Bachelor of Science

(B.SC- PCM)

Optics

(DBSPCO202T24)

Self-Learning Material

(SEM II)

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Course Code: DBSPCO202T24

Optics

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COURSE INTRODUCTION

Optics is an important branch of physics that is essential to many modern scientific and technological developments. This course provides a thorough explanation of light's characteristics, behaviour, and interactions with matter.

It includes fourteen units in the course. This course's Units 1 through 4 offer an in-depth explanation of the fundamental concepts and uses of interference of light. The course is designed to address not only the practical features and contemporary applications of these phenomena, but also their theoretical underpinnings.

Examine theories about light from ancient to the present, including the theories of Huygens' wave theory, Planck's quantum mechanics, Newton's corpuscular theory, Maxwell's electromagnetic theory, and the dual nature of light.

Furthermore, covered in the aforementioned sections will be the introduction of interference, Young's double slit experiment, the requirement for coherent sources of interference, different optical devices that measure light wavelengths, and the refractive index of different unknown materials.

The phenomenon of diffraction of light explained in units 5 through 7. Learners will also get a solid understanding of the fundamentals of diffraction, the capacity to evaluate diffraction patterns, and knowledge of the many uses of diffraction in the fields of science and technology. Those who possess this expertise will be well-prepared for postgraduate work in optics, physics, engineering, and related subjects.

The concept of polarization is discussed in the other unit that spans 8–10. The capacity to analyze and generate polarized light, as well as a thorough grasp of the polarization phenomena and its mathematical explanation, have all been covered in these sections. The final four units of the optics course, which cover units 11 through 14, discuss the numerous types of lasers, their practical applications in a variety of fields, and the basic principles regulating laser operation. As well as covers optical fibre, including its basic concepts, characteristics, and applications in science, technology.

You will have a strong foundation in these areas by the end of the course, providing you the capacity to apply the concepts in a range of scientific and technological contexts.

COURSE OUTCOMES

On satisfying the requirements of this course, students will have the knowledge and skills to:

1. Understand interaction of light with matter through interference, diffraction and polarization.
2. Measure the wave length and refractive index of liquids and glass using different optical instruments.
3. Understand the concept of diffraction grating and able to find the wavelength of spectral lines using plane diffraction grating.
4. Distinguish ordinary light with a laser light and to realize propagation of light through optical fibers.

5. Learn and explain the application of optical fiber in different area i.e. communication, defense, surgery, industries any many more.
6. Estimate the losses and analyze the propagation characteristics of an opticalsignal in different types of fibers.

ACKNOWLEDGEMENTS

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Unit-1

Interference of Light

1.1. Introduction

Geometrical optics is the study of light's characteristics, including reflection, refraction, dispersion, and so on, using the theory of rectilinear propagation—that is, light traveling in a straight line. This feature is also the foundation of optical instruments.

Physical optics studies the properties of light. Energy in the form of light is carried out from a source to the observer by material particles or wave wave disturbances that flow through a medium.

The ensuing theories of light were so put forth: This list includes: (i) Maxwell's electromagnetic theory of light (or radiation); (ii) Huygens' wave theory of light; (iv) Planck's theory of radiation

1.2. Light Theories

i. Newton's Theory (Corpuscular Theory)

Newton's corpuscular hypothesis states that light travels in the form of a stream of microscopic, undetectable particles known as corpuscles. They launch from the source and move quickly in all directions in a straight line. They cause the perception of vision when they come into contact with the eye. Newton ascribed various light colors to various particle sizes.

Success: Newton was able to explain the principles of reflection and the rectilinear propagation of light with this theory.

Consequences:

(1) This hypothesis states that light moves more quickly through denser media than through rarer media. This runs counter to the findings of the experiment.

(2) It is unable to account for polarization, diffraction, and interference. Thus, the theory was abandoned.

ii. Huygens' wave theory

According to Huygens' wave theory, every point in a light source emits waves that travel in all directions via an imaginary substance known as ether. In other words, light is a periodic disturbance that travels throughout space as mechanical longitudinal waves

moving at a constant speed due to ether. This hypothesis makes use of the Huygens' Principle-based wavefront notion.
Success: Rectangular propagation, reflection, refraction, interference, and diffraction could all be explained by this hypothesis.

Drawback:

(1) Because it assumes that light is transverse in nature, it is unable to explain polarization of light. Fresnel overcame this challenge by assuming that light propagation was transverse in nature. Fresnel altered the Huygens wave theory, although it still had a lot of flaws. It required the adoption of a fictitious

(2) An experimental proof of the existence of ether was not possible. The Michelson-Morley experiment was unable to prove ether's existence.

iii. Maxwell's theory

Maxwell Ian theory states that the light waves are space-propagating vector oscillations in the electric and magnetic fields. The direction that waves propagate and the vectors of the electric and magnetic fields are perpendicular to each other. An electromagnetic wave that moves transversely is called light.

Achievement:

(1) The characteristics of light, such as rectilinear propagation, reflection, refraction, interference, diffraction, and polarization, are explained by this theory.

(2) It also demonstrates how light can move across empty space.

(3) This theory combines optics, magnetism, and electricity.

(4) in free space as the expression for the velocity of light $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

where μo= 4π × 10-7Hm-1 = free space permeability

εo= 8.854 × 10−12 Fm-1 = free space permittivity

Shortcomings: Energy distribution in the black body radiation spectrum and the photoelectric effect are not explained by this theory.

iv. Planck's quantum theory

This theory contests the continuous nature of radiation emission and absorption provided by Maxwell's theory. However, it occurs in discrete energy packets known as photons, and each packet's quanta are the amounts of energy that are contained within. Every photon

has energy which is equal to h(Planck's constant = 6.625 x 10-34 Js) and its frequency.
Success: The black body radiation spectrum is explained by this idea. This idea was used by Einstein to explain the photoelectric effect. The Compton effect is also explained by this idea.
Cons: Due to the wave form of light, this theory is unable to explain features of light such as polarization, diffraction, and interference.

v. Dual nature of light

The idea that light travels in waves helps to explain the characteristics of light, including reflection, refraction, interference, diffraction, and polarization. If light only behaves like a particle, then its characteristics, such as the photoelectric effect and the processes of emission, absorption, and scattering, may be explained. Therefore, not every property of light can be explained by a single hypothesis. Thus, it can be concluded that light possesses both a particle and a wave character.

1.3. Huygens’ Wavefront

A point source of light put in an isotropic medium releases light waves in all directions, according to Huygens' hypothesis. These waves propagated at a speed of 3 × 108 □□−1, forming concentric circles. With the point source acting as the center, the disturbance will affect every particle on the surface of the sphere simultaneously.We refer to this kind of sphere as a wavefront. A wavefront is the location of every particle in the medium that is disturbed simultaneously and is in the same phase or vibrational state.
The form of the light source determines the wavefront's shape. 1. Spherical wavefront: This is caused by a light source that is point-like. 2. Cylindrical wavefront: This results from a light source that is linear. 3. Plane wavefront: A portion of the spherical or cylindrical wavefront might be regarded as a plane wavefront when a linear source's point source is positioned at a considerable distance.

1.4. Huygens’ Principle

Let S is the source of light sends out light waves in all directions from the center S. At any given time interval (t), every medium particle on a surface XY will vibrate in phase. The surface XY is a form a sphere of having radius vt. Here XY surface is the primary wavefront and v is the velocity of propagation of waves.

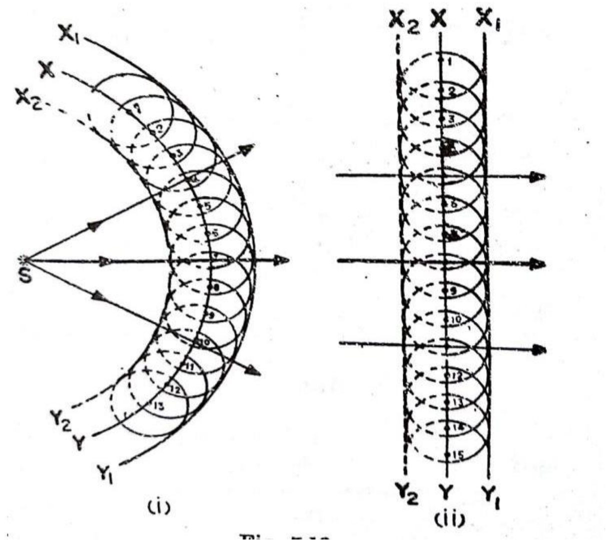


Figure 1.1

According to Huygens' principle, every point of the primary wavefront are secondary sources of waves. The original wave and the envelope of all the secondary waves are traveled at the same speed by the secondary waves originating from these sources. All these secondary wavelets after an interval of time gives rise to secondary wavefront. After time t the secondary waves travel with the points 1,2,3… having same distance or radius as original waves. As per Huygens'principle which is a backward wavefront will not be considered.

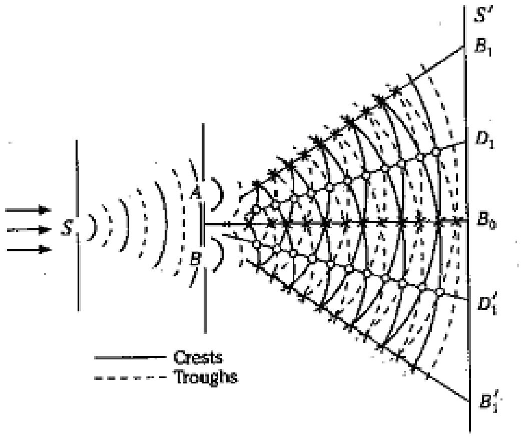
Light reflection and refraction can be explained by creating wavefronts, which is based on Huygens' wave theory and principle.

1.5. Interference of light

The validity of the wave theory of light has been demonstrated by the interference phenomenon. Thomas Young's work effectively shown how light can interfere.

1.6. Young's double slit experiment

A fine vertical slit S receives light from a monochromatic source. A thin beam of light is directed from S onto two equally distinct and parallel slits, A and B that are spaced slightly apart.



Two light sources are created by the two slits. Waves emanated from these two apertures in every direction. When these waves superpose, an interference pattern is created on a screen that is separated from the slits. Bright and dark bands alternate in the interference pattern. A brilliant band is created when two light waves that are coming in phase at one spot on the screen constructively interact with one another. This occurs when the crests of two waves overlap or when one wave's trough falls on top of another's trough. A dark band appears on the screen as a result of destructive interference caused by two light waves that arrive out of phase at that location. This occurs when the peak of one wave overlaps the trough of another, or vice versa. As a result, the following definition of the phenomena of interference

Interference is the change in the intensity of light energy caused by two or more light waves superimposing on one another.

The superposition principle provides the foundation for this occurrence. This concept states that the net effect at a place in a medium when two or more light waves pass through concurrently is the algebraic total of the effects caused by the individual waves. The displacement that results at any given time is the vector sum of the individual displacements generated by each wave.

Due to two separate sources of light, interference cannot be demonstrated. This is due to the possibility that the two sources' amplitudes, wavelengths, and phases could differ.

1.7. Coherent sources

It is necessary for the two light sources causing the interference to be coherent sources.

If the two light waves have a consistent phase difference or are in the same phase, the two light sources are considered coherent.

Additionally, the two sources' wavelengths, or frequencies, must match, and their amplitudes must be almost equal.

The two independent sources are incoherent in practice. However, the two virtual sources that were created from a single source can function as coherent sources for experimental purposes. These sources can be obtained in two ways.

1.8. Types of Interference

i. Division of wavefront

Two virtual sources which are originated from a single real source can function as coherent sources for experimental purposes. Coherence between an actual source and a virtual source can also be attained. In certain situations, a source's wavefront splits into two sections. For instance, the primary wavefront incident on the double slit in Young's double slit experiment is split into two sections. Another example is the Fresnel bi-prism, in which the wavefront also split and form two virtual sources.

ii. Division of amplitude

In this instance, the light source's wave amplitude is split into two sections, one of which is transmitted and the other of which is reflected. Interference is created by the superposition of these transmitted or reflected beams. When it comes to thin films, some of the incident light is refracted and partially reflected at the film's top surface. Refracted light exits the film parallel to the first reflected beam after reflecting once more at the bottom surface. These coherent tao rays cause interference when they superpose. Additional instances include colors in thin films, Michelson's interferometer, and Newton's rings.

Self-Assessment

Q.1. What is interference of light.

Q.2. Discuss the condition for sustained interference.

Q.3. Define coherent sources.

Q.4. Why two independent sources cannot produce interference?

Q.5. If Young’s double slit experiment pattern dipped in to the water, what change would you expect?

Q.6. Interference pattern not shown in which of the following phenomenon

a) Soap bubble

b) Excessively thin film

c) A thick film

d) Wedge Shaped film

Q.7. Interference is based on the ______________

a) Reflection phenomenon

b) scattering phenomenon

c) Quantum phenomenon

d) superposition phenomenon

Q.8. When Two waves of same amplitude interfere constructively, the intensity becomes ______________

a) Three times

b) zero

c) Four Times

d) One-third

Q.9. The interference produced fringes _____________

a) semicircular

b) Circular

c) parabolic

d) Elliptical

Q.10. If white light is used in place of monochromatic light in interference of light, we have

a) The pattern will not be visible

b) The shape of the pattern will change from hyperbolic to circular

c) Colored fringes will be observed with a white bright fringe at the center

d) The bright and dark fringes will change position

Unit-2

Interference by Division of Wave Front

2.1. Phase difference and path difference Expression

Consider the path difference between the two waves is λ, represented by letter x and the phase difference are equal to 2π represented by letter δ generally.

Then phase difference $\delta = \frac{2\pi}{\lambda} x$

$$Thus\ path\ difference = \frac{\lambda}{2\pi}\delta(Phase\ Difference)$$

2.2. Analytical treatment of interference

Think about two light waves flowing in the same direction through a medium with the same frequency and amplitude, "a." At any given time t, the displacement of any particle in the medium as a result of these waves is given by

$y1 = a \sin\omega t$ ....(1)

and $y2 = a \sin(\omega t+\delta)$ .....(2)

where ω is the angular frequency and δ is the phase difference between the two waves.

From the principle of superposition, the resultant displacement of the particle is, $y = y_1 + y_2 = a \sin\omega t + a \sin(\omega t + \delta) = a \sin\omega t + a(\sin\omega t \cos\delta + \cos\omega t \sin\delta)$

$= a \sin\omega t + a \sin\omega t \cos\delta + a \cos\omega t \sin\delta$

$= a \sin\omega t (1 + \cos\delta) + a \cos\omega t \sin\delta$

Let $a(1 + \cos\delta) = R\cos\theta$ ...... (3) and $a\sin\delta = R\sin\theta$......... (4)

Then, $y = R\sin\omega t\cos\theta + R\cos\omega t\sin\theta = R(\sin\omega t\cos\theta + \cos\omega t\sin\theta)$

or $y = R\sin(\omega t + \theta)$ ....(5)

Euation represents the resultant amplitude of the wave having phase difference of ‘θ’.

By Squaring and adding equations (3) and (4) we have,

$R^2 = a^2 + 2a^2\cos\delta + a^2\cos^2\delta + a^2\sin^2\delta$ Thus $R^2 = a^2 + a^2 + 2a^2\cos\delta$

or $R^2 = 2a^2 + 2a^2\cos\delta$ ...... (6)

$\boldsymbol{R^2 = 2a^2(1 + \cos\delta)}$ or $\boldsymbol{R^2 = 2a^2\, 2\cos^2\frac{\delta}{2}}$

or $\boldsymbol{R^2 = 4a^2\cos^2\frac{\delta}{2}}$

As the intensity of light is $I \propto R^2$, thus the resultant intensity of light due to superposition of waves is given by $\boldsymbol{I = 4a^2\cos^2\frac{\delta}{2}}$ .... (7)

2.3. Requirement for constructive interference and destructive interference

Constructive interference

When the superposition of two waves results in maximum net amplitude and hence maximum light intensity, the interference is referred to as constructive. Since I R2, I will be maximum in the region where resultant amplitude R is maximum.

The intensity is given by $I = 4a^2 \cos^2 \frac{\delta}{2}$

if the phase difference $\boldsymbol{\delta = 2m\pi}$, when m = 0, 1, 2, 3...., The intensity will be maximum

Thus, δ = 0, 2π, 4π .... that is even multiples of π.

$$\text{Path difference } x = \frac{\lambda}{2\pi} \times \delta = \frac{\lambda}{2\pi} \times 2m\pi$$

Destructive interference

When the superposition of two waves results in minimal net amplitude and a corresponding minimum light intensity, the interference is considered destructive. I will be at its minimum at the locations in the interference region where R is at its minimum because I ∝ R^2.

Thus, **path difference is given by**

$$\boldsymbol{x = (2m + 1)\frac{\lambda}{2}}$$

for destructive interference the path difference should be the odd integral multiples of λ/2. The minimum value of intensity is given by $\boldsymbol{I_{min} = 0}$.

If the phase difference is $\boldsymbol{\delta} = (\boldsymbol{2m + 1})\ \boldsymbol{\pi}$, where m = 0, 1, 2, 3.... The intensity will be minimum.

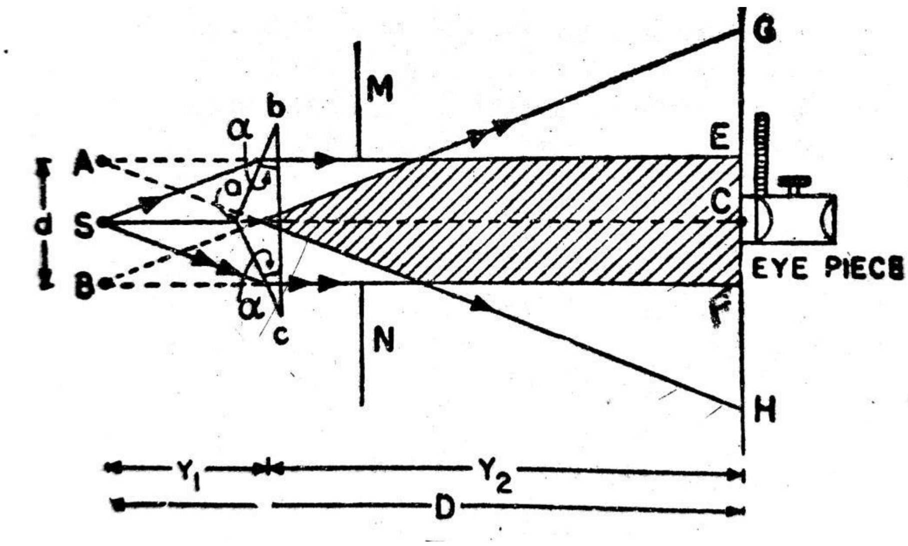
Thus, phase difference is the odd multiple of π.

Path difference x is given by

$$x = \frac{\lambda}{2\pi} \times \delta = \frac{\lambda}{2\pi}(2m+1)\pi$$

2.4. Fresnel's Biprism

Fresnel illustrated the interference phenomenon with a biprim. Two acutely angled prisms positioned base to base make up the biprism ABC.



It is built as a single prism with an oblique angle of around 1790. The other two angles are sharp, measuring thirty feet apiece. On a slit S, light from a monochromatic source is incident. The diagram illustrates how light from S strikes the biprism. The light that strikes the lower ac portion of the prism appears to be coming from point B because it is bent upward.

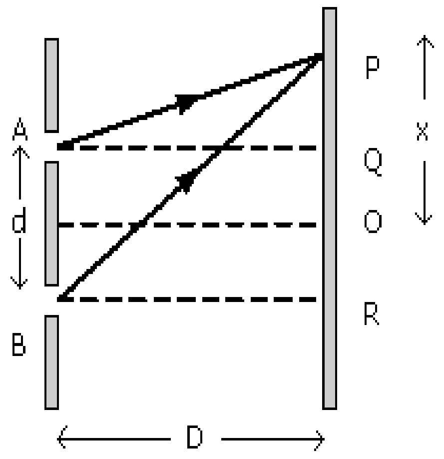
In a similar manner, light falling on the upper ab portion of the prism appears to originate from point A since it is bent downward. As a result, A and B function as virtual yet coherent sources. Let d be the distance in virtual terms between the sources. Interference fringes arise between E and F if a screen is positioned at C. When an eyepiece is positioned where the screen is, the field of view displays both bright and dark fringes.

In order to create coherent sources, biprism is employed to split the incident wavefront into two sections. Fringes are created by the interference of light from these coherent sources.

Theory

Fringe width expression:

When light from a monochromatic source S is incident, it splits into two distinct components i.e. producing two coherent sources A and B, separated by a small distance, d. The screen is placed at a large distance D from the sources. In the diagram AO = BO because O is the central point on the screen.



Thus, at O the central bright fringe is seen due to the path difference between the light waves is zero. Let an observation point P on the screen at a distance of x from O. Therefore, path difference at point P is given by

Path difference =BP – AP From From ΔBRP, $(BP)^2 = (BR)^2 + (RP)^2$

Thus $(BP)^2 = D^2 + \left(x + \frac{d}{2}\right)^2$ (i)

ΔAQP, $(AP)^2 = (AQ)^2 + (QP)^2$

$(AP)^2 = D^2 + \left(x - \frac{d}{2}\right)^2$ (ii)

$$(BP)^2 - (AP)^2 = \left[D^2 + \left(x + \frac{d}{2}\right)^2\right] - \left[D^2 + \left(x - \frac{d}{2}\right)^2\right]$$

$$(BP)^2 - (AP)^2 = \left(x + \frac{d}{2}\right)^2 - \left(x - \frac{d}{2}\right)^2$$

$$[(BP) - (AP)]\,[(BP) + (AP)] = 2xd$$

As d << D, BP=AP =D thus BP+AP = 2D

From the equation 2D (BP-AP) =2xd

Or BP - AP = $\frac{xd}{D}$

Thus $\frac{xd}{D} = m\lambda$

$x = \frac{m\lambda d}{d}$

To get a bright fringe at point P, the path difference = mλ

Thus $\frac{xd}{D} = m\lambda$ or $x = \frac{m\lambda D}{d}$

The distance of the mth bright fringe from the center O fringe is $x_m = \frac{m\lambda D}{d}$ (iii)

The distance of the (m-1)th bright fringe from the center O is $x_{m-1} = \frac{(m-1)\lambda D}{d}$ (iv)

The distance between two constructive bright fringes is $x_m - x_{m-1} = \frac{\lambda D}{d}$

The get a dark fringe at point P, the path difference = $(2m+1)\frac{\lambda}{2}$

Thus $\frac{xd}{D} = (2m+1)\frac{\lambda}{2}$ or $x = (2m+1)\frac{\lambda D}{2d}$

The distance of the mth dark fringe from the center O is $x_m = (2m+1)\frac{\lambda D}{2d}$

The distance of the (m-1)th dark fringe from the center O is $x_{m-1} = \frac{(2(m-1)+1)\lambda D}{2d}$

The distance between two consecutive dark fringes is $x_m - x_{m-1} = \frac{\lambda D}{d}$

Thus the distance between any two consecutive bright or dark fringes called **fringes width** is $\beta = \frac{\lambda D}{d}$

Features of the interference pattern obtained

(1) The widths of all the fringes are the same.

(2) The fringe widths depend on

- distance between the coherent sources (d)
- wavelength of the monochromatic light source used
- distance between the coherent sources and the screen (D)

(3) The fringe width will be increased by

- reducing the separation between the coherent sources,
- increasing the distance between the screen and sources
- increasing the wavelength of light

(4) The core bright band is white with colorful bands on each side of it if white light is used as the source.

2.5. Conditions for sustained interference pattern

1. The two light sources that are employed have to be monochromatic, meaning they should have the same frequency or wavelength.
2. The two superposing waves' amplitudes ought to be equal, or almost equivalent. The two waves have to be moving at the same speed and in the same direction.
3. There must be a consistent phase difference or two superposing waves that are in phase for the two sources causing the interference to be coherent.
4. The two light sources ought to be as close together as feasible.

5. The slits that serve as coherent sources have to be extremely small.
6. If there is polarization between the two interfering waves, then their planes of polarization must coincide.

Self-Assessment

Q.1. What is the principle a Fresnel biprism.

Q.2. Compare and contrast the interference patterns produced by a Fresnel biprism and a Young's double-slit experiment.

Q.3. State two methods of producing coherent sources of light?

Q.4. Explain why monochromatic light is preferred in Young's double-slit experiment.

Q.5. How does increasing the slit separation affect the interference pattern in Young's double-slit experiment?

Q.6. The Fresnel biprism experiment demonstrates which phenomenon?

i. Interference
ii. Diffraction
iii. Polarization
iv. Dispersion

Q.7. In the Fresnel biprism experiment, interference fringes are produced due to:

i. Refraction
ii. Diffraction
iii. Reflection
iv. Superposition of light waves

Q.8. What is the primary function of the Fresnel biprism in the setup?

i. To split the light beam into two coherent beams
ii. To create diffraction patterns
iii. To polarize the light
iv. To disperse light into its spectrum

Q.9. Which type of interference pattern is observed in the Fresnel biprism experiment?

i. Circular fringes
ii. Straight fringes
iii. Hyperbolic fringes
iv. Rectangular fringes

Q.10. The fringe visibility in the Fresnel biprism experiment depends on:

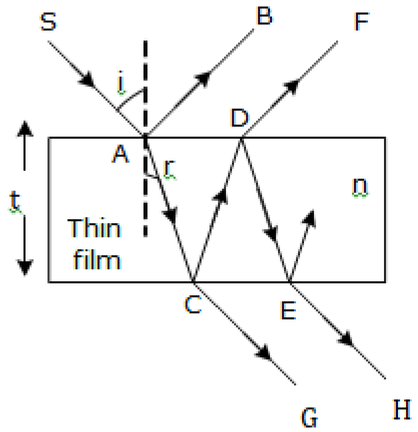
i. The coherence length of the light source
ii. The intensity of the light source
iii. The wavelength of light used
iv. All of the above

Unit-3

Interference by Division of Amplitude

3.1. Interference at thin films

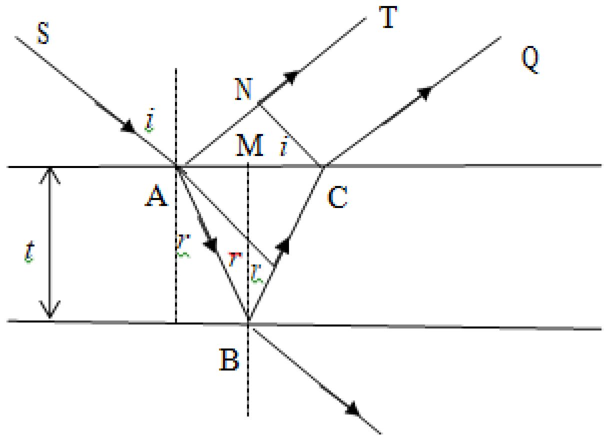
A thin film is an extremely thin layer of a transparent refracting substance. Examples of thin-film interference include the colors created by a soap bubble's thin layer and an oily layer on the surface of water.



Young was able to explain the phenomenon by pointing to the interference that occurs between light that is reflected from a thin film's top and bottom surfaces. It has been noted that both transmitted and reflected light cause interference in thin films. This is therefore predicated on the amplitude division.

3.2. Interference due to reflected light by a thin film

Think about a transparent film with a refractive index of n and a thickness of t. On the film's upper surface, a ray SA incident is partially refracted along AB and partially reflected along AT. It is somewhat reflected along BC at B and eventually comes out along CQ. The path difference between the two reflected rays, AT and CQ, must be determined. To AT, a normal CN is drawn, and to BC, a normal AM. Let r be the angle of refraction and *i* be the angle of incidence.



The reflected ray (AT) is a reflected ray from a denser medium to rarer medium. When light is reflected from the surface of a denser medium, we obtain a phase change of π or a path difference of $\lambda/2$.

Because of internal reflection and refraction in the film, the beam CQ has traveled a greater distance than it did along AT. However, this is not a phase transition. The path difference in the diagram is equal to the path traveled in the movie ABC minus the path traveled in the air AN.

The optical path difference is $x = n(AB + BC) - AN$ (i)

From the tringle ANC, $AN = AC \sin i$

Also from the diagram AC=AM+MC thus $AN = (AM + MC)\sin i$

Or $AN = (t \tan r + t \tan r)\sin i$

Since from the triangle, AMB and BMC, $AM = t \tan r$ *and* $MC = t \tan r$

$$AN = 2t \tan r \times \sin i = 2t \frac{\sin r}{\cos r} \times \sin i$$

(ii)

from the snell's law $= \dfrac{\sin i}{\sin r}$, thus $\sin i = n \sin r$

Equation (ii) now can be written as $AN = 2t \dfrac{\sin r}{\cos r} \times \sin i = 2t \dfrac{\sin r}{\cos r} \times n \sin r = 2nt \dfrac{\sin^2 r}{\cos r}$

Thus $AN = 2nt \dfrac{\sin^2 r}{\cos r}$

(iii)

Also from the triangle ABM, $AB = \dfrac{t}{\cos r}$ (iv) and from the triangle BMC, $BC = \frac{t}{\cos r}$ (v)

substituting for respective trems from (iii), (iv) and (v) in equation (i), we get

$$x = n(AB + BC) - AN = 2nt \frac{\sin^2 r}{\cos r}$$

Thus path difference $x = 2nt \frac{(1 - \sin^2 r)}{\cos r} = 2nt \frac{Cos^2 r}{\cos r} = 2nt Cosr$

The total path difference $x = 2nt Cosr - \frac{\lambda}{2}$

(vi)

Condition for Maxima and minima

1. If path difference $x = m\lambda$, where m = 0, 1, 2, 3,……. constructive interference occurs takes place and the film appears bright. Thus

$$m\lambda = 2ntCosr - \frac{\lambda}{2}$$

or $2ntCosr = (2m+1)\frac{\lambda}{2}$ (vii)

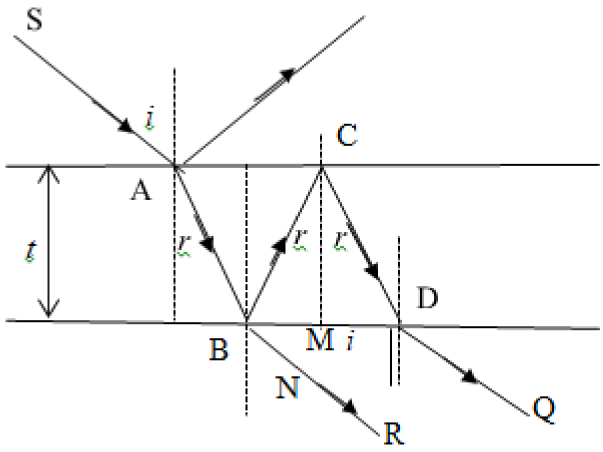
2. If path difference is $= (2m+1)\frac{\lambda}{2}$, where m=0,1,2,3,4,5,…………, destructive interference takes place and the film appears dark, Therefore $(2m+1)\frac{\lambda}{2} = 2ntCosr - \frac{\lambda}{2}$

$2ntCosr = (m+1))\lambda$. Here m is a integer only. Thus (m+1) is also an integer and can be taken as k. Thus

$2ntCosr = k\lambda$ (viii)

Where k=0,1,2,3…………….

Interference due to transmitted light



Consider a thin film of thickness (t) and refractive index of (n). let an incident ray SA incident with an angle of incident i on the surface of the film which is refracted along AB. At lower surface from B the ray is again partially refracted along BC and refracted along BR. Again At C, the ray gets reflected along C D and refracted along DQ. To calculate the The path difference between the two transmitted rays BR and DQ.

A normal DN is drawn to BR. Consider that the incident angle is i refracted angle is r.
A refracted ray from a denser medium is the one that is transmitted along BR. Therefore, there is no additional path difference when light is refracted from the denser to the rarer medium. The refraction and reflection within the film has caused the beam DQ to travel a longer journey than that along BR. However, this is not a phase transition.
Thus, the path difference = path traversed in the film BCD – path traversed in air BN.

The optical path difference is $x = (BC + CD) - BN$ (i)

From the Δ BND, BN $=$ BD sin i and from the diagram $BD = BM + MD$

Thus B$N = (BM + MD) \sin i$ or $BN = (t\tan r + t\tan r) \sin i$

$$BN = 2t \tan r \times \sin i = 2t \frac{\sin r}{\cos r} \times \sin i$$

(ii)

$$\text{from snell's law} = \frac{\sin i}{\sin r}, \text{thus } \sin i = n \sin r$$

Equation (ii) now can be written as $\text{BN} = 2\text{t} \dfrac{\sin r}{\cos r} \times n \sin r = 2nt \dfrac{\sin^2 r}{\cos r}$

$$BN = 2nt\frac{\sin^2 r}{\cos r} \quad \text{(iii)}$$

Also from B the triangle BMC, $BC = \frac{t}{\cos r}$

(iv)

nd from triangle MCD, $CD = \frac{t}{\cos r}$

(v)

substituting for respective terms from (iii), (iv) and (v) in (i), we get

$$x = n(BC + CD) - BN = 2nt\frac{\sin^2 r}{\cos r}$$

Thus, path difference $x = 2nt(1 - \sin^2 r) = \frac{2nt}{\cos r}\cos^2 r$

Thus $x = 2nt\cos r$

The total path difference

$x = 2nt\cos r$

(vi)

Condition for Maxima and minima

Thus $x = 2nt\cos r$

The path difference is $\boldsymbol{x = 2\, nt \cos r}$

(1) If the path difference $x = m\lambda$, where m = 0, 1, 2, 3, ……, constructive interference takes place and the film appears bright

Thus $\boldsymbol{2\, nt \cos r = m\lambda}$ where m = 0, 1, 2, 3,……

(2) If the path difference is = $(2m + 1)\, \lambda\, 2$, where m = 0, 1, 2, 3, ……., destructive interference takes place and the film appears dark. Therefore $(2m + 1)\, \lambda\, 2 = 2\, nt \cos r$ or $\boldsymbol{2\, nt \cos r = (2m + 1)\, \lambda\, 2}$ where m = 0, 1, 2, 3, ……

3.3. Colors of thin films

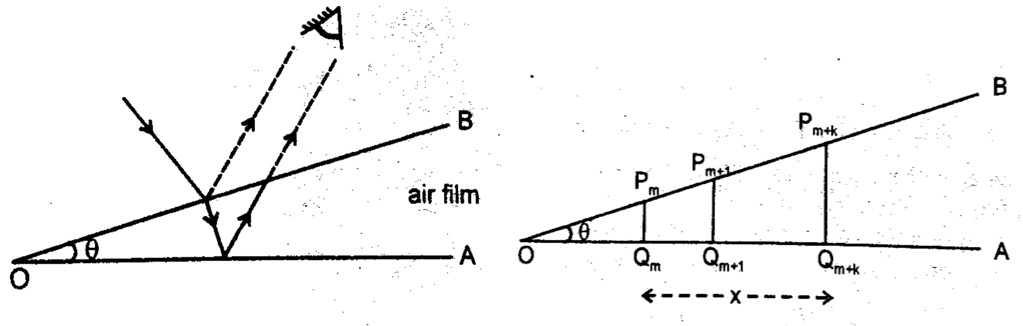
A thin film irradiated by white light will exhibit interference-colored reflections because of the hue of the film. The only colors that meet the requirements for constructive interference are those that are visible in the reflected light.

The film's thickness and incidence angle determine the color. Furthermore, various colors can be seen from different angles due to the dependence of path difference on angle of refraction and, angle of incidence.

Additionally, colors are seen in the transmitted beam. On the other hand, the transmitted system will lack the colors shown in the reflected system, and vice versa.

The examples of interference at thin films are soap bubble and an oil film over the water surface.

3.4. Wedge shaped films



Examine the two transparent, optically flat glass plates OA and OB, which are angled at θ in the diagram. A wedge-shaped air film is enclosed by such an arrangement.

From O to A, the air film becomes thicker. An interference fringe with equal parts of bright and dark regions is seen when such an air film is examined with monochromatic light that has been reflected, and it is parallel to the line where the two surfaces intersect. Superposition of light waves reflected from the air film based on the division of amplitude. Assume at P_m point m^{th} bright fringe occurs. The thickness of the air film at Pm is equal to $t = P_mQ_m$. As the angle of incidence is small, cos r = 1.

The condition for a bright fringe in case of a thin filem is, $2ntcos\, r = (2m+1)\frac{\lambda}{2}$

In our case thin film is a air medium , the refractive indies n=1 and as cos r =1, then the above equation can be written as $2t = (2m+1)\frac{\lambda}{2}$ or $2P_mQ_m = (2m+1)\frac{\lambda}{2}$

(i)

The next bright fringe (m+1) will occur at $p_{m+1,}$ such that

$2P_{m+1}Q_{m+1} = (2(m+1)+1)\frac{\lambda}{2}$

or $2P_{m+1}Q_{m+1} = (2m+3)\frac{\lambda}{2}$ (ii)

Subtracting (i) from (ii)

$$2P_{m+1}Q_{m+1} - 2P_mQ_m = \frac{\lambda}{2} \qquad \text{(iii)}$$

Next bright fringe will occur at the point when the thickness of the air film increases by $\frac{\lambda}{2}$, subppose the (m+k)th bright fringe is at p_{m+k}. Then there will be k bright fringes between pm and p_{m+k} Such that $P_{m+k}Q_{m+k} - P_mQ_m = k\frac{\lambda}{2}$ (iv)

If the distance $Q_{m+k}Q_m = x$

$$\theta = \frac{P_{m+k}Q_{m+k} - P_mQ_m}{Q_{m+k}Q_m} = \frac{k\frac{\lambda}{2}}{x} = \frac{k\lambda}{2x} \qquad \text{(v)}$$

$$\text{Or } x = \frac{k\lambda}{2\theta} \qquad \text{(vi)}$$

Here x is the distance corresponding to k fringes.

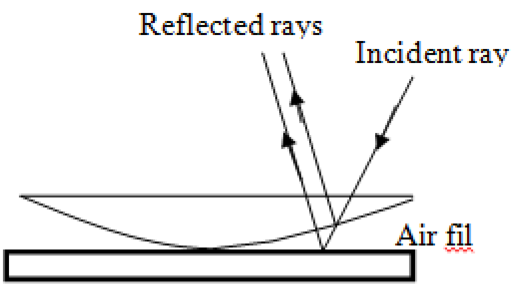
Thus the fringes width $\beta = \frac{x}{k} = \frac{\lambda}{2\theta}$

(vii)

If the thin wire of thichness (d) is places between the plates OA and OB to form a wedge shaped air film and l is the length of the air film, then $\theta = \frac{d}{l}$, thus the above equation is $\frac{d}{l} = \frac{\lambda}{2\beta}$ or $d = \frac{\lambda l}{2\beta}$

3.5. Newton's rings

A thin film of increasing thickness of air is created on a glass plate when a large focal length plano convex lens with a convex surface is placed on it.

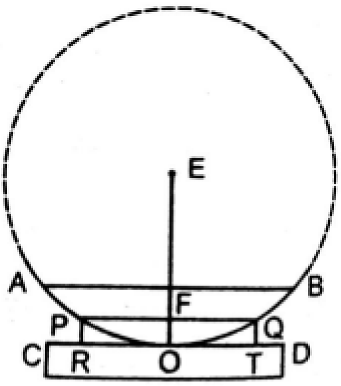


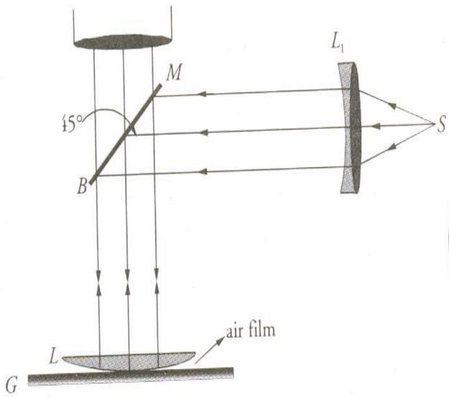
Bright and dark rings resembling circles form the interference fringes. This creation results from the superposition of transmitted or reflected waves from the air film due to an amplitude division. The fringes take on color in the presence of white light.

3.6. Newton's rings due to Reflected light

Let a plano-convex of lens of radius of curvature (R) and thickness of the air film is (t).

Interference is due to reflected light. Therefore for the bright ring.





On a flat glass plate, a thin layer of air with increasing thickness forms when a large focal length plano convex lens with a convex surface is added. Circular bright and dark rings are the interference fringes that form. This phenomenon results from the superposition of transmitted or reflected waves from the air film due to amplitude division. The fringes seem colored when exposed to white light.

Let t be the air film thickness at a distance of OT = r from the point of contact O in a plano convex with radius of curvature R. Here, reflected light is the reason of the interference.

Therefore, for the bright ring

$2ntcos\ r = (2m+1)\frac{\lambda}{2}$ where m = 0,1,2,3,……… (i)

As θ is small cos r =1 and for air n =1

Thus $2t = (2m+1)\frac{\lambda}{2}$ (ii)

For the dark fringes $2t = m\lambda$ (iii)

In the diagram, PF x FQ = OF x(2R-OF) (iv)

From Sagitta's Theorem

But from PF = FQ = r and OF =TQ = t and 2R-t = 2R (approximately)

The equation (iv) becomes $r^2 = 2Rt\ or\ t = \frac{r^2}{2R}$

Substituting the values of t in equation (ii) and (iii) we have

For the bright $2\frac{r^2}{2R} = (2m+1)\frac{\lambda}{2}$ or $r^2 = (2m+1)\frac{\lambda R}{2}$

$r = \sqrt{(2m+1)\frac{\lambda R}{2}}$ (v)

For the dark ring $2t = m\lambda$ or $2\frac{r^2}{2R} = m\lambda$ or $r = \sqrt{m\lambda R}$ (vi)

When m = 0, radius of the rings is zero. and the radius of the bright ring is $r = \sqrt{\frac{\lambda R}{2}}$. So that central is dark and alternatively dark and bright rings are formed.

Result: the radius of th dark ring is proportional to $\sqrt{m}, \sqrt{\lambda}$ *and* $\sqrt{R}$. Also the radius of the bright ring is proportional to $\sqrt{2m+1}, \sqrt{\lambda}$ *and* $\sqrt{R}$.

The diameter of a dark ring is D = 2r = $2\sqrt{m\lambda R}$. Thus, the diameter of central dark ring is zero. The diameter of the first dark ring is $D_1 = 2\sqrt{\lambda R}$. similarly for the second, third etc… are $D_1 = 2\sqrt{2\lambda R}$ and $D_1 = 2\sqrt{3\lambda R}$

The difference in diameter of 16th and 9th ring is $D_{16} - D_9 = 2\sqrt{16\lambda R} - 2\sqrt{9\lambda R} = 2\sqrt{\lambda R}$

Similarly $D_4 - D_1 = 2\sqrt{\lambda R}$.

As a result, the fringe width reduces with rising fringe order, and the fringes get closer as order increases.

In general, $D_m^2 - D_n^2 = 4(m-n)\lambda R$. The radius of curvature of the convex lens can be calculate using the relation $\frac{D_m^2 - D_n^2}{4(m-n)\lambda} = R$

The Newton's rings aperture consists of a Plano convex lens of large radius of curvature (L) placed on an optically flat glass plate (G), So that the convex surface is in contact with the glass plate as shown. Light from the source S is incident on a glass plate (B0 inclined at 45^o with the direction of incident rays.

The wavelength can be determine as $\frac{D_m^2 - D_n^2}{4(m-n)R} = \lambda\backslash$

3.7. Application of Newton's Rings

a. Refractive index of water using Newton's ring

The experiment is performed when there is air between the Plano convex lens and the glass plate. The lens arrangement is placed in a metal container C as shown. The diameters of the mth and (m + k)th dark rings are measured with the help of the travelling microscope.

For air the diameter of the mth dark ring $D_m^2 = 4m\lambda R$. and for (m+k)th dark ring

$D_{m+1}^2 = 4(m+1)\lambda R$

Thus $D_{m+k}^2 - D_m^2 = 4(m+k))\lambda R - 4m\lambda R$

$$D_{m+k}^2 - D_m^2 = 4k\lambda R \qquad \text{(i)}\backslash$$

Let the experimental liquid, whose refractive index is to be measured is poured in to the container without worrying the arrangement. Now the liquid replaces the lower surface of the lens and upper surface of the glass plate. The diameter of the mth and (m+k)th rings are determine using the traveling microscope. The condition for the dark ring in the presence of liquid of refrective index n is $2ntcos\, r = m\lambda \text{ or } 2nt = m\lambda$

But $t = \frac{r^2}{2R}$ $Thus\ 2n\frac{r^2}{2R} = m\lambda \text{ or } r^2 = \frac{mR\lambda}{n}$

$$r = \frac{D}{2}\ Thus\ D^2 = \frac{4m\lambda R}{n}$$

If D_m' and D_{m+k}'

Ar ethe diameter of the mth and (m+k)th dark fring in the presence of liquid, then

For liquid the diameter o the mth dark ring $D'^2_m = \frac{4m\lambda R}{n}$

And for the (m+k)th dark ring $D'^2_{m+k} = \frac{4(m+k)\lambda R}{n}$

$$D'^2_{m+k} - D'^2_m = \frac{4(m+k)\lambda R}{n} - = \frac{4m\lambda R}{n}$$

$$D'^2_{m+k} - D'^2_m = \frac{4k\lambda R}{n}$$

The refractive index of the liquid is calculated as $n = \frac{4k\lambda R}{D'^2_{m+k} - D'^2_m}$ (ii)

Also n can be determine bt dividing (ii) by (i), i.e. $n = \frac{D^2_{m+k} - D^2_m}{D'^2_{m+k} - D'^2_m}$

Self-Assessment

Q.1. Why an extended source is necessary to observe colors in thin film

Q.2. Explain why an excessively thick film shows no colour in reflected light.

Q.3. Why Newton's rings are circular.

Q.4. What is the phenomenon observed in Newton's rings experiment?

- a) Diffraction
- b) Interference
- c) Polarization
- d) Reflection

Q.5. Which of the following is crucial for the formation of Newton's rings?

- a) Monochromatic light
- b) White light
- c) Incoherent light

- d) Laser light

Q.6. In Newton's rings, the bright and dark rings are due to:

- a) Diffraction
- b) Reflection
- c) Interference
- d) Refraction

Q.7. The center of the Newton's rings pattern corresponds to:

- a) Minimum thickness of air film
- b) Maximum thickness of air film
- c) Zero thickness of air film
- d) Variable thickness of air film

Q.8. Which of the following factors affects the diameter of Newton's rings?

- a) Wavelength of light
- b) Temperature of the air film
- c) Pressure of the surrounding medium
- d) All of the above

Unit-4
Interferometer

4.1. Michelson Interferometer

Interferometers that operate on the interference principle. These fundamental optical instruments are used to measure an optical beam's wavelength, distance, index of refraction, temporal coherence, etc. exactly. Michelson, the first American scientist to win the Nobel Prize in the year 1907 for his work in optics, created amplitude-splitting interferometers in 1890. This interferometer was part of the famous set of experiments by Michelson and Morley that proved the existence of the ether. It remains a crucial tool in modern laboratories, where it is frequently employed to measure minuscule distances, examine optical medium, and determine the wavelength of an unknown light source.

Construction:

The Michelson interferometer's construction is depicted in the figure below. It is made up of the M1 and M2 mirrors, which are highly polished. Between the mirrors, two glass plates, a compensating glass plate (CP) and a beam splitter (BS), are positioned parallel to one another at a 450-degree angle. Glass plate BS is a semi-silvered plate that allows light from a source to be evenly reflected and transmitted through it. Division of amplitude occurs in this manner. Allow a monochromatic light of wavelength λ to fall on BS from a wide source. When light strikes BS, half of it is transferred toward mirror M2 and half is reflected towards mirror M1. Thus, BS is referred to as a beam splitter.

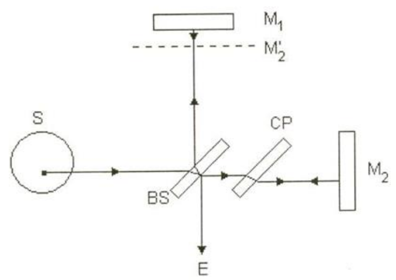


Figure-Construction of Michelson's Interferometer Optical Path

When dealing with non-monochromatic sources, place the glass plate CP between BS and M2. The paragraph that follows provides more details on the function of CP. Following their splitting, the two rays return to the plate BS after being reflected back by the mirrors M1 and M2. Both the ray reflected from M1 and the ray reflected from M2 are transmitted through BS and reflected back by BS. When the two rays from the two mirrors clash, fringes can be seen at E on a screen when using a laser or with the naked eye when using a light. In order to monitor the change in fringes, one of the mirrors is often positioned on a translation stage and moved back and forth.

The identical source that first caused an incident on plate BS is the source of the rays that fall on mirrors M1 and M2 (see Figure below). The wave enters the eye through M1's reflection and passes twice through BS. In the absence of a compensating plate CP, the route taken by the other wave that falls on the mirror M2 is entirely airborne. Thus, an additional optical route $2(\mu -1)$ t is introduced, where μ is the refractive index of the BS plate for the monochromatic light employed, and 't' is the plate thickness. If monochromatic light is used to make fringes, then the presence of CP is not necessary. But when white light is employed, it causes a significant issue. For all wavelengths, it becomes required to account for the additional optical path $2(\mu -1)$ t. This is accomplished by adding a another glass plate, CP, parallel to BS that has the same thickness and refractive index. The two waves will therefore interfere either constructively or destructively depending on the path difference parameters listed below, Δ:

$$\Delta = 2n\lambda/2 = n\lambda \qquad \text{(for maxima, n is an integer)}$$

$$\Delta = (2n+1)\lambda/2 \qquad \text{(for minima, n is an integer)}$$

4.2. Types of fringes

By shifting M1, the path difference between the two beams can be changed. Two surfaces of an air film are represented by mirror M1 and its virtual counterpart, mirror M2. Depending on the type of air film, the Michelson interferometer's fringes can be straight, curved, or round.

4.3. Concentric circular fringes, or fringes with an equal inclination

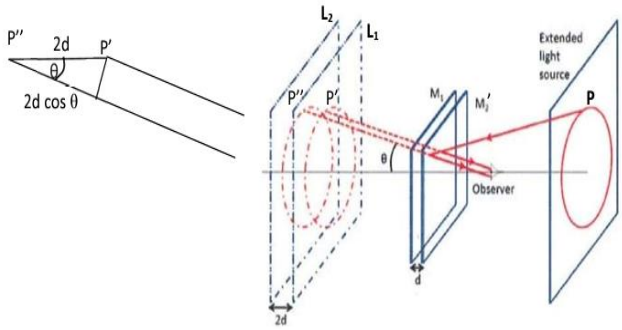
As seen in Figure below, concentrated circular fringes are produced if the air film is parallel. Parallel to M1, M2' is the virtual image of M2. Light source L is located at the observer's position for simplicity's sake. The coherent virtual pictures of L that are created by M1 and

M2' are L1 and L2. Given d as the separation between M1 and M2', 2d is the separation between L1 and L2. Let θ be the angle formed by the reflected beams from M1 and M2' and the incident beam that started at P.

Hence, 2d cosθ represents the path difference among the light beams coming from positions P' and P". When $2d\cos\theta = n\lambda$, a maximum (bright fringe) will form. When n, d, and θ are fixed, the contour of the maximum point takes on the shape of a ring, and θ is a constant value. The ring's center is perpendicular to the mirror plane and aligned with the observer. Every circular ring has a specific value of θ associated with it. As a result, the fringes are referred to as equal-inclination fringes.

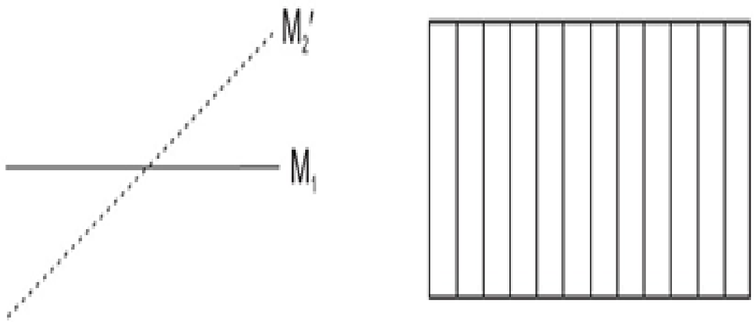
4.4. Curved fringes (fringes of equal thickness)

The enclosed film has a wedge form when M1 and the virtual image M2' are angled toward one another. Then, as seen in Figure, curved fringes are seen. Another name for this is equal-thickness fringes.



4.5. Straight line fringes

Straight line fringes are produced surrounding the junction point of M1 and virtual image M2' (see picture). Since there is no path difference along the line of intersection, all wavelengths have the same path difference.



A central achromatic brilliant fringe results from the usage of a white light source. A few colored straight fringes are seen on either side of the central fringe.

4.6. Application of Michelson's Interferometer

a. Determination of λ by circular fringes

One can ascertain the wavelength of the light source by observing circular fringes. The path difference is given as $2d = n\lambda$ for a certain separation 'd' between the mirrors M1 and M2 and normal incidence ($\theta=0$). If N rings appear or disappear at the center when one mirror is moved a distance Δd, then the route difference after moving the mirror is given as

$$2(d + \Delta d) = (n+N)\lambda$$

$$\boldsymbol{\lambda = 2(\Delta d)/N}$$

Self-Assessment

Q.1. How the interference fringes are produced in a Michelson interferometer.

Q.2. What factors determine the visibility of fringes in a Michelson interferometer?

Q.3. Draw a labeled diagram of a Michelson interferometer and explain the function of each component.

Q.4. What is the significance of coherence length in Michelson interferometry?

Q.5. What is the role of compensatory plate in Michelson interferometer

Q.6. What is the primary function of a Michelson interferometer?

a) Measure the speed of light
b) Determine the refractive index of a material
c) Measure small distances with high precision
d) Study interference patterns in thin films

Q.7. In a Michelson interferometer, what happens when the path difference between the two arms is equal to the wavelength of the light used?

a) Constructive interference
b) Destructive interference
c) No interference pattern observed
d) Interference pattern shifts randomly

Q.8. Which component in a Michelson interferometer is responsible for splitting the incident beam into two perpendicular paths?

a) Beam splitter
b) Mirrors
c) Detector
d) Collimator

Q.9. What is the purpose of using a compensating plate in a Michelson interferometer?

a) To increase the coherence length
b) To compensate for the dispersion in the interferometer
c) To adjust the path difference
d) To improve the visibility of interference fringes

Q.10. What happens to the interference fringes in a Michelson interferometer if the mirrors are not perfectly aligned?

a) A) Fringe visibility increases
b) B) Fringe visibility decreases
c) C) No effect on fringe visibility
d) D) Fringes disappear completely

Unit-5:
Diffraction of Light

5.1 Introduction

Bending of light at the corner of an obstacle or an aperture in the path of light and spreading in to geometrical shadow of an obstacle as shown is known as diffraction of light. The diffraction condition states that the obstacle's size must be comparable to the wavelength of the light being utilized. The diffraction is more appreciable when slit width is, $e=1.2\lambda$ i.e. comparable to the wavelength of light wave.

It is based on the Huygens's theory of light that each point of the wave front behaves as individual wavelets.

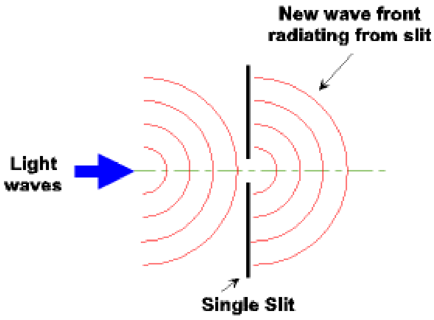


Fig. (5.1) Diffraction of light

5.2 Difference between interference and Diffraction

Interference	Diffraction
1: The phenomenon of interference occurs when light waves from two distinct sources or from different parts of the same source overlap.	1: Diffraction is due to the superposition of wave coming from different parts of the same wavefront.
2: Fringes forms may or may not be of same width.	2: Fringes are never of the same width.
3: Intensity of all bright fringes are same	3: Intensity of all bright fringes are not same as maximum light concentrated at central maxima.
4: Dark fringes are perfectly dark, so	4: Minimum intensity fringes are not perfectly

there is a contrast between maxima and minima.	dark, so the contrast between maxima and minima is very poor.
5: The spacing between consecutive fringes is same.	5: The spacing between consecutive fringes is not uniform.

5.3 Types of diffraction

b. Fresnel's diffraction

In the case of Fresnel's diffraction, either the light source and screen, or both, are positioned at a finite distance from the obstacle. No lens is used for converge of light beam [Fig.(a)] and the wave front is either cylindrical or spherical. In this diffraction distance plays an important role.

c. Fraunhofer diffraction

In Fraunhoffer's diffraction the source of light and screen are at infinite distance from obstacle [Fig.(b)]. The corresponding rays are not parallel so the wavefront is plane. A convex leas is used to render the ray parallel before it falls on aperture. Angular inclinations plays an important role rather than distance

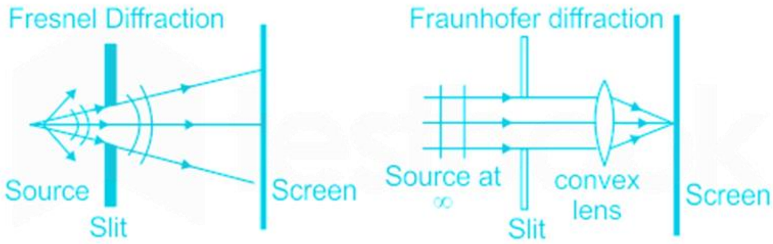


Fig. (5.2) (a) Fresnel Diffraction (b) Fraunhofer Diffraction

5.4 Difference between Fraunhofer and Fresnel's Diffraction

S.No.	Fraunhofer Diffraction	Fresnel Diffraction
1.	Plane wave fronts	Cylindrical or spherical wave fronts
2.	Source and screen are kept at infinite distance from obstacle.	Source and screen are kept at finite distance from obstacle.
3.	Position of source screen and aperture are fixed	Distance may vary
4.	Lens is required for focusing.	No lens is required.

5.	It play an important role in optical instruments	It is not useful for instruments.

Self-Assessment

Q.1. Define diffraction of light.

Q.2. Describe how diffraction of light occurs.

Q.3. Distinguish between Interference and Diffraction

Q.4. Explain why diffraction of light occurs more prominently when the wavelength of light is comparable to the size of the aperture or obstacle.

Q.5. Can we observe diffraction in our daily life?

Q.6. What is diffraction of light?

a) Reflection of light from a surface

b) Bending of light around obstacles and edges

c) Refraction of light through a prism

d) Absorption of light by a material

Q.7. Which of the following statements about diffraction is correct?

a) It occurs only with monochromatic light.

b) It occurs when light passes through an aperture or around an obstacle.

c) It is caused by total internal reflection.

d) It is unrelated to the wavelength of light.

Q.8. Why does diffraction occur more prominently when the wavelength of light is comparable to the size of the aperture or obstacle?

a) Because larger wavelengths bend more easily.

b) Because smaller wavelengths interfere constructively.

c) Because of the wave nature of light.

d) Because of the particle nature of light.

Q.9. In Fraunhofer diffraction, the incident wave front should be

a) elliptical

b) Plane

c) Spherical

d) Cylindrical

Q.10. The wave nature of light is demonstrated by which of the following?

a) The photoelectric effect

b) Color

c) The speed of light

d) Diffraction

Unit-6

Fraunhofer Diffraction

6.1 Fraunhofer Diffraction at a Single Slit

In the case of Fresnel's diffraction, either the light source and screen, or both, are positioned at a finite distance from the obstacle, while the wave front is plane.

The diagram in figure (2.3) illustrates an experimental setup where a parallel beam of monochromatic light emitted from a source S is directed perpendicularly onto a narrow slit AB with a width e, resulting in diffraction. A Convex lens L is positioned along the path of the diffracted beam, creating a diffraction pattern on the screen MN located in the focal plane of the lens. The diffracted light from the slit converges on the screen at point P, then the path difference

BE= AB $\sin\theta$ = e $\sin\theta$ ………(1)

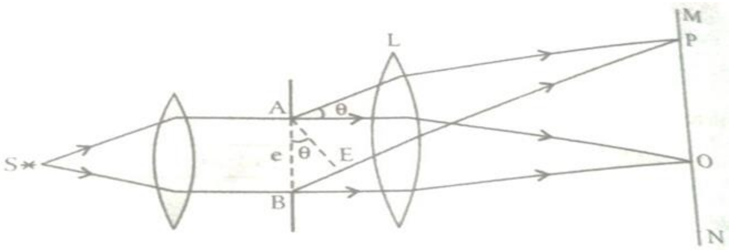


Fig. (6.1)

The corresponding phase difference = $\left(\frac{2\pi}{\lambda}\right)$ path difference

$$= \frac{2\pi}{\lambda} \, e \sin\theta \qquad \ldots.$$

Intensity Distribution:

If we assume that the slit AB divided into 'n' equal parts and each part behaves a secondary source. The amplitude of all the secondary wavelets reaching at P will be same and the difference in phase between the waves originating from two consecutive parts is,

$$= \frac{1}{n}\left(\frac{2\pi}{\lambda} e \sin\theta\right) = d \text{ (let)}$$

Hence, resultant amplitude at P is given by,

$$A = \frac{a \sin\left(\frac{nd}{2}\right)}{\sin\left(\frac{d}{2}\right)} = \frac{a \sin\left(\frac{\pi e \sin\theta}{\lambda}\right)}{\sin\left(\frac{\pi e \sin\theta}{n\lambda}\right)}$$

Let $\frac{\pi e \sin\theta}{\lambda} = \alpha$, *then*

$$A = \frac{a \sin\alpha}{\sin\left(\frac{\alpha}{n}\right)} = \frac{a \sin\alpha}{\alpha/n} = \frac{na \sin\alpha}{\alpha} \qquad \left(\because \frac{\alpha}{n} \text{ is very small}\right)$$

If n→ ∞, $\alpha \to 0$, *but* the product na remains finite.let na=A_0, then

So the resultant intensity at P will be, $A=\frac{A0\ sin\alpha}{\alpha}$

$$I=A^2 \text{ or } I=\left(\frac{A0\ sin\alpha}{\alpha}\right)^2 \qquad \ldots\ldots\ldots(3)$$

The intensity observed at any given point in the focal plane of the lens is determined by the values of α and $\boldsymbol{\theta}$. Consequently, a sequence of successive maxima and minima is obtained.

Condition for minima

From Eq. (3) the intensity is zero, if

$$Sin\boldsymbol{\alpha}=0 \qquad [\text{but } \alpha \neq 0, \frac{sin\alpha}{\alpha} = 1, When\ \alpha = 0]$$

Or $\boldsymbol{\alpha}=\pm n\boldsymbol{\pi}$ Where n=1,2,3……...

So, the positions of minima are, given by

$$\pi e sin\theta/\lambda = \pm n\pi \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

This $esin\theta = \pm n, = \pm\lambda, \pm 2\lambda, \pm 3\lambda$, equation gives the different order minima.

Condition for Maxima

From Eq.(3), the condition of maxima may be obtained by taking derivative of I with respect to α and equal to zero i.e.,

$$\frac{dI}{d\alpha}=0$$

$$\frac{d(\frac{A0\ sin\alpha}{\alpha})^2}{d\alpha}=0$$

$$A_0^2\ [\frac{\alpha^2\ 2\sin\alpha\cos\alpha - sin^2\alpha\ .2\alpha}{\alpha^4}]=0$$

$$\alpha^2\ \sin\alpha\cos\alpha - sin^2\alpha\ .\alpha=0$$

$$\alpha\sin\alpha[\alpha\cos\alpha - \sin\alpha] = 0$$

$$\alpha\sin\alpha = 0$$

$$\alpha\cos\alpha = [\sin\alpha]$$

or

$$\boldsymbol{\alpha}=\tan\boldsymbol{\alpha} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

We may solved above equation graphically by plotting two curves: one is ploted between Y and $\boldsymbol{\alpha}$ and other is between Y and tan $\boldsymbol{\alpha}$ on the same graph as shown. One curve is straight line and other is discontinuous curves having asymptotes branches at an interval of $\boldsymbol{\alpha}= \pi$ as shown in fig.(2.4)

The corresponding value of $\boldsymbol{\alpha}$ for minimum intensity is

$$\alpha = 0, \frac{3\pi}{2}, \frac{5\pi}{2}, \frac{7\pi ...}{2} .....$$

For $\boldsymbol{\alpha}$=0, we get position of Principal or Central maximum. For other values of $\boldsymbol{\alpha}$, we get different order secondary maxima by using Eq.(3)

$$I_{0_{\alpha\to 0}} = (\frac{A0\ sin0}{0})^2 = {A_0}^2$$

$$I_{0_{\alpha\to\frac{3\pi}{2}}} = (\frac{A0\ sin\frac{3\pi}{2}}{\frac{3\pi}{2}})^2 = \frac{4}{9\pi^2}{A_0}^2 = \frac{{A_0}^2}{22}$$

$$I_{0_{\alpha\to\frac{5\pi}{2}}} = (\frac{A0\ sin\frac{5\pi}{2}}{\frac{5\pi}{2}})^2 = \frac{4}{25\pi^2}{A_0}^2 = \frac{{A_0}^2}{61}$$

Thus, the intensity of the successive maxima is in the ratio

$$1:\frac{1}{22} : \frac{1}{61} : \frac{1}{121} ....$$

It is $\frac{\pi e sin\alpha}{\lambda} = 0$ and $\theta = 0$ showing that maximum intensity is distributed at $\boldsymbol{\alpha}=\mathbf{0}$ i.e.in the direction of the incident light.or

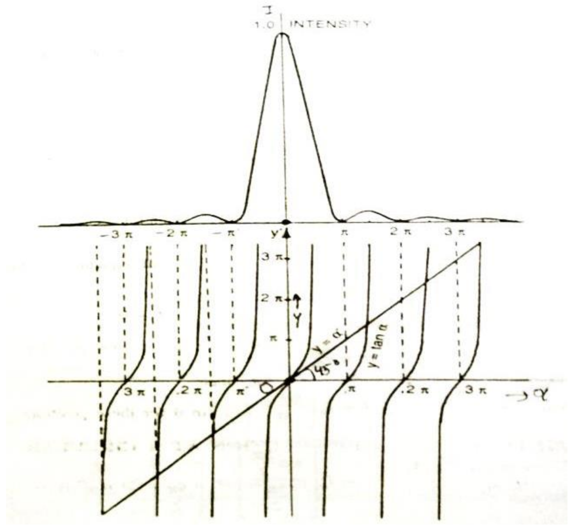


Fig. (6.2)

Weak maxima do not lie directly in the middle between two minima; rather, they are displaced towards the centre of the pattern by a decreasing amount as the order increases.

6.2 Fraunhofer Diffraction at a Circular Aperture

Fig. shows a circular aperture of diameter 'd' in which a plane wave front *WW*' is incident normally on this aperture. Different point of the wave front on the aperture acts as a source of secondary wavelets. These secondary wavelets diffracted from the source converge on the screen SS′ through the use of a convex lens (L) positioned between the aperture and the screen. The screen is located at the focal plane of the convex lens. Those diffracted rays converged at P_o.

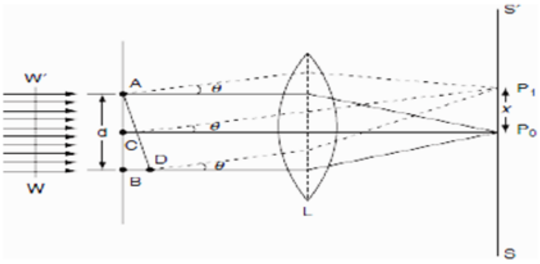


Fig. (6.3)

All these rays after passing through the lens converged at point P_o, as there is no path difference between them. The central maxima may be obtained at point P_o.

Now, let's assume that secondary waves diffracted at an angle θ at the corner of the aperture. A diffraction ring of radius x is produced by all these secondary wavelets on the screen. which centre is located at Po. The intensity at point P_1 is influenced by the path difference between the waves reaching P_1 from the aperture.

The path difference $BD = AB \sin\theta = d \sin\theta$, which is exactly same as due to a single slit. The intensity at P_1 depends upon this path difference.

For Maxima

$d \sin\theta = n\lambda$ for minima ……………………………(1)

For Minima

$d \sin\theta = (2n-1)\lambda/2$ for maxima ………………………………….(2)

where $n = 1, 2, 3, \ldots$ etc. and $n = 0$ corresponds to central maximum.

The optical phenomenon known as Airy's rings produces a distinct ring that is surrounded by alternating dark and bright concentric rings. The dark ring has an intensity of zero, while the brightness of the concentric rings decreases as we move radially from P_0 to P_1 on the screen. This phenomenon occurs when a converging lens (L) is positioned near to the aperture or when the screen is located at a considerable distance from the lens. Then

$$\sin\theta \approx \theta \approx x/f \qquad \text{..................(3)}$$

here f is the focal length of the lens.
Using Eq.(1), condition for first secondary minimum is

$$\sin\theta \approx \theta \approx \lambda/d \qquad \text{................(4)}$$

From Eqs. (3) and (4) we get

So, $x/f = \lambda/d$ or $x = f\lambda/d$

But according to Airy, the exact value of x

$$x = 1.22 f\lambda/d \qquad \text{.................... (5)}$$

It indicates that the radius of Airy's ring is inversely proportional to the diameter of the aperture. So by reducing the diameter of the aperture, size of Airy's disc increases.

6.3 Diffraction due to double slit

Fig. (2.6) shows two narrow and rectangular slits A_1B_1 and A_2B_2, placed perpendicular to the plane of the paper. Let us consider width of both the slits and opaque portions are 'e' and 'd' respectively. A convex lens is placed between slits and screen to converge light on the screen. A monochromatic light of wave length 'λ' is incident normally on both the slits as shown.

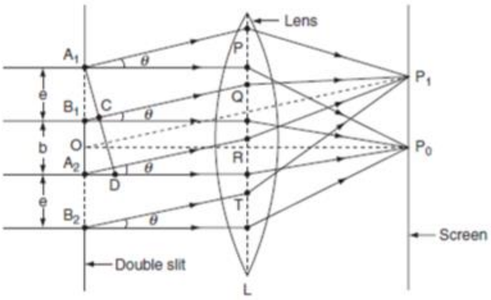


Fig. (6.4)

The secondary wavelets originating from different parts of the slits and moving towards the OP_0 direction converge at point P_0 on the screen SS′ through the use of a converging lens L. The central bright maximum is positioned at the centre point P_0. The resulting intensity distribution is a combination of the interference of diffracted secondary waves from the slits. The screen exhibits a high intensity along the path of the incident beam (i.e., along OP_0). Consequently, the maximum intensity is observed at P0, which is known as the principal maximum of zero order. By applying the Fraunhofer diffraction theory to a single slit and the interference of diffracted waves from two slits, intensity patterns of other orders can be obtained. As previously explained, the amplitude of wavelets on the screen due to a single slit at an angle θ with respect to the incident beam is.

The phase difference between the secondary wavelets generating at the end points of a slit is denoted as 2α

To find this phase difference, draw a normal from A_1 to B_1Q.

Now, In the triangle A_1B_1C

$$A_2D = (e+b)\sin\theta_n = \pm(2n-1)\frac{\lambda}{2},$$

$$\sin\theta = \frac{B_1C}{A_1B_1} = \frac{B_1C}{e} \quad \text{or} \quad B_1C = e\sin\theta.$$

B_1C represents the path discrepancy between the diffracted waves at an angle 'θ' at the aperture A_1B_1.

The corresponding phase difference

$$or, \alpha = \frac{\pi e Sin\theta}{\lambda}$$

$$(2\alpha) = \frac{2\pi}{\lambda} e \sin\theta$$

Amplitudes,(A sin α/α) produce combine interference. The path difference between the waves from corresponding points of the slits A_2D

$A_2D = A_1A_2 \sin\theta = (e + d) \sin\theta$ ……………(1)

The corresponding phase difference $(2\beta) = 2\pi(e + b)\sin\theta/\lambda$ …….(2)

The resultant wave amplitude at the two slits (R).

$R = 2ASin\alpha\ Cos\ \beta/\alpha$ …………….(3)

The intensity at P_1 is

$I = R^2 = 4A^2 \sin_2 \alpha. \cos^2 \beta/\alpha^2$

$= 4\ I_0\sin^2 \alpha. \cos^2 \beta/\alpha^2$ [Since $I_0 = A^2$]…………(4)

Eq. (4) signifies the intensity distribution on the screen. The intensity at any point depends on α and β. The intensity of central maximum is $4I_o$.

Eq. (4) consists of two terms: The first term $\cos^2\beta$ corresponds to interference and other term $\sin^2 \alpha/\alpha^2$ is due to diffraction.

Maxima and Minima due to Interference:

For the path difference $A_2D = (e + d) \sin \theta_n = \pm n\lambda$ where n = 1, 2, 3…

'θ_n' corresponds to the directions of the interference. The ± sign denotes maxima on both sides with respect to the central maximum. If the path difference is odd multiples of $\lambda/2$, directions of minima θ_n from the two slits on both sides with respect to the central maximum depends upon the value of 'θ_n'. i.e.,

$$e \sin \theta_n = \pm(2n-1)\frac{\lambda}{2}$$

Diffraction maxima and minima:

If the path difference B_1C is $e \sin \theta_n = \pm n\lambda$, where n = 1, 2, 3…, then the angle θn indicates the directions of various order diffraction minima. The ± symbol denotes minima on both sides in relation to the central maximum.

Fig. (2.7) illustrates the intensity distribution on the screen resulting from double slit diffraction. Part (a) displays the interference term graph, while part (b) depicts the diffraction term graph. Part (c) shows the combined distribution caused by the two slits.

Certain orders of interference maxima are absent in the resulting pattern due to the specific values of e and d.

The interference maxima are determined by the equation $(e + d) \sin \theta_n = n\lambda$, where n represents the order of the maxima. On the other hand, the diffraction minima can be found using the equation $e \sin \theta_m = m\lambda$, where m represents the order of the minima.

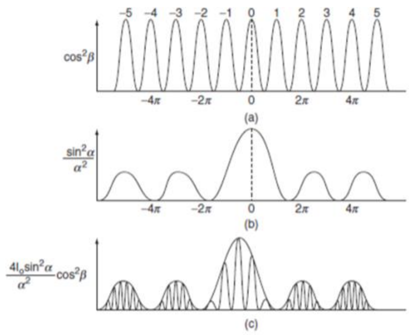


Fig. (6.5)

6.4 Missing order

The values of e and d are satisfied for some values of θ_n, and the interference maxima and the diffraction minima are formed. In the combined effect certain order interference maxima is missing. Now we examine missing order interference maxima for certain values of e and d.

(i) Let e = d

Then, 2e sin θ_n = $n\lambda$ and e sin θ_m = $m\lambda$

$$\therefore \frac{n}{m} = 2 \quad \text{or} \quad n = 2m$$

If m = 1, 2, 3 … we get n = 2, 4, 6… i.e., the interference orders 2, 4, 6 …missed in the diffraction pattern

(ii) If, 2e = d

Then, 3e sin θ_m = $n\lambda$ and e sin θ_m = $m\lambda$

$$\therefore \frac{n}{m} = 3 \quad \text{or} \quad n = 3m$$

For, m = 1, 2, 3…, n = 3, 6, 9… i.e the interference orders 3, 6, 9……… are missed in the diffraction pattern

(iii) if, e + d = e

i.e d = 0, the two slits are joined. Which gives, the diffraction pattern is due to a single slit of width 2e.

6.5 Diffraction Grating/Diffraction due to N slits

It consists of large numbers of parallel slits of equal width separated by opaque spaces. All opaque spaces have equal width. The width of line is called transparency and is denoted by 'e' where as the gap between lines represents the opacity with width'd'. then '(e +d)' is called grating element.

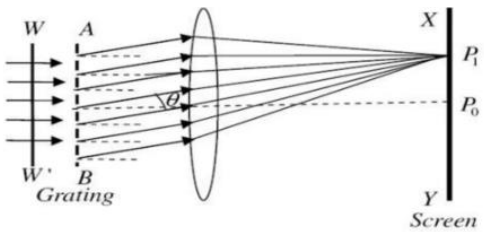


Fig. (6.6)

When a parallel beam of monochromatic light with a wavelength $'\lambda'$ is incident normally on an N-slit grating, Huygens's principle states that every point on the grating behaves as a source of secondary wavelets. These secondary waves travelling in the direction of incident light focuses at point P_O on the screen XY by the convex lens. The point P_O is the principal maximum. After diffracted at an angle $'\theta'$ the secondary waves focus at the point P_1 on the screen by the convex lens. This result the consecutive bright and dark alternate fringes on the screen on either side of P_O.

Based on the Fraunhoffer diffraction theory for a single slit, it is stated that the secondary waves originating from various points within the slit and propagating in the direction 'θ' will exhibit an amplitude of $\frac{A \sin \alpha}{\alpha}$, commencing from the centre of slit..

Here, $\alpha = \pi e \sin \theta / \lambda$

As number of slits are 'N', the path difference between two corresponding waves from any two consecutive slits is (e+d) sin θ.

Phase difference = $2\pi (e+d)\sin \theta / \lambda$

This phase difference is a constant and is equal to 2β say

i.e, $2\beta = 2\pi(e+d)\sin \theta / \lambda$

or, $\beta = \pi(e+d)\sin \theta / \lambda$ --------------------(1)

Using vector addition law , the resultant amplitude in the direction of 'θ' is given by

$R = a \sin (nd/ 2)/ \sin (d/ 2)$

In this case, $a = A \sin \alpha/\alpha$

n=N and d=2β

Now $R = \frac{A\sin \alpha}{\alpha} \frac{\sin N\beta}{\sin\beta}$ ---------------------------------(2)

Therefore the resultant intensity at P_1 on the screen is given by

$I = R^2 = (\frac{A\sin \alpha}{\alpha})^2 \frac{\sin^2 N\beta}{Sin^2\beta}$ -------------------------------(3)

The equation (3), the first term $A^2 \sin^2\alpha/\alpha^2$ represents the intensity distribution in the diffraction pattern due to a single slit and is called shape factor. The second term $\sin^2 N\beta/\sin^2\beta$ represents the interference of diffracted waves due to all the N-slits and is called grating factor.

Case1: Principle Maximum:

When sin β = 0, β = mπ where m= 0,1, 2, 3…..

By equation (1) we have , $\pi (e+d) \sin \theta/\lambda = m\pi$

$(e+d) \sin \theta = m \lambda$ --(4)

For this case $(\sin N\beta/\sin\beta) = \lim_{\beta\to m\pi} (d \sin N\beta /d \beta)/(d \sin\beta /d \beta) = N$

and $I = A = R^2 \sin^2\alpha\, N^2/ \alpha^2$ --(5)

Case2: Minimum:

When $\sin N\beta = 0$, Where $\sin \beta \neq 0$

$N\beta = m\pi$ where m= 0,1, 2, 3…..

By equation (1) we have, $N \pi (e+d) \sin \theta/\lambda = m\pi$

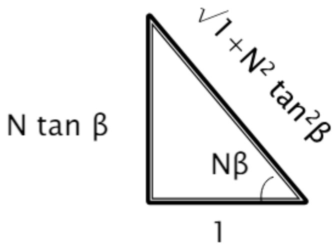
$(e+d) \sin \theta = m \lambda/N$ ---(6)

So Intensity , $I_{min} = 0$

Case3: Secondary Maxima:

For secondary maxima

$dI/d\beta = 0$, then from equation (3) we have,



$$\frac{d}{d\beta}\left(\frac{A\sin\alpha}{\alpha}\right)^2 \frac{\sin^2 N\beta}{Sin^2\beta} = 0$$

On solving, we have, $N \cos N\beta \sin \beta - \cos \beta \sin N\beta = 0$

or $\cos \beta \sin N\beta = N \cos N\beta \sin \beta$

$\tan N\beta = N\tan \beta$

From Figure: $\sin N\beta = N \tan \beta/\sqrt{(1+N^2 \tan^2\beta)}$

$\sin N\beta = N \tan \beta/\sqrt{(1+N^2 \tan^2\beta)}$

$\sin^2 N\beta = (N^2 \tan^2 \beta)/(1+N^2 \tan^2\beta)$

$\sin^2 N\beta/\sin^2\beta = (N^2 \tan^2 \beta)/ \sin^2\beta(1+N^2 \tan^2\beta)$

$\sin^2 N\beta/\sin^2\beta = N^2/ \sin^2\beta(\cot^2\beta + N^2)$

$\sin^2 N\beta/\sin^2\beta = N^2/ (\cos^2\beta + N2 \sin^2\beta)$

$\sin^2 N\beta/\sin^2\beta = N^2/ (1-\sin^2\beta + N^2 \sin^2\beta)$

$\sin^2 N\beta/\sin^2\beta = N^2/ \{1 + (N^2 - 1)\sin^2\beta\}$

Now put this in Equation (5),

we have Intensity expression for secondary maxima:

$I = R^2\sin^2\alpha\, N^2/ \alpha^2 \{1 + (N^2 - 1)\sin^2\beta\}$ ---(7)

or, $I = I_0/\{1 + (N^2 - 1)\sin^2\beta\}$

It is clear that by increasing in the number of slits, the intensity of secondary maxima in relation to principal maxima decreases and eventually becomes insignificant as N grows larger.

Variation of intensity due to the factors $\sin^2\alpha / \alpha^2$ and $\sin^2 N\beta/ \sin^2 \beta$ respectively is showing in Fig. (a) and (b). The resultant is shown in Fig. (c)

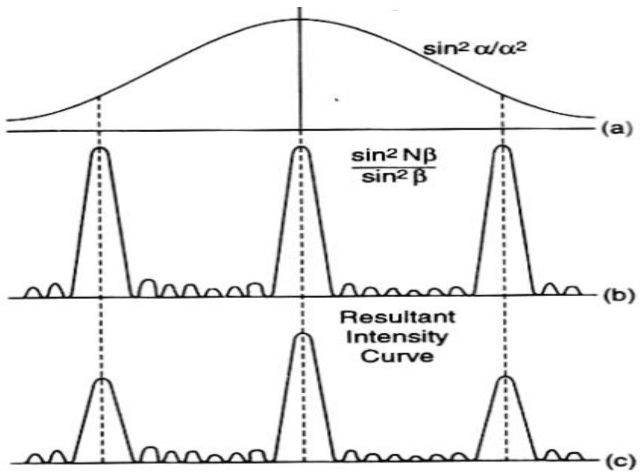


Fig.(6.7): Intensity distribution curve

6.6 Diffraction Grating

A diffraction grating refers to an arrangement consisting of numerous narrow slits of equal width placed side by side and separated by opaque spaces of equal size. Typically, it is created by drawing equidistant parallel lines on a transparent material, such as glass, using a fine diamond point. These ruled lines are opaque for light, while the spaces between them act as slits through which light can pass (refer to Fig.2.10). Original ruled gratings are quite rare, so for practical purposes, a replica of the grating is made from the original. This replica is produced by actual grating using a transparent film, like cellulose acetate. The cellulose acetate solution is poured onto the actual grating surface and allowed to harden, forming a thin film. When the hardened film is removed, it retains the impression of the original grating and is sandwiched between two glass plates. This arrangement is known as a replica of the grating.

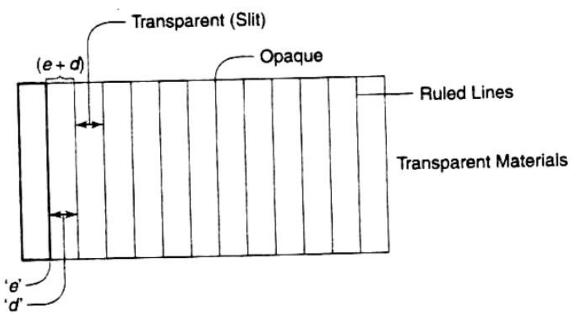


Fig.(6.8): Diffraction Grating

Let 'e' represent the width of the opaque line and 'd' denote the width of the slit. The sum of 'e' and 'd' is referred to as the grating element. If 'N' stands for the number of lines per inch on the grating, then.

N (e+d) =1”=2.54 cm

e+d= 2.54/ N cm

The order of lines on a grating are nearly 15000 to 30,000 lines per inch. The slit width is extremely narrow, similar to the wavelength of light. When light passes through the grating, it diffracts through each slit, resulting in enhanced diffraction and interference of diffracted light, ultimately forming a diffraction pattern. This pattern is commonly referred to as a diffraction spectrum.

6.7 Grating Spectrum

The grating equation is expressed as $(e + d) \sin\theta = n\lambda$(e+d) , here (e+d) represents the grating element. This equation is commonly referred to as the grating equation. It is evident from this equation that:

1. Angle of diffraction θ varies for principal maxima of different orders at each value of wavelength λ.

2. The large number of sharp, bright parallel lines is termed as spectral lines.

3. Different wavelengths of white light will be diffracted in different directions.

4. At θ =0, all the wavelength coincide and gives the maxima of all wavelengths .This forms zero order (Fig.2.11)

5. As angle of diffraction proportional to wavelength ,so longer the wavelength, greater is the angle of diffraction. Thus, violet colour will be in the innermost position and red being in the outermost position of the spectrum .

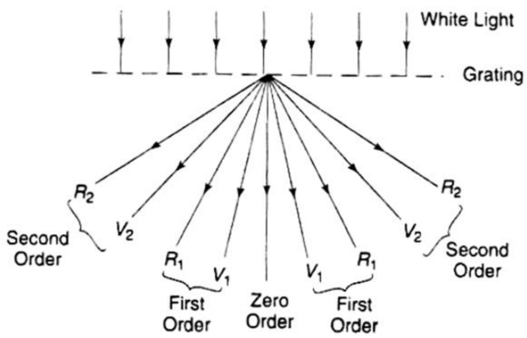


Fig.(6.9): Spectrum by Grating

6. Maximum intensity of the spectrum concentrated at zero order and the rest is distributed among other order maxima.

7. The different orders spectra are positioned on either side of the centre order.

8. The maximum orders obtained from grating is $n_{max} = e+d/\lambda$

6.8 Resolving Power

Resolving power refers to the capability of an instrument to separate two closely positioned objects

a. Resolving Power of Telescope

The ability of any astronomical telescope to form separate images of two neighbouring astronomical objects (e.g. stars) is called Resolving Power of Telescope. The least distance between two neighbouring objects for which astronomical telescope can just resolved is called the limit of resolution. The angular resolution between two objects is

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

$$\text{Resolving power} = \frac{1}{\triangle\theta} = \frac{d}{1.22\ \lambda}$$

Optical instruments of higher diameter have better the resolution. In order to achieve optimal resolution, optical telescopes are equipped with mirror diameters reaching up to 10 m. Also, resolving power decreases for larger wavelengths.

b. Resolving Power of a Grating

It is the ability of a grating to show two spectral lines of a spectra just separate. It is measured as the ratio of the any spectral line wavelength to the smallest possible change in wavelength for which spectral line can be just resolved.

Suppose the wavelengths of two neighbouring spectral lines are λ and λ + dλ

Then resolving power of the grating is given by

$$\text{R.P.} = \frac{\lambda}{d\lambda} = nN$$

Where n and N represent the order and total no. of lines in the given grating.

Thus, we can increase the resolving power of the diffraction grating by changing the order of spectrum or increasing the number of slits.

6.9 Dispersive Power of a Grating

Rate of change in angle of diffraction with wavelength called its dispersive power.

D.P. = dθ/dλ -------(1)

Derivation: we know equation of grating is: (e+a) sin θ = n λ ------(2)

On differentiating w.r.t. λ ,

$(e+d) \cos\theta \, d\theta/d\lambda = n$

or, $d\theta/d\lambda = n/(e+d)\cos\theta$

D.P. = $d\theta/d\lambda = n/(e+d)\cos\theta$

6.10 Differences between Grating Spectra and Prism Spectra

S.NO	Grating Spectra	Prism Spectra
1	A grating produces a number of spectra of different of different orders on either side of the zero order image.	A prism produces only one spectrum.
2	The grating spectra are formed due to diffraction of light.	The prism spectrum is produced due to dispersion of light.
3.	In any order, light of higher wavelength gets more diffraction.	In this case, light of higher wavelength has least angle of deviation
4.	In grating spectra, red colour is more diffracted than violet colour from zero order.	In prism spectrum red colour is least deviated and violet colour is most deviated.
5.	The spectral lines are straight and sharp by a grating spectra	In Prism case, the spectral lines are not perfectly straight and sharp.
6.	In grating spectra, most of the intensity is concentrated at zero order whereas rest is distributed among the other spectra.	In this case, all the spectral lines will have the same intensity.

Self-Assessment

Q.1. State Huygens' principle and explain its relevance to single-slit diffraction.

Q.2. How the width of the central maximum in single-slit diffraction changes with the slit width and wavelength of light.

Q.3. Draw the intensity distribution pattern due to single-slit diffraction.

Q.4. State the condition of principal maxima and minima in Fraunhofer diffraction due to a single slit.

Q.5. What is the difference between single-slit diffraction and double-slit interference?

Q.6. What are diffraction gratings?

Q.7. When the slit width decreases, the width of the central maximum in a single-slit diffraction pattern:

a) Decreases.

b) increases.

c) remains the same.

d) depends on the wavelength of light.

Q.8. In a double-slit experiment, what determines the angular separation between adjacent bright fringes?

a) Wavelength of light only

b) Slit separation only

c) Both wavelength of light and slit separation

d) Intensity of light source

Q.9. Which of the following is a characteristic of a double-slit diffraction pattern?

a) Single bright central maximum

b) Multiple bright fringes with varying intensities

c) No interference fringes

d) Uniform intensity across the screen

Q.10. Diffraction gratings are used in spectroscopy primarily because:

a) They produce a single bright fringe.

b) They disperse light into its component colors.

c) They absorb light efficiently.

d) They create a diffraction pattern with no interference.

Unit-7

Fresnel's Diffraction

7.1 Fresnel's Assumptions

The following assumptions made by Fresnel to explain diffraction phenomenon

- The entire wave front may be assume to be divided into a large number of zones of small area such that each of these acts as a source of secondary waves emitting waves in all directions.
- At centre point O spectrum has the central maxima.
- The combined effect of all waves reaching a specific point results in the secondary waves producing a resultant effect at that point.
- The resultant amplitude at any point is determined by combining the effects of waves reaching there and may be found according to principle of superposition.

7.2 Fresnel’s Haft Period Zones

Fresnel's theory suggests that the entire wavefront can be subdivided into multiple Fresnel's half period zones. These zones, formed by the superposition of secondary waves from various regions, collectively contribute to the resultant effect observed at any point on the screen.

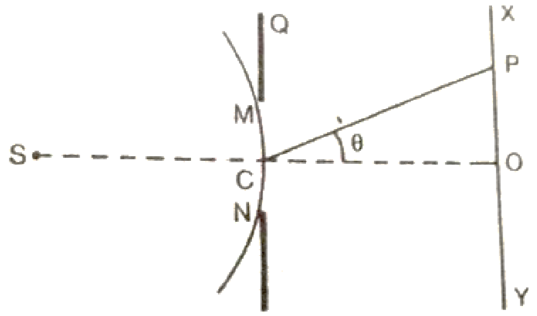


Fig. (7.1)

In the fig., A point source (S) that emits monochromatic light, while MN represents a small aperture. XY denotes the screen, with SO being a perpendicular line to XY. MCN represents the incident spherical wavefront caused by the point source S. Fresnel postulated that a wavefront can be divided into numerous strips or zones, referred to as Fresnel's half period zones. These zones are responsible for generating a combined intensity of light at a specific point P.

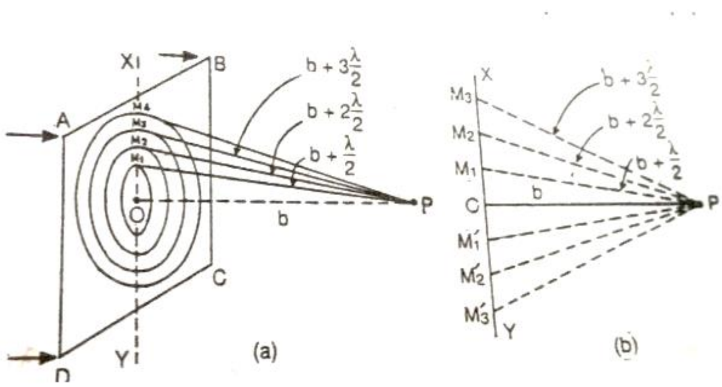


Fig. (7.2)

To determine the resulting intensity at point P caused by a wavefront, consider a source S that emits a plane wave front ABCD moving from left to right with a wavelength λ. Our objective is to analyze the impact of wavefront point P, located at a distance b from the wavefront. The wavefront can be divided into Fresnel's zones with P as the center and radii equal to b+ n λ/2 (with n = 1, 2, 3 …). This division will result in the cutting of areas with radii OM_1, OM_2, OM_3, ….etc in fig.(a). The enclosed area lies between O and M_1 and M_2.

As shown in Fig.(2.13), draw concentric spheres on the wavefront. The area between two spheres is termed a zone. The secondary waves originating from consecutive zones converge at point P with a path difference of A/2 (= T/2), which explains the name "half O period zones." In this context, T denotes the period. Point O is identified as the pole of the wavefront in relation to point P.

Calculation of Radii of Half Period Zone

$OM_1 = \sqrt{\{(b + \lambda/2)^2 - b^2\}} = \sqrt{(b\lambda)}$ (As b>>ʎ, so $ʎ^2$ is neglected)

$OM_2 = \sqrt{\{(b + 2\lambda/2)^2 - b^2\}} = \sqrt{(2b\lambda)}$

Similarly,

$OMn = \sqrt{\{(b+n\lambda/2)^2 - b^2\}} = \sqrt{(nbʎ)}$

Thus radii are proportional to the square roots of natural numbers.

Area of Half Period Zone: The area of nth zone will be

$= \pi \{(b+n\lambda/2)^2 - b^2\} - \pi \{((b+(n-1)\lambda/2)^2 - b^2\}$

$= \pi \{b\lambda + \lambda 2(2n-1)/4\} = \pi b\lambda$ ....(1)

(b>> λ so ʎ2 is neglected)

The area of nth zone will be= $\pi b\lambda$

which says that area of each half period zone is nearly the same.

The distance of point P from half period zone:

It is

$= [(b + n\lambda/2) + (b + (n - 1)\lambda/2)] / 2 = b + (2n- 1)\lambda/4$ .....(2)

Amplitude due to one zone at point P: It is calculated as

A_n = [zone area/ distance of point P from zone] * obliquity factor

Using Eq (1) and (2), we get the area

$$A_n = \pi\lambda (1 + \cos\theta_n)$$

The obliquity factor is represented by $(1+ \cos\theta_n)$, where θ_n is the angle between the normal to the zone and the line joining the zone to P. As n increases, $\cos\theta_n$ decreases, resulting in a decrease in A_n as well.

Resultant amplitude of point P due to whole wavefront

The amplitudes at point P from various zones, denoted as A_1, A_2, A_3, and so on, will result in resultant amplitude at the point. This is due to the fact that the path difference between the two consecutive zones is A/2, causing them to reach in opposite phases.

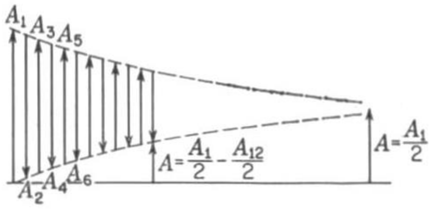


Fig. (7.3)

$A = A_1 - A_2 + A_3 - A_4 \dots (-1)^{n-1} An$

We can have

$A_2 = A_1 + A_3/2$ and $A_4 = A_3 + A_5/2$ and so on

$A = A_1/2 + A_n/2$ for n to be odd

$= A_1/2 + A_n/2 - A_n$ for n to be even

taking $A_{n-1} = An$ as n is very large, then

$A = A_1/2 + An/2$

$A = A_1/2$

Accordingly, the amplitude resulting from a large wavefront at a certain point is only half of what is caused by the first half period of the Fresnel zone. Therefore, the intensity can be determined.

$$I = A^2$$

So, $$I = A_1^2/4$$

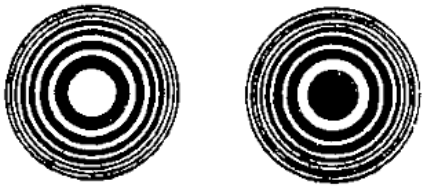
Hence the intensity at point O, caused by the complete wavefront, is only one fourth of the intensity from the first half-period zone.

7.3 Explanation of rectilinear propagation of light

The intensity at a point located in front of a wave front is directly proportional to $m_1/4$, where m_1 represents the amplitude of the first half period zone. Consequently, the intensity at point P is equivalent to one fourth of the intensity resulting from the first half period zone. As a result, only half of the area of the first half period zone is effective in generating the illumination at point P. If a small obstacle, measuring half the size of the area of the first half period zone, is positioned at O, it will completely obstruct the impact of the entire wavefront, causing the intensity at P due to the remaining wavefront to be zero. When dealing with the rectilinear propagation of light, the size of the obstacle used is significantly larger than the area of the first half period zone. Therefore, the bending effect of light around the corners of the obstacle, known as diffraction effects, cannot be observed. However, if the size of the obstacle placed in the path of light is very small and comparable to the wavelength of light, it becomes possible to observe illumination in the region of the geometrical shadow as well. Consequently, the rectilinear propagation of light is only an approximation.

7.4 Zone plate

A zone plate is a screen that is specifically made to block light in alternate zones. The accuracy of Fresnel's approach to dividing a wavefront into half period zones can be validated through the use of a zone plate.

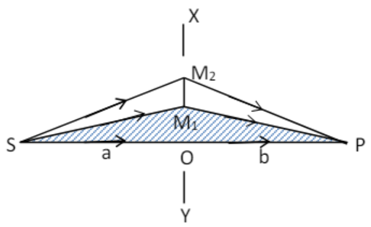


(a) (b)

A zone plate is created by sketching concentric circles on a blank sheet of paper, where the radii are scaled in proportion to the square root of the natural numbers. The circles with odd-numbered zones (1st, 3rd, 5th, etc.) are filled with black ink, and a scaled-down photograph is captured.

The negative of the photograph is depicted in Fig (a). In this negative, the odd zones allow incident light to pass through, while the even zones block the light. This configuration represents a positive zone plate. Conversely, if the odd zones are opaque and the even zones are transparent, it signifies a negative zone plate. Refer to Fig (b) for an illustration.

Theory



The point source of light, denoted as S, has a wavelength λ and is located at a distance a from the center O of the zone plate. Assume point P on a screen positioned at a distance of b, where the intensity of diffracted light is maximum.

Let r_1, r_2,r_3…….r_n be the radii of the 1^{st}, 2^{nd}, 3^{rd} ……n^{th} half period zones respectively.

The screen is positioned in a way that causes a growing path difference of $\lambda/2$ between adjacent zones.

$SM_1 + M_1P = a + b + \frac{\lambda}{2}$ …….(1)

Similarly $SM_2 + M_2P = a + b + \frac{2\lambda}{2}$ and so on

From the triangle SM_1O $SM_1 = (SO^2 + OM_1^2)^{1/2} = (a^2 + r_1^2)^{1/2}$

Similarly from the triangle PM_1O $M_1P = (OP^2 + OM_1^2)^{1/2} = (b^2 + r_1^2)^{1/2}$

Substituting the values of SM_1 and M_1P in equation (1), we get

$$(a^2 + r_1^2)^{1/2} + (b^2 + r_1^2)^{1/2} = a + b + \frac{\lambda}{2}$$

or $$a\left(1 + \frac{r_1^2}{a^2}\right)^{1/2} + b\left(1 + \frac{r_1^2}{b^2}\right)^{1/2} = a + b + \frac{\lambda}{2}$$

Expanding and simplifying the above equation, we get

$$a\left(1 + \frac{r_1^2}{2a^2}\right) + b\left(1 + \frac{r_1^2}{2b^2}\right) = a + b + \frac{\lambda}{2}$$

$$a + \frac{r_1^2}{2a} + b + \frac{r_1^2}{2b^2} = a + b + \frac{\lambda}{2}$$

or $\frac{r_1^2}{2}\left(\frac{1}{a} + \frac{1}{b}\right) = \frac{\lambda}{2}$ or $r_1^2\left(\frac{1}{a} + \frac{1}{b}\right) = \lambda$

Thus for the radius of the n[th] zone the above relation can be written as

$r_n^2\left(\frac{1}{a} + \frac{1}{b}\right) = n\,\lambda$ …..(2) or $r_n^2 = \frac{ab}{a+b} n\,\lambda$ or $r_n = \sqrt{\frac{ab\lambda}{a+b}}\,\sqrt{n}$

Thus, in the diagram $SO + OP = a$ + b

The radii of the half period zones are directly related to the square root of the natural numbers.

Now equation (2) can written as ($1/\boldsymbol{a}$ + $\mathbf{1}/\boldsymbol{b}$) = $\boldsymbol{n\lambda}/\ \boldsymbol{r_n^2}$ ………………………...(3)

Which is similar to the lens formula $1/u$ + $1/v$ = $1/f$ ………………………………(4)

On comparing equations (3) and (4) $\mathbf{1}/\boldsymbol{f}$ = $\boldsymbol{n\ \lambda}/\ \boldsymbol{r_n^2}$ or $\boldsymbol{f}$ = $\boldsymbol{r_n^2}/\boldsymbol{n\ \lambda}$

In the context of the zone plate, f represents the focal length and behaves like a convex lens with multiple focal points. The path difference between consecutive transparent zones is λ, while the phase difference is 2π. Waves from various zones reach at P in phase.

Focussing Zone plate

As the amplitude depends upon area of the zone, distance of the zone from P and obliquity factor.

The area of nth zone = $\pi r_n{}^2 - \pi\, r_{n-1}{}^2$

As $r_n{}^2 = (ab/\ a{+}b)\ \lambda$,

The area of the nth zone = $(ab/\ a{+}b)\ n\ \lambda - \pi\ (ab/\ a{+}b)\ (n-1)\ \lambda = \pi\ (ab\lambda/\ a{+}b)$

Area is independent of n. Area of all zones are same. But the distance of the zone from P and obliquity factor increases as n increases.

The resultant amplitude at P is

A = $m_1 + m_3 + m_5 + \ldots$.for positive zone plate

A = - $(m_2 + m_4 + m_6 + \ldots\ldots)$ for negative zone plate.

This is much greater than A = $m_1/2$ which is due to all zones.

As the intensity from the zone plate is very high, the zone plate is said to have focussing action

7.5 Differences between Zone plate and Convex lens

Zone plate	Convex lens
Focal length is $\mathbf{1}/\boldsymbol{f} = \boldsymbol{n}\ \boldsymbol{\lambda}/\ \boldsymbol{r_n^2}$	Focal length of lens is $1/u + 1/v = 1/f$
The focal length of an zone plate depends on the wavelength (λ) and exhibits chromatic aberration. Additionally, it forms a real image.	The focal length of an convex lens depends on the wavelength (λ) and exhibits chromatic aberration. Additionally, it forms a real image.
There are several points of focus. If each zone contains (2p - 1) half period elements. $\boldsymbol{f_p} = \boldsymbol{r_n}{}^2/(\mathbf{2}\boldsymbol{p}-\mathbf{1})\boldsymbol{n}\ \boldsymbol{\lambda}$	It has single focus. $1/f = (n-1)\ (\ 1/R_1 - 1/R_2\ )$
A path difference of λ is observed in all the waves reaching the image point through consecutive transparent zones.	The optical path remains constant for all waves that reach the image point.
$f_{violet} > f_{red}$	$f_{violet} < f_{red}$
Less Intensity image is form	Large Intensity image is form.

7.6 Fresnel Integrals

Fresnel integrals are a type of functions that are widely recognized for their significance in comprehending the diffraction patterns of light passing through an aperture, as well as their exceptional capability to produce the renowned "Cornu Spiral." Initially, we will establish the definition of the Fresnel integral as a collection of parametric equations. Subsequently, we will employ a power series expansion, which is a commonly employed method for evaluating the integral of a transcendental function. Lastly, we will explore the practical applications of Fresnel integrals in the realms of mathematics and physical science. $$\begin{cases} C(t) = \int_0^t \cos(bx^2)dx \\ S(t) = \int_0^t \sin(bx^2)dx \end{cases}$$

Here b are real-valued constants.

When equations are expressed in this form, they are referred to as parametric equations, indicating that the values of the equations are connected through an independent variable. In the given situation, the parameter t is used to symbolize the shared variable between the two functions.

7.7 Diffraction Pattern Due to a Straight Edge

Let S represent a narrow slit that is being illuminated by a source of monochromatic light with a specific wavelength. The length of the slit is perpendicular to the plane of the paper. AD is a straight edge that runs parallel to the length of the slit, as depicted in Figure 2.15. XY represents the incident cylindrical wave front. P denotes a point on the screen, while SAP forms a perpendicular line to the screen

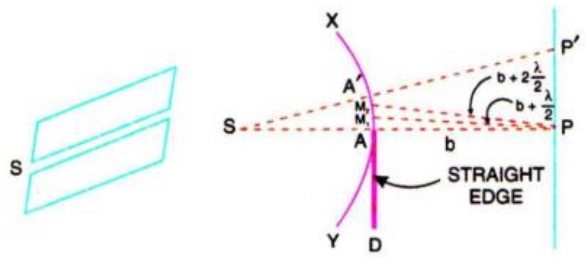


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Fig.(7.4)

The screen forms a perpendicular intersection with the plane of the paper. Below point P, there exists a geometrical shadow, whereas above point P, there is an illuminated portion. We can designate the distance AP as b. Figure 2.16 demonstrates the division of the wave front into several half period strips, with point P as the point of reference. The wave front is denoted as XY, while A represents the pole of the wave front. The measurements AM_1, M_1M_2, M_2M_3, and so on, indicate the thickness of the 1st, 2nd, 3rd, and subsequent half period strips. As the order of the strip increases, the area of each strip decreases.

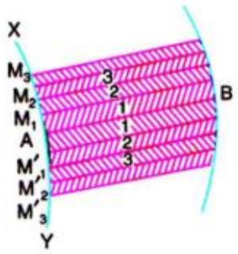


Fig.(7.5)

In Fig. 2.15, AP = b,

Positions of Maximum and Minimum Intensity:

Fig. (2.15) denotes the distance between the slit and the straight edge as 'a', and the distance between the straight edge and the screen as 'b'. Let PP' be x.

The path $\delta = AP' - BP'$ difference,

$$= (b^2 + x^2)^{1/2} - [SP' - SB]$$

$$= (b^2 + x^2)^{1/2} - \left(\sqrt{(a+b)^2 + x^2} - a\right)$$

$$= b\left[1 + \frac{x^2}{2b^2}\right] - (a+b)\left[1 + \frac{x^2}{2(a+b)^2}\right] + a$$

$$= \frac{x^2}{2}\left(\frac{1}{b} - \frac{1}{a+b}\right) = \frac{x^2}{2}\left(\frac{a+b-b}{b(a+b)}\right)$$

$$\therefore \quad \delta = \frac{x^2}{2} \cdot \frac{a}{b(a+b)}$$

The point P' will be of maximum intensity if $\delta = (2n+1)\frac{\lambda}{2}$

$$\therefore \quad (2n+1)\frac{\lambda}{2} = \frac{a x_n^2}{2b(a+b)}$$

$$x_n^2 = \frac{(2n+1)(a+b)b\lambda}{a}$$

$$x_n = \sqrt{\frac{(2n+1)(a+b)b\lambda}{a}}$$

Where x_n is the distance of the nth bright band from P. Similarly, P' will be of minimum intensity if

$$\delta = 2n\frac{\lambda}{2} \quad \therefore \quad 2n\frac{\lambda}{2} = \frac{a x_n^2}{2b(a+b)} \quad \text{or} \quad x_n = \frac{\sqrt{2n(a+b)b\lambda}}{a}$$

Here x_n represent the distance of the nth dark band from P. As a result, one can observe diffraction bands of varying intensity, which approximately correspond to maxima and minima, above the geometrical shadow, specifically above P. However, if P' is situated at a considerable distance from P, the bands disappear and uniform illumination is achieved.

Self-Assessment

Q.1. Discuss the differences between Fresnel and Fraunhofer diffraction patterns.

Q.2. Define the resolving power of a telescope. How does it relate to the telescope's ability to distinguish between two closely spaced objects?

Q.3. Explain the factors that affect the resolving power of a telescope.

Q.4. Define the resolving power of a grating. How does it differ from the resolving power of a telescope?

Q.5. Describe the principle of operation of a zone plate.

Q.6. Compare and contrast a zone plate with a conventional lens.

Q.7. The resolving power of a telescope depends primarily on:

a) Magnification
b) Aperture size
c) Focal length
d) Eyepiece design

Q.8. The Rayleigh criterion defines the resolving power of a telescope based on:

a) The diameter of the primary lens
b) The wavelength of light being observed
c) The magnification used
d) The spacing of the diffraction patterns formed by the telescope's optics

Q.9. Increasing the aperture of a telescope generally leads to:

a) Decreased resolving power
b) Improved resolving power
c) No change in resolving power
d) Decreased field of view

Q.10. The resolving power of a telescope is limited by:

a) The angular diameter of the primary mirror
b) Atmospheric turbulence
c) The design of the eyepiece
d) The diffraction limit of light

Unit-8

Polarization of Light

8.1. **Introduction**

The phenomenon of light in which electric field vectors is restricted to a specific direction in a plane that is perpendicular to the direction of light propagation is known as polarization.

Maxwell's electromagnetic theory signifies that light waves possess a transverse nature, in which electric and magnetic field vectors propagate perpendicular to each other as well as perpendicular to the wave propagation.

The vibrations of the electric field vector (E) represent the nature of light. In the case of ordinary or unpolarized light, the vibrations of the electric field vector lie in all directions as illustrated in the diagram.

8.2. **Types of Polarization**

a. Unpolarized or ordinary light

Electric field vectors vibrating in two directions i.e. in the plane of the paper (arrows) and horizontally perpendicular to the plane of the paper (dots)—represent the propagation of light.

Figure :8.1 Unpolarised Light

b. Plane Polarized light

Electric field vectors vibrating in two directions i.e. in the plane of the paper (arrows) and horizontally perpendicular to the plane of the paper (dots)—represent the propagation of light.

Figure :8.1 Unpolarised Light

8.3. **Plane of polarization and plane of vibration**

The plane that contains the direction of vibration and the direction in which light propagates is referred to as the plane of vibration in a plane polarized light.

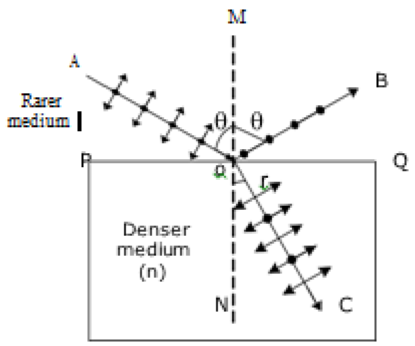
The plane which is perpendicular to the plane of vibration and in which polarized light propagates

is called **plane of polarization.** It also contains the direction of propagation of light.

8.4. **Methods of producing plane polarized light**

There are various methods to producing plane polarized or linearly polarized light some of them are Reflection, Refraction, Double refraction and Selective absorption Scattering

a. Polarization by reflection



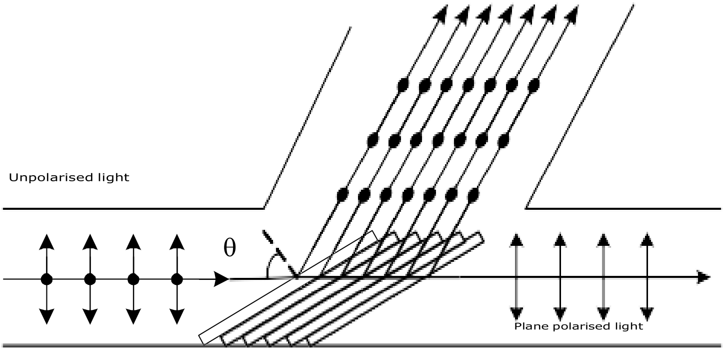
This method is discovered by Mallus in 1808, which revealed that the degree of polarization of light reflected from glass surfaces is influenced by the angle of incidence and can range from partial to total. As the angle of incidence increases, the degree of polarization also increases steadily. At a particular angle of incidence called the polarizing or Brewster's angle (i_p), the reflected light becomes completely polarized. Some of the aspects about the polarization by reflections are:

a) Firstly, if light incidence at a specific angle known as the polarizing angle, the reflected light becomes completely plane polarized.

b) Additionally, Brewster's law states that the refractive index of the medium in which light travel is equal to the tangent of the polarizing angle for that particular medium. This relationship is mathematically expressed as $\mu = \boldsymbol{tan\theta_P}$.

b. Polarisation by refraction

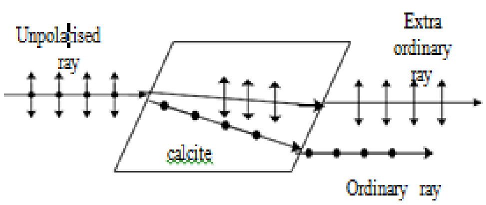
When unpolarized light hits several parallel glass plates at the polarising angle θ, the reflected light becomes completely polarized with vibrations perpendicular to the plane of incidence. As the refracted light undergoes reflections and refractions, only vibrations parallel to the plane of incidence remain, resulting in a plane polarized emergent beam.



Polarisation by selective absorption – Dichroism: Dichroism is the term used to describe the ability of a doubly refracting crystal to selectively absorb one of the refracted rays while allowing the other to pass through. Crystals that demonstrate this characteristic are known as dichroic crystals. An example of such a crystal is tourmaline, which absorbs the ordinary and extraordinary rays to varying degrees.

c. Polarisation by double refraction

Double refraction is the phenomenon observed in specific crystals where an incoming beam is divided into two refracted beams. This unique property was first identified by Esmus Bartholinus. Crystals such as calcite, quartz, and mica are known to display this characteristic. Crystals that demonstrate this property are described as exhibiting birefringence.



8.5. Difference between E-ray and O-ray

Ordinary Ray (O – Ray)	Extra ordinary ray (E – O - Ray)

1. The laws of refraction are followed by it. 2. The refractive index remains consistent regardless of the angle of incidence. 3. The O-ray maintains a uniform speed in all directions. 4. They exhibit plane polarization. 5. The O-ray is polarized within the plane of the principal section.	1. Does not follow the ordinary law of refraction 2. Refractive index changes as the angle of incidence change 3. The E-O Ray moves at different velocities in various directions 4. Plane polarization is observed 5. The E-O-ray is polarized in a plane that is perpendicular to the principal section
Note : The O-ray and the E-O-ray move at identical speeds in a specific direction within the crystal, known as the optic axis. Double refraction is not detected along the optic axis.	

Along the optic axis of a crystal, the velocity of both the ordinary ray and the extraordinary ray are equal, resulting in no double refraction. The velocity of the ordinary ray (vo) is different than the velocity of the extraordinary ray (ve) in a direction other than the optic axis, This phenomenon is characteristic of uniaxial and biaxial crystals and plays a significant role in their optical properties.

Note : A plane which contains the optic axis and perpendicular to the opposite faces of a crystal is called the **principal section of the crystal**. O-ray is polarised in the plane of principal section and the E-O-ray is polarised in a plane perpendicular to the principal section.

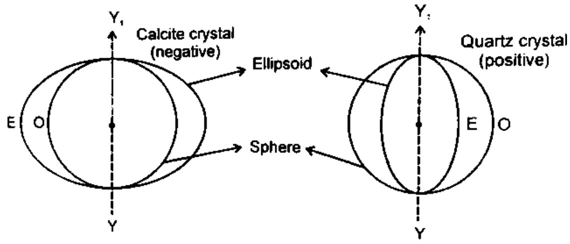
8.6. Huygens' theory of double refraction

1. Huygen proposed that each point situated on a wavefront functions as a new source of disturbance, emitting secondary wavelets in the process.
2. Upon encountering a doubly refracting crystal, each point within the crystal serves as the origin of two distinct wavefronts. These are the ordinary wavefront, associated with ordinary rays that move uniformly in all directions, generating spherical secondary wavefronts, and the extra-ordinary wavefront, linked to extra-ordinary rays that travel at varying speeds in different directions, producing ellipsoidal secondary wavefronts.
3. The sphere and ellipsoid intersect at points positioned along the optic axis (YY) of

the crystal due to the identical speed at which both ordinary and extra-ordinary rays travel along this axis.

4. Negative crystals, such as calcite, exhibit an interesting characteristic where the ellipsoid is situated outside the sphere. This indicates that the extraordinary wavefront moves faster than the ordinary wavefront, except when it travels along the optic axis.
5. Conversely, within positive crystals like quartz, the ellipsoid is found inside the sphere, signifying that the extraordinary wavefront moves at a slower rate compared to the ordinary wavefront, except when it progresses along the optic axis.

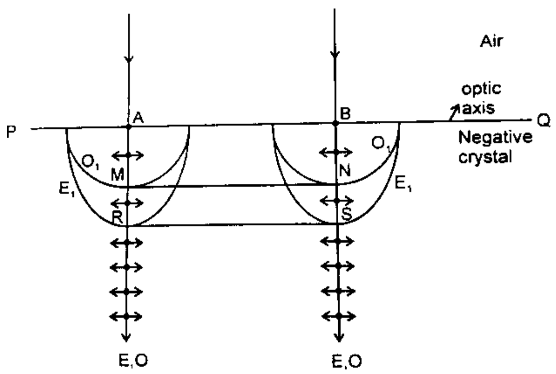
The application of Huygens' theory of double refraction to uniaxial crystals is expounded upon below.

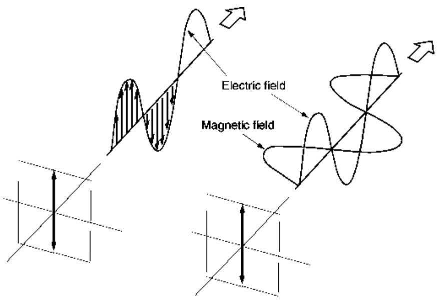


Refractive index of the medium for the extra-ordinary ray. Here $\mu_E < \mu$.

8.7. **Normal incidence**

The surface PQ of a negative crystal is being incident upon by the plane wavefront AB, which is normal to it. The XY axis of optics is situated within the plane of incidence. Upon the interaction of wavefront AB with the surface PQ of the crystal, Point A serves as the origin for two distinct wavefronts: the O1 ordinary spherical wavefront for the ordinary rays, and the E1 ellipsoidal wavefront for the extra-ordinary rays. The wavefronts for the ordinary and extra-ordinary rays, denoted as MN and RS respectively, run parallel to the refracting surface. As AO stands perpendicular to MN and AE stands perpendicular to RS, the ordinary and extra-ordinary rays travel in the same direction, albeit at different speeds. This discrepancy in velocity results in a definite phase difference between the two rays, which forms the fundamental principle behind quarter-wave plates and half-wave plates.





Self-Assessment

Q.1. Define polarization of light. How does it differ from unpolarized and polarized light?

Q.2. What is Malus' law? How does it relate to the intensity of light transmitted through a polarizer?

Q.3. Explain the concept of the electric field vector in the context of polarized light. How is it related to the direction of polarization?

Q.4. Discuss the significance of polarization in optical phenomena.

Q.5. Discuss Brewster's angle and its relevance in polarization by reflection. How does it affect the polarization state of reflected light?

Q.6. Polarization of light refers to:

a) The propagation of light through a medium.

b) The conversion of light into heat energy.

c) The orientation of the electric field vector of light waves.

d) The dispersion of light into its constituent colors.

Q.7. Unpolarized light can be converted into polarized light by:

a) Passing through a polarizer.

b) Refraction through a prism.

c) Reflection from a smooth surface.

d) Scattering from particles in the atmosphere.

Q.8. 3. Brewster's angle is the angle at which:

a) Light is completely absorbed by a surface.

b) The intensity of reflected light is maximized.

c) Refraction of light occurs without reflection.

d) Polarization by reflection occurs.

Q.9. Circularly polarized light is characterized by:

a) A single linear polarization component.

b) Two orthogonal linear polarization components with equal amplitudes.

c) Two orthogonal linear polarization components with unequal amplitudes.

d) A rotating electric field vector.

Q.10. Malus' law relates the intensity of transmitted light to the:

a) Angle of incidence.

b) Angle of refraction.

c) Angle between the polarization direction of incident light and the transmission axis of a polarizer.

d) Wavelength of light.

Unit-9

Production of Polarize Light

9.1. Introduction

There are different types of polarized light, including plane polarized light, circularly polarized light, and elliptically polarized light.

9.2.Theory of Plane, Circularly and Elliptical Polarised light

The phenomenon of **plane polarized light** occurs when the electric vector vibrations of light in a medium are restricted to a specific plane and are perpendicular to the direction in which the wave propagates.

The phenomenon of **circularly polarized light** occurs when two plane waves of equal amplitude are combined with a phase difference of 90°, leading to the light being circularly polarized.

The phenomenon of Elliptically polarized light occurs when two plane waves with varying amplitudes exhibit a phase difference of 90° or a different relative phase, resulting in the light being elliptically polarized.

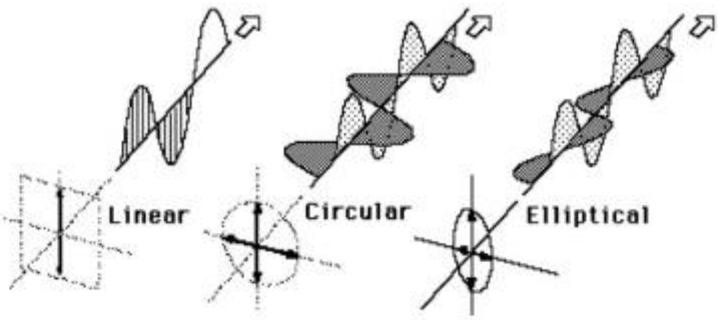


Figure 9.1: Plane, Circulary and Elliptically polarized light

The Nicol prism is an optical tool used to create and analyze polarized light. It was invented by William Nicol in 1828 and works based on double refraction. Made from a calcite crystal, the prism's length is three times its width. It is cut diagonally into two parts and then joined using Canada balsam cement. When unpolarized light is directed towards the Nicol prism, double refraction occurs, polarizing the O-ray and E-O-ray perpendicular to each other. The refractive index for the O-ray is 1.65, while the refractive index for the E-O-ray is 1.48. The refractive index of the Canada balsam is 1.55. Due to total internal reflection, the O-ray is eliminated (since $no > nc$), allowing only the E-O-ray, which is plane polarized, to emerge from the Nicol prism (since $ne < nc$).

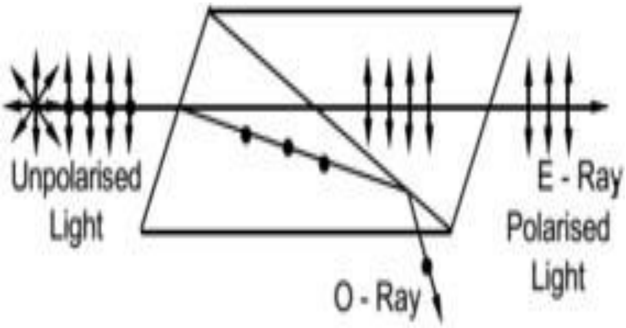


Figure 9.2: Nicol prism as polariser

Phase retardation plates are optical devices that change the phase of light waves as they pass through them. They are also known as phase shift plates. Quarter wave retardation plates are made from a doubly refracting uniaxial crystal like quartz or calcite. The faces of the plate are cut parallel to the optic axis direction, and the thickness is chosen to create a phase difference of 5/2 or a path difference of □/4 between ordinary and extraordinary rays. The thickness of the quarter wave plate is denoted as 'd', with 'no' and 'ne' representing the refractive indices of the medium for ordinary and extraordinary rays. The path difference between the extraordinary and ordinary rays can be calculated using a specific formula for normal incidence.

$path\ difference = d\ (n_o -\ \ )$ for the negative crystals and $path\ difference = d\ (n_e - n_o)$ for the positive crystals.

But the path difference for a quarter wave plate is equal to $\lambda/ 4$.

$$d = \frac{\lambda}{4(n_o \sim n_e)}$$

A half wave retardation plate is made from a uniaxial crystal like quartz or calcite. It is cut so that its refracting faces are parallel to the optic axis. The plate's thickness is chosen to create a phase difference of π or a path difference of $\lambda/2$ between the ordinary and extraordinary rays passing through it. Let d be the thickness of the plate, and n_o and n_e be the refractive indices of the medium for the ordinary and extraordinary rays. When the rays hit the plate at normal incidence, the path difference between the extraordinary and ordinary rays can be calculated based on the crystal's properties and the angle of incidence.

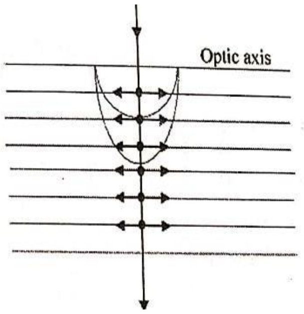
$path\ difference = d\ (no - ne)$ for the negative crystals and $path\ difference = d\ (ne - no)$ for the positive crystals.

But the path difference for a half wave plate is equal to $\lambda/2$

$$= \frac{\lambda}{2(n_o \sim n_e)}$$

9.3.Production of plane polarized, circularly and elliptically polarized light

Monochromatic light that is unpolarized becomes plane polarized upon passing through a Nicol prism. The resulting polarized light is then directed perpendicularly onto a doubly refracting uniaxial plate composed of calcite crystal, with its surfaces aligned parallel to the optic axis fig 9.3(a).



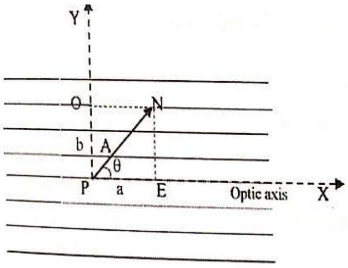


Figure 9.3 (a) : Uniaxial double refracting pl9.3 (b) Figure 1spiltting of E-ray and O- ray

The light incident on the crystal is separated into two types of rays: ordinary and extraordinary. The extraordinary ray has its vibrations aligned parallel to the optic axis, while the ordinary ray has its vibrations perpendicular to the optic axis, both moving in the same direction. Due to the crystal being negatively birefringent, the extraordinary ray travels faster than the ordinary ray. This speed difference leads to a phase shift δ between the two rays as they exit the crystal.

The amplitude of extra-ordinary vibrations along PE is given by the angle of incidence of polarized light with the optic axis.

$a = A\ cos\theta$ ....(1)

and the amplitude of the ordinary vibrations along PO is given by

$b = A\ sin\theta$ ...(2)

The crystal's two rays are simple harmonic vibrations with phase difference δ, and their displacement along PE is determined by the frequency of vibrations.

$x = a\ sin(\omega t + \delta)$ ..... (3)

The displacement O ray vibrations along PO is given by $= b\ sin\omega t$ ....(4)

where $\omega = 2\pi f$

Squaring the above equation $\frac{y^2}{b^2} = sin^2\omega t$ or $\frac{y^2}{b^2} = 1 - cos^2\omega t$

or $cos^2\omega t = 1 - \frac{y^2}{b^2}$ or $cos\omega t = \sqrt{1 - \frac{y^2}{b^2}}$ ......(6)

from equation (3) we have $\frac{x}{a} = sin\omega t\ cos\ \delta + cos\omega t \sin\delta$ ....(7)

substituting the terms of (5) and (6) in (7), we get $\frac{x}{a} = \frac{y}{b}\ cos\ \delta + \sqrt{1 - \frac{y^2}{b^2}} \sin\delta$

or $\frac{x}{a} - \frac{y}{b}\ cos\ \delta = \sqrt{1 - \frac{y^2}{b^2}} \sin\delta$

squaring the above equation, $\left(\frac{x}{a} - \frac{y}{b}\ cos\ \delta\right)^2 = \left(1 - \frac{y^2}{b^2}\right) sin^2\delta$

simplifying, $\frac{x^2}{a^2} + \frac{y^2}{b^2} cos^2\delta - \frac{2xy}{ab}\ cos\ \delta = sin^2\delta - \frac{y^2}{b^2}\ sin^2\delta$

or $\mathbf{\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{2xy}{ab}\ cos\ \delta = sin^2\delta}$ . .....(8)

Equation (4) can be rewritten as $sin\omega t = \frac{y}{b}$ ....(5)

Special cases:

Case (i): if $= 0, 2\pi, 4\pi, \ldots$.., $\cos\delta = 1$ and $\sin\delta = 0$.

$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{2xy}{ab} = 0$ or $\left(\frac{x}{a} - \frac{y}{b}\right)^2 = 0$

Case (ii): if $= \pi\ 2\ , 3\pi\ 2\ , 5\pi\ 2\ , \ldots \ldots$ $\cos\delta = 0$ and $\sin\delta = 1$

$\mathbf{\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1}$

Case (iii): if $= \pi\ 2\ , 3\pi\ 2\ , 5\pi\ 2\ , \ldots \ldots$ $\cos\delta = 0$ and $\sin\delta = 1$

$\mathbf{\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1}$ is $\mathbf{\frac{x^2}{a^2} + \frac{y^2}{a^2} = 1}$ or $\mathbf{x^2 + y^2 = a^2}$

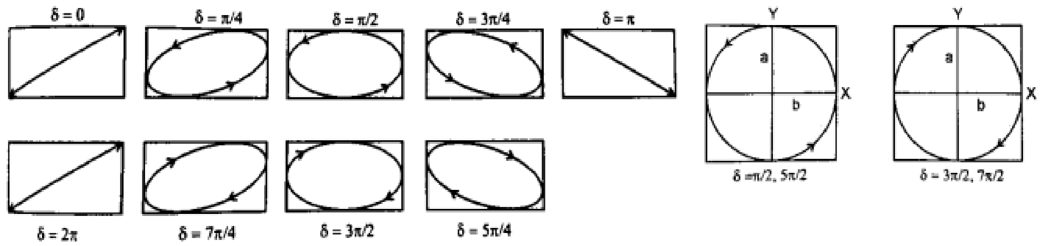


Figure 9.4: Production of plane, circularly and elliptically polarised Light

a. Plane polarized light

Production: The process of generating plane polarized light involves allowing unpolarized light to pass through a Nicol prism, which then splits the light into o-ray and e- rays. The o-ray is completely reflected by the Canada balsam material within the Nicol prism, leaving only the extraordinary ray with vibrations parallel to the principal section of the Nicol prism to emerge as plane polarized light.

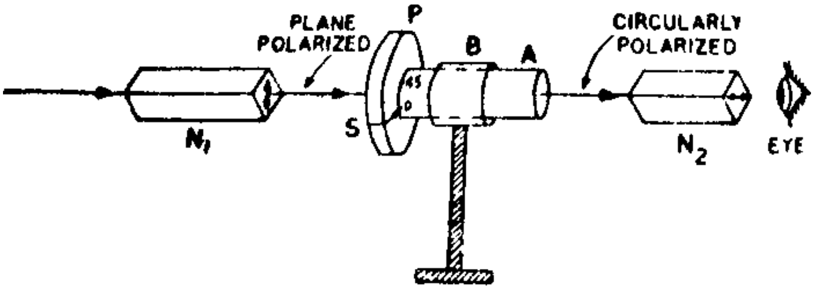


Figure 9.5: Polarimeter instrument

Detection : When a plane polarized light beam is directed towards a Nicol prism and the prism is rotated, the intensity of the light emitted decreases gradually until it reaches zero at two specific positions during each rotation. This variation in intensity, from zero to maximum, indicates that the incident light has become plane polarized.

b. Circularly Polarized Light

Production :

1. The setup involves a monochromatic light beam passing through Nicol prism N1, resulting in plane polarized light.
2. By introducing Nicol prism N2 and adjusting its position until the field of view is dark, the two nicols are crossed.
3. Inserting a quarter wave plate between the prisms initially does not darken the field of view, but rotating it does. This aligns the vibrations of the light parallel to the optic axis of the plate and perpendicular to N2.

4. Rotating the quarter wave plate by 45 degrees causes the light vibrations to be at a 45-degree angle to the optic axis, resulting in equal amplitudes and a phase difference of π, leading to circularly polarized light.
5. The key to producing circularly polarized light is ensuring that two waves vibrating at right angles with the same amplitude and time period have a phase difference of π or a path difference of $\lambda/4$.

Detection :

1. When the light beam falls on a Nicol prism, if the intensity of the emitted light remains the same after rotating the prism, it indicates that the light is either circularly polarised or unpolarised.
2. To distinguish between unpolarised and circularly polarised light, the light is first transmitted through a quarter wave plate and then through a Nicol prism.
3. If the beam is circularly polarised, passing through the quarter wave plate introduces an additional phase difference of $\lambda/4$ between the ordinary and extraordinary components, resulting in the conversion to plane polarised light. This allows the light to be extinguished at two specific angles when the Nicol prism is rotated.

    c. Elliptical polarized light

Production :

1. Elliptically polarized light can be produced by ensuring that two waves vibrating at right angles to each other with unequal amplitudes have a phase difference of $\pi/2$ or a path difference of $\lambda/4$.
2. The experimental setup involves a beam of monochromatic light passing through Nicol prism N1 to become plane polarized.
3. By introducing another Nicol prism N2 at a suitable distance and rotating it until the field of view is dark, the two nicols are considered crossed.
4. Inserting a quarter wave plate between the prisms will result in the field of view not being dark initially. Rotating the quarter wave plate until the field of view becomes dark indicates that the polarized light falling on the plate has vibrations parallel to the optic axis of the plate and perpendicular to N2.

5. Rotating the quarter wave plate through an angle other than 45 degrees will cause the vibrations of light falling on the plate to make an angle other than 45 degrees with the optic axis, resulting in unequal amplitudes and a phase difference of π between the two rays, leading to the production of elliptically polarized light.

Detection: The Nicol prism allows the light beam to fall on it, causing the intensity of the emitted light to vary from maximum to minimum when rotated, indicating either elliptical polarization or a combination of plane polarized and unpolarized light.

1. To distinguish between the two possibilities, the light is first transmitted through a quarter wave plate and then through the Nicol prism.
2. If the beam is elliptically polarized, passing through the quarter wave plate introduces an additional path difference of $\lambda/4$ between the O-ray and E-ray, resulting in conversion to plane polarized light.
3. Consequently, rotating the Nicol prism can extinguish the light. However, if the beam is a mixture of polarized and unpolarized light, it remains a mixture even after passing through the quarter wave plate, causing the intensity of the emitted light to vary from maximum to minimum when the Nicol prism is rotated.
4. By following this process, the nature of the light polarization can be determined accurately.

Self-Assessment

1. Explain how plane polarized light is produced using a polarizer.
2. Define circularly polarized light and explain how it differs from plane polarized light.
3. Define elliptically polarized light and explain how it can be produced using combinations of polarizers and wave plates.
4. Describe Brewster's law and its application in the production of plane polarized light.
5. Explain the principle of polarization by reflection and refraction. Provide examples of how plane polarized light can be produced using these principles.
6. Which of the following statements about plane polarized light is correct?
   a) It consists of waves vibrating in all planes perpendicular to the direction of propagation.
   b) It can be produced by passing unpolarized light through two perpendicular polarizers.

c) Its electric field vector oscillates in a single plane.
d) It is characterized by both right-handed and left-handed circular polarization.

7. Circularly polarized light is characterized by:
   a) Two orthogonal linear polarization components.
   b) A single linear polarization component.
   c) Right-handed and left-handed polarization states.
   d) A rotating electric field vector.
8. How can circularly polarized light be produced?
   a) By passing unpolarized light through a single polarizer.
   b) By passing linearly polarized light through a quarter-wave plate oriented at 45 degrees.
   c) By passing linearly polarized light through a half-wave plate oriented at 90 degrees.
   d) By passing linearly polarized light through two perpendicular polarizers.
9. Elliptically polarized light is characterized by:
   a) A rotating electric field vector.
   b) Two orthogonal linear polarization components with equal amplitudes.
   c) Two orthogonal linear polarization components with unequal amplitudes.
   d) A single linear polarization component.
10. What is the significance of quarter-wave plates in polarized light?
   a) They convert circularly polarized light into elliptically polarized light.
   b) They convert elliptically polarized light into linearly polarized light.
   c) They rotate the polarization plane of incident light.
   d) They selectively transmit light based on its polarization.

Unit-10

Polarimeter

10.1. Optical Activity

Optical activity is the characteristic of a substance that causes it to rotate the plane of polarization of incident light. Substances with this property are known as optically active substances. Examples include quartz, sugar solution, sodium chlorate, and quinine.

There are two types of optically active substances: dextro-rotatory or right-handed substances, which rotate the plane of polarization clockwise, and laevo-rotatory or left-handed substances, which rotate the plane of polarization anticlockwise. Cane sugar is an example of a dextro-rotatory substance, while fruit sugar is an example of a laevo-rotatory substance.

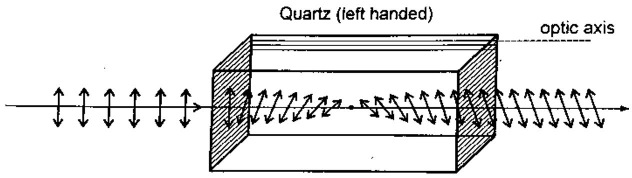


Figure 10.1: Optical Rotation of optically active substance (Quartz)

The specific rotation of an optically active solid substance is determined by the angle of rotation of the polarization plane caused by the substance at a specific temperature and wavelength of light, with a unit thickness. For optically active solutions, the angle of rotation (θ) is directly proportional to both the length of the solution (L) and the concentration of the solution (C), assuming the temperature and wavelength of light remain constant.

The specific rotation constant (S) represents the specific rotation or specific rotatory power of the solution and can be calculated as follows:

$$S = \frac{\theta}{L \times C}$$

The unit for specific rotation is degrees $(g/mL)^{-1}$ dm^{-1}.

The angle of rotation of the plane of polarization caused by an optically active solution of unit length and unit concentration at a specific temperature and wavelength of light is referred to as the specific rotatory power.

10.2. Types of Polarimeter

a. Half Shade

It is a tool used to detect the specific rotation of an optically active solution.

Construction

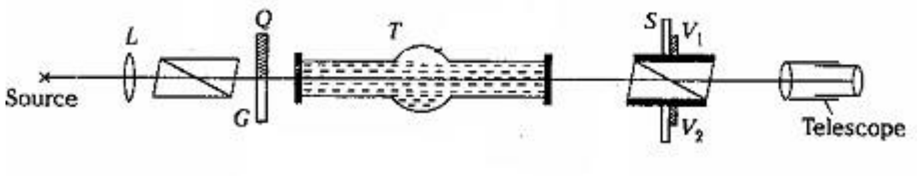


Fig 10.2 :Laurent's Half Shade Polarimeter

In this setup, a glass tube T placed between pair of polarizer and analyzer nicol prism. A half shade retardation plate GQ is placed between solution tube and polarizer. The half shade retardation plate made of two halfcircular plates in which one is made of quatz and the other is by glass material. To observation of light telescope is used. *S* is a circular scale fixed to the analyser using which angle of rotation can be determined.

Working :

1. The glass tube contains distilled water that is free from any air bubbles. A source of light is directed towards the polarizer, causing the beam that emerges from it to become plane polarized. This polarized light then falls onto the half shade arrangement.
2. When light passes through quartz, its plane of vibration undergoes rotation, and the plane of vibration remains unchanged when passing through glass. As a result of this the field view of the telescope will be divided into two halves.
3. The analyzer A is designed to be symmetric with respect to the planes of vibration of light passing through both quartz and glass. This symmetry ensures that both halves of the field of view appear equally bright. The reading R0 is recorded from the analyzer.
4. The optically active solution at a known concentration (C) is then poured into the glass tube. The vibration planes of the two halves rotate by the same angle as a result of this solution. As such, there will be another difference in brightness between the two sections.
5. The analyzer is then rotated until the two halves exhibit the same brightness, and the reading R is recorded. The relationship R ~ Ro = θ provides the angle of rotation.

If L is the length of the tube then specific rotation of the liquid is determine by the formula

$$S = \frac{\theta}{L \times C}$$

b. Biquartz Polarimeter

The bi-quartz polarimeter is utilized to determine the optical rotation of specific optically active solutions. Its design closely resembles that of Laurent's half-shade polarimeter, with the main difference being the use of white light instead of monochromatic light.

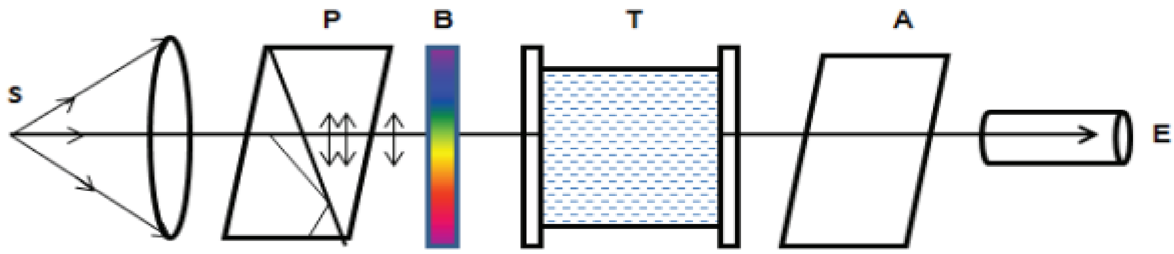


Figure 10.3: Bi- Quartz Polarimeter Instrument

The diagram illustrates the configuration of a bi-quartz polarimeter. In this experimental setup, light emitted from a source S (white light), which is a regular bulb, goes through a slit before reaching a convex lens L. The convex lens L transforms the emerging light into a parallel beam. Subsequently, this parallel light beam is directed towards a Nicol P (polarizer), causing the light that comes out of P to become plane polarized light.

This plane polarized light then passes through the Biquartz plate B, a glass tube T containing the solution of an optically active substance, and an analyzer (Nicol prism A). The light is observed through a telescope E. The analyzing Nicol A can be rotated around the axis of the tube, and its rotation can be determined using a vernier scale on the graduated circular scale C, which is divided into degrees and mounted on telescope E.

Self-Assessment

1. Define specific rotation. How is it calculated? Explain with an example.
2. Explain the principle behind the operation of a half shade device. How does it help in achieving precise readings of optical rotation?
3. Describe the role of the biquartz prism in a biquartz polarimeter. How does it enhance the accuracy of optical rotation measurements?
4. What factors can affect the specific rotation of a compound? Discuss.
5. How does temperature variation affect the measurements obtained using a polarimeter? What strategies can be employed to minimize these effects?
6. **What is optical rotation?**
   a. The bending of light rays through a medium
   b. The rotation of light's polarization plane as it passes through an optically active substance
   c. The dispersion of light into its component colors
   d. The absorption of light by a substance
7. **Optical rotation is dependent on:**

a. The temperature of the substance
b. The concentration of the substance
c. The path length through the substance
d. The wavelength of light passing through the substance

8. **What is the purpose of a half-shade device in polarimetry?**
   a. To measure the intensity of light passing through a sample
   b. To split light into its component colors
   c. To compensate for temperature variations in optical rotation measurements
   d. To detect the angle of optical rotation more accurately
9. **What is a Bi-quartz polarimeter?**
   a. A device that measures the birefringence of quartz crystals
   b. A device that measures the optical rotation of quartz crystals
   c. A device that measures the dispersion of light through quartz crystals
   d. A device that measures the absorption of light by quartz crystals
10. **How does a Bi-quartz polarimeter achieve accurate measurement of optical rotation?**
    a. By using multiple light sources
    b. By compensating for temperature changes automatically
    c. By rotating a quartz wedge to adjust the optical path length
    d. By converting optical rotation angles into digital signals

Unit-11

Laser

11.1. Introduction

LASER, pronounced "Light Amplification by Stimulated Emission of Radiation," is a powerful monochromatic light source with superior features, introduced by Einstein in 1917 and demonstrated by Dr. T.H. Maiman in 1960.

Light amplification is a technique that enhances a weak laser signal by stimulating photon emission in a gain medium, utilized in various fields like telecommunications and medicine.

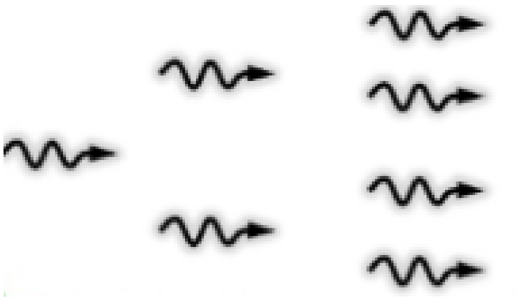


Figure 2: Light Amplication process

11.2. Properties of Lasers

Lasers have unique properties that set them apart from ordinary light.

a. Monochromaticity

Monochromaticity is the unique property of light containing only one wavelength or color. No source can emit monochromatic light. However, laser beams have a smaller wavelength or frequency bandwidth compared to ordinary light. An ordinary source of light has a bandwidth of about 10^{10} Hz, while a good quality laser has a bandwidth of about 500Hz. This highlights the difference in the monochromatic character of laser beams.

An ordinary light source emits light that spreads across a broad frequency range ($\boldsymbol{\Delta v = v_2 - v_1}$) centered the frequency $\boldsymbol{v_0}$. Conversely, a laser source spreads over a narrow frequency range ($\boldsymbol{\Delta v' = v'_2 - v'_1}$). The ratio $\Delta v/v_0$ serves as a measure of the light's monochromaticity.

Degree of monochromaticity $\varepsilon = \Delta v/v_0$,

Where Δv represents the bandwidth and v_0 is the central frequency of the light.

A light beam is considered perfectly monochromatic when its monochromaticity ε is zero, which is only possible if Δv = 0. Since Δv cannot be zero for any light beam, no light beam can achieve perfect monochromaticity.

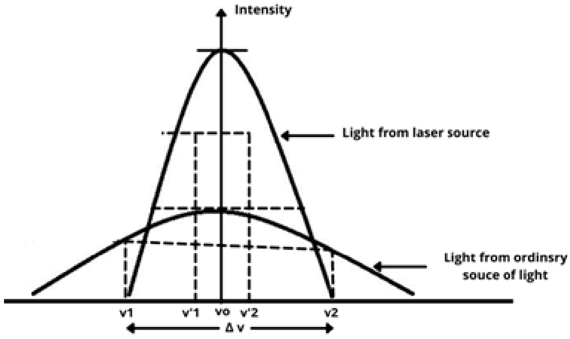


Figure 4.1: Frequency bandwidth of laser and Ordinary source

b. Directionality

Directionality refers to the property of a laser where it travels in a single direction without spreading apart. This characteristic is highly advantageous in various applications such as range finders, remote sensing, and surveying due to the laser beam's minimal divergence.

The Rayleigh range, which is the distance **d** from the laser source where the light rays remain parallel, can be calculated using the formula:

Rayleigh range = d^2 / λ

Furthermore, the divergence of the laser beam beyond the Rayleigh range can be determined by the equation:

$$\theta = \lambda / d$$

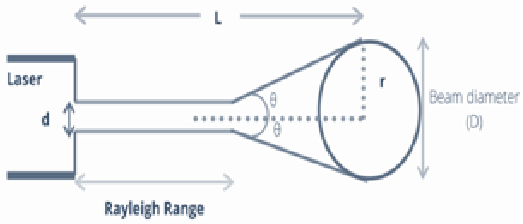


Figure 4.2: Directionality of laser beam

In these equations, d represents the aperture or diameter of the laser beam, while λ denotes the wavelength of light.

c. Coherence

The concept of coherence pertains to the characteristics of the connection between physical quantities within a single wave or among multiple waves. Coherence is observed when two waves exhibit a consistent relative phase or when they possess a constant or zero phase difference along with identical frequencies. There are two types of coherence:

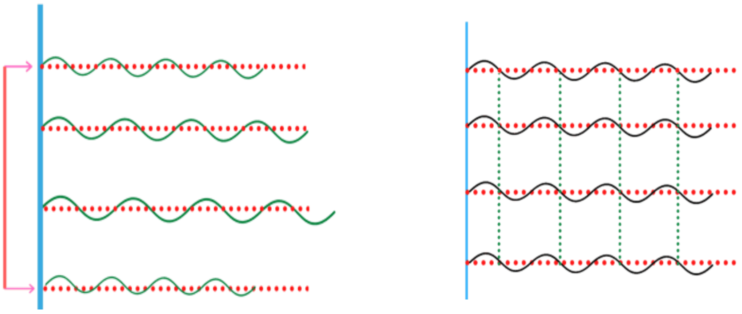


Figure 4. 3: Incoherent and Coherent wave

1. Temporal Coherence

Temporal coherence refers to correlation between an electric field at specific position in space and the same point at a different time, where the phase difference between the electric fields remains constant during the time interval $\Delta\tau = t_2 - t_1$.

To investigate the time-coherence of the radiation, let us reconsider the experiment conducted with Michelson's interferometer. In this particular experiment, a nearly monochromatic light source is utilized. For this investigation, a neon lamp can be used as the source (S), with a filter (F) placed in front of it to allow radiation of wavelength 6328 Å to fall on the beam-splitter G. The compensating plate represented by the glass plate G'.

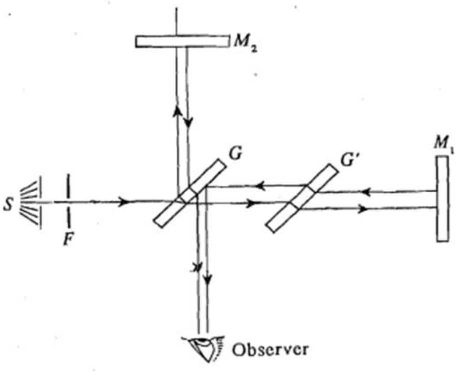


Figure 4. 4 : Michelson Interferometer

The diagram displayed in the illustration enables the viewing of circular patterns when the eye is placed in the correct position. These patterns are created by the interference of light beams reflected from mirrors M_I and M_2. It is important to ensure that the mirrors are at right angles to each other and that the path difference (GM_2 - GM_1) is minimized in order to observe these circular fringes.

When mirror M_2 is moved further from the beam splitter G, the clarity and sharpness of the interference patterns will gradually diminish, leading to the eventual disappearance of the fringe design. This highlights the significance of maintaining the correct positioning of the mirrors to sustain the visibility and contrast of the circular fringes produced by the interference of light beams.

The reason behind this phenomenon lies in the temporal coherence of the light waves emitted by the neon lamp.

In short, Coherence length, L_C, we may assume that the beam consists of all the wavelengths lying between λ and λ + Δλ with

$$\Delta\lambda = \frac{\lambda^2}{L_c}$$

2. Spatial Coherence

Spatial coherence refers to the phase relationship between waves that travel alongside each other at a specific distance. If the phase difference between light waves at two points on a plane perpendicular to its propagation direction remains constant over time, then the beam of light is considered to have spatial or lateral coherence.

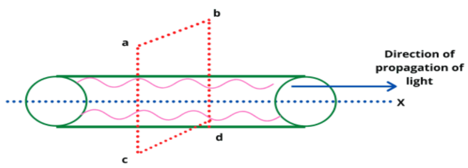


Figure 4.5: A spatially beam of light

A beam of light traveling along the X-axis is considered spatially coherent if the phase difference between waves at points P and Q remains constant at any given moment. This is due to the perpendicular nature of the beam of light with respect to the direction of propagation.

d. Intensity

The intensity of a wave can be established by quantifying the energy per unit time per unit area at a right angle to the wave's direction of propagation.

That is, intensity, **I = E/t/A = P/A (Watt/m^2)**

Lasers are highly concentrated light sources, with their intensity being a thousand times higher than 100W incandescent bulbs. A 1mW laser emits light into a narrow beam, resulting in a high intensity of 10^{13} Wm^{-2}. This high intensity makes lasers widely used for cutting and welding metal and alloys, making them ideal for various applications.

The above main four characteristics of lasers are essential for their utility in industrial applications and the medical field.

11.3. Interaction of radiation with matter

a. Absorption of Radiation: (B_{12})

An atom in its ground state absorbs a photon of energy E_1 and transitions to its excited state with energy E_2, known as absorption of radiation , with the energy difference calculated as $(E_2 – E_1) = hv$.

If there are many number of atoms in the ground state then each atom will absorb the energy from the incident photon and goes to the excited state then,

The probability of absorption (P_{12}) is proportional to,

$P_{12} \propto$ Energy density of incident radiation $u(\nu)$

$P_{12} \propto$ No. of atoms in the ground state (N_1)

$P_{12} = B_{12} N_1 u(\nu)$

Where B_{12} = Einstein coefficient of Absorption of radiation

b. Spontaneous emission of Radiation: (A_{21})

Coherence is the predictable relationship between amplitude and phase at different points. When light is coherent, it means that the wave patterns are identical in phase and direction. Lasers exhibit a high level of coherence. Atoms naturally strive to achieve the lowest energy state. Excited atoms quickly comeback to a lower energy state, releasing photon . This process, known as spontaneous emission, occurs without any external stimulation and is beyond control.

The probability of spontaneous emission P_{21} (Sp) is directly proportional to,

i.e. P_{21} (Sp) $\propto N_2$ number of atoms or molecules N present in the excited state

$$P_{21} (Sp) = A_{21} N_2$$

Here A_{21} = Einstein coefficient of spontaneous emission

c. Stimulated emission of Radiation : (B_{21})

The atom in the excited state E2 can be stimulated by an energy-hv photon to move to its ground state, resulting in the emission of an additional photon with the same energy, a process known as stimulated emission.

The rate of stimulated emission P21 (St) is proportional to,

$P_{21} \propto$ Energy density of incident radiation (u (ν))

$P_{21} \propto$ No. of atoms in the excited state (N2)

i.e. $$P_{21}\,(St) \propto u(\nu)\, N_2$$

$$P_{21}\,(St) = B_{21}\, u(\nu)\, N_2$$

Here B_{21} = Einstein coefficient of Stimulated radiation

Self-Assessment

1. What does LASER stand for?
2. What is the basic principle of laser operation?
3. How is coherence achieved in a laser beam?
4. Why is population inversion crucial for laser operation?
5. What is population inversion in a laser?

1. Which of the following is a characteristic of laser light?

a) Incoherence
b) Broad spectrum
c) Divergence
d) Monochromaticity

6. What is the primary mechanism that allows a laser to emit light?

a) Spontaneous emission
b) Stimulated absorption
c) Stimulated emission
d) Population inversion

7. What condition is necessary for a laser to achieve continuous light amplification?

a) High population of ground state atoms
b) Population inversion
c) Low energy pumping
d) High thermal energy

8. Which of the following is NOT a characteristic of laser light?
    a) Coherent
    b) Monochromatic
    c) Divergent
    d) Directional
9. What is "coherence" in the context of laser light?
    a) The light consists of multiple colors
    b) The light waves are in phase and have a fixed relationship with each other
    c) The light is scattered in many directions
    d) The light is absorbed by the medium

Unit-12

Component of Laser

12.1. Relation between Einstein's coefficient A and B Coefficient

Consider two energy levels E_1 and E_2 having number of atoms N_1 and N_2 respectively, as shown in figure.

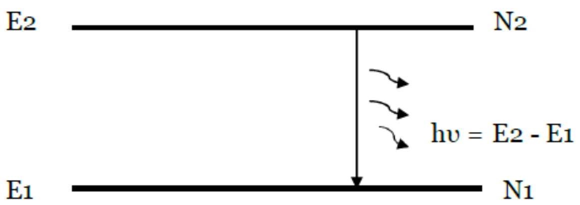


Figure 12.1 : Transition between Two Energy level

According to Einstein's theory,

Probability of Stimulated absorption is, $P_{12} = B_{12} N_1 u(\nu)$

Probability of Spontaneous Emission is, $P_{21} (Sp) = A_{21} N_2$

Probability of Stimulated Emission is, $P_{21} (St) = B_{21} u(\nu) N_2$

Where, A and B represents the Spontaneous and Stimulated process respectively. $u(\nu)$ is the energy density of radiation.

At thermal equilibrium,

The rate of absorption = The rate of emission

$$B_{12} N_1 u(\nu) = A_{21} N_2 + B_{21} u(\nu) N_2$$

$$u(\nu) [B_{12} N_1 - B_{21} N_2] = A_{21} N_2$$

$$u(\nu) = A21 / [B_{12} N_1 - B_{21} N_2]$$

Under thermal equilibrium, the number of atoms distributed in energy levels,

$$N_1 = N_0 \, e^{\frac{-E_1}{KT}}$$

$$N_2 = N_0 \, e^{\frac{-E_2}{KT}}$$

Where, K = 1.38×10^{-23} J / K (Boltzmann Constant)

T = Absolute temperature

N_0 =atom density per unit volume at absolute zero,

Since ,

Ratio of population between E_1 and E_2 is ,

$$\frac{N_1}{N_2} = e^{\frac{E_2 - E_1}{KT}}$$

since $E_2 - E_1 = h\nu$, we have

$$\therefore \quad \frac{N_1}{N_2} = e^{\frac{h\nu}{KT}}$$

$$u(\nu) = \frac{A_{21}}{B_{12} e^{\frac{h\nu}{KT}} - B_{21}}$$

According to Maxwell-Boltzman statistics

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h u^3}{c^3} \quad \text{and} \quad \frac{B_{21}}{B_{12}} = 1$$

hence $u(\nu) = \frac{8\pi h\nu^3}{c^3\{e^{\frac{h\nu}{KT}} - 1\}}$

This is the relation between Einstein's coefficient and Energy density of radiations u(ν).

12.2. **Population Inversion**

Population inversion is a fundamental principle in laser operation, involving the excited state of a laser medium, resulting in more high-energy atoms than the ground state, enabling stimulated emission and producing a coherent, monochromatic light beam.

In other words, Population Inversion refers to the stage where the population of the higher energy level surpasses that of the lower energy level.i.e. $\mathbf{E_2 > E_1}$ and $\mathbf{N_1 < N_2}$.

The number of atoms per unit volume in an energy level is distributed according to Boltzmann relation we have N= No exp{-E/kT}

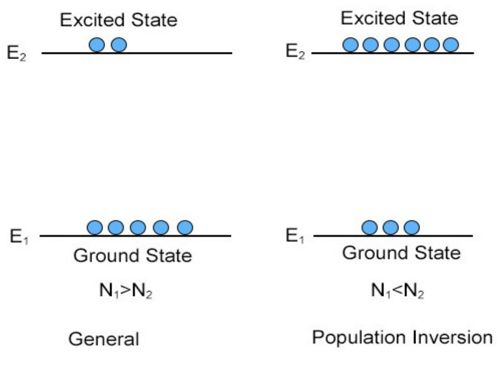


Figure 47: Population Inversion

12.3. Meta-stable state

In physics, a meta-stable state is defined as the excited state of an atom or system that exhibits a longer period of stability than other excited states.

12.4. Pumping

a. Optical Pumping

In order to achieve population inversion, it is necessary to consistently excite atoms or electron from a lower state to a higher state by the process of pumping. The laser must be pumped with the appropriate wavelength to attain population inversion.

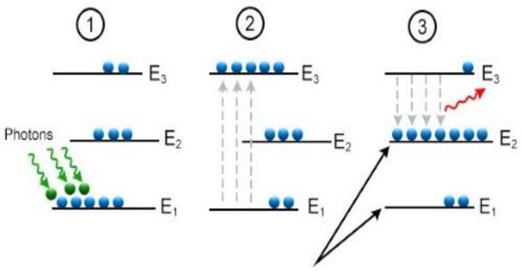


Figure 4.8: Optical Pumping

Optical pumping is a process where strong light sources increase the energy of atoms or molecules in higher energy states than the ground state. This energy causes electrons in the laser medium to transition from their lower energy state to the higher energy state E_3. However, these electrons are unstable and quickly de-excite to the mid-state E_2, which has a longer lifespan than the bottom energy state E_1. This results in population inversion, and is only used in solid-state lasers like ruby and Nd:YAG lasers.

12.5. Component of Laser

a. Source of energy (pump source),

b. Active medium (meta-stable state),

c. Optical Resonator or resonant cavity.

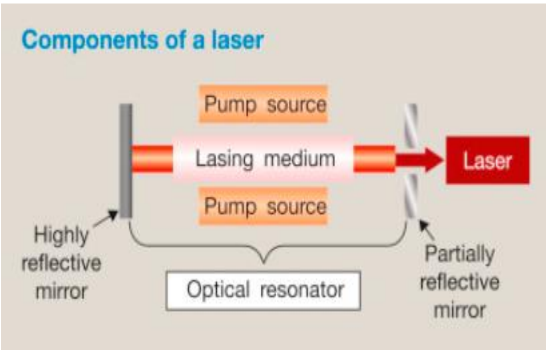


Figure 4.9: Component of Laser

The pump supplies energy for population inversion, and the active medium can be solid, liquid, gas, or semiconductor. The resonator is a feed-back device that directs photons through the laser medium.

12.6. Threshold condition of lasing Action

The laser threshold represents the minimum level of excitation at which the laser output is predominantly stimulated by emission rather than spontaneous emission. To achieve this, it is necessary to maintain a minimum population inversion. As the excitation or population inversion increases, the output power gradually increases, and the line width of the output narrows beyond the threshold. The laser oscillation threshold is attained when the optical gain of the laser amplifying medium is equal to the combined losses experienced by light.

12.7. Laser Rate Equation

Laser Rate equations determine the rate at which populations change under a pump and laser radiation. They provide a steady state population difference between levels, enabling the study of population inversion in transions and the minimum pumping rate needed to maintain steady population inversion for continuous laser wave operation.

12.8. Types of laser rate equation

a. Three Energy Level

In a three energy level laser system where all the energy levels are distinct, the pump energy is applied in the energy state from 1 → 3 transition, while the lasing transition occurs in the energy state 2 → 1 transition. The pump energy raises atoms from energy level 1 to level 3, and these atoms quickly decay to level 2 through a non radiative process. It is essential for level 2 to remain metastable as shown in fig 4.10.

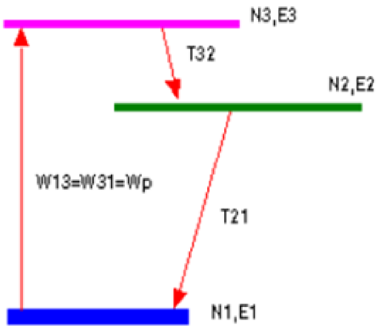


Figure 4.10: Three Energy Level laser systen

Let number of atoms per unit volume N_1, N_2, and N_3 populated at energy levels 1, 2, and 3, respectively.

Therefore, the total atom density per unit volume, N, can be expressed as:

$$N = N_1 + N_2 + N_3 \quad \text{-------------------------------}(1)$$

The change in the population of level 3 is given by:

$$\frac{dN_3}{dt} = W_p(N_1 - N_3) - N_3T_{32} \quad \text{---------------}(2)$$

Here, W_pN_1 = Rate of induced absorptions per unit time per unit volume leading to the energy level 1 → 3 transition, while W_pN_3 = rate of stimulated emissions per unit time per unit volume associated with the energy level 3 → 1 transition.

$$T_{32} = A_{32} + S_{32} \quad \text{--------------------(3)}$$

Where A32 is the Einstein A coefficient linking levels 3 and 2, and S32 is the nonradioactive transition rate from levels 3 to 2.

The rate of change of the population in level 2 is described by:

$$\frac{dN_2}{dt} = W1(N_1 - N2) + N_3T_{32} - N_2T_{21} \text{-------------------(4)}$$

Here $W_1 = B_{21}\, u(\nu)$ .and $T_{21} = 1/\tau_{21}$.

If this transition is mainly radiative, then $T_{21} \approx A_{21}$, where A_{21} is the Einstein coefficient.

$$\frac{dN_1}{dt} = W_p(N_3 - N_1) + W_1(N_2 - N_1) + N_2T_{21} \text{-------------------(5)}$$

Here $W_p = B_{31}\, u(\nu) = B_{13}\, u(\nu)$ .and $T_{21} = 1/\tau_{21}$.

----------------------------(6)

At Steady state, with the help of equation (6) , equation (2) can be written as

$$\frac{dN_1}{dt} + \frac{dN_2}{dt} + \frac{dN_3}{dt} = 0$$

Similarly, equation (4) can be written as

$$N_3 = \frac{W_p}{W_p + T_{32}} N_1$$

Therefore the population difference between the energy levels 2 and 1 is

$$N_2 = \left(W_l + \frac{T_{32}W_p}{W_p + T_{32}} \right) \frac{N_1}{W_l + T_{21}}$$

To achieve population inversion between levels 2 and 1, where $N_2 - N_1$ should be positive i.e. it is essential that T32 is greater than T21.

Furthermore, a minimum pump power is necessary to achieve this inversion.

$$\frac{N_2 - N_1}{N} = \frac{W_p(T_{32} - T_{21}) - T_{32}T_{21}}{3W_pW_l + 2W_pT_{21} + 2T_{32}W_l + T_{32}W_p + T_{32}T_{21}}$$

To obtain population inversion, Wp is required to be greater than W_{pt}.

$$W_{pt} = \frac{T_{32}T_{21}}{T_{32} - T_{21}}$$

b. Four Energy level

In this four level laser system, the ground level is represented by level 1, while levels 2, 3, and 4 are the excited levels. Through the use of a pumping source , atoms from level 1 are energized and raised to level 4. Subsequently, these atoms undergo a rapid decay through a nonradiative transition, bringing them to level 3. Level 3 is characterized as a metastable level due to its extended lifetime.

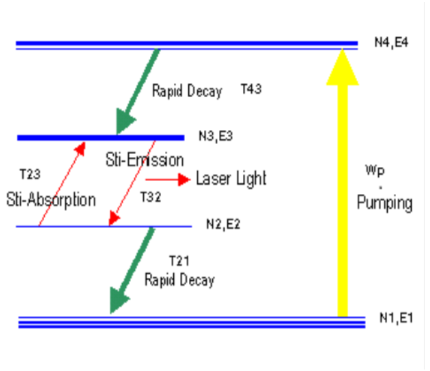


Figure 4.11: Four Energy Level laser systen

Let number of atoms per unit volume N_1, N_2, N_3, and N_4 populated by levels 1, 2, 3, and 4, respectively.

The population change in level 4 is expressed as.

$$\frac{dN_4}{dt} = W_p(N_1 - N_4) - T_4 N_4 \qquad \text{--------------(1)}$$

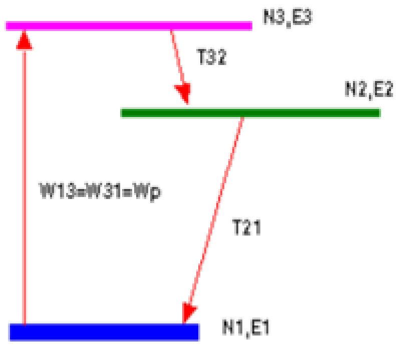


Figure 4.10: Three Energy Level laser systen

$W_p(N_1 - N_4)$ → The pumping rate of stimulated transitions between level 1 and 2 and T_4 is the relaxation rate.

$$T_4 = T_{43} + T_{42} + T_{41} \qquad \text{---------------------(2)}$$

Here T's → the total relaxation rates (both radiative and nonradiative).

Also $T_{43} >> T_{42}$ and T_{41}.

Similarly the rate equation for N_3 would be

$$\frac{dN_3}{dt} = T_{43}N_4 + W_l(N_2 - N_3) - T_3N_3 \qquad \text{--------------------------(3)}$$

Where $T_3 = T_{32} + T_{31}$.

Similarly the rate equations for N_2 and N_1 would be

$$\frac{dN_2}{dt} = T_{42}N_4 + W_l(N_3 - N_2) - T_{21}N_2 + T_{32}N_3 \qquad \text{-------------(4)}$$

$$\frac{dN_1}{dt} = W_p(N_4 - N_1) + T_{41}N_4 + T_{31}N_3 + T_{21}N_2 \qquad \text{--------------(5)}$$

As the total no. of atoms is constant , we have

$$N = N_1 + N_2 + N_3 + N_4 \qquad \text{-----------------(6)}$$

At steady state

$$\frac{dN_1}{dt} + \frac{dN_2}{dt} + \frac{dN_3}{dt} + \frac{dN_4}{dt} = 0 \qquad \text{-----------------------(7)}$$

Using equation (1) , (6) and (7) , we get -----------------------(8)

$$N_4 = \frac{W_p}{2W_p + T_4}(N - N_2 - N_3)$$

Using Eqns. (7),(8) ,(9) and (10) and we obtain

$$N_3\left[(W_l + T_3)\left(\frac{2W_p + T_4}{W_p}\right) + T_{43}\right] + N_2\left[T_{43} - \frac{W_l(2W_p + T_4)}{W_p}\right] = T_{43}N \qquad \text{-----------------------(9)}$$

$$N_3\left[T_{42} - (T_{32} + W_l)\left(\frac{2W_p + T_4}{W_p}\right)\right] + N_2\left[(T_{21} + W_l)\left(\frac{2W_p + T_4}{W_p}\right) + T_{42}\right] = NT_{42} \qquad \text{-------------------(10)}$$

The population difference between level 3 and 2, denoted as $N_3 - N_2$, can be determined by solving the pair of equations., $N_3 - N_2$. We have

$$\frac{N_3 - N_2}{N} = (T_{21}T_{43} - T_3T_{42} - T_{32}T_{43}) \times \left\{T_{43}(T_{21} + T_{32}) + T_3T_{42} + \left(\frac{2W_p + T_4}{W_p}\right)T_3T_{21} + W_l\left[2(T_{42} + T_{43}) + \left(\frac{2W_p + T_4}{W_p}\right)(T_{31} + T_{21})\right]\right\}^{-1}$$

The population difference in the steady state can be determined by this equation, which takes into account the pump power, laser power, and the lifetimes of the different states involved in the four level system. In the majority of four-level systems, the atom tends to relax primarily from level 4 to level 3 and hence

$$T_{42}, T_{41} << T_{43}$$

For good laser action one must have $T_3 << T_{43}$ and $T_{21} >> T_{32}$ so that $\beta \rightarrow 0$. Also $T_4 \approx T_{43}$.

Therefore

$$\frac{N_3 - N_2}{N} = \frac{W_p/T_3}{1 + W_p/T_3}$$

When comparing the population difference at steady state between a three level and four level laser system, it becomes evident that achieving inversion is significantly easier in a four level scheme compared to a three level system.

Self-Assessment

1. What are the main components of a laser?
2. What is the role of the optical resonator in a laser?
3. What is the function of the gain medium in a laser?
4. What is the significance of the output coupler in a laser?
5. Describe the purpose of the optical resonator in a laser.
6. How do mirrors in the optical resonator affect the laser beam?
7. What role does the energy source or pump play in a laser?
8. Which component of a laser ensures the light remains coherent and monochromatic?

A) Gain medium B) Optical resonator C) Energy source D) Output coupler

9. What role do the mirrors in a laser's optical cavity play?

A) Absorb excess energy B) Pump the gain medium

C) Reflect light back and forth to amplify it D) Disperse the light

10. Which component in a laser ensures that only light of a specific wavelength is amplified?

A. The laser medium B. The optical cavity (resonator)

B. The power supply D. The cooling system

11. What is the role of the energy source (pump) in a laser?

A) To cool the system

B) To produce spontaneous emission

C) To excite the electrons to higher energy levels

D) To focus the laser beam

12. In laser terminology, what is a "pumping mechanism"?

A. The method used to cool the laser medium

B. The process of emitting laser light

C. The process of supplying energy to the laser medium to achieve population inversion

D. The process of aligning the mirrors in the laser cavity

Unit-13

Types and Application of LASER

13.1. Types of Laser

Various types of lasers are now in operation which can be broadly classified into.

a. Solid State Lasers : Ruby Laser

Rby laser is a three level strong state laser and was developed by Mainmann in 1960. Ruby (Al2O3+Cr2O3) is a precious stone of Aluminum oxide, wherein 0.05% of Al+3 particles are supplanted by the Cr^{+3} particles. The shade of the pole is pink. The dynamic medium in the ruby pole is Cr^{+3} particles.

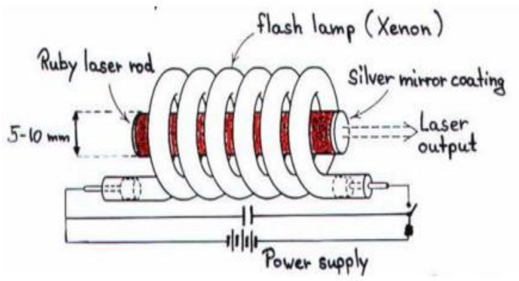


Figure 13.12: Block Diagram of Ruby

Laser Medium:

- A solitary crystal of ruby (Al_2O_3) is used as the host material, with a minimal addition of Cr_2O_3 (0.05%) acting as the dopant.

Pumping Source:

- A flashtube is used as the pumping source, absorbing energy amounting to several thousand joules.
- The heat produced is removed by liquid nitrogen, while blue and green radiation is absorbed by the Ruby.

Optical Resonator:

- The cylindrical ruby rod is placed between two mirrors with optical coating.
- The mirrors are fully or partially silvered, reflecting light and allowing a portion to pass out as output laser light.
- The optical pumping results when incident photons of wavelength 5500Å raise the

chromium Ion from ground state to higher excited state, producing population inversion.

Working of the Ruby Laser:

- The laser is a three-level solid-state laser, with optical pumping done by a helical xenon flash lamp.
- The laser medium consists of three energy levels: ground energy state E_1, metastable state E_2, and excited state E_3.
- When light energy is supplied to the laser medium, the electrons in the lower energy state gain enough energy to jump into the excited state.
- The excited electrons come down to the metastable state, increasing the number of electrons in the metastable state, achieving population inversion.

With the use of mirrors at both ends, photons are able to travel through the active medium millions of times.

- A strong laser pulse emits with a wavelength of 694.3 nm or 6943Å. when the requirements for laser action are met.

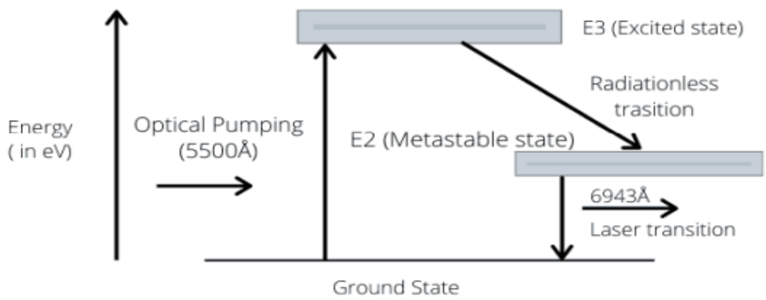


Figure 4.13: **Energy Level laser systen**

Applications of Ruby Lasers:

1. Measuring distances with the 'pulse echo' method.
2. Creating holograms.
3. Determining the height of the atmosphere and measuring how light scatters.
4. Shaping resistors.
5. Creating precise holes.
6. Creating markers for targets and devices that measure distances in military and other fields.
7. Removing tattoos and hair.

b. Gaseous Lasers : He- Ne Laser

The Ruby laser operates as a pulse laser, despite its significant power output. To maintain a continuous laser beam, gas lasers are employed. Gas lasers enable the attainment of exceptional coherence, directionality, and monochromaticity in the beam. The power of a gas laser's output typically ranges from a few milliwatts. The first gas laser was He-Ne laser constructed by Ali Javan in 1961. The He-Ne laser is a four-level laser with a wavelength of 632.8 nm, typically used in Continuous Working (CW) mode in the red portion of the visible spectrum.

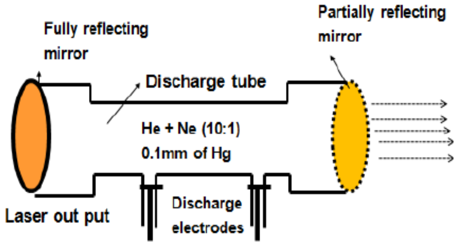


Figure 4.14: **Block Diagram of He-Ne laser**

He-Ne Laser Components and Functions

Laser Medium : A gas laser is a narrow quartz tube filled with a mixture of Helium and Neon gases, with Ne atoms acting as active centers and He atoms aiding in excitation. The tube measures 50 cm in length and 1 cm in diameter, with Ne atoms responsible for laser action.

Pumping Source: The pumping process is achieved by utilizing electrical sparks through the use of electrodes linked to a high-frequency alternating current power supply.

Optical Resonator:

To build the optical resonator cavity, two side-by-side mirrors are positioned at the tube's ends. One mirror is partially transparent, and the other is completely reflective. The distance between the mirrors is set to match the exact multiple of half-wavelengths of the laser light.

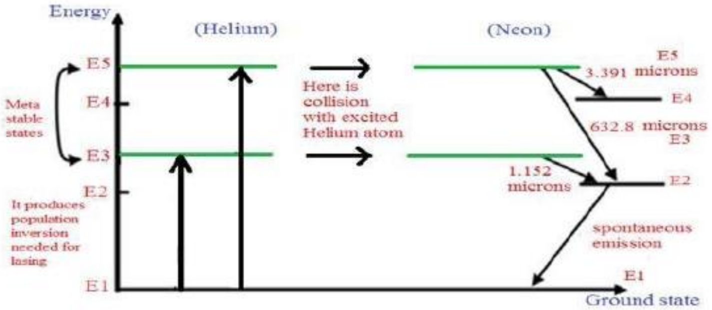


Figure 4.15: **Energy Level laser system of He-**

Working of the He- Ne Laser: The helium-neon gas laser utilizes a combination of Helium and Neon gases in a glass tube with parallel mirrors, one of which is partially transparent at each end. An electric discharge is created in the gas through electrodes connected to a high-frequency alternating current source, leading to collisions that excite Helium and Neon atoms to metastable states.

- The laser transition in Neon involves emission of a 650nm photon from a metastable state to an excited state, followed by the spontaneous emission of another photon during a transition to a lower metastable state, resulting in incoherent light.

Applications of He-Ne Lasers:

1. Interferometry study
2. Applications in metrology
3. Reading bar codes
4. Image manipulation
5. The Hologram

c. Semiconductor Lasers : Gas laser or injection laser

A p-n junction device known as a semiconductor diode laser is capable of emitting coherent light when it is forward biased. The initial semiconductor laser was developed by R.N Hall and his colleagues in 1962. This laser is constructed using Gallium arsenide (GaAs), a direct band gap semiconductor that operates at low temperatures and emits light in the near IR region. Nowadays, p-n junction lasers can emit light across a wide range of the spectrum, from UV to IR. Diode lasers are impressively compact, measuring only 0.1mm in length, and exhibit a high efficiency of approximately 40%.

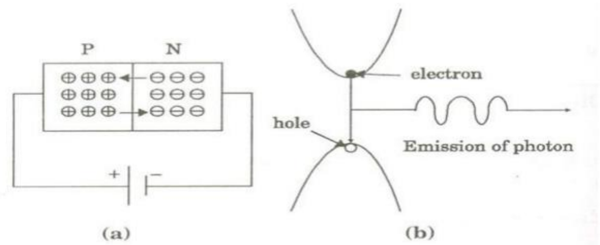


Figure 4.16: Recombination process of electron-hole

Semiconductor Laser Components and Functions

- The p-n junction diode is constructed using a single crystal of gallium arsenide, cut into a platter shape with a 0.5µ mm thickness.
- This diode is sandwich of n-type and p-type semiconductor materials , allowing for photon emission in a thin layer of the PN junction.
- An electrode on the upper surface of the crystal applies an electrical voltage, while the diode's well-polished end faces function as an optical resonator for the emitted light.

Working of the Semiconductor Laser:

When a large applied voltage is used to forward bias the PN junction, a significant concentration of electrons and holes is injected into the junction region.

- The region surrounding the junction contains a high number of electrons in the conduction band and a substantial number of holes in the valence band.
- If the population density is sufficiently high, population inversion occurs.
- Recombination of electrons and holes takes place, resulting in the emission of radiation in the form of light.
- As the forward-biased voltage increases, the emission of light photons intensifies, leading to a stronger light production.
- These photons initiate a chain of stimulated recombination, causing the release of photons in phase.
- The photons travel back and forth along the plane of the junction through reflection between two parallel and opposite sides, gradually gaining strength.
- Once the photons have gained enough strength, they emit a laser beam with a wavelength of 8400 Å.

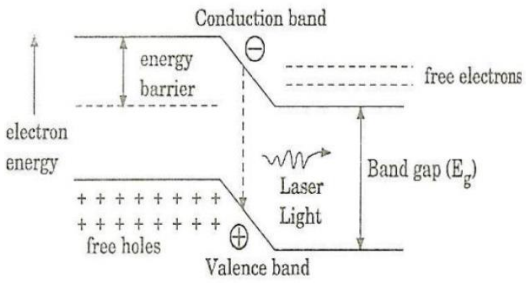


Figure 4.17: Laser transition process in

13.2. Applications of Lasers

Laser cutting is a process where a laser is used to cut thin metal sheets by focusing the laser onto a specific area for an extended period of time, resulting in the sheet being cut due to the thermal effect.

- Laser welding is a technique that avoids damaging the surrounding material by focusing the laser beam onto the area to be welded, melting and joining only that specific area without affecting the rest of the material.
- High power lasers have a wide range of industrial applications, including welding, melting, cutting, and material quality testing, without causing damage to the structure of the materials.
- Laser cosmetics surgery is a medical procedure that utilizes lasers to eliminate tattoos, scars, stretch marks, sunspots, wrinkles, and unwanted hair.

- Dermatology utilizes various types of lasers such as Ruby (694nm), pulsed diode arrays (810nm), Nd: YAG (1064nm), and Er: YAG (2940nm) for different treatments.
- Laser eye surgery is a medical intervention that utilizes lasers to reshape the eye's surface, correcting issues like short-sightedness, long-sightedness, and astigmatism.
- Soft tissue laser surgery involves the precise use of laser beams to vaporize soft tissue with high water content, finding applications in general surgery, neurosurgery, ENT, dentistry, oral surgery, and veterinary surgical fields.

Self-Assessment

1. What is the active lasing medium in a Ruby laser?
2. What is the primary mechanism for achieving population inversion in a Ruby laser?
3. Describe one common application of a He-Ne laser.
4. What type of laser is a Ruby laser classified as: solid-state, gas, dye, or semiconductor?
5. Describe one common application of a Ruby laser.
6. Which type of laser uses a semiconductor as the gain medium?

A) Gas laser

B) Dye laser

C) Solid-state laser

D) Semiconductor laser

7. In a gas laser, what is typically used as the gain medium?

A) A semiconductor material B) A liquid dye

C) A gas or mixture of gases D) A solid crystal

8. Which of the following statements is true about the Ruby laser?

a) The Ruby laser operates at a wavelength of 1064 nm.

b) The active medium in a Ruby laser is a crystal of aluminum oxide doped with chromium.

c) The Ruby laser emits light in the ultraviolet region.

d) The Ruby laser is a continuous wave (CW) laser.

9. In a He-Ne laser, which gas is primarily responsible for the lasing action?

A. Helium B. Neon C. Argon D. Krypton

10. The wavelength of light emitted by a standard He-Ne laser in nanometer :

A. 694 B. 632.8 C. 1064 D. 532

Unit-14

Optical Fiber

14.1. Optical Fibre

Optical fibre is a thin, flexible, and transparent wire that is specifically designed for the propagation of light. The main purpose of constructing optical fibres is to enable the transmission of light waves over long distances without any significant loss.

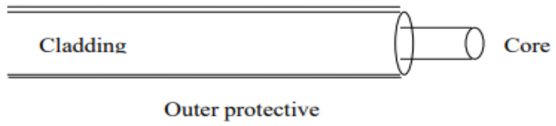


Figure 4.18: Block diagram of Optical Fibre

Optical fibres have a wide range of applications in various industries and medical fields.

14.2. Light propagation through optical fiber

The phenomenon of total internal reflection occurs when light travels through an optical fiber. This is achieved through a process called "Total internal reflection", which can be explained by the following reasons.

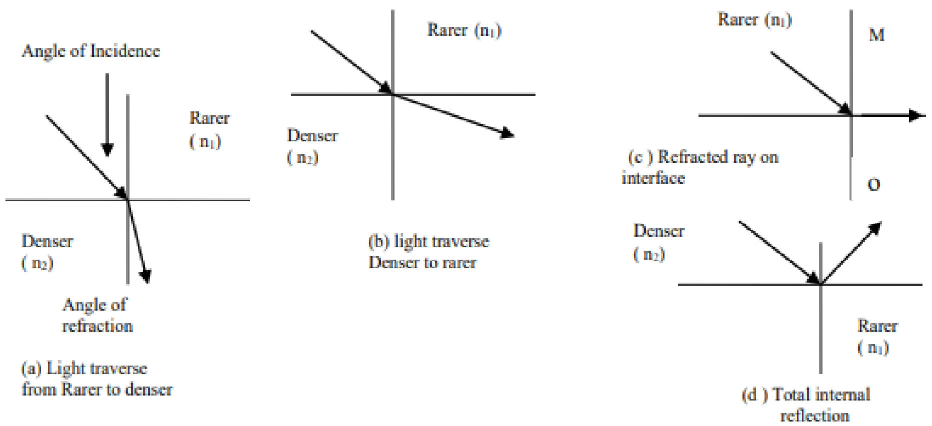


Figure 4.19: Light propagation through optical fiber

Light behaves differently when it moves from a less dense medium to a denser one or vice versa. In the first case, the refracted ray moves towards the normal drawn on the interface between the two media fig (a) . On the other hand, in the second case, the refracted ray moves away from the normal fig (b) .

As the angle of incidence increases, there is a point where the refracted ray aligns with the interface of the two media. This specific angle is called the critical angle fig (c).

If the incident angle exceeds the critical angle, the refracted ray does not leave the denser medium but instead undergoes reflection within it fig (d) . This phenomenon is known as total internal reflection.

To summarize, total internal reflection happens under the following conditions:

1. The light ray must transition from a denser medium to a less dense one optically.
2. The angle at which the light ray strikes the surface must be larger than the critical angle ($\theta i > \theta c$).

According to law of reflection ,

$$n_1 \sin\theta_i = n_2 \sin 90^0$$

$$\sin\theta_i = \frac{n_2}{n_1}$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

14.3. Classification of Optical Fibre

The classification of optical fibers based on refractive index includes two main types:

a. Step index fibers
b. Graded index fibers
c. Single mode fibers
d. Multimode fibers.

14.4. Acceptance angle

The highest angle at which a light ray can enter the end face of an Optical fiber and still be transmitted along the Core-Cladding interface is referred to as the maximum Acceptance angle. This angle is also commonly known as the Acceptance cone half angle.

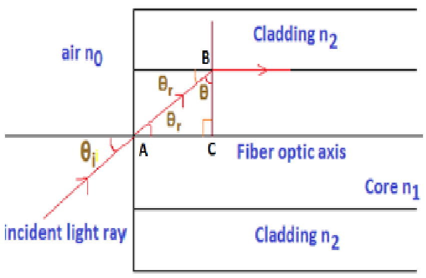


Figure 4.22: Acceptance Angle

$$NA = \sin\theta_i = \sqrt{n_1^2 - n_2^2} \qquad \theta_i = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

$$\sin\theta_i = \sqrt{n_1^2 - n_2^2} \qquad \theta_a = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right) = \sin^{-1}(NA)$$

14.5. Numerical aperture NA

Light gathering power of the optical fiber represented by Numerical Aperture, it is directly related to the Acceptance Angle. The Numerical Aperture is mathematically equivalent to the sine of the smallest Acceptance Angle.

$$NA = \sin\theta_{max}$$

$$\sin\theta_{max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$$

$$NA = \sqrt{{n_1}^2 - {n_2}^2}$$

$$NA = \sqrt{(n_1 + n_2)(n_1 - n_2)}$$

14.6. Applications of Optical Fiber

An effective optical fiber communication system necessitates a high information carrying capacity for voice signals, video signals, and other data over long distances with minimal repeaters. The system is comprised of the following components: Encoder, Transmitter, Wave Guide, Receiver, and Decoder.

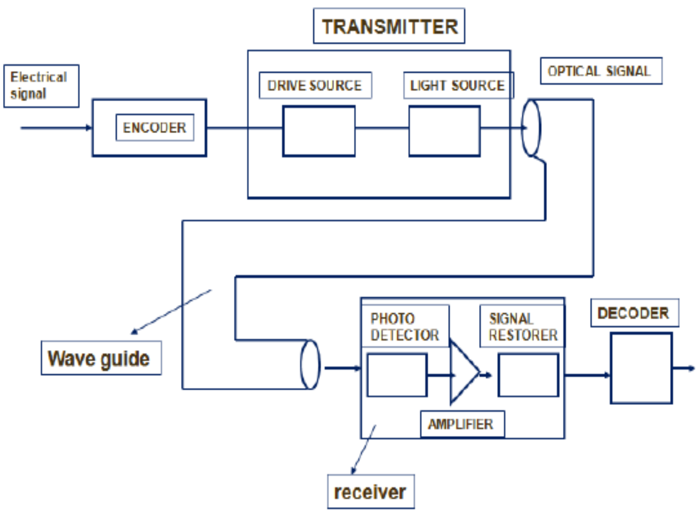


Figure 4.23: **Optical Fibre Communication**

1. Encoder: This component converts analog information, such as voice, figures, and objects, into binary data. The binary data is then transmitted as a stream of electrical pulses.

2. Transmitter: The transmitter comprises of a drive circuit and a light source, where the drive circuit delivers electric pulses to the light source originating from the encoder. Usually, a LED or diode laser is employed as the light source, transforming electrical signals into optical signals that are subsequently introduced into the wave guide.
3. Wave Guide: The wave guide carries the optical signals over the desired distance.
4. Receiver: The receiver consists of a photo detector, amplifier, and signal restorer. The photo detector converts optical signals back into electrical signals, which may have weakened over long distances. The amplifier boosts the weak signal, which is then processed by the signal restorer to organize the signals received from the wave guide and photo detector.
5. Decoder: Finally, the signals are decoded and sent in their original form.

Self-Assessment

1. What are fiber optics and how do they work?
2. What are some applications of fiber optics?
3. What is total internal reflection and how does it apply to optical fibers?
4. What are the main applications of optical fibers in telecommunications?
5. What are some challenges and limitations of optical fiber technology?
6. What is the core function of the cladding in an optical fiber?

a) To absorb the light signal
b) To reflect the light back into the core
c) To transmit the light signal
d) To amplify the light signal

7. Which of the following types of optical fibers is typically used for long-distance communication?

a) Single-mode fiber
b) Multi-mode fiber
c) Plastic optical fiber
d) Quantum fiber

8. What is the primary material used in the core of most optical fibers?

a) Plastic
b) Copper
c) Silicon
d) Glass (silica)

9. In fiber optics, what is "total internal reflection"?
a) The process of light being absorbed by the core
b) The bending of light at the interface between two media
c) The complete reflection of light within the core of the fiber
d) The dispersion of light as it passes through the fiber

10. Which of the following components is NOT typically part of an optical fiber communication system?
a) Optical transmitter
b) Optical receiver
c) Optical repeater
d) Radio frequency modulator

Keywords

Interference: The phenomenon where two or more waves superpose to form a resultant wave of greater, lower, or the same amplitude.

Coherence: The property of waves where they have a constant phase relationship or a fixed phase difference.

Constructive interference: When two waves meet in phase, resulting in a wave with greater amplitude.

Destructive interference: When two waves meet out of phase, resulting in a wave with reduced or zero amplitude.

Young's double-slit experiment: An experiment demonstrating the interference of light, showing light passing through two slits produces an interference pattern.

Huygens' Principle: States that each point on a wavefront acts as a source of secondary spherical wavelets, and the wavefront at a later time is the envelope of these wavelets.

Wave front: A surface or line representing constant phase in a wave propagation.

Fresnel Biprism: An optical device consisting of a thin transparent wedge with a small angle between its two faces, used to split a single beam of light into two coherent beams.

Coherent Sources: Light sources that emit waves with a constant phase relationship, crucial for producing interference patterns.

Interference Fringes: The bright and dark bands observed when the split beams from the Fresnel biprism interfere with each other, indicating regions of constructive and destructive interference.

Fresnel Distance: The distance at which the spherical wavelets from the two slits of the biprism overlap and interfere to form a coherent interference pattern.

Monochromatic Light: Light consisting of a single wavelength or color, essential for producing clear interference fringes.

Path difference: The difference in the distances traveled by two waves.

Thin-film interference: Interference occurring due to reflection and transmission of light through thin films, resulting in colorful patterns.

Phase difference: The difference in phase between two waves at a specific point in space and time, often expressed in degrees or radians.

Interference fringes: Patterns of light and dark regions produced by interference, indicating constructive and destructive interference.

Newton's Rings: Circular interference fringes observed when monochromatic light is reflected between a spherical surface (convex lens) and a flat surface (glass plate), forming concentric rings.

Monochromatic Light: Light consisting of a single wavelength or color, essential for producing clear and distinct Newton's rings.

Radius of Curvature: The radius of the spherical surface of the lens in Newton's rings experiment, determining the curvature and spacing of the interference pattern.

Michelson Interferometer: An optical instrument used to measure small displacements, differences in refractive index, and wavelengths of light based on interference patterns.

Interference Pattern: The pattern of light and dark fringes observed when coherent light waves interfere after splitting and recombining in the interferometer.

Michelson interferometer: A device used to measure small displacements, changes in refractive index, and wavelengths of light based on interference patterns.

Fringe Visibility: The contrast and visibility of interference fringes in the interferometer, affected by factors such as the coherence length of the light source.

Diffraction: The bending and spreading of light waves around obstacles and through apertures, resulting in interference patterns and deviations from geometric optics predictions.

Aperture: An opening or hole through which light passes, affecting the diffraction pattern and resolution of an optical system.

Fraunhofer Diffraction: light source, diffracting element (such as a slit or grating), and observing screen are all at a considerable distance from each other.

Fresnel Diffraction: light source, diffracting element (such as a slit or grating), and observing screen are all at comparable to the wavelength of light.

Single-Slit Diffraction: Diffraction pattern produced when light passes through a narrow slit, characterized by a central bright fringe and alternating dark and bright fringes on either side.

Diffraction Grating: Optical device consisting of closely spaced parallel slits or grooves that produce multiple diffraction orders and interference patterns, used in spectrometers and wavelength analysis.

Diffraction Limit: The minimum achievable size of the spot to which a light beam can be focused due to diffraction effects, limiting the resolution of optical systems.

Intensity Distribution: Distribution of light intensity across the diffraction pattern, influenced by the size and shape of the diffracting element and wavelength of light.

Circular Aperture: An opening through which light passes, producing a diffraction pattern characterized by concentric rings (Airy pattern) in Fraunhofer diffraction.

Wavefront Curvature: The bending of light waves around obstacles or through apertures, influencing the diffraction pattern observed in Fresnel diffraction.

Fresnel Zone Plate: A diffractive optical element resembling a lens, used to focus light or other electromagnetic waves based on diffraction principles.

Polarization: The orientation of the electric field vector of a light wave, which defines the direction of oscillation of the wave in a plane perpendicular to its wave propagation direction.

Transverse Wave: In which oscillations of the wave occur perpendicular to the direction of wave propagation.

Electromagnetic Wave: A wave consisting of synchronized oscillations of electric and magnetic fields, propagating through space, including visible light.

Electric Field Vector: A vector that represents the strength and direction of the electric field at a point in space, used to describe the polarization of light.

Unpolarized Light: Light in which the electric field vectors oscillate randomly in all directions of propagation.

Linear Polarization: Light in which the electric field vector propagates in a single plane along the direction of propagation.

Circular Polarization: Light in which the electric field vector traces out a circular path as it propagates, with a constant magnitude and rotating direction.

Elliptical Polarization: Light in which the electric field vector traces out an elliptical path as it propagates, with varying magnitudes and changing direction.

Malus's Law: It states that the intensity of transmitted light through a polarizer is proportional to the square of the cosine of the angle between the optic axis of the polarizer and the direction of the incident light.

Brewster's Angle: The angle of incidence at which light waves polarized parallel to the interface of a transparent dielectric material are perfectly transmitted, minimizing reflection.

Polarimeter: An instrument used to measure and analyze the polarization properties of light, often based on principles such as transmission through polarizers or rotation by optical activity.

Optical Activity: The ability of certain materials (such as chiral molecules) to rotate the plane of polarization of light passing through them.

Polarizer: An optical device that confine the light in particular plane /direction..

Laser: Abbreviated as "Light Amplification by Stimulated Emission of Radiation" that emits highly coherent directional monochromatic light.

Coherence: The property of light waves emitted by a laser to have a constant phase relationship over a long distance, resulting in interference patterns and sharp fringes.

Monochromatic: Light emitted by a laser that has a very narrow wavelength range, typically with a linewidth much narrower than conventional light sources.

Stimulated Emission: A process in which a photon from the source stimulate the excited atom and produce laser .

Population Inversion: An excited state of atoms or ions in which there are more particles in an excited state than in lower energy states, crucial for laser operation.

Amplification: The process by which the energy of photons passing through the laser medium is increased, leading to the emission of coherent light.

Optical Resonator: A cavity formed by two mirrors, one fully reflective and one partially reflective, which traps and amplifies light within the laser medium.

Gain Medium: The material within a laser where stimulated emission occurs, typically a crystal, gas, or semiconductor with specific energy levels.

Pump Source: The external energy source (such as flash lamps or diode lasers) used to excite atoms or ions in the gain medium to achieve population inversion.

Ruby Rod: The solid cylindrical rod of synthetic ruby used as the gain medium in a ruby laser.

Gas Discharge Tube: The tube containing the helium-neon gas mixture, through which an electrical discharge excites the gas atoms to produce laser light.

Four-Level Laser System: Laser system where four energy levels are involved in lasing action, characteristic of He-Ne lasers.

Optical Fiber: A fine thin wire of glass based on total internal reflection used to transmit electromagnetic wave .

Core: The central region of an optical fiber through which light is transmitted, typically made of high-purity glass or plastic.

Cladding: It is outer layer surrounding the core and has a lower refractive index .

Total Internal Reflection: The phenomenon where light waves traveling within the core of an optical fiber are reflected back into the core due to the difference in refractive index between the core and cladding.

Multimode Fiber: An optical fiber with a larger core diameter that allows multiple light modes to propagate, used for shorter-distance communication.

Single-mode Fiber: An optical fiber with a small core diameter that allows only a single light mode to propagate, enabling longer-distance communication with lower attenuation.

Attenuation: It is defined as the loss of signal during the propagation of light through an optical fibre which measure in dB/km.

Dispersion: The spreading of light pulses as they travel through an optical fiber due to variations in the speed of light at different wavelengths.