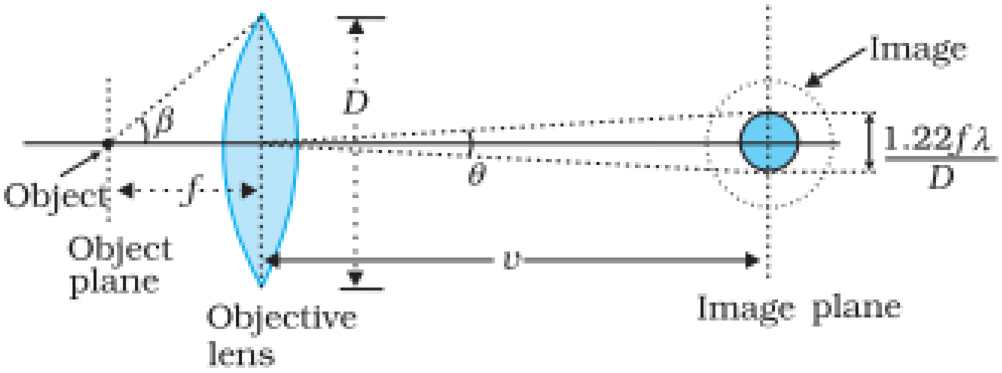
The magnification $= \frac{\text{size of image}}{\text{size of object}}$

$$m = \frac{v}{f}$$

It can be seen from the following figure that

$$\frac{\mathbf{D}}{\mathbf{f}} = \mathbf{2tan\beta}$$

where 2β is the angle subtended by the diameter of the objective lens at the focus of the microscope.



Real image formed by the objective lens of the microscope.

When the separation between two points in a microscopic specimen is comparable to the wavelength λ of the light, the diffraction effects become important.

The image of a point object will again be a diffraction pattern whose size in the image plane will be

$$v\theta = v\left(\frac{1.22\lambda}{D}\right)$$

Two objects whose images are closer than this distance will not be resolved, they will be seen as one.

The corresponding minimum separation, d_{min}, in the object plane is given by

$$d_{min} = \left(v\left[\frac{1.22\lambda}{D}\right]\right)/m$$

$$= \frac{1.22\lambda}{D} \times \frac{v}{m}$$

$$= \frac{1.22\, f\, \lambda}{D}$$

But $\frac{D}{f}$ **= 2 tan β**

$$\mathbf{d_{min}} = \frac{\mathbf{1.22\lambda}}{\mathbf{2tan\beta}}$$

If **the medium between the object and the objective lens** is not air but a medium of refractive index n, the above equation is modified gets modified to

$$\mathbf{d_{min}} = \frac{\mathbf{1.22\lambda}}{\mathbf{2\ n\ sin\beta}}$$

The product **n sinβ is called the numerical aperture** and is sometimes marked on the objective.

The resolving power of the microscope is given by the reciprocal of the minimum separation of two points seen as distinct.

The resolving power can be increased by

- choosing a medium of higher refractive index.
- Usually an oil having a refractive index close to that of the objective glass is used.
- Such an arrangement is called an **'oil immersion objective'**.

Notice that it is not possible to make **sinβ larger than unity**.

Thus, we see that the resolving power of a microscope is basically determined by the **wavelength of the light used**.

There is a likelihood of confusion between resolution and magnification, and similarly between the role of a telescope and a microscope to deal with these parameters.

A telescope produces images of far objects nearer to our eye. Therefore objects which are not resolved at far distance, can be resolved by looking at them through a telescope.

A microscope, on the other hand, magnifies objects (which are near to us) and produces their larger image.

We may be looking at two stars or two satellites of a far-away planet, or we may be looking at different regions of a living cell. In this context, it is good to **remember that a telescope resolves whereas a microscope magnifies.**

MAGNIFYING POWER AND RESOLVING POWER OF A MICROSCOPE

The magnifying power of a microscope is defined as the ratio of the angle subtended by the image at the eye and the angle subtended by the object seen directly, when both are at least distance of distinct vision.

The magnifying power of a microscope is given by

$$m = \frac{\mathrm{v}}{\mathrm{u}}\left(1 + \frac{\mathrm{D}}{\mathrm{f_e}}\right) = \left(1 - \frac{\mathrm{v}}{\mathrm{f_o}}\right)\left(1 + \frac{\mathrm{D}}{\mathrm{f_e}}\right)$$

distances u and v are from the objective lens

Resolving power of a microscope is defined as the reciprocal of the minimum distance 'd' (also called limit of resolution) between two point objects which can just be seen through the microscope as resolved.

$$resolving\ power = \frac{1}{d} = \frac{2\ n\ sin\theta}{\lambda}$$

Where n is the refractive index of the material between the object and the objective lens. θ is half the angle of cone of light from the point object?

MAGNIFYING POWER AND RESOLVING POWER OF A TELESCOPE

Magnifying power of a telescope in normal adjustment is defined as the ratio of the angle subtended by the image at the eye as seen through the telescope to the angle subtended by the object directly

Here object and its image are both at infinity

In normal adjustment

$$m = \frac{f_o}{f_e}$$

$$when\ the\ final\ image\ is\ formed\ at\ least\ distance\ of\ distinct\ vision$$

$$m = \frac{f_o}{f_e}\left(1 + \frac{f_e}{D}\right)$$

The resolving power of a telescope is defined as the reciprocal of the smallest separation between two distant objects, which are viewed resolved by the telescope

$$resolving\ power = \frac{1}{limit\ of\ resolution\ \Delta\theta} = \frac{D}{1.22\lambda}$$

D is the diameter of the objective lens and λ is the wavelength of light used

THINK ABOUT THESE

- **How does the magnifying power and the resolving power of a telescope change on increasing the diameter of the objective?**
- **What factors will affect the magnifying power and resolving power of a refracting astronomical telescope?**
- **What factors will affect the magnifying power and resolving power of a microscope?**
- **Can changing the colour of light in which we observe a slide under a microscope help you see an object better?**

7. THE VALIDITY OF RAY OPTICS

If the beam of light diverges as it passing through, will ray optics be relevant?

An aperture (i.e., slit or hole) of size a illuminated by a parallel beam sends diffracted light into an angle of approximately ≈ λ/a.

This is the angular size of the bright central maximum.

In travelling a distance z, the diffracted beam therefore acquires a width z λ/a due to diffraction.

It is interesting to ask at what value of z the spreading due to diffraction becomes comparable to the size ‘a’ of the aperture.

Because, an aperture (i.e., slit or hole) of size ‘a’, illuminated by a parallel beam sends diffracted light into an angle of approximately ≈ λ/a

This is the angular size of the bright central maximum.

In travelling a distance z, the diffracted beam therefore acquires a width zλ/a due to diffraction.

For this reason, we ask at what value of z the spreading due to diffraction becomes comparable to the size 'a' of the aperture.

We thus approximately equate $z\,\lambda/a$ with a.

This **gives the distance beyond which divergence of the beam of width *a* becomes significant.**

We want

$$\frac{2z\,\lambda}{a} \geq a$$

Or $\mathbf{z \geq \frac{a^2}{2\lambda}}$

We define a quantity z_F called the **Fresnel distance** by the following equation

$$Z_F = \frac{a^2}{\lambda}$$

This shows that

- **For distances much smaller than Z_F, the spreading due to diffraction is smaller compared to the size of the beam.**
- It becomes comparable when the distance is approximately Z_F.
- For **distances much greater than Z_F, the spreading due to diffraction dominates over that due to ray optics** (i.e., the size a of the aperture).
- Equation also shows that ray optics is valid in the limit of wavelength tending to zero.

EXAMPLE

For what distance is ray optics a good approximation when the aperture is 3 mm wide and the wavelength is 500 nm?

SOLUTION

$$\mathbf{Z_F = \frac{a^2}{\lambda} = \frac{(3 \times 10^{-3})^2}{5 \times 10^{-7}} = 18m}$$

This example shows that even with a small aperture, diffraction spreading can be neglected for rays many meters in length.

Thus, ray optics is valid in many common situations.

EXAMPLE

Estimate the distance for which ray optics is good approximation for an aperture of 4 mm and wavelength 400 nm.

$$Z_F = \frac{a^2}{\lambda} = \frac{(4 \times 10^{-3})^2}{4 \times 10^{-7}} = 10\text{m}$$

8. REAL LIFE CHALLENGES

(i) Diffraction at edges

Diffraction is not limited to situation in which light passes through a small opening like slits and pinholes but also sharp edges. the diffraction pattern lines are seen parallel to the edge, so the geometrical shadow as predicted by ray optics does not exist

(ii) Megaphones used for crowd management

Diffraction is a wave effect. It occurs with light and other types of waves.

https://cdn.pixabay.com/photo/2017/01/31/17/58/bullhorn-2026013_960_720.png

If on the sports fields instructions were given by a teacher to students in a school, no one will hear because the sound waves diffract when they pass through the narrow opening of the teachers mouth, speaking into a megaphone the flaring is reduced.

(iii) Human vision

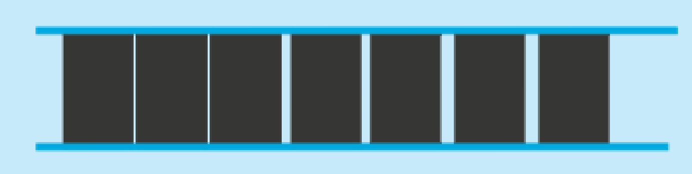
Applying Rayleigh's criterion for resolving power of the eye, we only approximate our vision. As brightness of the source and surrounding, turbulence of air between source and us, eye health will together influence our vision.

So if the angular separation between the source is greater than $\Delta\boldsymbol{\theta} = \frac{\mathbf{1.22}\boldsymbol{\lambda}}{\boldsymbol{D}}$

We can visually resolve the sources but, if the angular separation is lesser then we cannot.

TEST THE RESOLVING POWER OF YOUR EYE

You can estimate the resolving power of your eye with a simple experiment. Make black stripes of equal width separated by white stripes; see figure here.



All the black stripes should be of equal width, while the width of the intermediate white stripes should increase as you go from the left to the right.

For example, let all black stripes have a width of 5 mm.

Let the width of the first two white stripes be 0.5 mm each, the next two white stripes be 1 mm each, the next two 1.5 mm each, etc.

Paste this pattern on a wall in a room or laboratory, at the height of your eye. Now watch the pattern, preferably with one eye.

By moving away or closer to the wall, find the position where you can just see some two black stripes as separate stripes. All the black stripes to the left of this stripe would merge into one another and would not be distinguishable.

On the other hand, the black stripes to the right of this would be more and more clearly visible. Note **the width d of the white stripe which separates the two regions, and measure the distance D of the wall from your eye.**

Then d/D is the resolution of your eye.

You have watched specks of dust floating in air in a sunbeam entering through your window. Find the distance (of a speck) which you can clearly see and distinguish from neighboring specks.

Knowing the resolution of your eye and the distance of the speck, estimate the size of the speck of dust.

EXAMPLE

Two point white dots are 1mm apart on a black paper. They are viewed by eye of pupil diameter 3mm approximately. What is the minimum distance at which the eye will resolve these dots?

Take the wavelength of light = 500nm

Solution

Limit of resolution of the eye

$$d\theta = \frac{1.22\lambda}{D}$$

If the two sots are separated by a distance d can be resolved by the eye at a distance y then

$$d\theta = \frac{d}{y}$$

$$\frac{1.22\lambda}{D} = \frac{d}{y}$$

$$\mathrm{y} = \frac{\mathrm{Dd}}{1.22\lambda} = \frac{3 \times 10^{-3} \times 1 \times 10^{-3}}{1.22 \times 500 \times 10^{=9}} = 4.92\mathrm{m}$$

(i) Automobile headlamps and tail lamps

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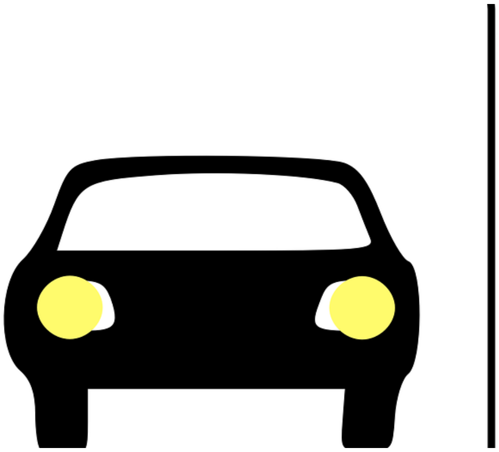

A cluster of LED bulbs is placed about 0.5 cm apart. Suitable polycarbonate lens- red for tail light, colorless head lamps are placed in front of the cluster. The LED bulbs are

- small,
- use very little energy and
- give out bright light
- have long life

The diffraction at the lens gives a continuous beam of light which does not hurt the eye. Do you think street lights; traffic lights use the same principle?

(ii) Astronomical telescope

- **The objective aperture has the ability to capture more light, the image of a distant object is bright**
- **Larger aperture of the objective increases the resolving power of the telescope**

(iii)Shadow patterns under a tree at night created by street lamps

Walk on the pavement at night when the street lights are on. Observe the pattern on the ground under trees due to diffraction of light through the leaves. The effect is amazing!!

View the pattern to enjoy the effect of diffraction

We must think of diffraction when ever there is a narrow slit or sharp edge through which light passes.

9. SUMMARY

You have learnt the following in the lesson

- **Diffraction of light is the phenomenon of bending of light around corners of small obstacles and aperetures.as a consequence light seems to travel beyond the realm of ray optics**
- **Diffraction at a single slit gives a pattern on a screen, when light is intercepted, the central maxima is larger than the size of the slit.**
- **A set of secondary maxima of diminishing intensity are formed on either side of the central maxima**
- **Diffraction by a single circular opening in the path of light gives a pattern with concentric circles**
- **The angular spread of the central maxima for diffraction of light at a circular aperture of diameter d is given by**

  $$\sin\theta = 1.22\frac{\lambda}{d} \quad \text{or } \theta = 1.22\frac{\lambda}{d}$$

- If D is the distance at which the effect is observed, or where a screen is placed to see the diffraction pattern then linear spread

  $X = D\sin\theta = D\theta$

- **Limit of resolution is the smallest linear or angular separation between two point objects at which they can be just resolved by an optical instrument**
- **Resolving power of an optical instrument is the ability of the instrument to resolve or separate the images of two close point objects so that they can be seen distinctly.**
- **Resolving power is reciprocal of the limit of resolution**
- **Rayleigh/s criterion for resolution the images of two point objects are just resolved when the central maximum of the diffraction pattern one falls over the first minima of the diffraction pattern of the other**
- **Resolving power of a microscope is defined as the reciprocal of the minimum distance ‘d’ (also called limit of resolution) between two point objects which can just be seen through the microscope as resolved.**

$$resolving\ power = \frac{1}{d} = \frac{2\,n\,sin\theta}{\lambda}$$

here n is the refractive index of the material between the object and the objective lens. θ is half the angle of cone of light from the point object

- **The resolving power of a telescope is defined as the reciprocal of the smallest separation between two distant objects, which are viewed resolved by the telescope**

$$resolving\ power = \frac{1}{limit\ of\ resolution\ \Delta\theta} = \frac{D}{1.22\lambda}$$

D is the diameter of the objective lens and λ is the wavelength of light used

- **Resolving power of human eye, the human eye can see two point objects distinctly if they subtend at the eye, as angle equal to 1minute of an arc. this angle is called limit of resolution of the eye. the reciprocal of this angle is equal to the resolving power of the eye.**

- **A number of examples from daily life show the effect of diffraction.**