ICT 1107: Physics

Dr M Mahbubur Rahman

Associate Professor

Department of Physics

Jahangirnagar University, Savar, Dhaka 1342

Email: **M.Rahman@juniv.edu**

ICT 1107: Physics

4. Physical Optics

Theories of light; Interference of light, Young's double slit experiment; Displacements of fringes and its uses; Fresnel Bi-prism, interference at wedge shaped films, Newton's rings, interferometers; Diffraction of light: Fresnel and Fraunhoffer diffraction, diffraction by single slit, diffraction from a circular aperture, resolving power of optical instruments, diffraction at double slit & N-slits-diffraction grating; Polarization: production and analysis of polarized light, Brewster's law, Malus law, Polarization by double refraction, retardation plates, Nicol prism, optical activity, polarimeters, polaroid.

7 Lectures

Chapter 3: Physical Optics

Books Recommended

1. Fundamentals of Optics- F A Jenkins, H E White
2. Optics- A Ghatak
3. A Text Book of Optics- N Subramanyam, Brijlal, M S Avadhanulu
4. Geometrical and Physical Optics- P K Chakrabarti
5. Physics for Engineers Vol 1- Giasuddin Ahmed

Chapter 3: Physical Optics

Interference of Light

Read the following pages: 1149-1154, 1157-1165, & 1200-1208

Book: Physics for Engineers Vol.1

Theories of Light

1) Corpuscular theory (*Sir Isaac Newton*, 1672)

2) Wave theory (In 1678, Dutch physicist, *Christiaan Huygens)*

3) Electromagnetic theory (Scottish Physicist *James Clerk Maxwell*, 1865)

4) Quantum theory (In 1900 *Max Planck*, and in 1905 *Albert Einstein)*

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Corpuscular Theory (Sir Isaac Newton, 1672)

Light is made up of small discrete particles called ‘corpuscles’ which travel in a straight line with a finite velocity.

It was successful in explaining rectilinear propagation of light, reflection, and refraction.

However failed to explain interference, diffraction, and polarization.

Also failed to explain the force of attraction and repulsion experienced perpendicular to the reflecting and refracting surfaces

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Wave theory (*Christiaan Huygens*, 1678)

i. Waves are mechanical and longitudinal in nature

ii. light propagates in the form of waves and need a medium to propagate in all possible direction.

iii. he gave a hypothetical medium which is known as ether .

iv. The velocity of the light was calculated as $v = \sqrt{\frac{E}{\rho}}$, where E is the elasticity of the medium and ρ is the density of that medium

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Wave Theory (*Christiaan Huygens*, 1678)

v. The energy is distributed equally in all possible directions
vi. It was successful in explaining the reflection, refraction, double reflection, and interference of light
vii. Fresnel said the light wave is transverse in nature
viii. Fresnel given the concept of ether

Limitations:

1. Can’t explain the rectilinear propagation
2. Can't explain polarization

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Electromagnetic theory (*James Clerk Maxwell*, 1865)

i. Maxwell demonstrated that light as having electric and magnetic fields travel through space as waves moving at the speed of light

ii. The speed of light is given as $c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}}$, μ_0 is the permeability of free space and ε_0 is the permittivity of free space

iii. EM-waves don't need any medium to traverse. Can propagate through medium. But in can travel through media as well but the speed will be changed.

Electromagnetic Theory (*James Clerk Maxwell*, 1865)

Limitations: The following aspects can't be explained through the em-theory

1. Photoelectric effect
2. Compton effect
3. Raman effect
4. Black body radiation

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Quantum theory (*M Planck & A Einstein*, 1900-1905)

Quantum theory tells us that both light and matter consists of tiny particles which have **wavelike properties** associated with them.

Light is composed of particles called photons, and matter is composed of particles called electrons, protons, neutrons. It's only when the mass of a particle gets small enough that its wavelike properties show up.

To help understand all this we need to look at how light behaves as a wave and as a particle.

Chapter 3: Physical Optics

i. It talk about the wave–particle duality

ii. It expresses the inability of the classical concepts 'particle' or 'wave' to fully describe the behaviour of quantum-scale objects

iii. Sometimes the one theory and sometimes the other, while at times we may use either. Since, we have two contradictory pictures of reality; separately none of them fully explains the phenomena of light, but together they do.

iv. The photons or quanta are massless particles and the energy of a photon or quanta is given by

$$E = h\nu, \text{ where } h \text{ is the Planck's constant}$$

Huygens Principle or Construction

Christiaan Huygens

Dutch Physicist, Mathematician, Astronomer, and Inventor, who is widely regarded as one of the greatest scientists of all time and a major figure in the scientific revolution.

Huygens Principle or Construction

An approximate geometrical procedure for determining the propagation of electromagnetic waves.

According to this construction, every point of a wave front in a medium at any instant is the source of secondary spherical wavelets propagating with the phase velocity of the medium. The envelope of all these wavelets then determines the wave front at a later instant.

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According to Huygens' principle, each point on a wavefront acts as a secondary source of light producing secondary wavelets in all directions. Alternately, we can say

Huygens principle postulated that points on the wavefronts themselves are the source of small waves and that they combined to produce further wavefronts.

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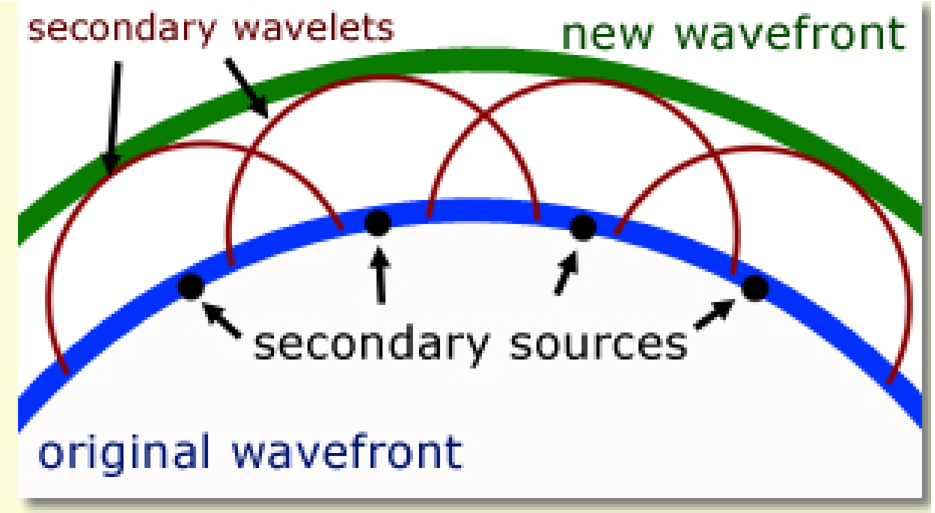

Principle of Superposition

Whenever two or more waves travelling through the same medium at the same time without being disturbed by each other, then the net displacement of the medium at any point in space or time, is simply the sum of the individual wave displacements. This is true of waves which are finite in length or which are continuous sine waves.

This known as the superposition principle.

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Sample Question

Q.1. Describe the principle of superposition of light.

Q2. State and explain the Huygens principle of secondary waves or secondary wavefronts.

Coherent Sources

1. Coherent sources are those sources of light which emit continuous light waves of same wavelength , same frequency and are in same phase or have constant phase difference.

2. For observing interference phenomenon coherence of light waves is a must.

3. For light waves emitted by two sources of light , to remain coherent the initial phase difference between waves should remain constant in time. If the phase difference changes continuously or randomly with time then the sources are incoherent.

Coherent Sources

4. Two independent sources of light are not coherent and hence can not produce interference because light beam is emitted by millions of atoms radiating independently so the phase difference between waves from such sources fluctuates randomly many times per second.

5. The coherent sources can be obtained either by the source and obtaining its virtual image or by obtaining two virtual images of the same source. This is because any change of phase in real source will cause a simultaneous and equal change in its image.

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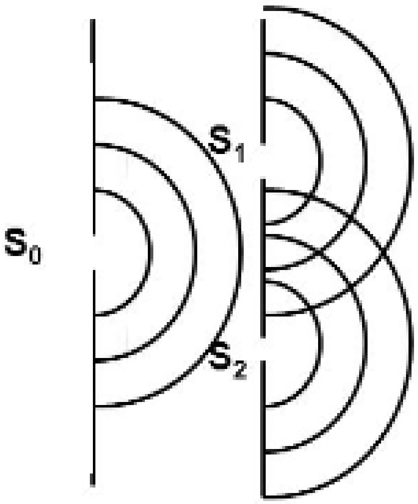
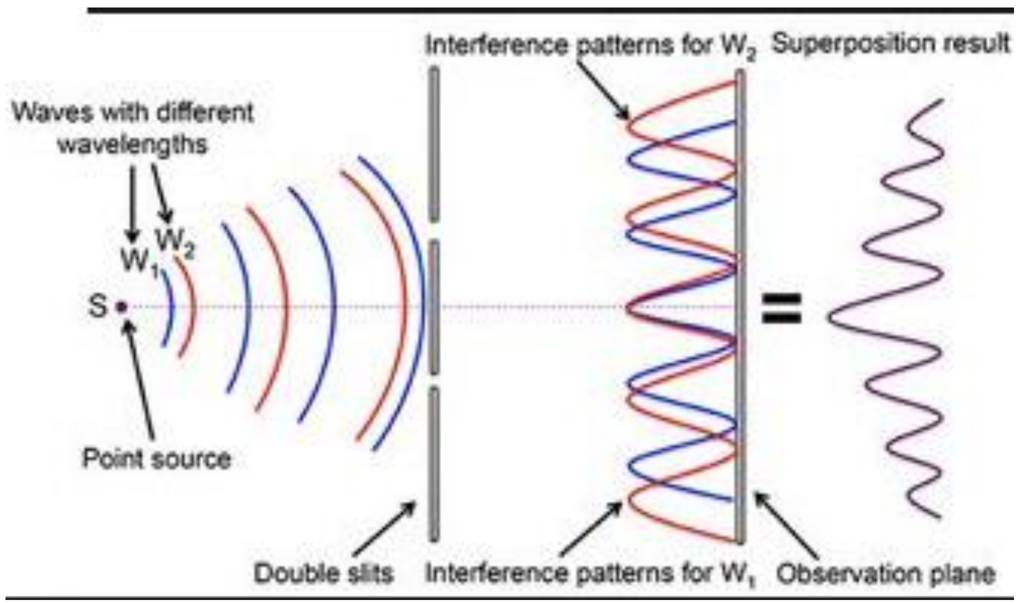
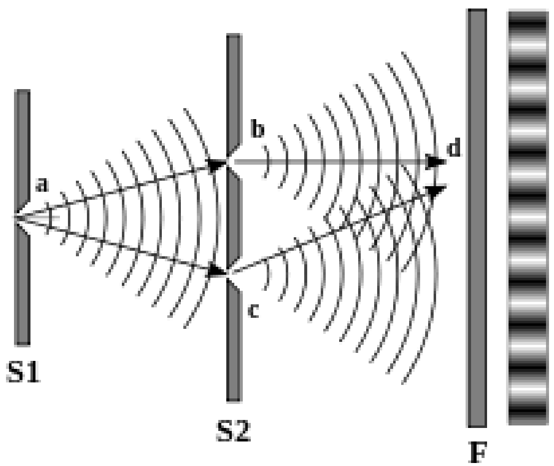
Coherent Sources







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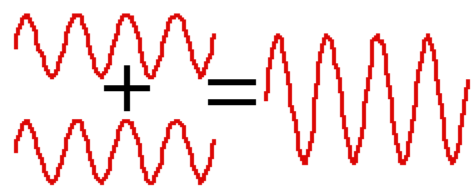
Interference of Light

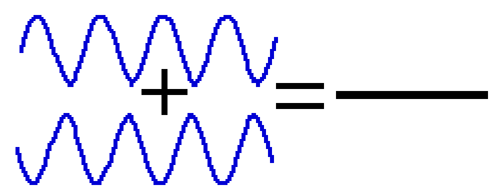
When two or more propagating waves of same type (nearly same frequency and same amplitudes) are incident on the same point, the resultant amplitude at that point is equal to the vector sum of the amplitudes of the individual waves.

Interference is of two types:

1. Constructive interference



2. Destructive interference



Constructive Interference

If two waves superimpose with each other in the same phase, the amplitude of the resultant is equal to the sum of the amplitudes of individual waves resulting in the maximum intensity of light, this is known as constructive interference.

Destructive Interference

If two waves superimpose with each other in opposite phase, the amplitude of the resultant is equal to the difference in amplitude of individual waves, resulting in the minimum intensity of light, this is known as destructive interference.

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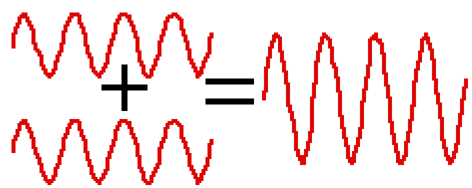
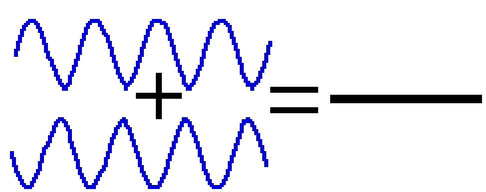
Interference of Light

When two waves meet in such a way that their crests line up together, then it's called **constructive interference**. The resulting wave has a higher amplitude.



In **destructive interference**, the crest of one wave meets the trough of another, and the result is a lower total amplitude.

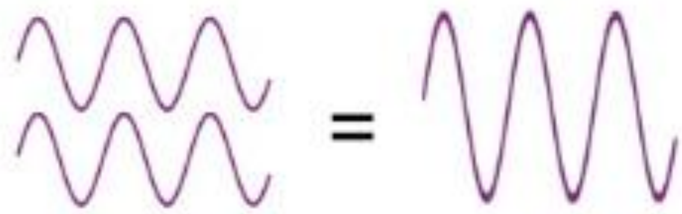


Chapter 3: Physical Optics

Interference of Light

1. **Constructive interference**

Waves that combine **in phase** add up to relatively high irradiance.



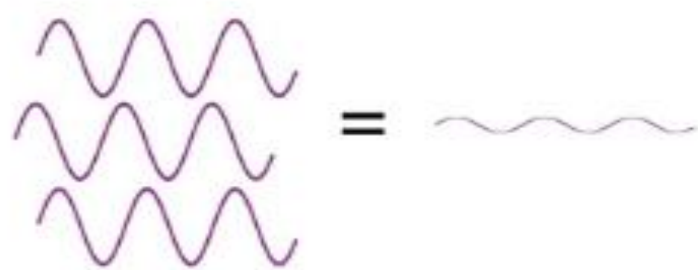
Constructive interference (coherent)

2. **Destructive interference**

Waves that combine **180° out of phase** cancel out and yield zero irradiance.

Destructive interference (coherent)

Waves that combine with **lots of different phases** nearly cancel out and yield very low irradiance.



Incoherent addition

Conditions of Constructive and Destructive Interferences

Constructive interference occurs when the phase difference between the waves is an even multiple of 2π, whereas destructive interference occurs when the difference is an odd multiple of π.

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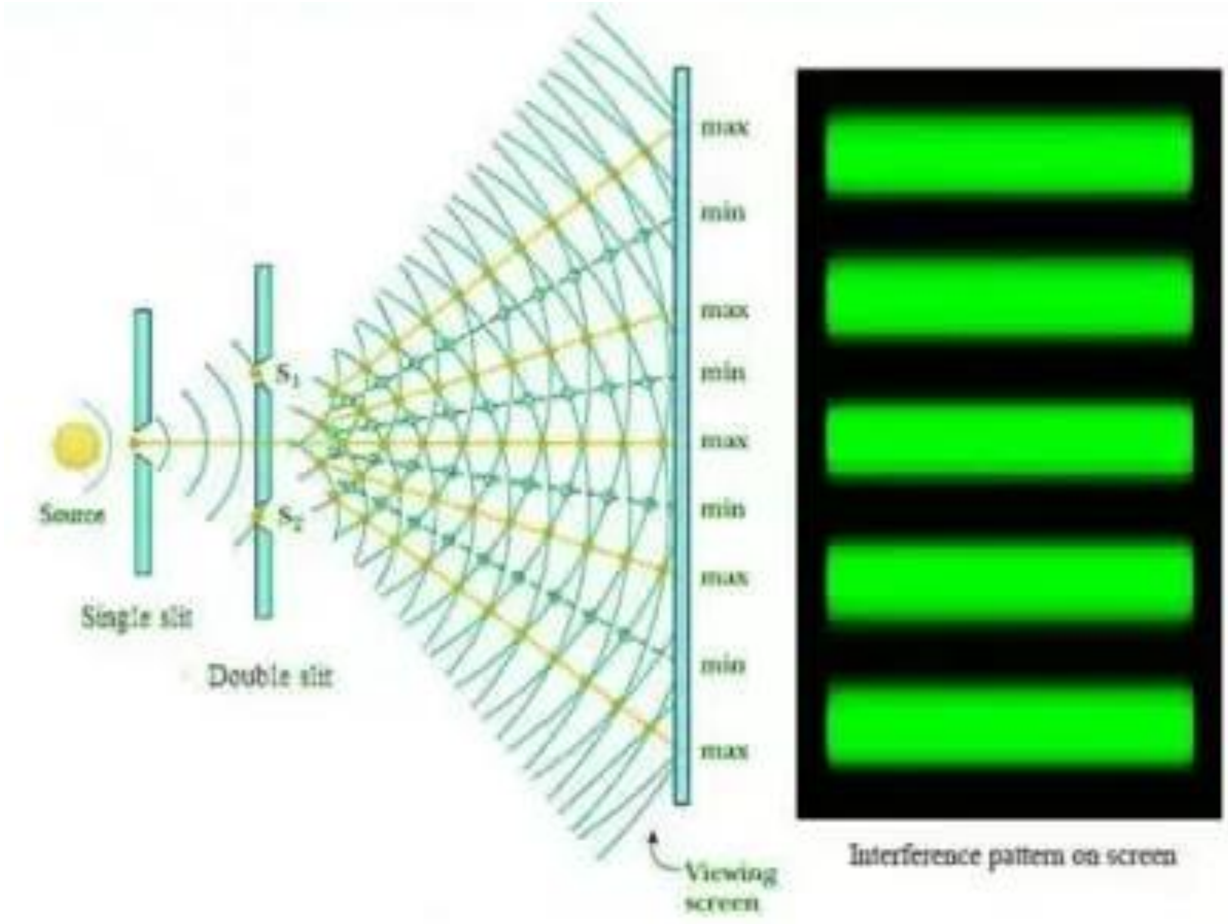
Interference of Light



Conditions of Interference of Light

1. Two sources must be coherent and narrow
2. The two interfering waves must have the same amplitude; otherwise the intensity will not be zero at the regions of destructive interference
3. The separation between the light sources should be as small as possible.
4. The original source must be monochromatic
5. The fringe width should be reasonably as large as possible that each fringe can be recognized distinctly
6. The two interfering waves must be propagated in almost same direction. The small separation between the two sources ensures this.

7. If the beams are polarized, they must be in the same state of polarization.

8. The distance of the screen from the sources should be quite large.

9. The phase difference of the interfering beams should remain constant through out the process.

10. The two interfering waves should have nearly same frequency.

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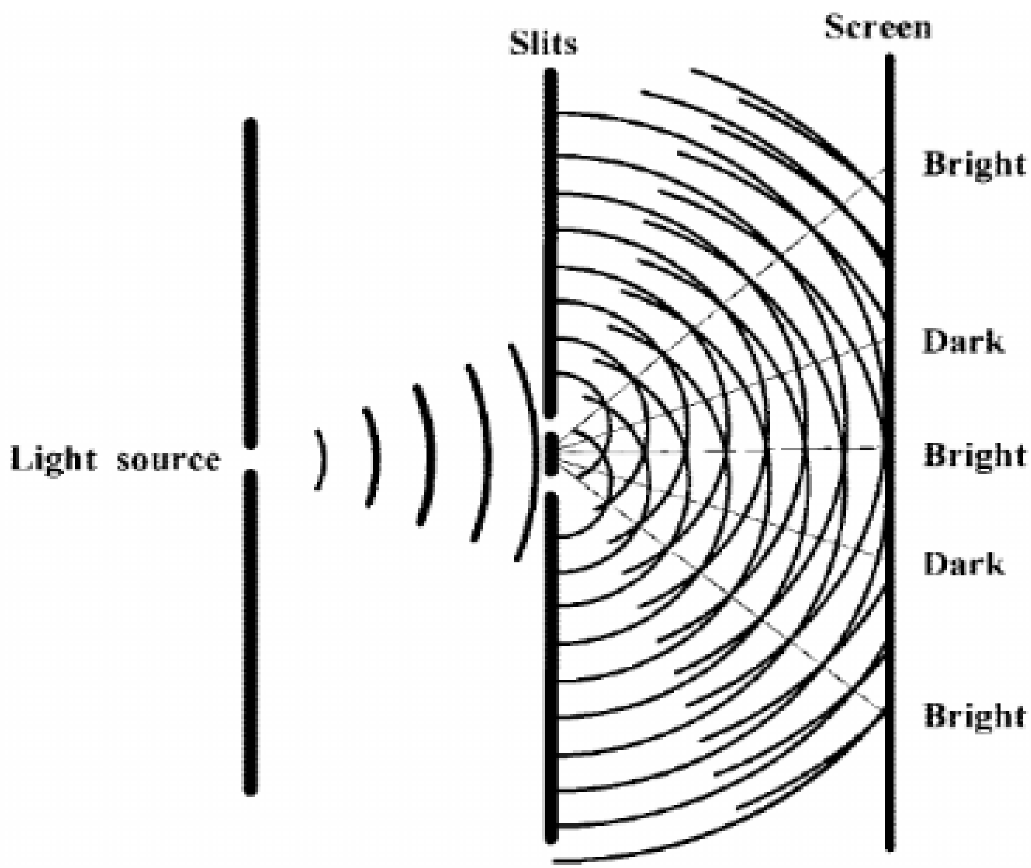
Young's Double-slit Experiment

Thomas Young (1799), English Physician and Physicist



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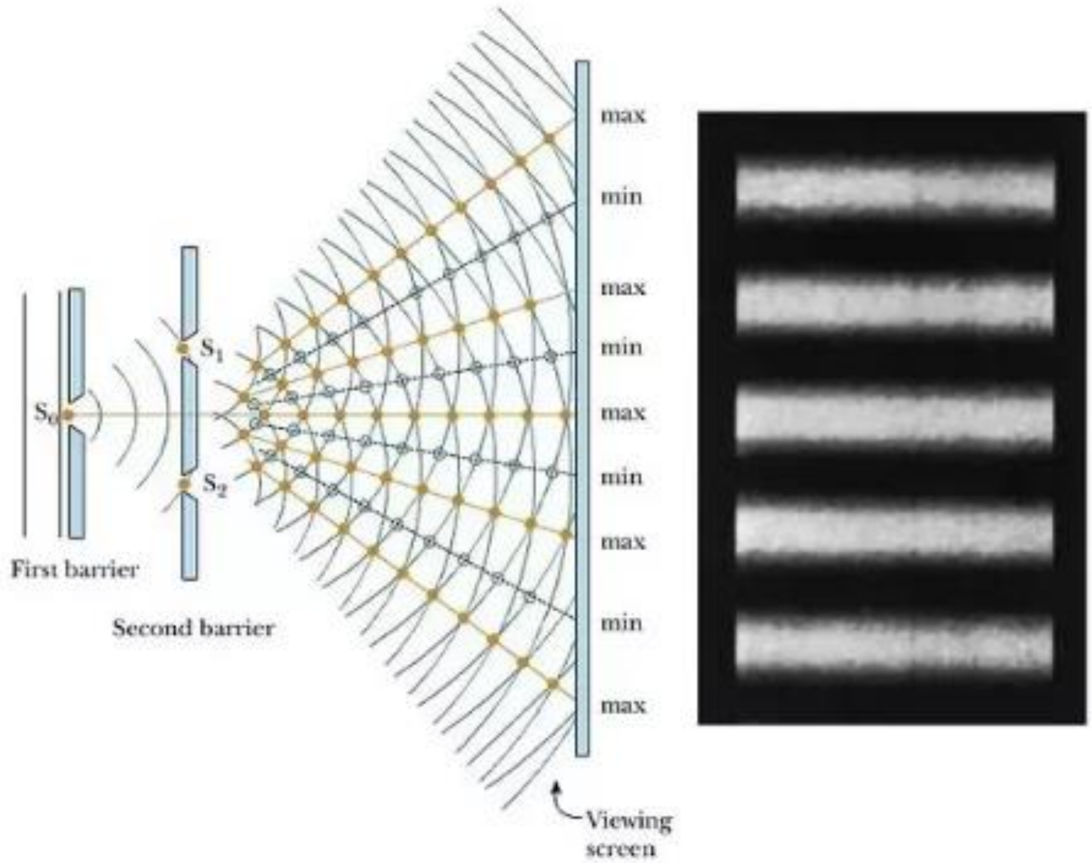

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Analytical Treatment of Interference of Light

$y_1 = a \sin \omega t$

$y_2 = a \sin (\omega t + \delta)$

$y = y_1 + y_2 = a \sin \omega t + a \sin (\omega t + \delta)$

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

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

Taking $a(1 + \cos \delta) = R \cos \theta$ (i)

and , $a \sin \delta = R \sin \theta$ (ii)

$Y = R \sin \omega t \cos \theta + R \cos \omega t \sin \theta$

$Y = R \sin (\omega t + \theta)$ (iii)

which represents the equation of simple harmonic vibration of amplitude **R**.

Chapter 3: Physical Optics

Analytical Treatment of Interference of Light

Squaring **(i)** and **(ii)** and adding.

$$R^2 \sin^2\theta = R^2 \cos^2\theta = a^2 \sin^2\delta + a^2 (1 + \cos \delta)^2$$

$$R^2 = a^2 \sin^2\delta + a^2 (1 + \cos^2\delta + 2\cos\delta)$$

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

$$= 2a^2 (1 + \cos \delta)$$

$$R^2 = 2a^2 + 2 \cos^2 \delta/2 = 4a^2 \cos^2 \delta/2$$

Chapter 3: Physical Optics

Analytical Treatment of Interference of Light

The intensity at a point is given by the square of the amplitude

$\therefore$ **$I = R^2$**

Or, **$I = 4a^2 \cos^2 \delta/2$** **(iv)**

Special cases: (i) When the phase difference **$\delta = 0, 2\pi, 2(2\pi), \ldots\ldots n(2\pi)$**, or the path difference **$x = 0, \lambda, 2\lambda, n\lambda$**.

Intensity is maximum when the phase difference is a whole number multiple of **2π** or the path difference is a whole number multiple of wavelength.

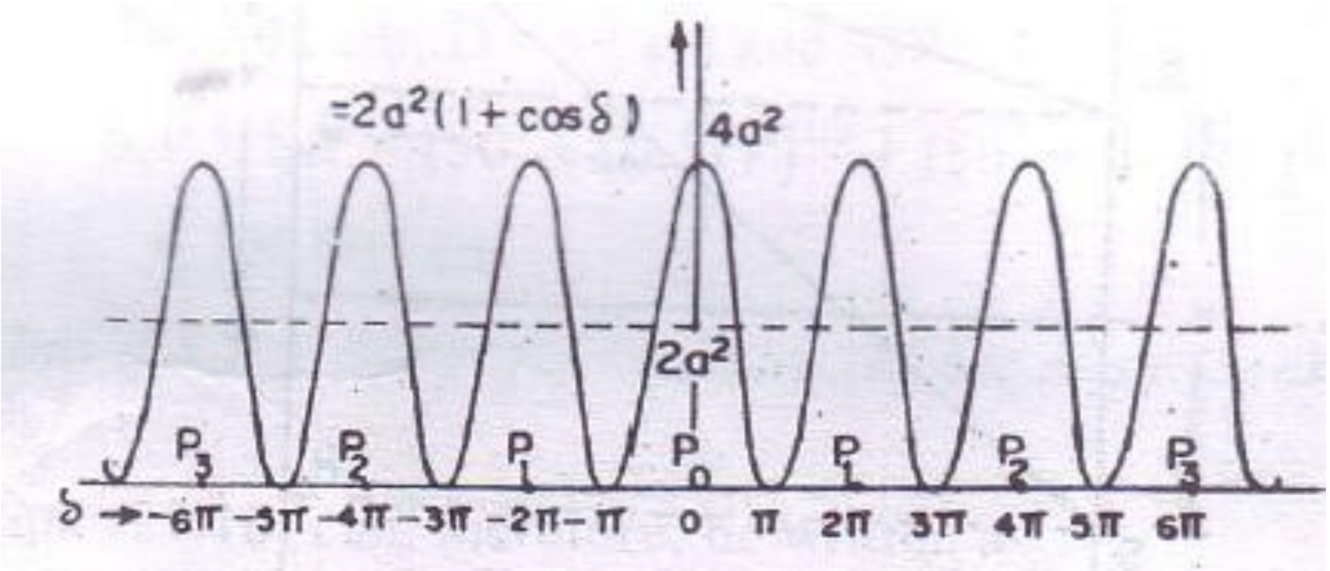
(ii) When the phase difference, **$\delta = \pi, 3\pi, \ldots. (2n + 1)\pi$**, or the path difference **$x = \lambda/2, 3\lambda/2, 5\lambda/2, \ldots. (2n + 1)\lambda/2$**.

Intensity is minimum when the path difference is an odd number multiple of half wavelength.

Chapter 3: Physical Optics

Energy Distribution of Interference Patterns

From equation **(iv)**, it is found that the intensity at bright points is $\mathbf{4a^2}$ and at dark points it is zero. According to the law of conservation of energy, the energy cannot be destroyed. Here also the energy is not destroyed but only transferred from the points of minimum intensity. For, at bright points, the intensity due to the two waves should be $\mathbf{2a^2}$ but actually it is $\mathbf{4a^2}$. As shown in fig. the intensity varies from **0** to $\mathbf{4a^2}$, and the average is still $\mathbf{2a^2}$. It is equal to the uniform intensity $\mathbf{2a^2}$ which will be present in the absence of the interference phenomenon due to the two waves. Therefore the formation of interference fringes is in accordance with the law of conservation of energy.



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Sample Questions

Q.3. What is meant by the interference of light? Explain the analytical treatment of the interference of light and hence obtain the conditions of maximum and minimum intensities.

Q.4. Explain the interference of light. What are the conditions of interference of light.

"Thank You"