PART – 1: Wave Theory of Light and Huygens' Principle

1.1 Introduction to Wave Optics

In Ray Optics, light is considered to travel in the form of straight-line rays.
However, several phenomena such as Interference, Diffraction, and Polarisation cannot be explained by ray optics alone. These phenomena establish the **wave nature of light**. The study of these phenomena is called **Wave Optics**.

1.2 Wave Nature of Light

According to the wave theory, light travels in the form of waves.
A light wave is an electromagnetic wave consisting of:

- Electric field
- Magnetic field

The electric field and magnetic field are mutually perpendicular and also perpendicular to the direction of propagation.
Therefore, light is a **transverse electromagnetic wave**.

1.3 Wave Equation

A progressive sinusoidal wave may be represented as:

$$y = A\,sin(kx - \omega t + \varphi)$$

Where,
A = amplitude of wave
k = wave number
ω = angular frequency
φ = initial phase
x = position
t = time

1.4 Important Wave Relations

The basic relation between velocity, frequency and wavelength is:

$$v = f\lambda$$

Where,
v = velocity of wave
f = frequency
λ = wavelength
Since,

$$f = \frac{1}{T}$$

Therefore,

$$\boxed{v = \frac{\lambda}{T}}$$

1.4.1 Time Period

Time period is the time taken by a wave to complete one cycle.

$$T = 1/f$$

Therefore,

$$f = 1/T$$

1.4.2 Angular Frequency

Angular frequency is given by:

$$\omega = 2\pi f$$

Since,

$$f = 1/T$$

Therefore,

$$\omega = 2\pi/T$$

Hence,

$$\boxed{T = 2\pi/\omega}$$

1.4.3 Wave Number

Wave number is defined as the number of wavelengths contained in 2π radians of phase.

$$k = 2\pi/\lambda$$

Therefore,

$$\lambda = 2\pi/k$$

1.4.4 Relation between Wave Velocity, Angular Frequency and Wave Number

We know:

$$v = f\lambda$$

Using,

$$f = \omega/(2\pi)$$

and

$$\lambda = 2\pi/k$$

Therefore,

$$v = (\omega/2\pi)(2\pi/k)$$

Hence,

$$\boxed{\boldsymbol{v = \omega/k}}$$

This is an important relation for numerical problems.

1.5 Wavefront

A **wavefront** is an imaginary surface joining all the points of a wave which are in the same phase of vibration.

In simple words:

A wavefront is a surface of constant phase.

For example, all points on a wavefront have the same phase of vibration. For a wavefront corresponding to a crest, all points reach maximum displacement simultaneously.

1.5.1 Important Properties of Wavefront

1. All points on a wavefront are in the same phase.
2. The distance between two successive wavefronts is equal to one wavelength.
   Distance between successive wavefronts = λ
3. A light ray is always perpendicular to the wavefront.
4. The direction of propagation of the wave is normal to the wavefront.

1.6 Types of Wavefront

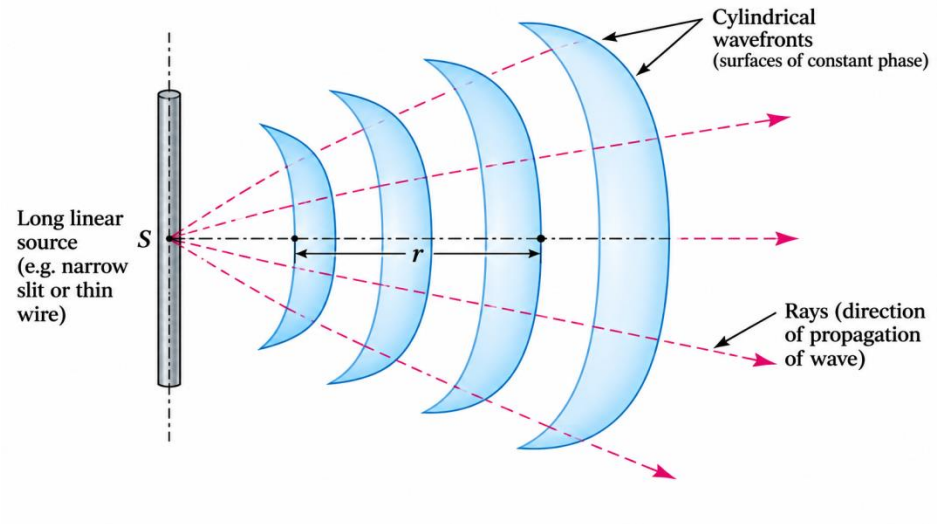
There are mainly three types of wavefronts:

1. Cylindrical wavefront
2. Spherical wavefront
3. Plane wavefront

1.6.1 Cylindrical Wavefront

When light originates from a long linear source, the wavefronts are approximately cylindrical.

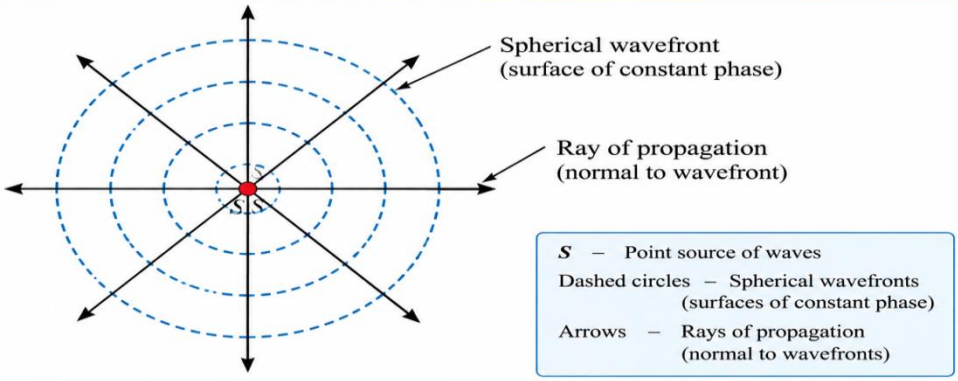
Figure 10.1 : Cylindrical Wavefront



1.6.2 Spherical Wavefront

When light originates from a point source, the wavefronts are spherical.
The source acts as the centre of the spherical wavefront.
As the wave travels outward, successive spherical surfaces are formed.

Figure 10.2 | Spherical Wavefront

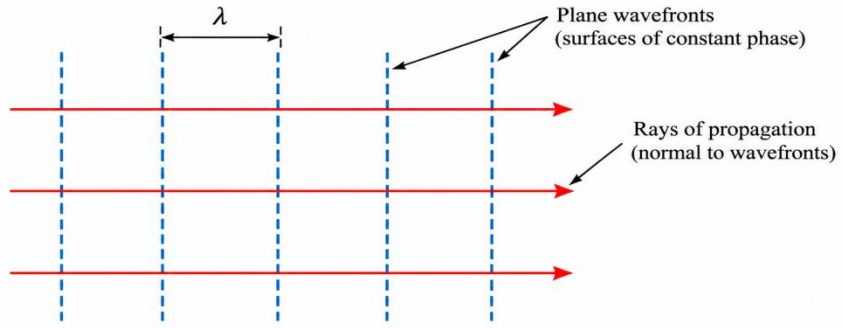


A point source *S* in a homogeneous medium produces spherical wavefronts, which are concentric spheres (circles in a two-dimensional diagram). Rays of propagation are perpendicular (normal) to the wavefronts.

1.6.3 Plane Wavefront

When the source is very far away, the curvature of the spherical wavefront becomes very small. The wavefront can then be considered approximately plane.
Thus, light coming from a distant source produces nearly plane wavefronts.

Figure 10.3 | Plane Wavefront



A plane wavefront consists of a family of parallel planes (represented by parallel dashed lines) of constant phase. The rays of propagation are straight, parallel and perpendicular (normal) to the plane wavefronts.

λ – Wavelength (distance between two successive plane wavefronts)

1.7 Relation between Wavefront and Light Ray

A light ray represents the direction in which the wave propagates.
The ray is always normal (perpendicular) to the wavefront.
Therefore:

Light ray ⊥ Wavefront

For a plane wavefront, the rays are parallel.
For a spherical wavefront, the rays are radial.

1.8 Huygens' Principle

The wave nature of light was explained geometrically by **Christiaan Huygens**.
According to Huygens' principle:
Every point on a wavefront acts as a source of secondary wavelets which spread out in the forward direction with the same speed as the wave. The new wavefront is obtained by drawing a common tangent to these secondary wavelets.

1.8.1 Main Points of Huygens' Principle

According to Huygens:

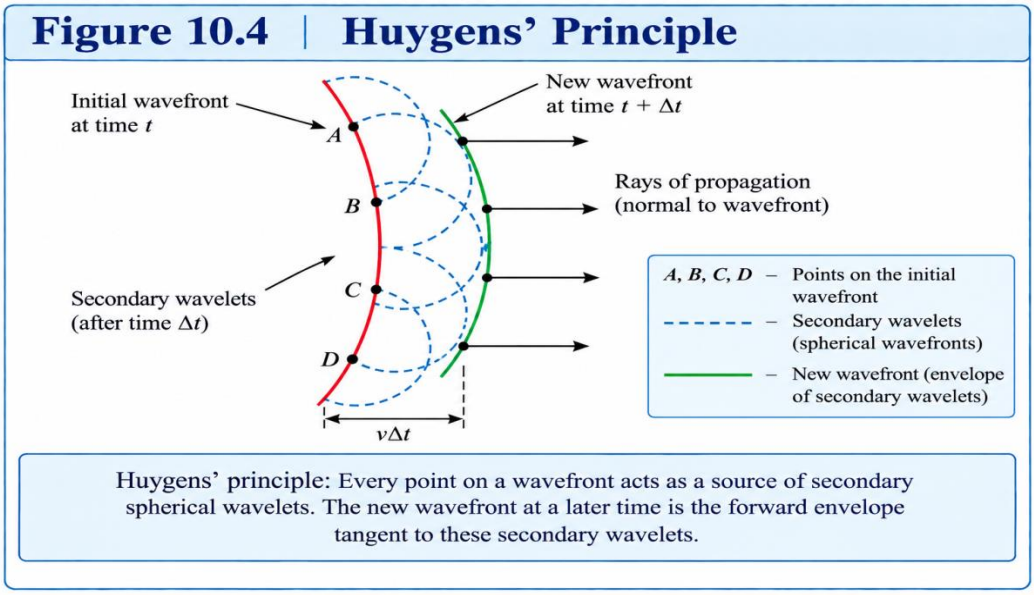
1. Every point on a wavefront acts as a source of secondary wavelets.
2. Secondary wavelets spread in all directions in the medium. The new wavefront is obtained by drawing the forward envelope (common tangent) to these secondary wavelets.
3. The secondary wavelets travel with the same speed as the original wave.
4. The new wavefront is the forward envelope or common tangent to the secondary wavelets.

1.9 Secondary Wavelets

Suppose AB is an original wavefront.
After a small time dt, every point on AB produces secondary wavelets.
If the velocity of light in the medium is v, then the radius of each secondary wavelet is:

$$r = v\,dt$$

The common tangent to these wavelets gives the new wavefront.



1.10 Propagation of a Plane Wavefront

Consider a plane wavefront AB.
Every point on AB produces secondary wavelets.
After time dt, the radius of each wavelet is: $r = v\,dt$
A tangent drawn to these wavelets gives the new plane wavefront A′B′.
Thus, the wavefront moves forward without changing its shape.

1.11 Huygens' Principle and Reflection

Huygens' Principle can be used to explain the laws of reflection.
Consider a plane wavefront AB incident on a plane reflecting surface XY.
Different points of the wavefront reach the reflecting surface at different times.
Each point of the surface acts as a source of secondary wavelets.
The reflected wavefront is obtained as the tangent to these reflected wavelets.
From the geometrical construction, we obtain: $i = r$
Where,
i = angle of incidence
r = angle of reflection
Thus, Huygens' Principle gives the second law of reflection:

Angle of incidence = Angle of reflection

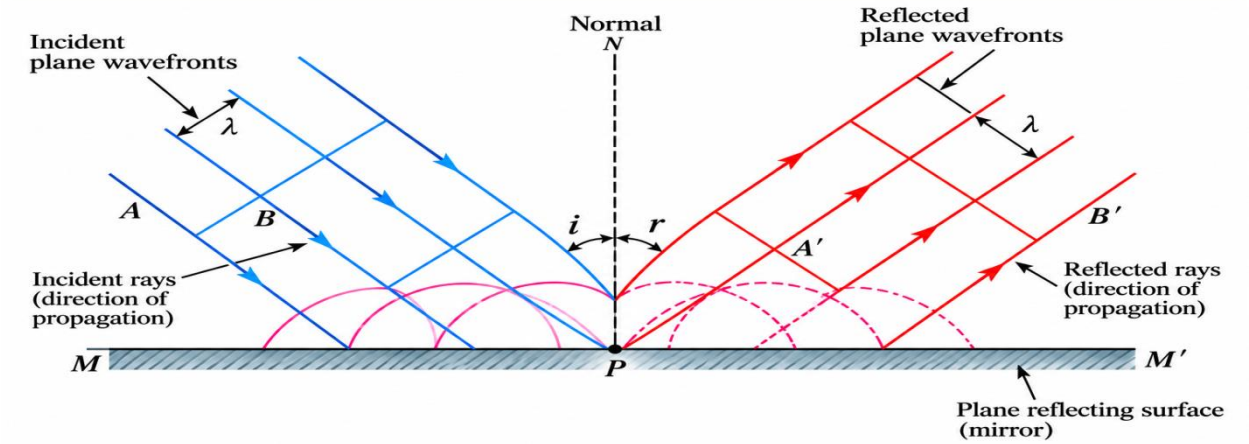
1.11.1 Laws of Reflection

The laws of reflection are:

First law: The incident ray, reflected ray and normal at the point of incidence lie in the same plane.

Second law: The angle of incidence is equal to the angle of reflection. $i = r$

Figure 10.5 : Reflection of Plane Wavefront Using Huygen's Principle



1.12 Huygens' Principle and Refraction

"Huygens' Principle also explains the refraction of light."

When light passes from one transparent medium to another, its speed changes.

Suppose:

Velocity of light in medium 1 = v_1

Velocity of light in medium 2 = v_2

If the refractive indices are n_1 and n_2, then:

$$n_1 = c/v_1 \; and \; n_2 = c/v_2$$

Therefore,

$$n_2/n_1 = v_1/v_2$$

This relation is very useful in numerical problems.

1.13 Snell's Law from Huygens' Principle

Using Huygens' construction for refraction, we obtain:

$$sin\, i/sin\, r = v_1/v_2$$

Since,

$$v_1/v_2 = n_2/n_1$$

Therefore,

$$sin\, i/sin\, r = n_2/n_1$$

Hence,

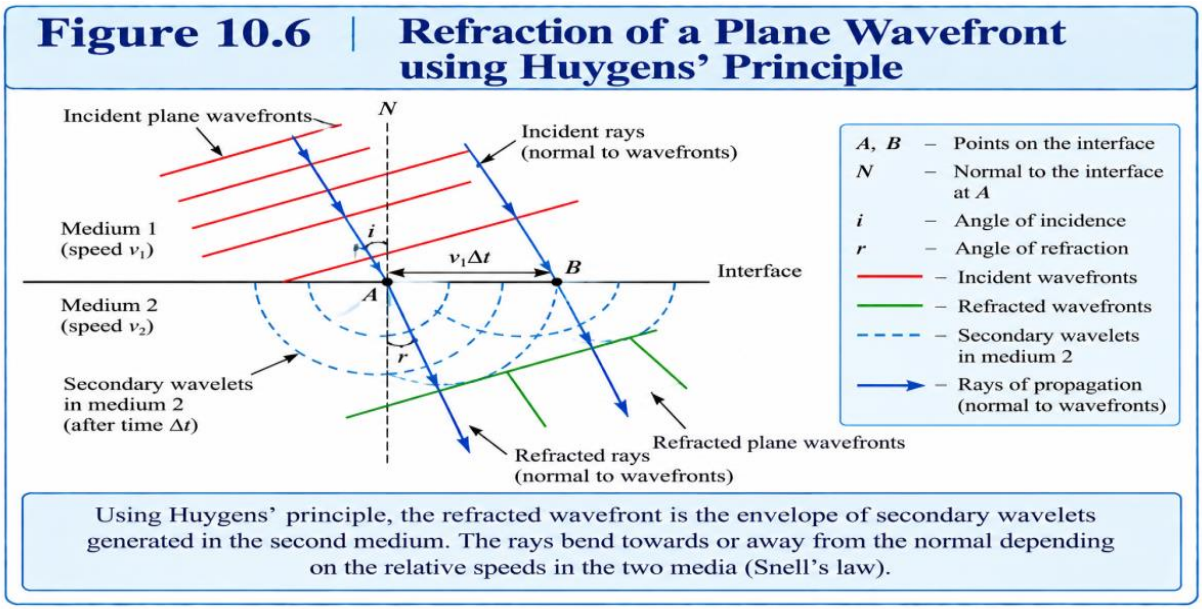
$$\boldsymbol{n_1 \, sin \, i = n_2 \, sin \, r}$$

This is known as **Snell's law**.

1.13.1 Important Cases

Light travelling from rarer to denser medium

If: $n_2 > n_1$, then the ray bends **towards the normal**.



Light travelling from denser to rarer medium

If: $n_2 < n_1$, then the ray bends **away from the normal**.

1.14 Refractive Index and Speed of Light

The absolute refractive index of a medium is:

$$n = c/v$$

Where,
n = refractive index of medium
c = speed of light in vacuum
v = speed of light in the medium
Therefore:

$$v = c/n$$

Important conclusion

Greater refractive index means smaller speed of light.

$$n \propto 1/v$$

1.15 Wavelength of Light in a Medium

When light enters another medium, its velocity and wavelength change, but its frequency remains unchanged.
We know:

$$v = f\lambda$$

Since frequency remains constant:

$$v_1/v_2 = \lambda_1/\lambda_2$$

But,

$$v_1/v_2 = n_2/n_1$$

Therefore:

$$\boldsymbol{\lambda_1/\lambda_2 = n_2/n_1}$$

Or,

$$\boldsymbol{\lambda_2/\lambda_1 = n_1/n_2}$$

For light travelling from vacuum into a medium of refractive index μ:

$$\lambda = \lambda_0/\mu$$

Where, λ_0 = wavelength in vacuum, λ = wavelength in the medium

---

1.16 Important Concept: Frequency Does Not Change

When light passes from one medium to another:

Frequency remains unchanged.

But:

- Speed changes
- Wavelength changes

Therefore:

$$f_1 = f_2$$

but generally,

$$v_1 \neq v_2$$

and

$$\lambda_1 \neq \lambda_2$$

This is a very important **Board + NEET + JEE concept**.

1.17 Solved Numerical

Example – 1

Question

A light wave has frequency 5×10^{14} Hz and wavelength 600 nm in vacuum. Find its speed.

Solution

Given: f = 5×10^{14} Hz; λ = 600 nm = 600×10^{-9} m

Using:

$$v = f\lambda$$

Therefore:

$$v = (5 \times 10^{14})(600 \times 10^{-9})$$

$$v = 3 \times 10^8\, m/s$$

Answer: $v = 3 \times 10^8\, m/s$

Example – 2

Question

The refractive index of glass is 1.5. Find the speed of light in glass.

Solution

Given: $n = 1.5$; $c = 3 \times 10^8\, m/s$;

Solution:

Using:

$$n = c/v$$

Therefore:

$$v = c/n$$

$$v = (3 \times 10^8)/1.5$$

Hence: $\boldsymbol{v = 2 \times 10^8\, m/s}$

1.18 JEE Main / Advanced Insight

Concept 1

If refractive index increases, speed decreases.

$$n \propto 1/v$$

Concept 2

For a fixed frequency:

$$v \propto \lambda$$

Therefore, when light enters a denser medium:

$$v \downarrow \; and \; therefore: \; \lambda \downarrow \; but: f = constant$$

Concept 3

For two media:

$$n_{21} = n_2/n_1$$

Therefore:

$$n_{21} = v_1/v_2$$

and also:

$$n_{21} = \lambda_1/\lambda_2$$

PART – 2: Superposition of Waves and Interference

2.1 Introduction

When two or more waves meet at a point, they overlap and produce a resultant disturbance.
This phenomenon is explained by the **principle of superposition**.
The redistribution of intensity produced due to the superposition of two coherent light waves is called **interference of light**.
Interference is one of the most important experimental evidences of the wave nature of light.

2.2 Principle of Superposition

According to the principle of superposition:
When two or more waves meet simultaneously at a point, the resultant displacement is equal to the algebraic sum of the individual displacements produced by the waves.
If two waves produce displacements y_1 and y_2, then:

$$y = y_1 + y_2$$

For three waves:

$$y = y_1 + y_2 + y_3$$

In general:

$$y = y_1 + y_2 + y_3 + \dots\dots$$

2.3 Superposition of Two Sinusoidal Waves

Consider two waves having the same angular frequency.
The first wave is:

$$y_1 = a_1 \sin \omega t$$

The second wave is:

$$y_2 = a_2 \sin(\omega t + \varphi)$$

Where,
a_1 = amplitude of first wave
a_2 = amplitude of second wave
φ = phase difference between the two waves
According to the principle of superposition:

$$y = y_1 + y_2$$

Therefore:

$$y = a_1 \sin \omega t + a_2 \sin(\omega t + \varphi)$$

The resultant wave is also sinusoidal.
Its amplitude depends upon the phase difference φ.

2.4 Resultant Amplitude

For two waves of amplitudes a_1 and a_2 having phase difference φ, the resultant amplitude is:

$$\boxed{A = \sqrt{[{a_1}^2 + {a_2}^2 + 2a_1a_2 \cos\varphi]}}$$

This is an important formula for numerical problems.

2.4.1 Special Cases

Case 1: Constructive Interference

When: $\varphi = 0$, then: $\cos\varphi = 1$

Therefore:

$$A = \sqrt{(a_1{}^2 + a_2{}^2 + 2a_1a_2)}$$

Hence:

$$\boxed{\boldsymbol{A = a_1 + a_2}}$$

Thus, the resultant amplitude is maximum.

Case 2: Destructive Interference

When: $\varphi = \pi$, then: $\cos\varphi = -1$

Therefore:

$$A = \sqrt{(a_1{}^2 + a_2{}^2 - 2a_1a_2)}$$

Hence:

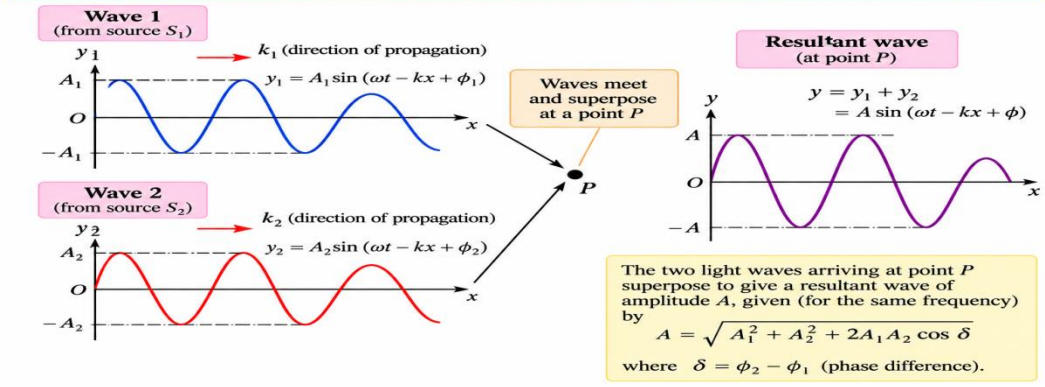
$$\boldsymbol{A = |a_1 - a_2|}$$

Thus, the resultant amplitude is minimum.

2.5 Interference of Light

When two coherent light waves superpose, the intensity of light is redistributed.
Some points become brighter and some points become darker.
This phenomenon is called **interference of light**.
The bright regions are called **bright fringes**.
The dark regions are called **dark fringes**.

Figure 10.7 : Superposition of Two Light Waves



2.6 Coherent Sources

For sustained and clear interference, the two sources must be **coherent**.
Two sources are said to be coherent if they have:

1. The same frequency.
2. A constant phase difference.

Thus:

Coherent sources = Same frequency + Constant phase difference

"For good fringe visibility, the intensities of the two waves should be comparable."

2.7 Why Are Independent Light Sources Not Coherent?

Suppose two independent bulbs are used as two sources.
Their emitted waves have random and rapidly changing phase differences.

Therefore, the phase difference does not remain constant.
Hence, sustained interference is not observed.
For this reason, in Young's Double-Slit Experiment, the two coherent sources are obtained from a **single source**.

2.8 Constructive Interference

When two waves meet in the same phase, their amplitudes add.
This produces maximum intensity.
This is called **constructive interference**.
The condition for constructive interference in terms of phase difference is:

$\varphi = 2n\pi$

Where:

n = 0, 1, 2, 3 …

2.8.1 Condition for Constructive Interference in Terms of Path Difference

The phase difference and path difference are related by:

$$\varphi = 2\pi\Delta/\lambda$$

For constructive interference:

$$\varphi = 2n\pi$$

Therefore:

$$2\pi\Delta/\lambda = 2n\pi$$

Hence:

$$\boxed{\boldsymbol{\Delta = n\lambda}}$$

Where:

n = 0, 1, 2, 3 …

Thus, constructive interference occurs when the path difference is an integral multiple of wavelength.

2.8.2 Bright Fringe

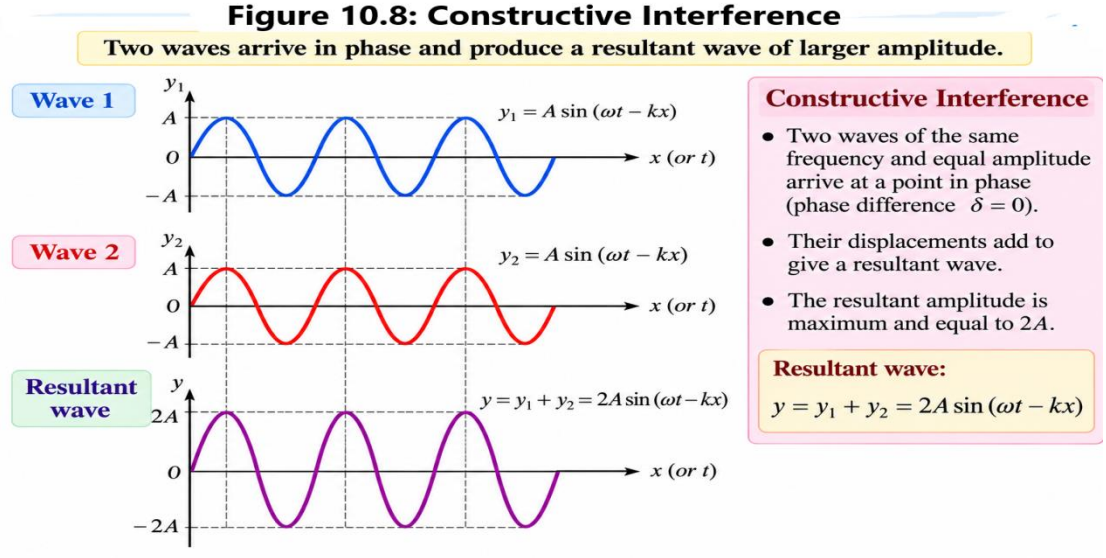
Constructive interference produces a bright fringe.
Therefore:

$$\boxed{\boldsymbol{Path\ difference = n\lambda}}$$

And

$$\boxed{\boldsymbol{Phase\ difference = 2n\pi}}$$

for a bright fringe.



2.9 Destructive Interference

When two waves meet in opposite phase, their amplitudes tend to cancel each other.
This produces minimum intensity.
This is called **destructive interference**.
The condition for destructive interference in terms of phase difference is:

$$\varphi = (2n + 1)\,\pi$$

Where:

n = 0, 1, 2, 3 …

2.9.1 Condition for Destructive Interference in Terms of Path Difference

We know:

$$\varphi = 2\pi\Delta/\lambda$$

For destructive interference:

$$\varphi = (2n + 1)\pi$$

Therefore:

$$2\pi\Delta/\lambda = (2n + 1)\,\pi$$

Hence:

$$\boldsymbol{\Delta = (2n + 1)\lambda/2}$$

Thus, destructive interference occurs when the path difference is an odd integral multiple of half wavelength.

2.9.2 Dark Fringe

Destructive interference produces a dark fringe.
Therefore:

Path difference = (2n + 1) λ/2

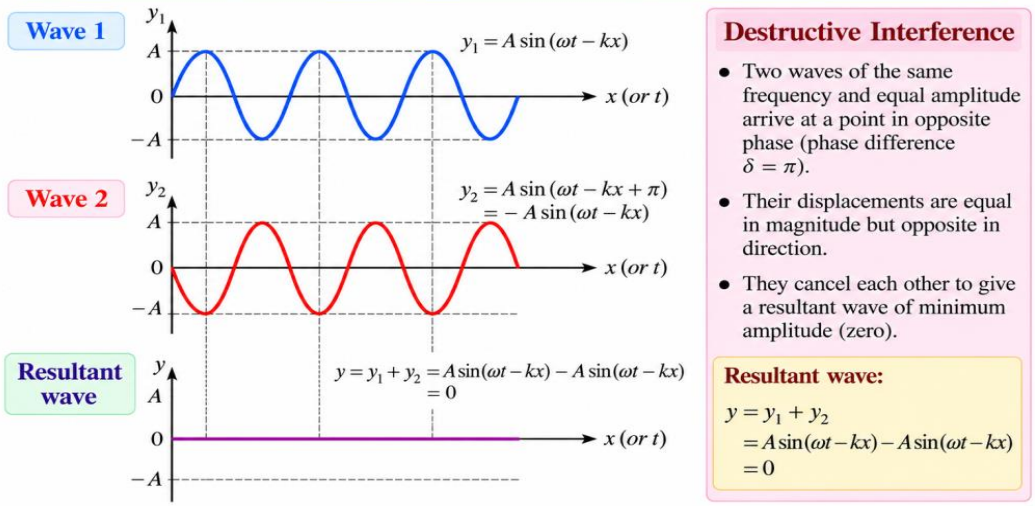
and

Phase difference = (2n + 1) π

for a dark fringe.

Figure 10.9 : Destructive Interference

Two waves arrive in opposite phase and produce a resultant wave of minimum (zero) amplitude.



Destructive Interference

- Two waves of the same frequency and equal amplitude arrive at a point in opposite phase (phase difference $\delta = \pi$).
- Their displacements are equal in magnitude but opposite in direction.
- They cancel each other to give a resultant wave of minimum amplitude (zero).

Resultant wave:

$y = y_1 + y_2$
$= A \sin(\omega t - kx) - A \sin(\omega t - kx)$
$= 0$

2.10 Intensity of Interfering Waves

The intensity of a wave is proportional to the square of its amplitude.
Therefore:

$$I \propto A^2$$

Let the intensities of two waves be I_1 and I_2.
Their amplitudes are proportional to:

$$a_1 \propto \sqrt{I_1}$$

and

$$a_2 \propto \sqrt{I_2}$$

For phase difference φ, the resultant intensity is:

$$\boldsymbol{I = I_1 + I_2 + 2\sqrt{(I_1 I_2)}\, cos\varphi}$$

This is one of the most important formulas of Wave Optics.

2.11 Maximum Intensity

For constructive interference:

$$\varphi = 0$$

Therefore:

$$cos\varphi = 1$$

Hence:

$$Imax = I_1 + I_2 + 2\sqrt{(I_1 I_2)}$$

Therefore:

$$\boldsymbol{Imax = (\sqrt{I_1} + \sqrt{I_2})^2}$$

2.12 Minimum Intensity

For destructive interference:

$$\varphi = \pi$$

Therefore:

$$cos\varphi = -1$$

Hence:

$$Imin = I_1 + I_2 - 2\sqrt{(I_1 I_2)}$$

Therefore:

$$\boldsymbol{Imin = (\sqrt{I_1} - \sqrt{I_2})^2}$$

2.13 Important Special Case: Equal Intensities

Suppose:

$$I_1 = I_2 = I$$

Then:

$$I_{res} = I + I + 2\sqrt{(I \times I)}\, cos\varphi$$

Therefore:

$$I_{res} = 2I + 2I\, cos\varphi$$

Using:

$$1 + cos\varphi = 2cos^2(\varphi/2)$$

We get:

$$\boldsymbol{I_{res} = 4I\, cos^2\,(\varphi/2)}$$

This formula is very important for numerical problems.

Let

$$I_0 = 4I$$

Or,

$$I = I_0/4$$

Where,

I_0 = Intensity of central maxima on the screen,

I_{res} = Resultant intensity on the screen

Therefore,

$$\boxed{I_{res} = I_0 cos^2(\varphi/2)}$$

2.13.1 Maximum Intensity for Equal Intensities

For: φ = 0

We get:

$$Imax = 4I_0$$

2.13.2 Minimum Intensity for Equal Intensities

For: $\varphi = \pi$

We get: $Imin = 0$

Therefore, for two equal-intensity coherent waves:

$$\boldsymbol{Imax = 4I_0}$$

$$\boldsymbol{Imin = 0}$$

2.14 Amplitude and Intensity in Interference

For equal amplitudes:

$$a_1 = a_2 = a$$

At constructive interference:

$$Amax = 2a$$

Since:

$$I \propto A^2$$

Therefore:

$$Imax \propto (2a)^2$$

$$Imax \propto 4a^2$$

At destructive interference:

$$Amin = 0$$

Therefore:

$$Imin = 0$$

This explains why the intensity at a dark fringe can become zero for equal-intensity waves.

2.15 Relation between Phase Difference and Path Difference

The phase difference corresponding to a path difference Δ is:

$$\boxed{\boldsymbol{\varphi = 2\pi\Delta/\lambda}}$$

Therefore:

$$\boxed{\Delta = \lambda\varphi/(2\pi)}$$

2.15.1 Important Values

If: Δ = 0, then: φ = 0
This gives constructive interference.
If: Δ = λ, then: φ = 2π
This also gives constructive interference.
If: Δ = λ/2, then: φ = π
This gives destructive interference.
If: Δ = 3λ/2,then: φ = 3π
This also gives destructive interference.

2.16 Interference Conditions – Quick Table

Condition	Phase Difference	Path Difference	Result
Constructive	2nπ	nλ	Bright
Destructive	(2n+1)π	(2n+1)λ/2	Dark

Here: n = 0, 1, 2, 3 …

2.17 Visibility of Interference Fringes

The visibility or contrast of interference fringes is defined as:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Using:

$$Imax = (\sqrt{I_1} + \sqrt{I_2})^2$$

And

$$Imin = (\sqrt{I_1} - \sqrt{I_2})^2$$

We obtain:

$$\boxed{V = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}}$$

2.17.1 Maximum Visibility

If: $I_1 = I_2$, then: $V = 1$

Therefore, maximum visibility occurs when the intensities of the two waves are equal.

2.18 Interference Pattern

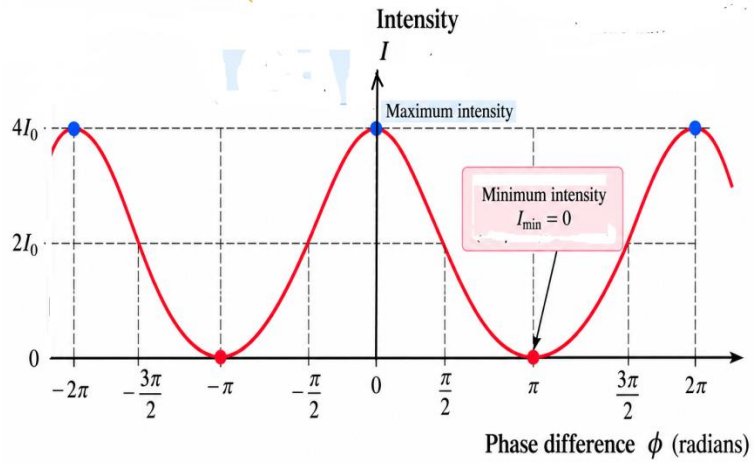
When coherent light waves interfere, alternate bright and dark regions are obtained.
The intensity varies periodically with phase difference.
For equal intensities:

$$I_{res} = I_0 \cos^2(\varphi/2)$$

Therefore:

- At φ = 0 → maximum intensity
- At φ = π → minimum intensity
- At φ = 2π → maximum intensity
- At φ = 3π → minimum intensity
- At φ = 4π → maximum intensity

Figure 10.10 : Intensity versus Phase difference



2.19 Solved Numerical

Example – 1

Question

Two coherent waves have amplitudes 3 cm and 4 cm and are in the same phase. Find the resultant amplitude.

Solution

Given: $a_1 = 3$ cm; $a_2 = 4$ cm; For same phase: $\varphi = 0$
Therefore: $A = a_1 + a_2$
$A = 3 + 4$
Hence: **A = 7 cm**

Example – 2

Question

Two waves have amplitudes 5 cm and 3 cm and are in opposite phase. Find the resultant amplitude.

Solution

For opposite phase:

$\varphi = \pi$

Therefore:

$A = |a_1 - a_2|$

$A = |5 - 3|$

Hence: **A = 2 cm**

Example – 3

Question

Two coherent waves have equal intensities I_0. What is the resultant intensity when their phase difference is $\pi/2$?

Solution

For equal intensities, I_0:

$$I_{res} = 4I_0 \cos^2(\varphi/2)$$

Given:

$\varphi = \pi/2$

Therefore:

$$I = 4I_0 \cos^2(\pi/4)$$

Since:

$$\cos(\pi/4) = 1/\sqrt{2}$$

Therefore:

$$I = 4I_0 \times 1/2$$

Hence: $\boldsymbol{I = 2I_0}$

Example – 4

Question

Two coherent waves have intensities 4 units and 9 units. Find the maximum and minimum intensities.

Solution

Given: $I_1 = 4$, $I_2 = 9$

For maximum intensity:

$$Imax = (\sqrt{I_1} + \sqrt{I_2})^2$$

$$Imax = (2 + 3)^2$$

Hence:

Imax = 25 units

For minimum intensity:

$$Imin = (\sqrt{I_1} - \sqrt{I_2})^2$$

$$Imin = (2 - 3)^2$$

Hence: $\boldsymbol{Imin = 1\ unit}$

2.20 NEET Focus

For numerical problems, remember these formulas:

$$A = \sqrt{[a_1{}^2 + a_2{}^2 + 2a_1a_2\,cos\varphi]}$$

$$I = I_1 + I_2 + 2\sqrt{(I_1I_2)}\,cos\varphi$$

$$Imax = (\sqrt{I_1} + \sqrt{I_2})^2$$

$$Imin = (\sqrt{I_1} - \sqrt{I_2})^2$$

$$\varphi = 2\pi\Delta/\lambda$$

Constructive:

$$\Delta = n\lambda$$

Destructive:

$$\Delta = (2n + 1)\lambda/2$$

2.21 JEE Main / Advanced Insight

Insight 1

If the amplitudes are equal:

$$a_1 = a_2$$

then complete destructive interference is possible.

Therefore:

$$Amin = 0$$

and:

$$Imin = 0$$

Insight 2

If the amplitudes are unequal, complete darkness is not possible.

For example:

$$a_1 \neq a_2$$

Then:

$$Amin = |a_1 - a_2|$$

Therefore:

$$Imin \neq 0$$

Insight 3

Maximum visibility occurs when:

$$I_1 = I_2$$

Therefore:

$$Vmax = 1$$

PART – 3: Young's Double-Slit Experiment (YDSE)

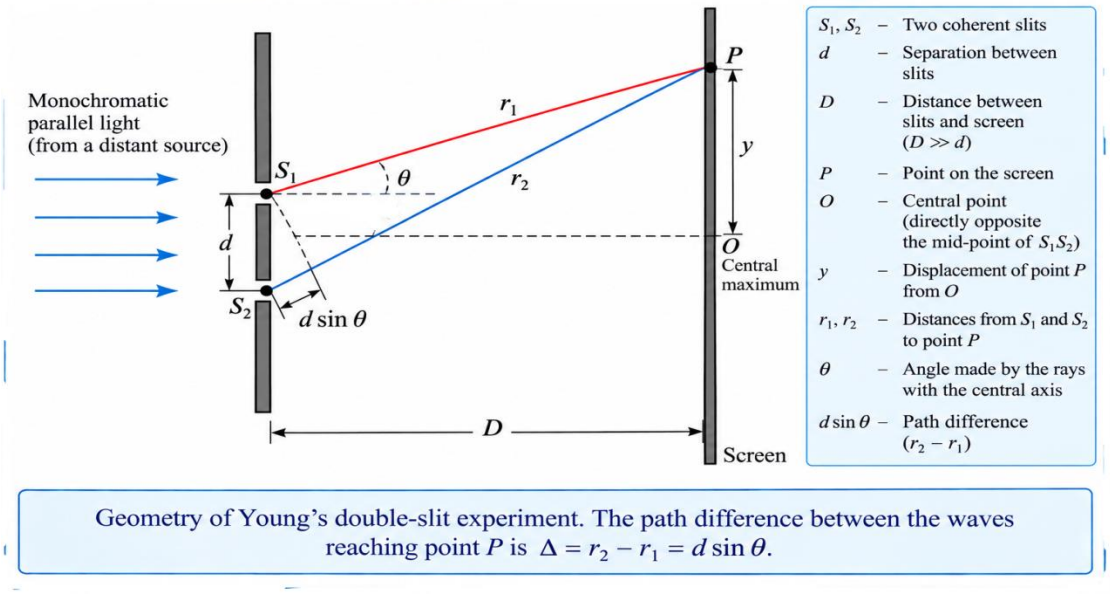
3.1 Introduction

Young's Double-Slit Experiment, commonly called **YDSE**, is one of the most important experiments demonstrating the **wave nature of light**.
In this experiment, light from a single source is allowed to pass through two narrow slits.
The two slits act as coherent sources.
The waves coming from the two slits overlap on a screen and produce alternate:

- Bright fringes
- Dark fringes

This pattern is called an **interference pattern**.

Figure 10.11: Young's Double Slit Experiment (Geometry)



Geometry of Young's double-slit experiment. The path difference between the waves reaching point P is $\Delta = r_2 - r_1 = d \sin\theta$.

3.2 Experimental Arrangement

Consider two narrow slits: S_1 and S_2
The separation between the two slits is: d
The distance between the slits and the screen is: D
Usually:

$$D >> d$$

A monochromatic light source is used.
The two slits are illuminated by the same source so that they act as **coherent sources**.

3.3 Why Is a Single Source used?

For sustained interference, the sources must have a constant phase difference.
Two independent light sources generally do not maintain a constant phase relationship.
Therefore, in YDSE, both slits are illuminated by the **same source**.
Thus:

S_1 and S_2 act as coherent sources.

3.4 Geometry of YDSE

Let: S_1 and S_2 = two coherent slits

$$S_1S_2 = d$$

D = distance between slits and screen
O = central point on screen
P = any point on screen
OP = y
Let:

$\angle S_1PO = \theta$

The path difference between the waves reaching P is:

$\Delta = S_2P - S_1P$

For the usual YDSE arrangement:

$$\boxed{\Delta = d\sin\theta}$$

This is the fundamental equation for path difference.

3.5 Approximation for Small Angle

In YDSE:

$$D >> d$$

Therefore, θ is generally small.
For small angles:

$$\sin\theta \approx \tan\theta$$

From the geometry:

$$\tan\theta = y/D$$

Therefore:

$$\sin\theta \approx y/D$$

Hence:

$$\Delta = d\sin\theta$$

becomes:

$$\boxed{\Delta = dy/D}$$

This is one of the most important formulas for YDSE numerical problems.

3.6 Condition for Bright Fringe

A bright fringe is produced due to **constructive interference**.
From Part 2:
For constructive interference:

$$\Delta = n\lambda$$

Where:

$$n = 0, 1, 2, 3, \ldots\ldots$$

Using:

$$\Delta = dy/D$$

we get:

$$dy/D = n\lambda$$

Therefore:

$$y = n\lambda D/d$$

Hence, the position of the nth bright fringe is:

$$\boxed{y_n = n\lambda D/d}$$

3.7 Central Bright Fringe

For the central point O:

$$y = 0$$

Therefore:

$$\Delta = 0$$

Hence, the two waves reach O in the same phase.
Therefore, the central fringe is bright.
For n = 0:

$$y_0 = 0$$

Thus:

$$\boldsymbol{Central\ fringe = Bright}$$

3.8 Positions of Bright Fringes

The position of nth bright fringe is:

$$\boxed{y_n = n\lambda D/d}$$

Therefore:
For first bright fringe:

$$y_1 = \lambda D/d$$

For second bright fringe:

$$y_2 = 2\lambda D/d$$

For third bright fringe:

$$y_3 = 3\lambda D/d$$

and so on.

3.9 Condition for Dark Fringe

A dark fringe is produced due to **destructive interference**.
The condition is:

$$\Delta = (2n + 1)\lambda/2$$

Where:

$$n = 0,1,2,3, \ldots \ldots$$

Using:

$$\Delta = dy/D$$

We get:

$$dy/D = (2n + 1)\lambda/2$$

Therefore:

$$\boxed{y_n = (2n + 1)\lambda D/(2d)}$$

This gives the position of the nth dark fringe.

3.10 Positions of Dark Fringes

For first dark fringe, n = 0:

$$y = \lambda D/(2d)$$

For second dark fringe, n = 1:

$$y = 3\lambda D/(2d)$$

For third dark fringe, n = 2:

$$y = 5\lambda D/(2d)$$

and so on.

3.11 Fringe Width

The distance between two successive bright fringes or two successive dark fringes is called **fringe width**.

It is represented by: β

3.11.1 Derivation of Fringe Width

Position of nth bright fringe:

$$y_n = n\lambda D/d$$

Position of (n + 1)th bright fringe:

$$y_{n+1} = (n + 1)\lambda D/d$$

Therefore:

$$\beta = y_{n+1} - y_n$$

$$\beta = [(n + 1)\lambda D/d] - [n\lambda D/d]$$

$$\beta = [(n + 1 - n)\lambda D]/d$$

Hence:

$$\boxed{\boldsymbol{\beta = \lambda D/d}}$$

This is the most important formula of YDSE.

3.12 Fringe Width for Dark Fringes

Position of nth dark fringe:

$$y_n = (2n + 1)\lambda D/(2d)$$

Position of next dark fringe:

$$y_{n+1} = [2(n + 1) - 1]\lambda D/(2d)$$

Therefore:

$$\beta = y_{n+1} - y_n$$

After simplification:

$$\boxed{\boldsymbol{\beta = \lambda D/d}}$$

Thus, the fringe width of bright fringes and dark fringes is the same.

3.13 Important Result

The fringe width is:

$$\boldsymbol{\beta = \lambda D/d}$$

Therefore:

$$\beta \propto \lambda$$

$$\beta \propto D$$

$$\beta \propto 1/d$$

Thus:

- Greater wavelength → greater fringe width
- Greater screen distance → greater fringe width
- Greater slit separation → smaller fringe width

3.14 Effect of Wavelength

From:

$$\beta = \lambda D/d$$

If D and d remain constant:

$$\beta \propto \lambda$$

Therefore, increasing wavelength increases fringe width.
For example:
Red light has a larger wavelength than blue light.
Therefore:

$$\boxed{\beta_{red} > \beta_{blue}}$$

3.15 Effect of Slit Separation

From:

$$\beta = \lambda D/d$$

Therefore:

$$\beta \propto 1/d$$

If slit separation increases, fringe width decreases.
If slit separation decreases, fringe width increases.

3.16 Effect of Screen Distance

From:

$$\beta = \lambda D/d$$

Therefore:

$$\beta \propto D$$

If the screen is moved farther away:

$$\boxed{D \uparrow Therefore: \beta \uparrow}$$

If the screen is brought closer:

$$\boxed{D \downarrow Therefore: \quad \beta \downarrow}$$

3.17 Angular Fringe Width

The angular separation between two successive bright fringes or two successive dark fringes is called **angular fringe width**.
It is given by:

$$\Delta\theta = \lambda/d$$

Therefore:

$$\boxed{\boldsymbol{Angular\ fringe\ width = \lambda/d}}$$

The relation between linear and angular fringe width is:

$$\boxed{\beta = D\Delta\theta}$$

3.18 Intensity Distribution in YDSE

For two coherent waves having equal intensities I:

$$I_{res} = 4I\ cos^2(\varphi/2)$$

We know:

$$\varphi = 2\pi\Delta/\lambda$$

Therefore:

$$\varphi/2 = \pi\Delta/\lambda$$

Hence:

$$\boldsymbol{I_{res} = 4I\ cos^2(\pi\Delta/\lambda)}$$

This gives the intensity at different points on the screen.

3.19 Intensity at Bright Fringe

For a bright fringe:

$$\Delta = n\lambda$$

Therefore:

$$\pi\Delta/\lambda = n\pi$$

Hence:

$$cos^2(n\pi) = 1$$

Therefore:

$$\boldsymbol{Imax = 4I}$$

Thus, maximum intensity occurs at bright fringes.

3.20. Intensity at Dark Fringe

For a dark fringe:

$$\Delta = (2n + 1)\lambda/2$$

Therefore:

$$\pi\Delta/\lambda = (2n + 1)\pi/2$$

Hence:

$$cos^2[(2n + 1)\pi/2] = 0$$

Therefore:

$$\boldsymbol{Imin = 0}$$

for equal-intensity coherent waves.

3.21 Complete YDSE Intensity Formula

The intensity at any point on the screen is:

$$\boldsymbol{I_{res} = I_1 + I_2 + 2\sqrt{(I_1 I_2)}\ cos\varphi}$$

Where:

$$\varphi = 2\pi\Delta/\lambda$$

For equal intensities:

$$I_1 = I_2 = I$$

Therefore:

$$\boldsymbol{I = 4I\ cos^2(\pi\Delta/\lambda)}$$

3.22 Interference Pattern on the Screen

The screen contains alternate bright and dark fringes.
Starting from the centre:

$$Bright \rightarrow Dark \rightarrow Bright \rightarrow Dark \rightarrow Bright \rightarrow \ldots\ldots$$

The central fringe is bright.
The fringes are equally spaced when the standard YDSE approximation is valid.

3.23 Fringe Width in a Medium

Suppose the entire YDSE arrangement is placed in a transparent medium having refractive index: μ
The wavelength of light in the medium becomes:

$$\lambda_m = \lambda_0/\mu$$

Where:
λ_0 = wavelength in vacuum/air
λ_m = wavelength in medium
The fringe width is:

$$\beta_m = \lambda_m D/d$$

Therefore:

$$\lambda_m = (\lambda_0/\mu)D/d$$

Hence:

$$\boxed{\boldsymbol{\beta_m = \beta_0/\mu}}$$

where β_0 is the fringe width in air/vacuum.

3.24 Important Result in Medium

Since:

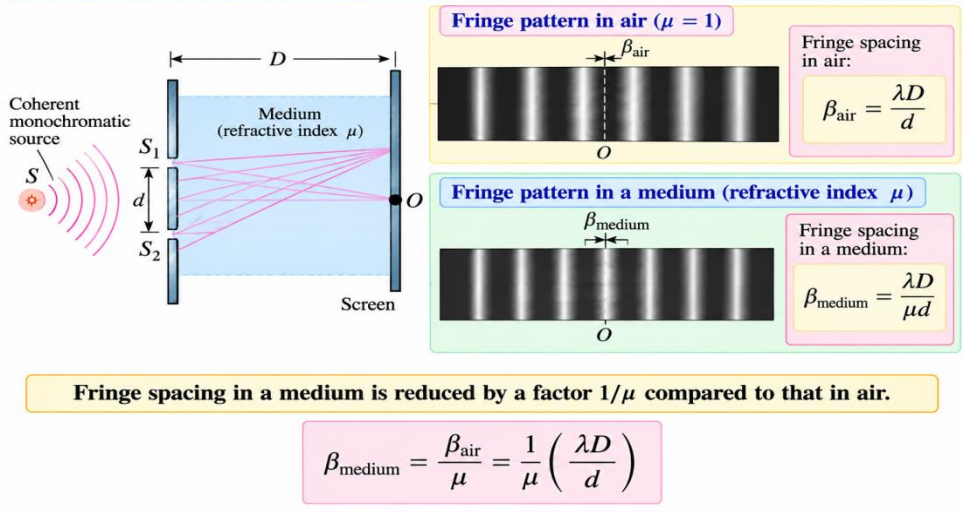
$$\mu > 1$$

therefore:

$$\beta_m < \beta_0$$

Thus, when the YDSE apparatus is immersed in a medium, the fringes become closer.

Figure 10.12 : YDSE Pattern in a Medium



Fringe spacing in a medium is reduced by a factor $1/\mu$ compared to that in air.

$$\beta_{medium} = \frac{\beta_{air}}{\mu} = \frac{1}{\mu}\left(\frac{\lambda D}{d}\right)$$

3.25 Effect of Changing Medium

If refractive index changes from μ_1 to μ_2:

$$\beta_1 = \beta_0/\mu_1$$
$$\beta_2 = \beta_0/\mu_2$$

Therefore:

$$\beta_2/\beta_1 = \mu_1/\mu_2$$

This is useful in numerical problems.

3.26 Solved Numerical

Example – 1

Question

In a Young's double-slit experiment, wavelength of light is 600 nm, slit separation is 1 mm and screen distance is 2 m. Find the fringe width.

Solution

Given: $\lambda = 600$ nm = $\lambda = 600 \times 10^{-9}$ m; D = 2 m; d = 1 mm = d = 1×10^{-3} m

Using:

$$\beta = \lambda D/d$$

Therefore:

$$\beta = [(600 \times 10^{-9}) \times 2]/(1 \times 10^{-3})$$

Hence:

$$\boldsymbol{\beta = 1.2 \times 10^{-3}\, m}$$

or:

$$\boldsymbol{\beta = 1.2\, mm}$$

Example – 2

Question

In YDSE, $\lambda = 500$ nm, D = 1 m and d = 0.5 mm. Find the position of the first bright fringe.

Solution

For first bright fringe: n = 1

Using:

$$y_n = n\lambda D/d$$

Therefore:

$$y_1 = \lambda D/d$$

Substituting:

$$y_1 = [(500 \times 10^{-9}) \times 1]/(0.5 \times 10^{-3})$$

Hence: $\mathbf{y_1 = 1 \times 10^{-3}\ m}$

or:

$$\boldsymbol{y_1 = 1\, mm}$$

Example – 3

Question

In YDSE, the fringe width is 2 mm. If the wavelength is doubled while all other quantities remain unchanged, find the new fringe width.

Solution
We know:

$$\beta = \lambda D/d$$

Therefore:

$$\beta \propto \lambda$$

If:

$$\lambda_2 = 2\lambda_1$$

Then:

$$\beta_2 = 2\beta_1$$

Given:

$$\beta_1 = 2\,mm$$

Therefore:

$$\beta_2 = 2 \times 2$$

Hence:

$$\boldsymbol{\beta_2 = 4\,mm}$$

Example – 4

Question

The wavelength of light in air is 600 nm. The YDSE experiment is performed in a medium of refractive index 1.5. If fringe width in air is 3 mm, find the fringe width in the medium.

Solution

Using:

$$\beta_{\mathrm{m}} = \beta_0/\mu$$

Given: $\beta_0 = 3$ mm, $\mu = 1.5$
Therefore:

$$\beta_{\mathrm{m}} = 3/1.5$$

Hence:

$$\boldsymbol{\beta_{\mathrm{m}} = 2\,mm}$$

Example – 5

Question

In YDSE, the path difference at a point is λ/4. Find the phase difference.

Solution

We know:

$$\varphi = 2\pi\Delta/\lambda$$

Given: $\Delta = \lambda/4$
Therefore:

$$\varphi = 2\pi\,(\lambda/4)\,/\lambda = 2\pi/4$$

Hence:

$$\boldsymbol{\varphi = \pi/2}$$

3.27 NEET Focus

For quick numerical solving, remember:

$$\Delta = d\,sin\theta$$

For small angle:

$$\Delta = dy/D$$

Bright fringe:

$$y_n = n\lambda D/d$$

Dark fringe:

$$y_n = (2n + 1)\,\lambda D/(2d)$$

Fringe width:

$$\boldsymbol{\beta = \lambda D/d}$$

Angular fringe width:

$$\boldsymbol{\Delta\theta = \lambda/d}$$

In medium:

$$\boldsymbol{\beta_m = \beta_0/\mu}$$

3.28 JEE Main / Advanced Insight

Insight 1: Ratio Method

Since:

$$\beta = \lambda D/d$$

Therefore:

$$\beta_2/\beta_1 = (\lambda_2 D_2 d_1)/(\lambda_1 D_1 d_2)$$

This is very useful for comparison questions.

Insight 2: Same Fringe Width

If:

$$\lambda_1 D_1/d_1 = \lambda_2 D_2/d_2$$

Then:

$$\beta_1 = \beta_2$$

Insight 3: Fringe Shift

If an additional optical path difference is introduced, the entire interference pattern may shift.
The important idea is:

$$\boxed{\boldsymbol{Fringe\ position\ depends\ upon\ path\ difference}.}$$

Insight 4: Medium

When the complete setup is immersed in a medium:

$$\lambda \rightarrow \lambda/\mu$$

Therefore:

$$\beta \rightarrow \beta/\mu$$

The fringe width decreases.

PART – 4: DIFFRACTION OF LIGHT

4.1 Introduction

"When light passes through a narrow aperture or around an obstacle, it spreads into the region of the geometrical shadow. This phenomenon is called diffraction."
This is called bending and spreading phenomenon of light.

Diffraction of Light

Diffraction is also the important evidence of wave nature of light.

4.2 What is Diffraction?

Diffraction is the phenomenon of bending or spreading of light waves around the edges of an obstacle or through a narrow aperture.

"Diffraction is most noticeable when the size of the aperture or obstacle is comparable to the wavelength of light."
That is,

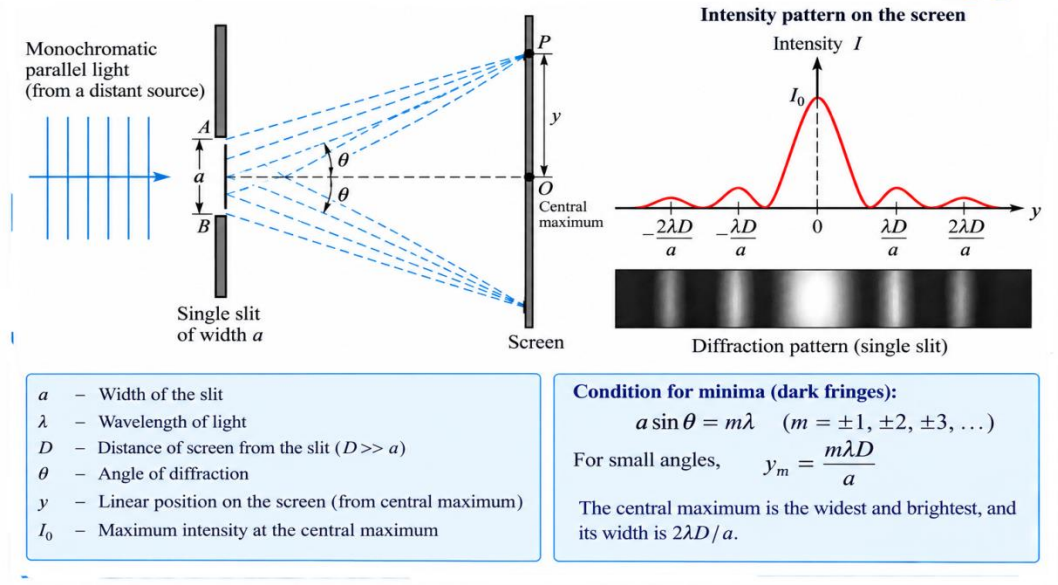
$$\boxed{a \approx \lambda}$$

Where,
a = width of aperture
λ = wavelength of light

4.3 Why Does Diffraction Occur?

According to Huygens' principle, every point acts as a source of secondary wavelet on a wavefront.
"When a wave passes through a narrow slit, secondary wavelets originate from different points across the slit."
These wavelets superpose on each other and light intensity redistributes in different directions.
The diffraction pattern is obtained due to this reason.

Figure 10.13: Diffraction Due to a Single Slit



a	–	Width of the slit
λ	–	Wavelength of light
D	–	Distance of screen from the slit ($D >> a$)
θ	–	Angle of diffraction
y	–	Linear position on the screen (from central maximum)
I_0	–	Maximum intensity at the central maximum

Condition for minima (dark fringes):

$$a \sin\theta = m\lambda \quad (m = \pm 1, \pm 2, \pm 3, \ldots)$$

For small angles, $y_m = \frac{m\lambda D}{a}$

The central maximum is the widest and brightest, and its width is $2\lambda D / a$.

4.4 Single-Slit Diffraction

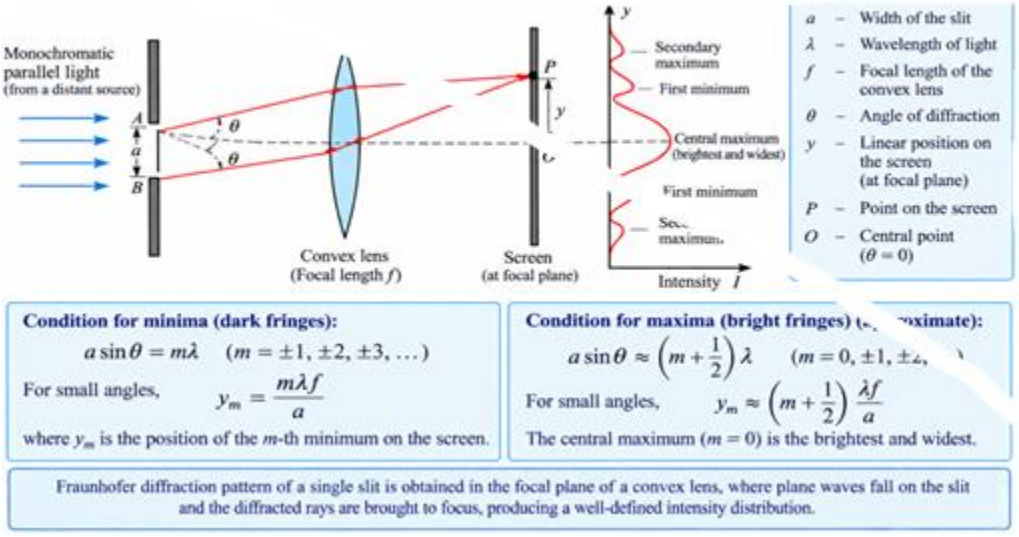
Monochromatic light is passed through a narrow slit in simple diffraction arrangement. Let width of slit: a

After light passes through the slit, light is not uniformly distributed on the screen.

Instead:

- A broad central maximum
- weaker secondary maxima on both sides of central maximum
- Dark minima separate the central maximum from the weaker secondary maxima on both sides. Weaker secondary maxima are also observed on either side of the central maximum.

Figure 10.14: Fraunhofer Diffraction at Single Slit Using a Convex Lens



4.5 Diffraction Pattern

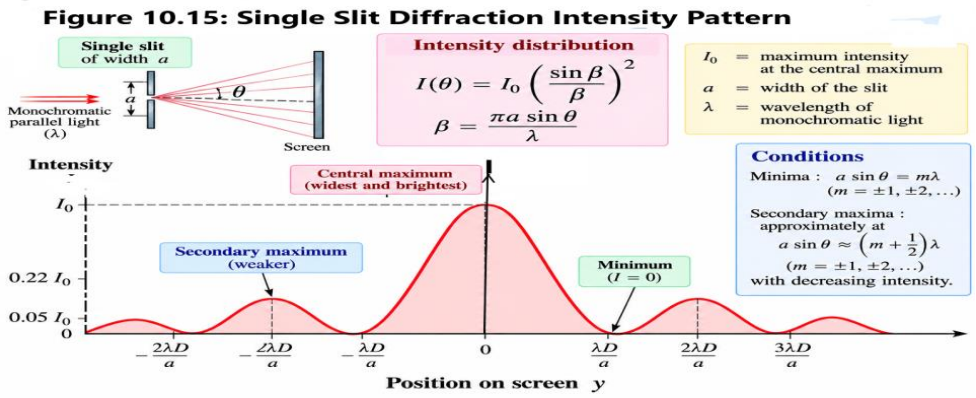
Central maximum is the most important point in Single-slit diffraction pattern.

Dark regions and weaker secondary maxima are obtained on both sides of central maximum.

Central maximum:

- mostly intense
- maxima wider in comparison of other maxima

Figure 10.15: Single Slit Diffraction Intensity Pattern



4.6 Path Difference in Single-Slit Diffraction

Let monochromatic light passes through the slit of width a.
The path difference between extreme points for a travelling wave at any angle θ:

$$\boldsymbol{\Delta = a\,sin\theta}$$

This is a fundamental geometrical relation of single-slit diffraction.

4.7 Condition for First Minimum

First minima in single slit diffraction is obtained, where: a sinθ = λ
That is,

$$\boldsymbol{a\,sin\theta_1 = \lambda}$$

This relation is very useful in numerical problems.
For small θ:

$$sin\theta \approx \theta$$

Therefore:

$$\boldsymbol{\theta_1 \approx \lambda/a}$$

Where, θ_1 = angular position of first minimum.

4.8 General Condition for Minima

Competitive examinations में single-slit diffraction के minima के लिए:

$$a\,sin\theta = m\lambda$$

Where,

$$m = 1, 2, 3, \ldots \ldots$$

Here, m = 1 for first minimum, m = 2 for second minimum, so on.
Therefore:
For first minimum:

$$a\,sin\theta_1 = \lambda$$

For second minimum:

$$a\,sin\theta_2 = 2\lambda$$

For third minimum:

$$a\,sin\theta_3 = 3\lambda$$

4.9 Angular Position of First Minimum

For first minimum:

$$a\,sin\theta_1 = \lambda$$

Therefore:

$$sin\theta_1 = \lambda/a$$

For small angles:

$$\boldsymbol{\theta_1 \approx \lambda/a}$$

This is clear that:

$$\theta_1 \propto \lambda$$

And

$$\theta_1 \propto 1/a$$

That is, increasing the wavelength, diffraction spreading increases. Increasing the Slit width, diffraction spreading decreases.

4.10 Central Maximum

Central maximum lies between two first minima in single-slit diffraction.
First minimum:

$$\theta_1 \approx \lambda/a$$

At other side, first minimum:

$$-\theta_1 \approx -\lambda/a$$

Therefore, angular width of central maximum:

$$\Delta\theta = \theta_1 - (-\theta_1)$$

Hence:

$$\boxed{\boldsymbol{\Delta\theta = 2\lambda/a}}$$

4.11 Angular Width of Central Maximum

Therefore:

$$\boxed{\boldsymbol{Angular\ width\ of\ central\ maximum = 2\lambda/a}}$$

This formula is mainly **NEET/JEE competitive numerical extension**.

4.12 Linear Width of Central Maximum

Let screen be at distance D from the slit.
For small angle:

$$tan\theta \approx \theta$$

Therefore:

$$y_1 \approx D\theta_1$$

Since:

$$\theta_1 \approx \lambda/a$$

Therefore:

$$y_1 \approx D\lambda/a$$

Central maximum की total width:
$W = 2y_1$
Hence:

$$\boxed{\boldsymbol{W = 2\lambda D/a}}$$

4.13 Important Formula

Single-slit diffraction के central maximum की linear width:

$$\boxed{\boldsymbol{W = 2\lambda D/a}}$$

Where:
W = width of central maximum
λ = wavelength
D = slit-screen distance
a = slit width

4.14 Dependence of Central Maximum Width on Wavelength

We know:

$$W = 2\lambda D/a$$

If D and a are constant:

$$W \propto \lambda$$

Therefore:

Width of central maximum increases upon increasing the wavelength. For example:
The wavelength of red light is greater than that of violet light.
Therefore, for the same slit, red light has greater diffraction spreading than other visible light.

4.15 Dependence on Slit Width

From:

$$W = 2\lambda D/a$$

Therefore:

$$W \propto 1/a$$

Thus:

$$\boxed{\boldsymbol{Narrower\ slit \rightarrow wider\ diffraction\ pattern}}$$

$$\boxed{\boldsymbol{Wider\ slit \rightarrow narrower\ diffraction\ pattern}}$$

This is the important concept of diffraction pattern.

4.16 Dependence on Screen Distance

From:

$$W = 2\lambda D/a$$

Therefore:

$$W \propto D$$

Thus:
Increasing the screen distance, :
D ↑ Therefore: W ↑
Decreasing the screen distance:
D ↓ Therefore: W ↓

4.17 Central Maximum is Wider

The width of central maximum in Single-slit diffraction is approximately:

$$\frac{2\lambda D}{a}$$

Whereas, characteristic spacing between successive secondary maxima/minima is approximately:

$$\lambda D/a$$

Therefore, central maximum is comparatively wider.

4.18 Secondary Maxima

Weaker maxima are obtained on both sides of central maxima on the screen. These have lesser intensity than the intensity of central maxima.
Hence, in diffraction pattern:

$$Central\ maximum \rightarrow brightest$$

And,

$$Secondary\ maxima \rightarrow weaker$$

4.19 Interference and Diffraction – Basic Difference

Interference and diffraction are both wave phenomena, but there are important differences between them.

Interference	Diffraction
Two or more coherent waves superpose	Different parts of same wavefront superpose
Usually two coherent sources are considered	Single slit can produce diffraction
Fringes can have nearly equal spacing	Central maximum is relatively broad
For equal amplitudes, dark fringes can have zero intensity	Secondary maxima generally have weaker intensity
Fringe width: $\beta = \lambda D/d$	Central maximum width: $W = 2\lambda D/a$

4.20 Diffraction vs Geometrical Shadow

According to geometrical optics, light travels in straight lines and a sharp shadow is expected. But due to diffraction, waves spread into the geometrical shadow region.

Therefore:

Diffraction becomes important when obstacle/aperture size is comparable to wavelength.

If:

$$a >> \lambda$$

diffraction effects are relatively small.

If:

$$a \approx \lambda$$

diffraction becomes significant.

4.21 Solved Numerical

Example – 1

Question

Monochromatic light of wavelength 500 nm is incident normally on a single slit of width 0.5 mm. Find the approximate angular position of the first minimum.

Solution

Given:

- $a = 0.5\,mm = 0.5 \times 10^{-3}\,m$
- $\lambda = 500\,nm = 500 \times 10^{-9}\,m$

For first minimum:

$$\theta_1 \approx \lambda/a$$

Therefore:

$$\theta_1 = (500 \times 10^{-9})/(0.5 \times 10^{-3})$$

Hence:

$$\boldsymbol{\theta_1 = 1 \times 10^{-3}\,rad}$$

Example – 2

Question

A single slit of width 0.2 mm is illuminated by light of wavelength 600 nm. The screen is 2 m away. Find the approximate width of the central maximum.

Solution

Given:

- $a = 0.2 \times 10^{-3}\, m$
- $\lambda = 600 \times 10^{-9}\, m$
- $D = 2\, m$

Using:

$$W = 2\lambda D/a$$

Therefore:

$$W = [2 \times 600 \times 10^{-9} \times 2]/(0.2 \times 10^{-3})$$

Hence:

$$\boldsymbol{W = 12 \times 10^{-3}\, m}$$

Or:

$$\boldsymbol{W = 12\, mm}$$

Example – 3

Question

The width of the central maximum is 4 mm. If the wavelength of light is doubled, what will be the new width, keeping other quantities constant?

Solution

We know:

$$W = 2\lambda D/a$$

Therefore:

$$W \propto \lambda$$

If:

$$\lambda_2 = 2\lambda_1$$

Then:

$$W_2 = 2W_1$$

Given: W_1 = 4 mm

Therefore:

$$W_2 = 2 \times 4$$

Hence:

$$\boldsymbol{W_2 = 8\, mm}$$

Example – 4

Question

The width of the central maximum is W for a slit of width a. If the slit width is doubled, find the new width.

Solution

We know:

$$W = 2\lambda D/a$$

Therefore:

$$W \propto 1/a$$

If:

$$a_2 = 2a_1$$

Then:

$$W_2 = W_1/2$$

Hence:

$$\boldsymbol{New\ width = W/2}$$

4.22 NEET Focus

Important competitive formulas:

$$\Delta = a\ sin\theta$$

First minimum:

$$a\ sin\theta_1 = \lambda$$

General minima:

$$a\ sin\theta = m\lambda$$

For small angle:

$$\theta_1 \approx \lambda/a$$

Angular width of central maximum:

$$\boldsymbol{\Delta\theta \approx 2\lambda/a}$$

Linear width:

$$\boldsymbol{W = 2\lambda D/a}$$

4.23 JEE Main / Advanced Insight

Insight 1: Diffraction becomes more prominent when a decreases because: $\theta_1 \propto 1/a$

Insight 2

Diffraction increases with wavelength:

$$\theta_1 \propto \lambda$$

Therefore, longer wavelength produces greater angular spreading.

Insight 3

Central maximum width:

$$W = 2\lambda D/a$$

Therefore:

$$W \propto \lambda D/a$$

This relation is extremely useful in ratio-based questions.

Insight 4: Ratio Formula

For two different situations:

$$W_2/W_1 = (\lambda_2 D_2 a_1)/(\lambda_1 D_1 a_2)$$

This can quickly solve many numerical comparison problems.

PART – 5: POLARISATION OF LIGHT

5.1 Introduction

Light is an electromagnetic wave.
Electromagnetic waves are **transverse waves**, meaning that the electric and magnetic fields oscillate perpendicular to the direction of propagation.
Polarisation is a phenomenon that demonstrates the **transverse nature of light**.

5.2 What is Polarisation?

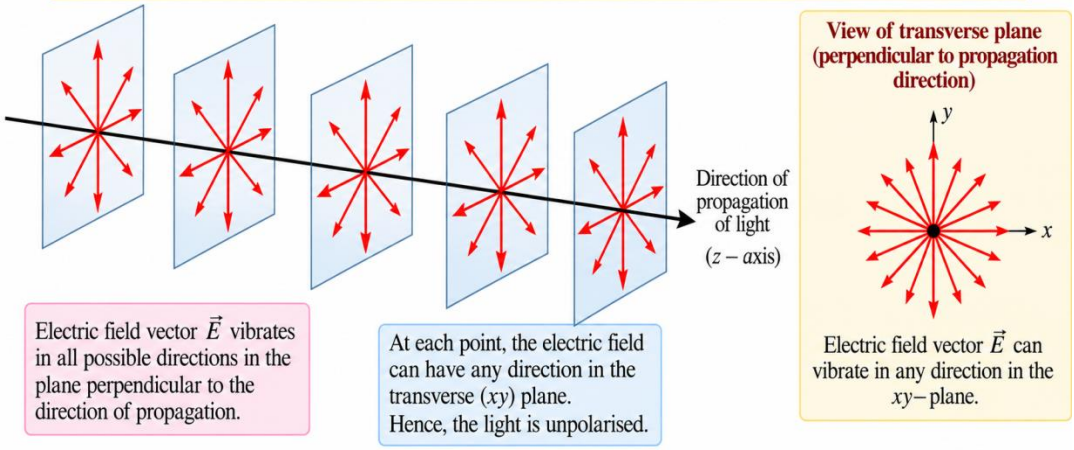
Polarisation is the phenomenon of restricting the vibrations of a transverse light wave to a particular direction perpendicular to the direction of propagation.
In ordinary light, the electric field vibrates in many different directions perpendicular to the direction of propagation.
After polarisation, the vibrations are restricted to one particular direction.

5.3 Unpolarised Light

In ordinary light, the electric field vector vibrates randomly in all directions perpendicular to the direction of propagation.
Such light is called **unpolarised light**.
Examples include ordinary light from:

- Sun
- Candle
- Electric bulb

Figure 10.16: Unpolarised Light

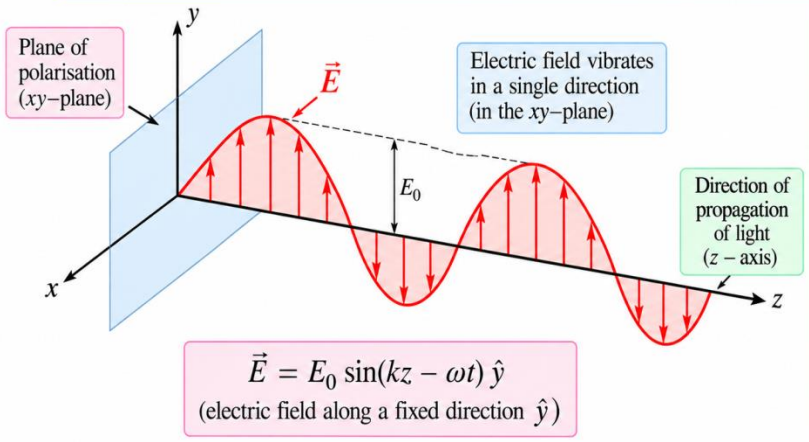


5.4 Plane-Polarised Light

If the vibrations of the electric field are restricted to one particular direction, the light is called **plane-polarised light** or **linearly polarised light**.

Figure 10.17: Plane Polarised Light

In plane polarised light, the electric field vibrates in a single fixed direction (in one plane) perpendicular to the direction of propagation.



Key points:

- Light propagates along the z–axis.
- The electric field vector $\vec{E}$ vibrates in a single fixed direction (here along the y–axis).
- The vibrations are restricted to one plane (xy–plane).
- Hence, the light is plane polarised (linearly polarised).

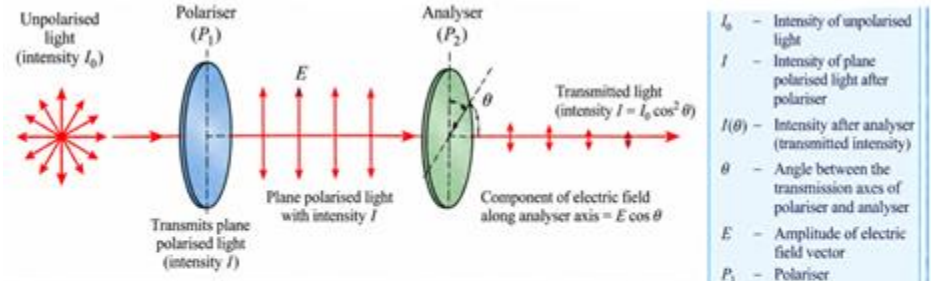
5.5 Polariser

A device that converts unpolarised light into plane-polarised light is called a **polariser**.
A polariser allows vibrations along one particular direction to pass through it.
The direction in which the electric field is transmitted is called the **transmission axis**.

5.6 Analyser

A device used to examine whether light is polarised, is called an **analyser**.
An analyser is essentially a polariser whose transmission axis can be rotated.
When polarised light passes through an analyser, the transmitted intensity depends upon the angle between their transmission axes.

Figure 10.18: Law of Malus (Intensity of Plane Polarised Light)



I_0 – Intensity of unpolarised light
I – Intensity of plane polarised light after polariser
$I(\theta)$ – Intensity after analyser (transmitted intensity)
θ – Angle between the transmission axes of polariser and analyser
E – Amplitude of electric field vector
P_1 – Polariser
P_2 – Analyser

Law of Malus:

$$I = I_0 \cos^2\theta$$

The intensity of plane polarised light transmitted through an analyser is directly proportional to the square of the cosine of the angle θ between the transmission axes of the polariser and analyser.

Special cases:

1. $\theta = 0° \rightarrow I = I_0$ (maximum intensity)
2. $\theta = 90° \rightarrow I = 0$ (minimum intensity, extinction)
3. $\theta = 45° \rightarrow I = I_0/2$
4. $\theta = 60° \rightarrow I = I_0/4$

Law of Malus shows that the intensity of plane polarised light depends on the relative orientation of the polariser and analyser.

5.7 Polarisation by Polaroid

A **Polaroid** is a material that can produce plane-polarised light.
When unpolarised light falls on an ideal Polaroid, the transmitted intensity becomes half the incident intensity.
Therefore:

$$\boldsymbol{I = I_0/2}$$

where:
I_0 = intensity of incident unpolarised light
I = intensity after one ideal polariser

5.8 Important Concept

For an ideal polariser:
Unpolarised light → Intensity becomes half
Therefore:

$$I = I_0/2$$

This is a very important NEET numerical result.

5.9 Malus' Law

Suppose plane-polarised light of intensity I_0 falls on an analyser.
Let θ be the angle between the transmission axes of the polariser and analyser.
According to **Malus' law**:

$$\boldsymbol{I = I_0 \cos^2\theta}$$

Where:
I_0 = intensity incident on the analyser
I = transmitted intensity
θ = angle between transmission axes.

5.10 Derivation of Malus' Law

Let the amplitude of the incident electric field be: E_0
When the electric field passes through an analyser whose transmission axis makes an angle θ with the direction of vibration:

$$E = E_0 \cos\theta$$

We know that intensity is proportional to the square of amplitude:

$$I \propto E^2$$

Therefore:

$$I/I_0 = E^2/{E_0}^2$$

Substituting:

$$I/I_0 = {E_0}^2 \cos^2\theta/{E_0}^2$$

Hence:

$$\boldsymbol{I = I_0 \cos^2\theta}$$

This is Malus' law.

5.11 Special Cases of Malus' Law

Case 1: θ = 0°
The polariser and analyser axes are parallel.

Therefore:

$$I = I_0 \cos^2 0°$$

Or,

$$I = I_0$$

Hence:

$$\boxed{I = I_0}$$

Maximum transmission occurs.

Case 2: θ = 90°

The polariser and analyser axes are perpendicular.

Therefore:

$$I = I_0 \cos^2 90°$$

Hence:

$$I = 0$$

No light is transmitted.

The polariser and analyser are said to be **crossed**.

Case 3: θ = 45°

$$I = I_0 \cos^2 45°$$

Since:

$\cos 45° = 1/\sqrt{2}$

Therefore:

$$I = I_0/2$$

Hence:

$$\boxed{I = I_0/2}$$

Case 4: θ = 60°

$$I = I_0 \cos^2 60°$$

Or,

$$I = I_0(1/2)^2$$

Hence:

$$\boxed{I = I_0/4}$$

5.12 Malus' Law – Quick Table

Angle θ	Transmitted intensity
0°	I_0
30°	$3I_0/4$
45°	$I_0/2$
60°	$I_0/4$
90°	0

5.13 Intensity Variation with Angle

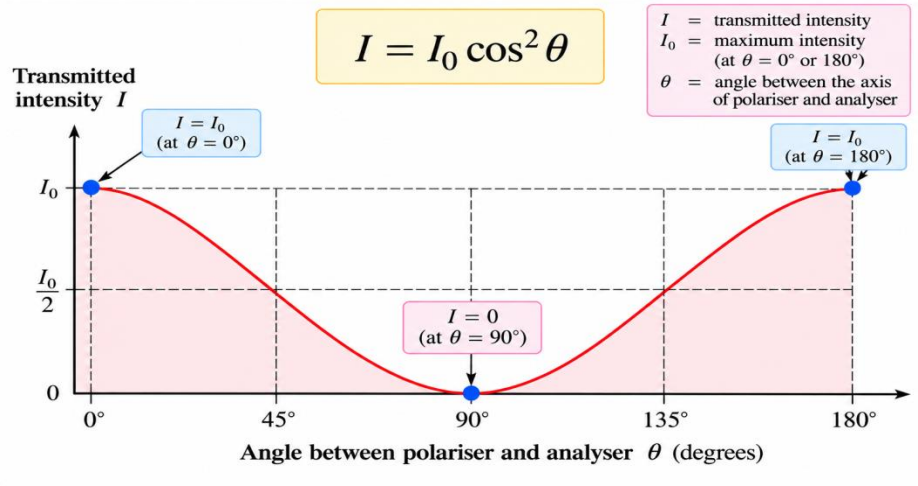
According to Malus' law:

$$I = I_0 \cos^2\theta$$

Therefore, intensity varies as the square of cosine of the angle.

At: θ = 0°, intensity is maximum.
At: θ = 90°, intensity becomes zero.

Figure 10.19 : Malus' Law Graph



5.14 Unpolarised Light Through Polariser and Analyser

Suppose unpolarised light of intensity I_0 falls on a polariser.
After the polariser:

$$I_1 = I_0/2$$

Now this plane-polarised light falls on an analyser at angle θ.
Using Malus' law:

$$I = I_1 \cos^2\theta$$

Therefore:

$$\boldsymbol{I = (I_0/2)\cos^2\theta}$$

This is an extremely important formula for numerical problems.

5.15 Crossed Polariser and Analyser

If the polariser and analyser are crossed: θ = 90°
Therefore:

$$I = (I_0/2)\cos^2 90°$$

Hence:

$$\boldsymbol{I = 0}$$

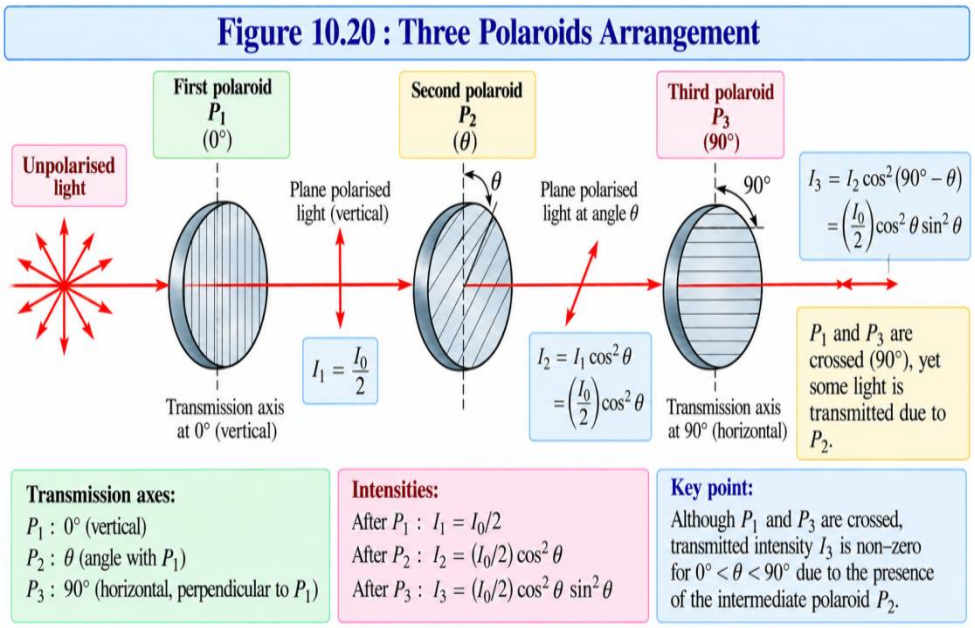
Thus, no light emerges from the analyser.

5.16 Three Polaroids

Three Polaroids can produce interesting intensity effects.
Suppose:

- First Polaroid has transmission axis at 0°.
- Second Polaroid is at angle θ.
- Third Polaroid is at 90° to the first.

Thus, first and third Polaroids are crossed.



5.17 Intensity Through Three Polaroids

Let the initial unpolarised intensity be: I_0

After first Polaroid:

$$I_1 = I_0/2$$

After second Polaroid:

$$I_2 = (I_0/2)cos^2\theta$$

The angle between the second and third Polaroids is: $90° - \theta$

Therefore, after the third Polaroid:

$$I_3 = I_2\, cos^2(90° - \theta)$$

Since:

$$cos(90° - \theta) = sin\theta$$

Therefore:

$$I_3 = (I_0/2)cos^2\theta\, sin^2\theta$$

Hence:

$$\boldsymbol{I_3 = (I_0/2)cos^2\theta\, sin^2\theta}$$

Using:

$$sin2\theta = 2sin\theta\, cos\theta$$

we get:

$$sin^2 2\theta = 4sin^2\theta\, cos^2\theta$$

Therefore:

$$\boldsymbol{I_3 = (I_0/8)sin^2 2\theta}$$

5.18 Maximum Intensity with Three Polaroids

We have:

$$I_3 = (I_0/8)sin^2 2\theta$$

For maximum intensity:

$$sin^2 2\theta = 1$$

Therefore:

$$sin2\theta = \pm 1$$

For:

$$2\theta = 90°$$

We get:

$$\boldsymbol{\theta = 45°}$$

Therefore, the intermediate Polaroid should be at 45° to the first one for maximum transmission.
At θ = 45°:

$$I_3 = I_0/8$$

Hence:

$$\boxed{\boldsymbol{Imax = I_0/8}}$$

5.19 Important Concept – Three Polaroids

An interesting result is obtained when the first and third Polaroids are crossed.
Without the middle Polaroid:

$$I = 0$$

But, when a middle Polaroid is inserted at 45°:

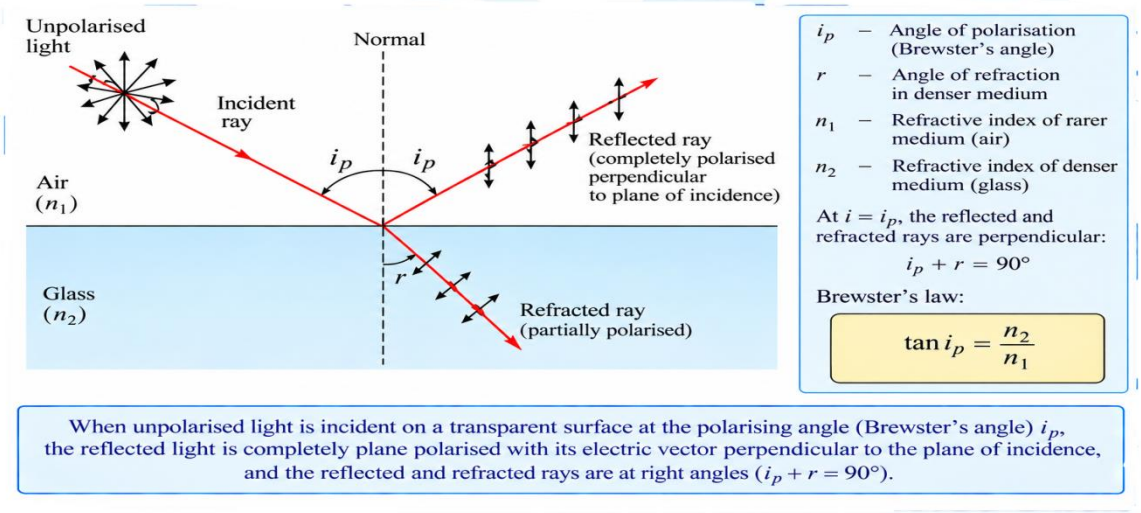
$$I = I_0/8$$

Thus, **some light can pass through three Polaroids even when the first and last are crossed.**
This is an important conceptual question.

5.20 Polarisation by Reflection

Light can also become partially or completely plane-polarised by reflection from a transparent surface at a particular angle.
The angle of incidence at which the reflected light becomes completely plane-polarised is called the **polarising angle** or **Brewster angle**.
It is represented by: i_P

Figure 10.21: Polarisation by Reflection (Brewster's Law)



When unpolarised light is incident on a transparent surface at the polarising angle (Brewster's angle) i_p, the reflected light is completely plane polarised with its electric vector perpendicular to the plane of incidence, and the reflected and refracted rays are at right angles ($i_p + r = 90°$).

5.21 Brewster's Law

According to Brewster's law:

$$\boxed{\mu = tan\, i_P}$$

Where:
μ = refractive index of the transparent medium
i_P = polarising angle
This is an important formula for numerical problems.

5.22 Derivation of Brewster's Law

At the polarising angle:

$$i = i_P$$

The reflected and refracted rays are perpendicular to each other.
Therefore:

$$i_P + r = 90°$$

Hence:

$$r = 90° - i_P$$

Using Snell's law:

$$\mu = \sin i_P / \sin r$$

Since:

$$r = 90° - i_P$$

Therefore:

$$\sin r = \cos i_P$$

Hence:

$$\mu = \sin i_P / \cos i_P$$

Therefore:

$$\boxed{\boldsymbol{\mu = \tan i_P}}$$

This is Brewster's law.
At Brewster's angle, the reflected light is completely plane-polarised, with its electric field perpendicular to the plane of incidence.

5.23 Important Result at Brewster Angle

At polarising angle:

$$\boldsymbol{i_P + r = 90°}$$

Therefore:

$$\boxed{\boldsymbol{Reflected\ ray \perp Refracted\ ray}}$$

This is an important conceptual point.

5.24 General Form of Brewster's Law

For light travels from medium 1 to medium 2:

$$\boldsymbol{n_2/n_1 = \tan i_p}$$

For light travelling from air into a medium:

$$n_1 \approx 1$$

Therefore:

$$\mu = \tan i_p$$

5.25 Applications of Polarisation

Polarisation has many practical applications.

1. Anti-glare sunglasses

Polaroids reduce glare caused by reflected light.

2. Photography

Polarising filters are used to reduce unwanted reflections from:

- Water
- Glass
- Shiny surfaces

---

3. LCD Screens

Liquid crystal displays use polarisation principles.

---

4. Stress Analysis

Polarised light can be used to study stress distribution in transparent materials.

---

5. Optical Instruments

Polarising devices are used in several optical instruments and laboratory applications.

5.26 Polarisation and Transverse Nature of Light

Only transverse waves can be polarised.
Longitudinal waves cannot be polarised in the same way.
Since light can be polarised:

Light is a transverse wave.

This is one of the most important conceptual conclusions of the chapter.

5.27 Solved Numerical

Example – 1

Question

Plane-polarised light of intensity I_0 falls on an analyser. The angle between their transmission axes is 60°. Find the transmitted intensity.

Solution

Using Malus' law:

$$I = I_0 \cos^2\theta$$

Given: $\theta = 60°$

Therefore:

$$I = I_0 \cos^2 60°$$

Or,

$$I = I_0/4$$

Hence:

$$\boxed{\boldsymbol{I = I_0/4}}$$

Example – 2

Question

Unpolarised light of intensity 100 W/m² passes through an ideal polariser. Find the transmitted intensity.

Solution

For unpolarised light:

$$I = I_0/2$$

Given: $I_0 = 100$ W/m²

Therefore:

$$I = 100/2$$

Hence:

$$\boxed{\boldsymbol{I = 50\, W/m^2}}$$

Example – 3

Question

Unpolarised light of intensity I_0 passes through a polariser and then an analyser kept at 60° to the polariser. Find the final intensity.

Solution

After first polariser:

$$I_1 = I_0/2$$

After analyser:

$$I = I_1 \cos^2 60°$$

Therefore:

$$I = (I_0/2)(1/4)$$

Hence:

$$\boldsymbol{I = I_0/8}$$

Example – 4

Question

The refractive index of a transparent material is √3. Find its polarising angle.

Solution

Using Brewster's law:

$$\mu = \tan i_p$$

Given: $\mu = \sqrt{3}$

Therefore:

$$\tan i_P = \sqrt{3}$$

Hence:

$$\boldsymbol{i_P = 60°}$$

Example – 5

Question

In a three-Polaroid arrangement, the first and third Polaroids are crossed. At what angle should the middle Polaroid be placed with respect to the first Polaroid for maximum transmitted intensity?

Solution
For three Polaroids:

$$I = (I_0/8)sin^2 2\theta$$

For maximum intensity:

$$sin^2 2\theta = 1$$

Therefore:

$$2\theta = 90°$$

Hence:

$$\boxed{\boldsymbol{\theta = 45°}}$$

5.28 NEET Focus

Remember these formulas:

$$I = I_0 \, cos^2\theta$$

For unpolarised light through one polariser:

$$I = I_0/2$$

Unpolarised light followed by analyser:

$$I = (I_0/2)cos^2\theta$$

Three Polaroids:

$$I = (I_0/8)sin^2 2\theta$$

Brewster's law:

$$\mu = tan \, i_p$$

At Brewster angle:

$$i_p + r = 90°$$

5.29 JEE Main / Advanced Insight

Insight 1

Intensity is proportional to square of electric-field amplitude:

$$I \propto E^2$$

Therefore, if:

$$E = E_0 \, cos\theta$$

then:

$$I = I_0 \, cos^2\theta$$

Insight 2

For unpolarised light:

$$I_1 = I_0/2$$

after an ideal polariser.

Insight 3

Two crossed Polaroids:

$$I = 0$$

But inserting a third Polaroid between them can produce non-zero transmitted intensity.
Maximum occurs when the middle Polaroid is at: **45°**

Insight 4

At Brewster angle:

$$Reflected\ ray \perp Refracted\ ray$$

Therefore:

$$i_p + r = 90°$$

5.30 Concept Map of Wave Optics

Wave Nature of Light
↓
Wavefront
↓
Huygens' Principle
↓
Reflection + Refraction
↓
Superposition
↓
Interference
↓
YDSE
↓
Diffraction
↓
Polarisation

5.31 Important YDSE Numerical Relations

For two different situations:

$$\beta_1 = \lambda_1 D_1/d_1$$
$$\beta_2 = \lambda_2 D_2/d_2$$

Therefore:

$$\boxed{\boldsymbol{\beta_2/\beta_1 = (\lambda_2 D_2 d_1)/(\lambda_1 D_1 d_2)}}$$

This is very useful for JEE numerical problems.

5.32 JEE Conceptual Traps

Trap 1

Frequency changes during refraction.

×Incorrect

Correct:

f = constant

Trap 2

Greater refractive index means greater speed.

×Incorrect

Correct:

$$v = c/n$$

Therefore:

$$n \uparrow \rightarrow v \downarrow$$

Trap 3

Increasing slit separation increases fringe width.

×Incorrect

Since:

$$\beta = \lambda D/d$$

Therefore:

$$d \uparrow \rightarrow \beta \downarrow$$

Trap 4

Increasing slit width increases diffraction.

×Incorrect

Since:

$$W \propto 1/a$$

therefore:

$$a \uparrow \rightarrow W \downarrow$$

Trap 5

Malus' law is directly applied to unpolarised light.

×Incorrect

First:

$$I_1 = I_0/2$$

Then:

$$I = I_1 cos^2\theta$$

5.33 NEET Formula Selection Guide

Question asks for	Use this formula
Wave velocity	$v = f\lambda$
Refractive index	$n = c/v$
Refraction	$n_1 \sin i = n_2 \sin r$
Phase difference	$\varphi = 2\pi\Delta/\lambda$
Bright fringe	$\Delta = n\lambda$
Dark fringe	$\Delta = (2n+1)\lambda/2$
YDSE path difference	$\Delta = dy/D$
Fringe width	$\beta = \lambda D/d$
Diffraction first minimum	$a \sin\theta = \lambda$
Central maximum width	$W = 2\lambda D/a$
Malus' law	$I = I_0 \cos^2\theta$
Unpolarised → polariser	$I = I_0/2$
Brewster angle	$\mu = \tan i_P$

5.34 Competency-Based Question

Question

In a YDSE experiment, the slit separation is reduced while wavelength and screen distance remain unchanged.
What happens to the fringe width?

Solution

We know:

$$\beta = \lambda D/d$$

Since: d ↓, Therefore: **β** ↑
Hence, fringe width increases.

5.35 Competency-Based Question – 2

Question

A beam of unpolarised light passes through an ideal polariser and then an analyser placed at 60° to it. What fraction of the original intensity emerges?

Solution

After polariser: $I_1 = I_0/2$
After analyser: $I = I_1 \cos^2 60°$
Therefore: $I = (I_0/2)(1/4)$
Hence:

$$\mathbf{I = I_0/8}$$

Therefore, one-eighth of the original intensity emerges.

5.36 Important Numerical Shortcuts

Shortcut 1 – YDSE

If only wavelength changes:

$$\beta_2/\beta_1 = \lambda_2/\lambda_1$$

Shortcut 2 – Slit separation

If only slit separation changes:

$$\beta_2/\beta_1 = d_1/d_2$$

Shortcut 3 – Screen distance

If only screen distance changes:

$$\beta_2/\beta_1 = D_2/D_1$$

Shortcut 4 – Diffraction

If only slit width changes:

$$W_2/W_1 = a_1/a_2$$

Shortcut 5 – Medium:

$$\beta_m/\beta_0 = 1/\mu$$
