

Topic 15.1 Wavefront

Nature of Light

Light is a type of energy which produces the sensation of vision. The question is how light transmits energy from one point to another, as a wave or as a stream of particles.

Wave Theory

In about 1678 Huygens, an eminent Dutch scientist, proposed that light energy from a luminous source travels in space by means of wave motion. Young's interference experiment, performed in 1801, proved the wave nature of light and established Huygens' wave theory.

Electromagnetic Waves

In 1860 Maxwell proposed that light consists of electromagnetic waves. Oscillating electric charges produce changing electric and magnetic fields that mutually regenerate each other and can propagate through vacuum.

Dual Nature

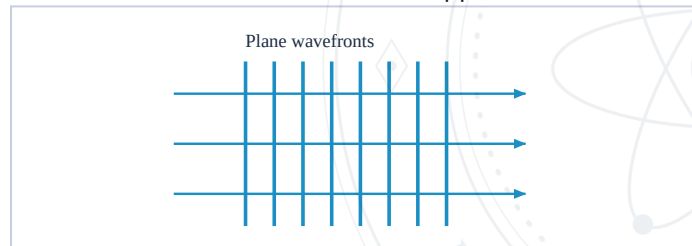
In the early twentieth century quantum mechanics revealed the dual nature of light. It propagates as an electromagnetic wave but interacts with matter as discrete, massless particles called photons. The wave theory still explains interference and diffraction successfully.

Wavefront

A wavefront is an imaginary surface that connects all the points where the waves have the same phase of vibration.

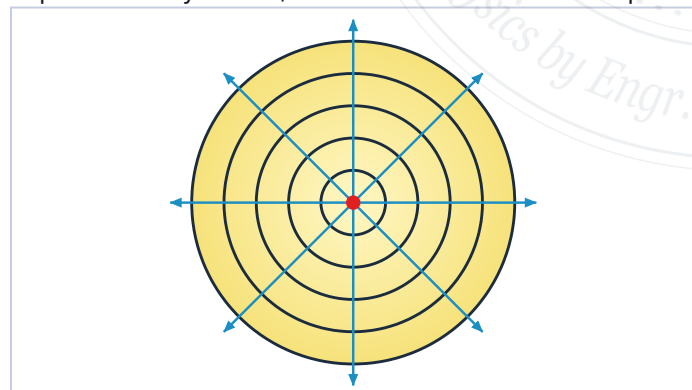
Plane Wavefronts

Represented as straight lines, like light waves from the distant stars and water waves in a ripple tank.



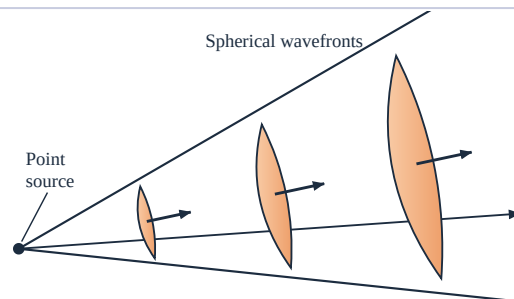
Circular Wavefronts

Represented by circles, as formed in water inside a pond.



Spherical Wavefronts

Formed in three-dimensional space by a sound or light wave. For a point source in space the wavefronts are always spherical, that is they spread out in all directions.



Properties

- For very large distances, as for the rays coming from the Sun, the wavefronts can be taken as planes.
- The shortest distance between wavefronts is always equal to the wavelength of the wave.
- The direction of transfer of energy is always perpendicular to the wavefront at every point.
- A periodic source produces a succession of wavefronts, all of the same shape.

Ray

A line at right angles to a wavefront which shows its direction of travel is called a ray.

Sources of Plane Wavefronts

Plane wavefronts are produced by a plane source or by any source at a distant point. A line source, such as the vibrator in a ripple tank, creates wavefronts that are plane and straight in two dimensions. If a source of light is placed at the focal point of a lens, plane wavefronts are formed on the other side of the lens.

SHORT QUESTIONS

SQ 15.1.1 What is a wavefront? Name its three types.

Wavefront

An imaginary surface that connects all the points where the waves have the same phase of vibration.

Types

Plane, circular and spherical wavefronts.

SQ 15.1.2 What is the distance between two consecutive wavefronts, and in which direction does a wave carry energy?

Distance between wavefronts

The shortest distance between wavefronts is always one wavelength.

Direction of energy

Perpendicular to the wavefront at every point, that is along the ray.

SQ 15.1.3 Why are the wavefronts of sunlight reaching the Earth taken as plane?

Sunlight wavefronts

The Sun is a very distant source. At such a large distance a spherical wavefront has so large a radius that any small part of it is practically flat, so it is taken as a plane.

SQ 15.1.4 How can plane wavefronts of light be obtained from a point source?

Plane wavefronts from a lens

Place the source at the focal point of a lens. Plane wavefronts are then formed on the other side of the lens.

MCQ 15.1.1 A wavefront joins all the points that have the same:

- | | |
|-----------------------------|---------------------|
| A amplitude | B speed |
| C phase of vibration | D displacement only |

SOLUTION: By definition a wavefront is a surface of constant phase.

MCQ 15.1.2 The wavefronts from a point source in space are:

- A plane
C elliptical
B straight lines
D **spherical**

SOLUTION: A point source spreads its waves equally in all directions.

MCQ 15.1.3 The shortest distance between two consecutive wavefronts is:

- A half a wavelength
C the amplitude
B **one wavelength**
D two wavelengths

SOLUTION: Consecutive wavefronts are one full cycle, one wavelength, apart.

MCQ 15.1.4 The angle between a ray and its wavefront is:

- A 90°
C 45°
B 0°
D 180°

SOLUTION: A ray is drawn at right angles to the wavefront.

MCQ 15.1.5 A straight vibrator in a ripple tank produces:

- A circular wavefronts
C no wavefronts
B spherical wavefronts
D **plane wavefronts**

SOLUTION: A line source gives wavefronts that are plane and straight in two dimensions.

Topic 15.2 Huygen's Principle

Geometrical Method

Christiaan Huygens, a Dutch scientist, used a geometrical method for finding, from the known shape of a wavefront at some instant, the shape of the wavefront at some later time.

Huygen's Principle

Every point of a wavefront may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the wave.

New Wavefront

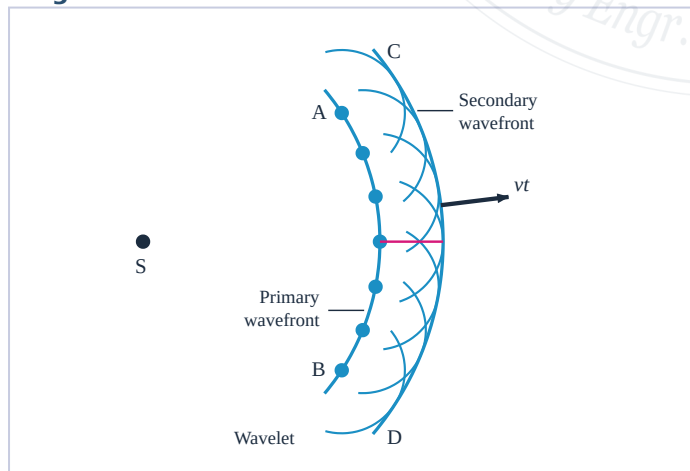
The new wavefront at a later time is found by constructing a surface tangent to the secondary wavelets, called the envelope of the wavelets.

Construction

The original wavefront AB travels outward from a source S. The speed of propagation v is the same at all points, so in a time t the wavefront travels a distance $s = vt$.

Several circles, the traces of spherical wavelets of radius vt , are drawn with their centres on AB. The trace of the envelope of these wavelets is the new wavefront CD.

Diagram



Maxwell's Equations

All the results obtained from Huygens' principle can also be obtained from Maxwell's equations, but Huygens' simple model is easier to use.

SHORT QUESTIONS

SQ 15.2.1 State Huygen's principle.

Huygen's principle

Every point of a wavefront may be considered the source of secondary wavelets that spread out in all directions with the speed of the wave. The new wavefront is the surface tangent to these wavelets.

SQ 15.2.2 In Huygens' construction, what radius is given to the secondary wavelets for a time interval t ?

Radius of the wavelets

In time t each wavelet spreads out through the distance travelled by the wave.

$$r = vt$$

So the new wavefront lies a distance vt ahead of the old one.

SQ 15.2.3 What is the envelope of the secondary wavelets?

Envelope of the wavelets

The surface drawn tangent to all the secondary wavelets at a given instant. It is the new position of the wavefront.

MCQ 15.2.1 According to Huygens, every point of a wavefront acts as a source of:

- A primary waves
C **secondary wavelets**
B photons
D standing waves

SOLUTION: Each point sends out secondary wavelets at the speed of the wave.

MCQ 15.2.2 The secondary wavelets spread out with a speed equal to:

- A **the speed of the wave**
C twice the speed of the wave
B half the speed of the wave
D zero

SOLUTION: This is part of Huygens' assumption.

MCQ 15.2.3 In a time t the radius of each secondary wavelet is:

- A v/t
C t/v
B vt
D v^2t

SOLUTION: Distance equals speed multiplied by time.

MCQ 15.2.4 The new wavefront in Huygens' construction is the:

- A line joining the centres of the wavelets
C source of the wavelets
B normal to the wavelets
D **envelope of the secondary wavelets**

SOLUTION: It is the surface tangent to all the wavelets.

Topic 15.3 Interference

LQ 1 starts here — *interference of light, coherent sources, and why coherent sources are necessary for sustained interference*

Complex Waves

Adding waves of different wavelengths and amplitudes results in complex waves. Interesting effects appear when two waves of the same wavelength overlap at a point.

Interference

Two coherent waves, when they meet in a region, reinforce each other at some points and cancel each other at some other points, forming a pattern called interference.

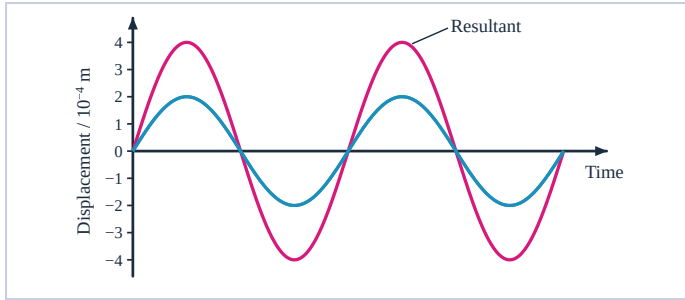
Two Loudspeakers

Two loudspeakers connected to the same source emit sounds of the same frequency and wavelength, in phase. At each point in front of them waves arrive from both loudspeakers.

Constructive Interference

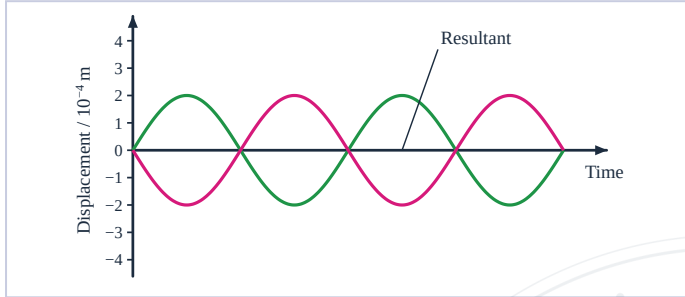
Where the two waves arrive in phase and with equal amplitude, the principle of superposition predicts a

resultant of twice the amplitude of a single wave, and a louder sound is heard.



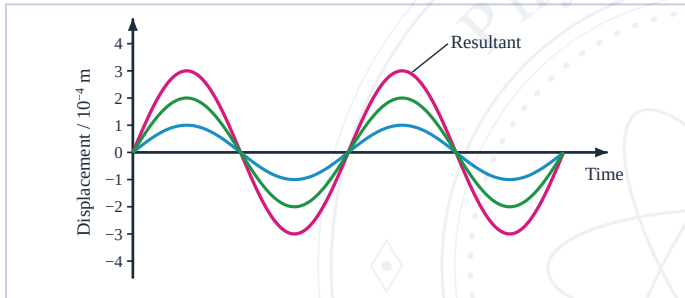
Destructive Interference

Where the two waves arrive in antiphase, they cancel each other and the resultant is zero.



Different Amplitudes

Waves of different amplitudes can also interfere constructively.



Conditions for Interference

- The waves must be of the same type, that is sound waves can only produce interference with other sound waves.
- The waves must be coherent, having a constant phase difference.
- The waves must be moving in the same direction.

Coherence

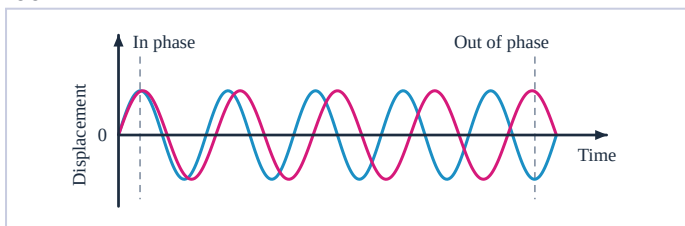
Waves reach us from all directions, as visible light, infrared, radio waves and sound, yet interference patterns are not observed all the time. Specially arranged conditions are needed to produce interference effects that can be measured.

Everyday Interference

Halo of light around street lamps or the moon on a foggy night, and the bright and dark bands seen when looking through fabric at a bright source, are interference effects.

Different Frequencies

If the two loudspeakers were connected to different signal generators of slightly different frequencies, the waves might start in phase but would soon go out of phase. The sound would be loud, then soft, then loud again, and the pattern would keep shifting around the room.



Coherent Sources

Connected to the same signal generator, the two loudspeakers produce sound waves that are constantly

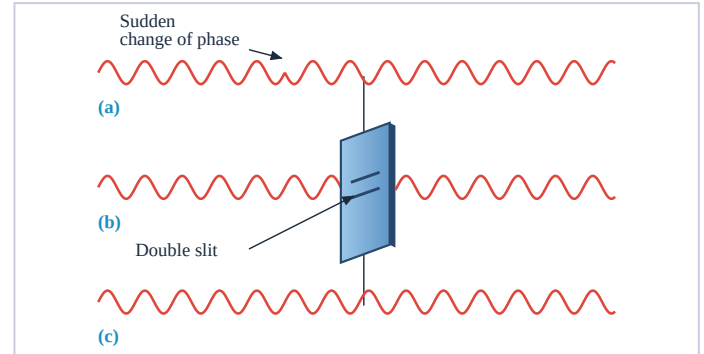
in phase. Coherent sources emit waves that have a constant phase difference.

Condition for Coherence

Two waves can only have a constant phase difference if their frequencies are the same and remain constant.

Light from Lasers

The light from a laser can be thought of as many separate bursts of light. The bursts from two lasers cannot be guaranteed to stay in phase, even if the lasers produce exactly the same frequency.



One Laser and Two Slits

The problem is overcome by using a single laser and dividing its light with two slits. The slits act as two coherent sources, constantly in phase or with a constant phase difference between them.

Why Coherence Is Necessary

If the sources were not coherent, the interference pattern would change constantly, far too fast for the eye to detect, and only a uniform band of light would be seen, without definite bright and dark regions. To observe interference, two coherent sources of waves are needed.

LQ 1 ends here

SHORT QUESTIONS

SQ 15.3.1 What happens to the loudness at a point where the sound waves from two loudspeakers arrive in phase with equal amplitude?

The sound is louder.

Constructive interference

The resultant has twice the amplitude of a single wave.

$$A = A_1 + A_2 = 2A_1$$

SQ 15.3.2 What is the resultant when two waves of equal amplitude meet in antiphase?

Destructive interference

The two waves cancel each other, so the resultant displacement is zero at every instant.

$$A = A_1 - A_2 = 0$$

SQ 15.3.3 Why is no steady interference pattern produced by two loudspeakers driven by separate generators of slightly different frequencies?

Changing phase difference

The waves start in phase but soon drift out of phase. The sound is loud, then soft, then loud again, and the pattern keeps shifting around the room.

SQ 15.3.4 Why cannot two separate lasers of the same frequency act as coherent sources?

Bursts of laser light

The light of a laser is made of many separate bursts, and the bursts from two lasers cannot be guaranteed to stay in phase. Their phase difference is therefore not constant.

SQ 15.3.5 Give two everyday examples of the interference of light.

Everyday interference

- Haloes of light around street lamps or the moon on a foggy night.
- Bright and dark bands seen when looking through fabric at a bright source of light.

MCQ 15.3.1 Two waves, each of amplitude a , meet in phase. The resultant amplitude is:

- A a B $2a$
C zero D $a/2$

SOLUTION: In phase the displacements add, $a + a = 2a$.

MCQ 15.3.2 Waves of amplitudes 1 unit and 2 units meet in phase. The resultant amplitude is:

- A 1 unit B 2 units
C 3 units D 5 units

SOLUTION: The amplitudes add, $1 + 2 = 3$ units.

MCQ 15.3.3 Two equal waves interfere destructively when their phase difference is:

- A 180° B 0°
C 360° D 90°

SOLUTION: In antiphase a crest of one meets a trough of the other.

MCQ 15.3.4 Coherent sources must have:

- A equal amplitudes B different frequencies
C a random phase difference D a constant phase difference

SOLUTION: That is the definition of coherent sources.

MCQ 15.3.5 Two loudspeakers on generators of slightly different frequencies give a sound that is:

- A alternately loud and soft B always loud
C always silent D of constant loudness

SOLUTION: The waves drift in and out of phase, so the pattern keeps shifting.

MCQ 15.3.6 Haloes of light seen around street lamps on a foggy night are an effect of:

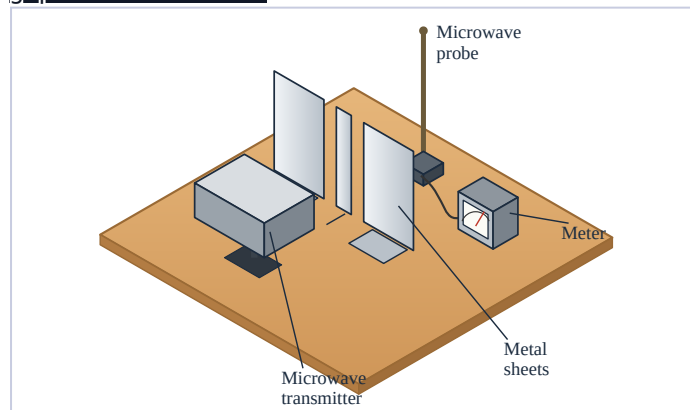
- A polarization B interference
C dispersion by a prism D total internal reflection

SOLUTION: The book gives them as everyday interference effects.

Topic 15.4 Interference of Microwaves

Apparatus

Microwave equipment of wavelength 2.8 cm is used. The microwave transmitter is directed towards the double gap in a metal barrier.



Working

The microwaves are diffracted at the two gaps, so they spread out into the region beyond, where they are

detected with the probe receiver. Moving the probe around detects regions of high intensity, constructive interference, and of low intensity, destructive interference.

Output

The probe may be connected to a meter, or to an audio amplifier and loudspeaker to give an audible output.

Why Easily Observed

Microwaves have wavelengths comparable to the size of the metal barrier apparatus, so the pattern is easily observable and measurable.

Path Difference

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

Maxima (Bright Region)

$$\Delta x = m\lambda$$

Minima (Dark Region)

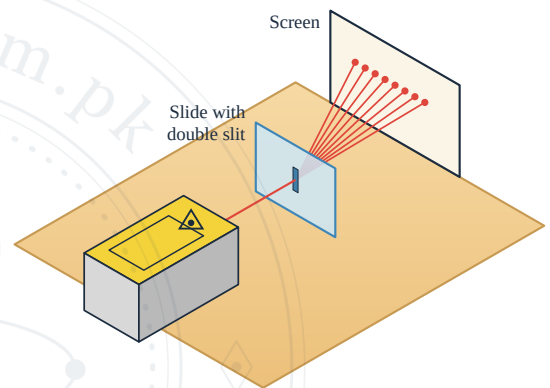
$$\Delta x = \left(m + \frac{1}{2}\right)\lambda$$

For Your Information

A microwave oven has a metal grid in the door to keep microwaves in and let light out.

Interference of Light Waves

Light from a laser is directed through two slits, two clear lines on a black slide separated by a few millimetres. Where the light falls on the screen a series of equally spaced dots of light is seen.



Fringes

The bright dots are called interference fringes. They are regions where the waves from the two slits arrive in phase, so there is constructive interference, and the dark regions in between result from destructive interference.

Comparison with Sound

Bright fringes correspond to loud sound and dark fringes to quiet sound or silence, like the loud and quiet regions of the two loudspeakers.

Light from Both Slits

Mark a dark fringe on the screen and cover one slit. The fringes disappear and a broad band of light, the diffraction pattern of a single slit, appears across the screen, so the point that was dark is now bright. Covering the other slit gives the same effect. Light therefore arrives from both slits, and at the dark fringes the two beams cancel each other.

SHORT QUESTIONS

SQ 15.4.1 What wavelength of microwaves is used to show interference, and why is the pattern easily observed?

Microwave wavelength

Microwaves of wavelength 2.8 cm are used.

Easy to observe

The wavelength is comparable to the size of the gaps in the metal barrier, so the pattern is easily observed and measured.

SQ 15.4.2 Write the conditions for maxima and minima in the microwave interference experiment.

Path difference

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

Conditions

Maxima occur where the path difference is a whole number of wavelengths, and minima where it is an odd number of half wavelengths.

$$\Delta x = m\lambda$$

$$\Delta x = \left(m + \frac{1}{2}\right)\lambda$$

SQ 15.4.3 Why does a microwave oven have a metal grid in its door?

Metal grid in the door

The grid keeps the microwaves in and lets light out, so the food can be seen while the microwaves stay inside the oven.

SQ 15.4.4 How can it be shown that light reaches a dark fringe from both slits?

Covering one slit

When one slit is covered the fringes disappear, a broad band of light appears and the point that was dark becomes bright. So at a dark fringe light arrives from both slits and the two beams cancel.

MCQ 15.4.1 The wavelength of the microwaves used to show interference is about:

- | | |
|-----------------|----------|
| A 2.8 mm | B 2.8 m |
| C 2.8 cm | D 280 nm |

SOLUTION: It is comparable to the size of the metal barrier.

MCQ 15.4.2 In the microwave experiment the path difference is:

- | | |
|-------------------|---------------------|
| A $d \cos \theta$ | B $d \sin \theta$ |
| C $d \tan \theta$ | D $d / \sin \theta$ |

SOLUTION: The same geometry as for two slits.

MCQ 15.4.3 A minimum of the microwave pattern occurs where the path difference is:

- | | |
|------------------------------|---------------|
| A $m\lambda$ | B $2m\lambda$ |
| C $(m + \frac{1}{2})\lambda$ | D zero |

SOLUTION: The waves arrive in antiphase and cancel.

MCQ 15.4.4 The probe of the microwave experiment can give an audible output when connected to:

- | | |
|---------------|---|
| A a battery | B a transformer |
| C a rectifier | D an audio amplifier and loudspeaker |

SOLUTION: It may also be connected to a meter.

MCQ 15.4.5 If one slit of a double slit is covered, the fringes are replaced by:

- | | |
|--------------------------------|-----------------------|
| A a broad band of light | B darkness everywhere |
| C brighter fringes | D narrower fringes |

SOLUTION: One slit alone gives only its single-slit diffraction pattern.

Topic 15.5 Young's Double-Slit Experiment

LQ 2 starts here — the arrangement of Young's double-slit experiment, the expression for fringe width, and how it demonstrates the wave nature of light

Young's Experiment

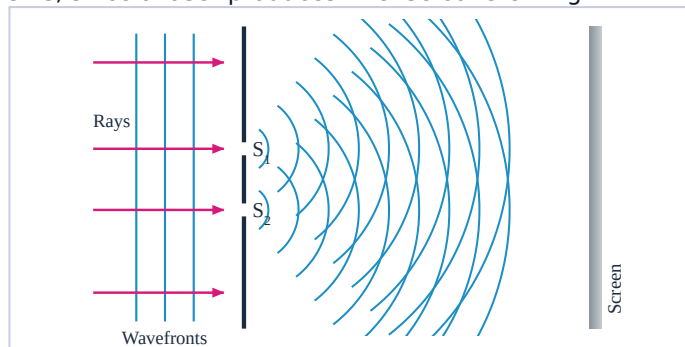
Thomas Young performed this experiment in 1801 to show the wave nature of light.

Arrangement

A beam of light falls on a pair of parallel slits placed at right angles to the beam. Light diffracts and spreads outwards from each slit into the space beyond, and the light from the two slits overlaps on a screen, forming an interference pattern of bright and dark bands called fringes.

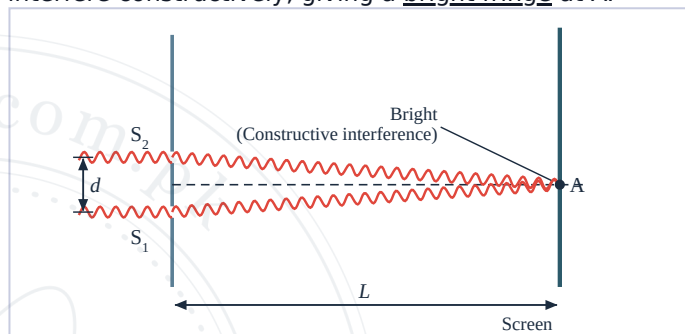
Coherent Sources

The phase difference between the waves emitted at the two sources must remain constant, which also means the waves have the same wavelength. This is achieved by passing a single beam of laser light through the two slits, since a laser produces intense coherent light.



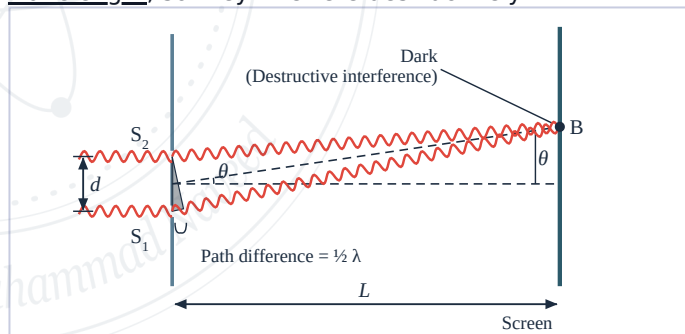
Point A

Point A is directly opposite the mid-point of the double slit and is equidistant from S_1 and S_2 . The path difference is zero, so the two rays arrive in phase and interfere constructively, giving a bright fringe at A.



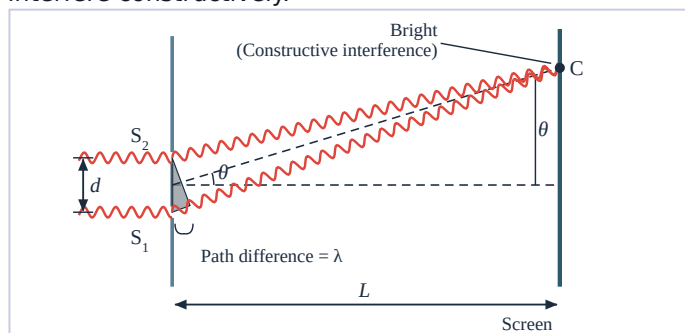
Point B

Point B is the mid-point of the first dark fringe. The light from slit 1 travels slightly further than the light from slit 2, and at B the two rays are in antiphase, a phase difference of 180° . The path difference is half a wavelength, so they interfere destructively.



Point C

Point C is the mid-point of the next bright fringe. The ray from S_1 travels an extra distance equal to a whole wavelength λ , so the rays are in phase at the screen and interfere constructively.



Path Difference

The distance L from the slits to the screen is very large compared with the slit separation d , which is typically a few millimetres while the screen may be a metre or more away. The rays from S_1 and S_2 are then nearly parallel.

$$\text{Path difference} = d \sin \theta$$

Here θ is the angle between a line from the slits to the screen and the normal to the plane of the slits.

Bright Fringes

Constructive interference occurs where the path difference is a whole number of wavelengths.

$$d \sin \theta = m\lambda$$

$$m = 0, 1, 2, 3, \dots$$

Dark Fringes

Destructive interference occurs where the path difference is a half-integer number of wavelengths.

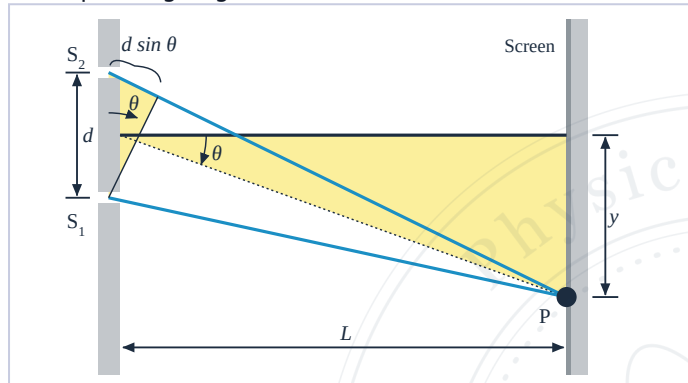
$$d \sin \theta = \left(m + \frac{1}{2}\right)\lambda$$

$$m = 0, 1, 2, 3, \dots$$

The pattern on the screen is a succession of bright and dark bands parallel to the slits.

Position of the Bright Fringes

Let y_m be the distance from the centre of the pattern to the centre of the m th bright fringe, and θ the corresponding angle.



From the figure

$$y_m = L \tan \theta$$

Small Angles

The distances y_m are much smaller than L , so θ is very small and its sine and tangent are nearly equal.

$$y_m = L \sin \theta$$

From the bright-fringe condition

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

$$y_m = \frac{mL\lambda}{d}$$

Position of the Dark Fringes

$$y_m = \left(m + \frac{1}{2}\right) \frac{L\lambda}{d}$$

For the first order dark fringe m is zero.

Fringe Width

The distance between two consecutive bright fringes is called the fringe width or fringe spacing.

$$y_m = \frac{mL\lambda}{d}$$

$$y_{m+1} = \frac{(m+1)L\lambda}{d}$$

$$\Delta y = y_{m+1} - y_m = \frac{(m+1)L\lambda}{d} - \frac{mL\lambda}{d}$$

$$\Delta y = \frac{L\lambda}{d}$$

Dependence on the Slit Separation

For a given screen distance and wavelength

$$L\lambda = \text{constant}$$

$$\Delta y \propto \frac{1}{d}$$

The fringe spacing is inversely proportional to the slit separation. The closer together the slits, the more the pattern spreads out; when the slits are far apart the bands are closer together.

Any Type of Wave

These results are valid for any type of wave, provided the resultant wave from two coherent sources is detected at a point far away in comparison to the separation d .

Wave Nature of Light

Bright and dark fringes are formed only by the superposition of waves, reinforcing where they arrive in phase and cancelling where they arrive in antiphase. The fringes therefore prove the wave nature of light, which is how Young's experiment established Huygens' wave theory.

LQ 2 ends here

BOOK EXAMPLES

Example 15.5.1 The distance between two consecutive slits in Young's experiment is 0.25 cm. Screen is at a distance of 100 cm from slits. Calculate distance of third order dark fringe from centre of screen, if wavelength of light used is $\lambda = 519 \text{ nm}$.

Given Data

$$d = 0.25 \text{ cm} = 0.25 \times 10^{-2} \text{ m}$$

$$L = 100 \text{ cm} = 1.0 \text{ m}$$

$$\lambda = 519 \text{ nm} = 519 \times 10^{-9} \text{ m}$$

To Find

Distance of the third dark fringe $y = ?$

Formula

$$y = \left(m + \frac{1}{2}\right) \frac{L\lambda}{d}$$

For the third dark fringe m is 2, since the first dark fringe has m equal to zero.

Solution

Putting the values in the formula

$$y = \left(2 + \frac{1}{2}\right) \frac{1.0 \text{ m} \times 519 \times 10^{-9} \text{ m}}{0.25 \times 10^{-2} \text{ m}}$$

$$= 5.19 \times 10^{-4} \text{ m}$$

Result

$$y = 5.19 \times 10^{-4} \text{ m}$$

Note

The book prints the answer as $5.9 \times 10^{-4} \text{ m}$; its own working gives $5.19 \times 10^{-4} \text{ m}$.

SHORT QUESTIONS

SQ 15.5.1 Why is the central fringe in Young's experiment always bright?

Central bright fringe

The centre of the screen is equidistant from the two slits, so the path difference is zero.

$$d \sin \theta = 0$$

The waves arrive in phase and interfere constructively.

SQ 15.5.2 What are the phase difference and the path difference at the first dark fringe?

First dark fringe

The two rays arrive in antiphase, a phase difference of 180° , and the path difference is half a wavelength.

$$\text{Path difference} = \frac{\lambda}{2}$$

SQ 15.5.3 Why can the sine of the angle be replaced by its tangent in Young's experiment?

Small angle

The fringe distances y_m are much smaller than the slit-to-screen distance L , so the angle is very small, and for a small angle the sine and the tangent are nearly equal.

SQ 15.5.4 How does the fringe spacing change if the screen is moved further from the slits?

Fringe spacing and screen distance

For a given wavelength and slit separation

$$\frac{\lambda}{d} = \text{constant}$$

$$\Delta y \propto L$$

So moving the screen further away increases the fringe spacing.

SQ 15.5.5 Write the position of the m th dark fringe from the centre of the screen.

Position of a dark fringe

$$y_m = \left(m + \frac{1}{2}\right) \frac{L\lambda}{d}$$

For the first dark fringe m is zero, so it lies half a fringe spacing from the centre.

SQ 15.5.6 Why is a laser used as the source in Young's experiment today?

Laser as the source

A laser produces intense coherent light. A single beam passing through the two slits makes them coherent sources of the same wavelength with a constant phase difference.

SQ 15.5.7 Are the fringes near the centre of the pattern equally spaced?

Yes, they are.

Equal spacing

$$\Delta y = \frac{L\lambda}{d}$$

The spacing does not contain m , so near the centre the fringes are equally spaced.

MCQ 15.5.1 Young performed his double-slit experiment in:

- | | |
|--------|--------|
| A 1678 | B 1860 |
| C 1914 | D 1801 |

SOLUTION: It proved the wave nature of light.

MCQ 15.5.2 At the centre of the screen in Young's experiment the path difference is:

- | | |
|---------------|--------------|
| A $\lambda/2$ | B zero |
| C λ | D 2λ |

SOLUTION: The centre is equidistant from the two slits.

MCQ 15.5.3 At the first dark fringe the path difference is:

- | | |
|---------------|----------------|
| A λ | B zero |
| C $\lambda/2$ | D $3\lambda/2$ |

SOLUTION: The waves arrive in antiphase.

MCQ 15.5.4 The condition for a bright fringe is:

- | | |
|------------------------------|--|
| A $d \sin \theta = m\lambda$ | B $d \sin \theta = (m + \frac{1}{2})\lambda$ |
| C $d \cos \theta = m\lambda$ | D $d = m\lambda \sin \theta$ |

SOLUTION: The path difference must be a whole number of wavelengths.

MCQ 15.5.5 The fringe spacing in Young's experiment is:

- | | |
|----------------|----------------|
| A $L\lambda/d$ | B $d\lambda/L$ |
| C Ld/λ | D λ/Ld |

SOLUTION: It is the difference between the positions of consecutive bright fringes.

MCQ 15.5.6 Light of wavelength 600 nm falls on slits 0.3 mm apart, and the screen is 1.5 m away. The fringe spacing is:

- | | |
|----------|---------|
| A 0.3 mm | B 30 mm |
| C 6 mm | D 3 mm |

SOLUTION:

$$\Delta y = L\lambda/d = 1.5 \times 600 \times 10^{-9} / 0.3 \times 10^{-3} = 3 \times 10^{-3} \text{ m.}$$

MCQ 15.5.7 The second bright fringe lies 4 mm from the centre. The fringe spacing is:

- | | |
|--------|--------|
| A 4 mm | B 2 mm |
| C 8 mm | D 1 mm |

SOLUTION: Since $y_m = m\Delta y$, the spacing is $4/2 = 2$ mm.

MCQ 15.5.8 The first dark fringe lies from the centre at a distance of:

- | | |
|-----------------|-----------------|
| A $L\lambda/d$ | B $2L\lambda/d$ |
| C $L\lambda/2d$ | D zero |

SOLUTION: With $m = 0$ in $y_m = (m + \frac{1}{2})L\lambda/d$.

Topic 15.6 Interference in Thin Films

LQ 3 starts here — the formation of interference in thin films, with bright and dark fringes

Thin Film

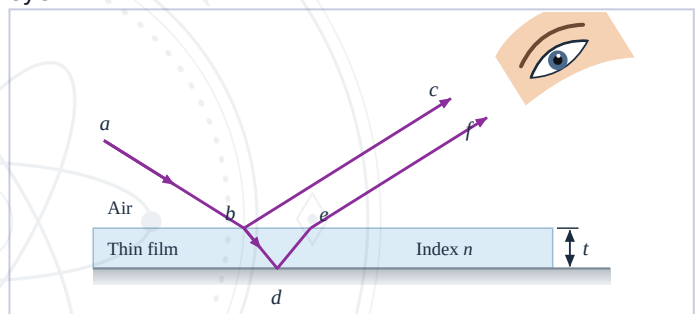
A film whose thickness is of the order of the wavelength of light is called a thin film.

Colours of Thin Films

Bright bands of colour are seen when light reflects from a thin layer of oil floating on water or from a soap bubble. Light waves are reflected from the front and back surfaces of the film, and constructive interference between the two reflected waves, with different path lengths, occurs in different places for different wavelengths.

Two Reflected Waves

Light falling on the upper surface of a film of thickness t is partly reflected at the upper surface, path abc. Light transmitted through the upper surface is partly reflected at the lower surface, path abdef. The two reflected waves come together at a point P on the retina of the eye.

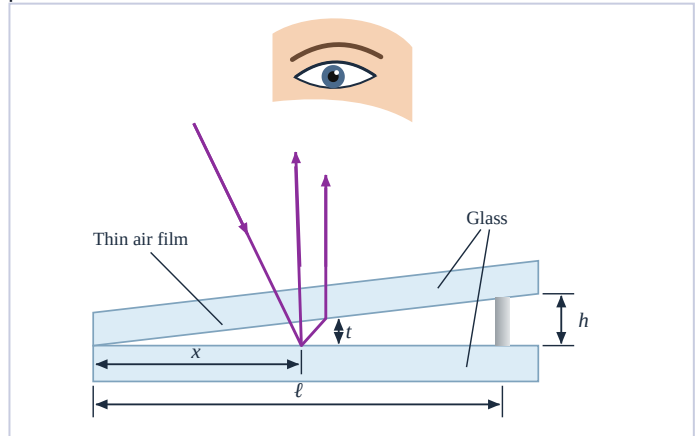


Constructive or Destructive

Depending on their phase relationship the two waves interfere constructively or destructively. Different colours have different wavelengths, so the interference may be constructive for some colours and destructive for others, which is why coloured patterns are seen in thin films such as the walls of a soap bubble. The complex shapes of the patterns result from variations in the thickness of the film.

Thin Air Film

Two glass plates are separated by a thin wedge of air, and monochromatic light reflects from the two nearly parallel surfaces adjacent to the air wedge at nearly normal incidence. The reflections at the top surface of the upper plate and at the bottom surface of the lower plate are left out.



Path Difference

The path difference between the two waves is just twice the thickness t of the air film at each point.

$$\text{Path difference} = 2t$$

Bright Fringes

Where $2t$ is a whole number of wavelengths, constructive interference and a bright area are expected.
 $2t = m\lambda$

Dark Fringes

Where $2t$ is a half-integer number of wavelengths, destructive interference and a dark area are expected.

$$2t = \left(m + \frac{1}{2}\right)\lambda$$

At the Line of Contact

Where the plates are in contact there is practically no path difference, so a bright area is expected.

Observed Result

In the experiment the bright and dark fringes appear but are interchanged. Along the line where the plates are in contact a dark fringe is found, not a bright one.

Phase Shift

One of the reflected waves undergoes a half cycle phase shift during its reflection, so the two waves reflected at the line of contact are half a cycle out of phase even though they have the same path length. This phase shift can be predicted from Maxwell's equations and the electromagnetic nature of light.

LQ 3 ends here

SHORT QUESTIONS

SQ 15.6.1 What is a thin film? Give two examples.

Thin film

A film whose thickness is of the order of the wavelength of light.

Examples

A thin layer of oil floating on water, and the wall of a soap bubble.

SQ 15.6.2 Why do the coloured patterns of a thin film have complex shapes?

Varying thickness

The path difference depends on the thickness of the film, which varies from place to place, so each colour is reinforced along its own irregular band.

SQ 15.6.3 What is the path difference between the waves reflected from the two surfaces of a thin air wedge?

Path difference in an air wedge

At nearly normal incidence the lower wave crosses the air film twice.

$$\text{Path difference} = 2t$$

Here t is the thickness of the air film at that point.

SQ 15.6.4 What condition would give a bright fringe in an air wedge if there were no phase change on reflection?

Bright fringe condition

Where twice the thickness is a whole number of wavelengths the reflected waves reinforce.

$$2t = m\lambda$$

SQ 15.6.5 What predicts the half-cycle phase shift on reflection in an air wedge?

Source of the phase shift

It is predicted by Maxwell's equations and follows from the electromagnetic nature of light.

MCQ 15.6.1 A thin film has a thickness of the order of:

- | | |
|-------------------------|----------------------------------|
| A a millimetre | B a centimetre |
| C the size of a nucleus | D the wavelength of light |

SOLUTION: That is the definition of a thin film.

MCQ 15.6.2 In an air wedge the path difference between the two reflected waves is:

- | | |
|--------|---------|
| A t | B $t/2$ |
| C $2t$ | D $4t$ |

SOLUTION: The lower wave crosses the air film twice.

MCQ 15.6.3 The bright and dark fringes of an air wedge are interchanged because one reflected wave suffers a phase shift of:

- | | |
|------------------------|-----------------------|
| A a whole cycle | B half a cycle |
| C a quarter of a cycle | D nothing |

SOLUTION: This half-cycle shift can be predicted from Maxwell's equations.

MCQ 15.6.4 The coloured bands of a thin film vary from place to place because of variations in its:

- | | |
|--------------------|---------------|
| A thickness | B temperature |
| C mass | D colour |

SOLUTION: The path difference depends on the thickness at each point.

MCQ 15.6.5 Ignoring the phase shift, a dark fringe of an air wedge would occur where $2t$ equals:

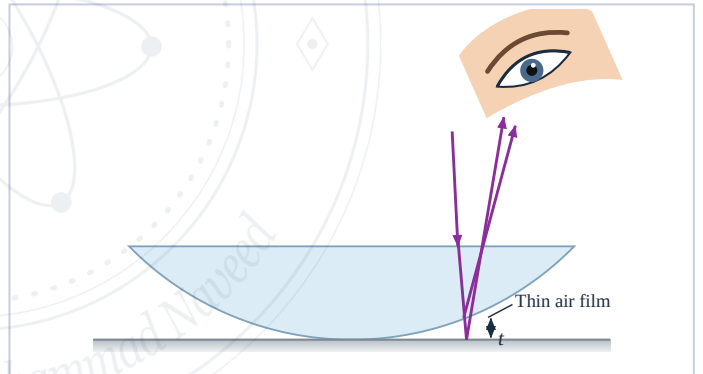
- | | |
|------------------------------|--------------|
| A $(m + \frac{1}{2})\lambda$ | B $m\lambda$ |
| C $2m\lambda$ | D zero |

SOLUTION: The two waves would then arrive in antiphase.

Topic 15.7 Newton's Rings

Arrangement

A plano-convex lens is placed in contact with a plane glass plate, and a thin film of air is formed between the two surfaces.

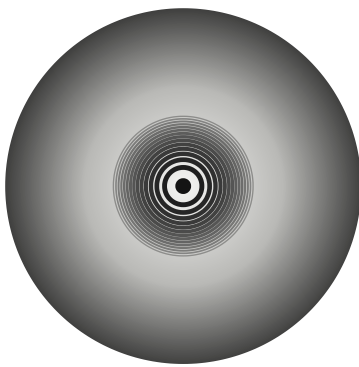


Newton's Rings

When the thin air film enclosed between a plano-convex lens and a glass plate is viewed with monochromatic light, alternate bright and dark circular interference fringes are formed. They were studied by Newton and are called Newton's rings.

Formation

Light from a monochromatic source reflects off both the top and the bottom surfaces of the air film. The reflected rays interfere constructively, giving bright rings, or destructively, giving dark rings, depending on the path difference and the phase shift between them.



Uses

- To calculate the wavelength of monochromatic light.
- To determine the radius of curvature of lenses.
- In precision optics, to detect surface irregularities.

Do You Know

The different colours seen on the surface of a soap bubble are due to the interference of white light falling on it and reflecting from it.

SHORT QUESTIONS

SQ 15.7.1 What are Newton's rings?

Newton's rings

Alternate bright and dark circular interference fringes, seen in monochromatic light, when a thin air film is enclosed between a plano-convex lens and a plane glass plate.

SQ 15.7.2 Why are Newton's rings circular?

Circular fringes

The air film has the same thickness at all points the same distance from the point of contact, so each fringe is a circle about that point.

SQ 15.7.3 Give three uses of Newton's rings.

Uses

- To find the wavelength of monochromatic light.
- To find the radius of curvature of a lens.
- To detect surface irregularities in precision optics.

MCQ 15.7.1 Newton's rings are formed by interference in a thin film of:

- | | |
|--------|--------------|
| A oil | B water |
| C soap | D air |

SOLUTION: The film lies between the lens and the glass plate.

MCQ 15.7.2 Newton's rings are formed between:

- | | |
|--|---------------------------------|
| A two plane mirrors | B two prisms |
| C a plano-convex lens and a plane glass plate | D a concave mirror and a screen |

SOLUTION: The curved face of the lens rests on the flat plate.

MCQ 15.7.3 The fringes of Newton's rings are:

- | | |
|--------------|-------------------|
| A straight | B circular |
| C elliptical | D parabolic |

SOLUTION: The air film has the same thickness all round the point of contact.

MCQ 15.7.4 Newton's rings are used to determine the:

- | | |
|------------------|--|
| A speed of light | B charge on an electron |
| C mass of a lens | D radius of curvature of a lens |

SOLUTION: They also give the wavelength of monochromatic light.

Topic 15.8 Diffraction Grating

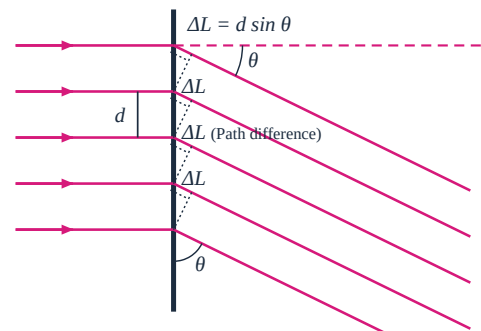
More Slits

If the number of slits in an interference experiment is increased, keeping the spacing of adjacent slits constant, the maxima stay in the same positions but become progressively narrower than with two slits. Because they

are so narrow, their angular position, and hence the wavelength, can be measured to very high precision.

Diffraction Grating

An array of a large number of parallel slits, all of the same width and spaced equal distances d between centres, is called a diffraction grating. The first one was constructed by Fraunhofer using fine wires.



Making a Grating

Gratings are made by scratching many equally spaced grooves on a glass or metal surface with a diamond point, or by photographic reduction of a pattern of black and white stripes on paper. For a grating the slits are often called rulings or lines.

Diffraction

The property of bending of light around obstacles and spreading of light waves into the geometrical shadow of an obstacle is called diffraction.

Transmission Grating

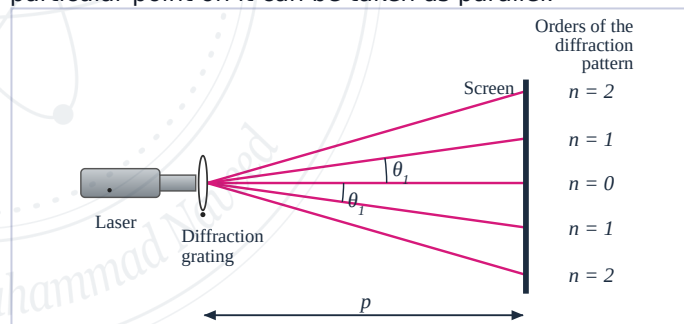
The slits are perpendicular to the plane of the page, and the interference pattern is formed by the light transmitted through them. An actual grating may contain several thousand slits.

Grating Spacing

The spacing d between the centres of adjacent slits is called the grating spacing.

Fraunhofer Conditions

A plane monochromatic wave falls normally on the grating from the left. The screen is far enough away that all the rays emerging from the grating and going to a particular point on it can be taken as parallel.



Principal Maxima

The maxima occur in the same directions as for two slits, where the path difference for adjacent slits is a whole number of wavelengths.

$$d \sin \theta = n\lambda$$

$$n = 0, \pm 1, \pm 2, \pm 3, \dots$$

Orders

The lines for ± 1 are called the first-order lines, those for ± 2 the second-order lines, and so on. With many slits the pattern is a series of very sharp lines.

Determination of Wavelength

If the number of lines per mm or per cm is known, d is its reciprocal. For 600 lines per mm

$$d = \frac{1}{600} \text{ mm} = 1.67 \times 10^{-6} \text{ m}$$

The grating is illuminated with monochromatic light or a spectral line. If θ is the diffraction angle for a particular order n , usually the first or the second, then

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

White Light

With white light each value of n gives a continuous spectrum. Long wavelengths, the red end of the spectrum, lie at larger angles than the shorter wavelengths of the blue end.

Visible Gratings

Gratings for visible light of wavelength 400 to 700 nm usually have about 1000 slits per millimetre, so d is of the order of 1000 nm.

Tidbit

A diffraction grating can split white light into its constituent colours, but the central fringe remains white.

Do You Know

A CD ROM acts as a reflection diffraction grating. White light is reflected and diffracted at its surface, producing a display of spectral colours.

SHORT QUESTIONS

SQ 15.8.1 What is a diffraction grating, and who constructed the first one?

Diffraction grating

An array of a large number of parallel slits of the same width, spaced equal distances apart between centres.

First grating

It was constructed by Fraunhofer, using fine wires.

SQ 15.8.2 Define diffraction.

Diffraction

The bending of light around obstacles and the spreading of light waves into the geometrical shadow of an obstacle.

SQ 15.8.3 Find the grating spacing of a grating ruled with 500 lines per mm.

Grating spacing

The spacing is the reciprocal of the number of lines per unit length.

$$d = \frac{1}{500} \text{ mm} = 2 \times 10^{-6} \text{ m}$$

SQ 15.8.4 How are diffraction gratings made?

Making gratings

- By scratching many equally spaced grooves on glass or metal with a diamond point.
- By photographic reduction of a pattern of black and white stripes on paper.

SQ 15.8.5 Why does the central maximum stay white when white light falls on a grating?

White central fringe

For the central maximum

$$d \sin \theta = 0$$

It lies straight ahead for every wavelength, so all the colours overlap there and it remains white.

SQ 15.8.6 What is meant by Fraunhofer conditions?

Fraunhofer conditions

The screen is far enough from the grating that all the rays going to one point on it can be treated as parallel.

MCQ 15.8.1 The first diffraction grating was made by Fraunhofer using:

- | | |
|-------------------|---------------------|
| A a diamond point | B fine wires |
| C photography | D glass prisms |

SOLUTION: Later gratings were ruled or made photographically.

MCQ 15.8.2 Increasing the number of slits at the same spacing makes the maxima:

- | | |
|-------------------|-------------|
| A wider | B fewer |
| C narrower | D disappear |

SOLUTION: They stay in the same positions but become progressively narrower.

MCQ 15.8.3 A grating has 600 lines per mm. Its grating spacing is:

- | | |
|-----------------------------------|--------------------------------|
| A $1.67 \times 10^{-6} \text{ m}$ | B $6 \times 10^{-4} \text{ m}$ |
| C $1.67 \times 10^{-3} \text{ m}$ | D $6 \times 10^5 \text{ m}$ |

SOLUTION: $d = 1/600 \text{ mm} = 1.67 \times 10^{-6} \text{ m}$.

MCQ 15.8.4 The principal maxima of a grating occur where:

- | | |
|-------------------------------|--|
| A $d \cos \theta = n\lambda$ | B $d \sin \theta = n\lambda$ |
| C $2d \sin \theta = n\lambda$ | D $d \sin \theta = (n + \frac{1}{2})\lambda$ |

SOLUTION: The path difference for adjacent slits is a whole number of wavelengths.

MCQ 15.8.5 Gratings for visible light usually have about:

- | | |
|-----------------------|----------------------------|
| A 10 slits per mm | B 10 slits per m |
| C 10^6 slits per mm | D 1000 slits per mm |

SOLUTION: This makes d of the order of 1000 nm.

MCQ 15.8.6 A grating of spacing $2 \times 10^{-6} \text{ m}$ gives a first-order maximum at 17.5° . The wavelength is:

- | | |
|-----------------|----------|
| A 600 nm | B 300 nm |
| C 1200 nm | D 450 nm |

SOLUTION: $\lambda = d \sin \theta = 2 \times 10^{-6} \times 0.301 = 6.0 \times 10^{-7} \text{ m}$.

MCQ 15.8.7 The bending of light into the geometrical shadow of an obstacle is called:

- | | |
|----------------------|----------------|
| A interference | B refraction |
| C diffraction | D polarization |

SOLUTION: That is the definition of diffraction.

Topic 15.9 Diffraction of X-ray by Crystals and Bragg's Law

LQ 4 starts here — X-ray diffraction and the derivation of Bragg's equation

X-rays

X-rays are electromagnetic radiation of much shorter wavelength, about 10^{-10} m .

Crystal as a Grating

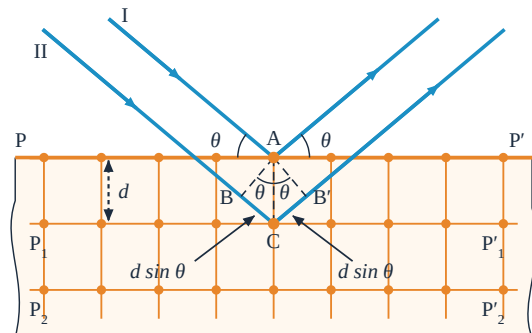
To observe diffraction the grating spacing must be of the order of the wavelength used. The regular array of atoms in a crystal forms a natural diffraction grating with a spacing of typically 10^{-10} m , and the scattering of X-rays from its atoms gives diffraction effects very similar to those of visible light on an ordinary grating.

Bragg's Discovery

In 1914 W.H. Bragg and W.L. Bragg found that a monochromatic beam of X-rays was reflected from a crystal plane as if the plane acted like a mirror.

Atomic Planes

A series of atomic planes of constant interplanar spacing d , parallel to a crystal face, is shown by the lines PP' , $P_1P'_1$, $P_2P'_2$ and so on.



Path Difference

An X-ray beam falls at an angle θ on the planes and is reflected from both the upper and the lower planes of atoms. The beam reflected from the lower plane travels some extra distance.

Path difference = $BC + B'C$

In Triangle ABC

$$\frac{BC}{AC} = \sin \theta$$

AC corresponds to the distance d between the planes, so

$$BC = d \sin \theta$$

In Triangle AB'C

$$\frac{B'C}{AC} = \sin \theta$$

$$B'C = d \sin \theta$$

Total Path Difference

$$\text{Path difference} = d \sin \theta + d \sin \theta = 2d \sin \theta$$

Bragg Equation

For reinforcement the path difference must be a whole number of wavelengths.

$$2d \sin \theta = n\lambda$$

Here n is the order of reflection. The equation is known as the Bragg equation.

Use

It is used to determine the interplanar spacing between similar parallel planes of a crystal when X-rays of known wavelength are diffracted from the crystal.

Applications

X-ray diffraction has been very useful in determining the structure of biologically important molecules such as hemoglobin, an important constituent of blood, and the double helix structure of DNA.

LQ 4 ends here

BOOK EXAMPLES

Example 15.9.1 For a NaCl crystal, the interplanar spacing for (100) planes is $d = 0.282 \text{ nm}$. Copper K_α X-rays have $\lambda = 0.154 \text{ nm}$. Find the Bragg's angle θ for first-order ($n = 1$) reflection.

Given Data

$$d = 0.282 \text{ nm} = 0.282 \times 10^{-9} \text{ m}$$

$$\lambda = 0.154 \times 10^{-9} \text{ m}$$

$$n = 1$$

To Find

Bragg angle $\theta = ?$

Formula

$$2d \sin \theta = n\lambda$$

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

Solution

Putting the values in the formula

$$\sin \theta = \frac{1 \times 0.154 \times 10^{-9} \text{ m}}{2 \times 0.282 \times 10^{-9} \text{ m}} = 0.273$$

$$\theta = \sin^{-1}(0.273) = 15.9^\circ$$

Result

$$\theta = 15.9^\circ$$

Example 15.9.2 For the NaCl at what angle would the second-order ($n = 2$) reflection occur?

Given Data

$$n = 2$$

$$\lambda = 0.154 \times 10^{-9} \text{ m}$$

$$d = 0.282 \times 10^{-9} \text{ m}$$

To Find

Bragg angle $\theta = ?$

Formula

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

Solution

Putting the values in the formula

$$\sin \theta = \frac{2 \times 0.154 \times 10^{-9} \text{ m}}{2 \times 0.282 \times 10^{-9} \text{ m}} = 0.546$$

$$\theta = \sin^{-1}(0.546) = 33.1^\circ$$

Result

$$\theta \approx 33.1^\circ$$

Example 15.9.3 In an X-ray diffraction experiment using $\lambda = 0.071 \text{ nm}$ ($\text{Mo } K_\alpha$), a first-order reflection from a crystal is observed at $\theta = 12.0^\circ$. Calculate the interplanar spacing d .

Given Data

$$n = 1$$

$$\lambda = 0.071 \times 10^{-9} \text{ m}$$

$$\theta = 12.0^\circ$$

To Find

Interplanar spacing $d = ?$

Formula

$$2d \sin \theta = n\lambda$$

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

Solution

Putting the values in the formula

$$d = \frac{1 \times 0.071 \times 10^{-9} \text{ m}}{2 \sin 12^\circ} = \frac{0.071 \times 10^{-9} \text{ m}}{2 \times 0.2079} = 0.171 \times 10^{-9} \text{ m}$$

Result

$$d = 0.171 \text{ nm}$$

This spacing corresponds to a particular set of planes in the crystal lattice.

SHORT QUESTIONS

SQ 15.9.1 Why can a ruled grating not diffract X-rays, while a crystal can?

Crystal as a grating

Diffraction needs a spacing of the order of the wavelength. X-rays have a wavelength of about 10^{-10} m , far smaller than the spacing of any ruled grating, but the atoms of a crystal are about that far apart, so a crystal acts as a natural grating.

SQ 15.9.2 What is meant by the order of reflection in Bragg's equation?

Order of reflection

The whole number n in the Bragg equation. It is the number of wavelengths in the path difference between the waves reflected from neighbouring planes.

$$2d \sin \theta = n\lambda$$

SQ 15.9.3 What is the highest order of Bragg reflection possible for a crystal of spacing d ?

Highest order

The sine of the angle cannot exceed one, so

$$n \leq \frac{2d}{\lambda}$$

The highest order is the largest whole number not greater than this ratio.

SQ 15.9.4 Give two uses of X-ray diffraction.

Uses

- Finding the interplanar spacing of a crystal with X-rays of known wavelength.
- Finding the structure of biologically important molecules such as hemoglobin and the double helix of DNA.

MCQ 15.9.1 The wavelength of X-rays is about:

- A 10^{-6} m B 10^{-3} m
 C 10^{-15} m D 10^{-10} m

SOLUTION: It is of the same order as the spacing of atoms in a crystal.

MCQ 15.9.2 Bragg's equation is:

- A $d \sin \theta = n\lambda$ B $2d \cos \theta = n\lambda$
 C $2d \sin \theta = n\lambda$ D $d \sin \theta = 2n\lambda$

SOLUTION: The path difference $2d \sin \theta$ must be a whole number of wavelengths.

MCQ 15.9.3 The path difference between X-rays reflected from adjacent planes is:

- A $d \sin \theta$ B $2d \sin \theta$
 C $d \cos \theta$ D $2d \cos \theta$

SOLUTION: It is $BC + B'C$, each equal to $d \sin \theta$.

MCQ 15.9.4 The study of crystal structure by X-rays was begun in 1914 by:

- A W.H. Bragg and W.L. Bragg B Thomas Young
 C Christiaan Huygens D Fraunhofer

SOLUTION: They found that X-rays reflect from a crystal plane as from a mirror.

MCQ 15.9.5 X-rays of wavelength 0.1 nm give a first-order Bragg reflection at 30° . The interplanar spacing is:

- A 0.1 nm B 0.05 nm
 C 0.2 nm D 0.4 nm

SOLUTION: $d = n\lambda / 2 \sin \theta = 0.1 / (2 \times 0.5) = 0.1$ nm.

MCQ 15.9.6 X-ray diffraction revealed the structure of:

- A the nucleus B the electron
 C the double helix of DNA D the neutron

SOLUTION: It is used to find the structure of biologically important molecules.

water, what will be the effect on fringes?

The fringes become narrower.

Fringe spacing in water

In water of refractive index n the wavelength is reduced.

$$\lambda_w = \frac{\lambda}{n}$$

$$\Delta y = \frac{L\lambda}{nd}$$

For water n is 1.33, so the fringe spacing falls to about three quarters of its value in air.

SQ 15.5 Compare the double-slit experimental arrangements for light and sound waves, similarities and differences.

Feature	Light waves	Sound waves
Sources	Two slits lit by one laser	Two loudspeakers on one signal generator
Nature of wave	Transverse, electromagnetic	Longitudinal, mechanical
Wavelength	About 500 nm	About 1 m
Source separation	A few millimetres	About a metre
Detector	Screen	Ear or microphone
Pattern	Bright and dark fringes	Loud and quiet regions
Condition	Coherent sources needed	Coherent sources needed
Fringe spacing	$\Delta y = L\lambda/d$	$\Delta y = L\lambda/d$

SQ 15.6 For a diffraction grating, what are the advantages of using: (a) many slits (b) narrow slits (c) closely spaced slits?**Advantages of the slits**

- Many slits make the maxima sharp and bright, so their angles, and hence the wavelength, are measured precisely.
- Narrow slits spread the light widely, so many orders appear.
- Closely spaced slits give each order a larger angle, so the orders and colours are well separated.

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

SQ 15.7 How the number of orders in a given diffraction grating can be increased?**Increasing the orders**

The sine of the angle cannot exceed one, so

$$n \leq \frac{d}{\lambda}$$

For a given grating the number of orders is increased by using light of shorter wavelength.

SQ 15.8 How the pattern would change if red light is replaced with blue light in a given diffraction grating?

The lines move closer to the centre.

Pattern with blue light

Blue light has a shorter wavelength than red, so each order appears at a smaller angle, and more orders can be seen.

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

SQ 15.9 Why central spot in Newton's rings is dark?**Phase change at reflection**

At the point of contact the air film has zero thickness, so the path difference is zero. The wave reflected from the glass plate below suffers a half cycle phase shift, so the two reflected waves meet in antiphase and cancel, giving a dark spot.

Chapter Exercise**SQ 15.1** Can Huygen's principle be applied on sound and water waves? Explain briefly.

Yes, it can.

Huygen's principle for all waves

It is a geometrical construction for any wave that spreads out from a source. Every point of a wavefront of sound or of water waves also acts as a source of secondary wavelets moving at the wave speed, and their envelope gives the new wavefront.

SQ 15.2 Why interference pattern is not produced due to headlights of a car? Explain briefly.**Headlights are not coherent**

The two headlights are independent sources that emit light in random bursts, so their phase difference changes rapidly and randomly. Any pattern would shift far too fast for the eye, and the light is white rather than monochromatic, so a uniform glow is seen.

SQ 15.3 Why interference pattern is observed on soap bubbles but not on window glass or windscreens of cars?**Thickness of the film**

A soap film is a thin film, its thickness of the order of the wavelength of light, so the waves reflected from its two surfaces interfere.

Thick glass

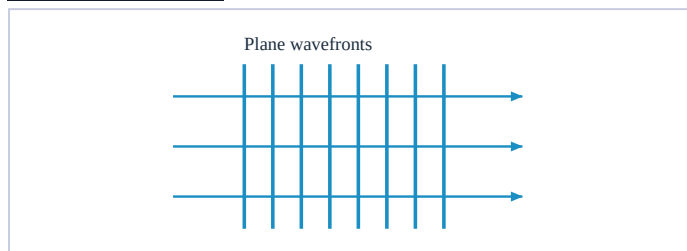
Window glass is thousands of wavelengths thick. The path difference is far too large for the two reflected waves to stay coherent, so no pattern is seen.

SQ 15.4 If the whole apparatus of Young's double-slit experiment is submerged in

CRQ 15.1 Light is sometimes described as rays and sometimes as waves. Construct diagrams to explain differences in both.

Rays and wavefronts

In the ray picture light is drawn as straight lines with arrows along its direction of travel. In the wave picture it is drawn as wavefronts, surfaces of equal phase one wavelength apart, and the rays are lines perpendicular to the wavefronts.



Difference

Rays explain straight-line travel, reflection and refraction, but only waves explain interference and diffraction.

CRQ 15.2 Suppose white light is falling on a double slit arrangement, such that one slit is covered with red filter (650 nm) and other is with blue filter (450 nm), explain what would be observed on the screen?

No interference fringes are seen.

Different wavelengths

The two slits now send out red and blue light. Waves of different wavelengths cannot keep a constant phase difference, so they do not interfere; the screen shows the red and the blue single-slit diffraction patterns overlapping.

CRQ 15.3 What will be the effect on width and brightness of the fringes in a double-slit interference experiment, if we decrease the width of one slit to half keeping all other factors same?

The fringe width is unchanged, but the fringes lose contrast.

Fringe width

$$\Delta y = \frac{L\lambda}{d}$$

It does not depend on the width of a slit.

Brightness

The narrower slit passes less light, so its wave has a smaller amplitude. The bright fringes become less bright and the dark fringes are no longer completely dark.

CRQ 15.4 Why can we readily observe diffraction effects for sound waves and water waves, but not for light waves? Is this because light travels so much faster than these other waves? Explain.

No, the speed is not the reason.

Size of the wavelength

Diffraction is noticeable only when a gap or an obstacle is comparable to the wavelength. Sound and water waves have wavelengths of centimetres to metres, like doors and gaps, while light has a wavelength of about 5×10^{-7} m, far smaller than everyday openings.

CRQ 15.5 What is the significance of path difference in deriving Bragg's equation? Explain.

Path difference in Bragg's law

X-rays reflected from successive planes travel different distances, and the extra path is

$$\text{Path difference} = 2d \sin \theta$$

Significance

Only when it is a whole number of wavelengths do the reflected waves reinforce. This gives the Bragg equation, which links the measured angle to the interplanar spacing.

$$2d \sin \theta = n\lambda$$

MCQ 15.1 When the light from two lamps falls on a screen, no interference pattern can be obtained. Why is this?

- | | |
|---|--|
| A The lamps are not point sources | B The lamps emit light of different amplitudes |
| C The light from the lamps is not coherent | D The light from the lamps is white |

SOLUTION: Two separate lamps emit in random bursts, so their phase difference is never constant.

MCQ 15.2 Monochromatic light illuminates two narrow parallel slits. The interference pattern which results is observed on a screen some distance beyond the slits. Which change increases the separation between the dark lines of the interference pattern?

- | | |
|--|---|
| A Decreasing the distance between the screen and the slits | B Increasing the distance between the slits |
| C Monochromatic light of higher frequency | D Using monochromatic light of longer wavelength |

SOLUTION: The spacing is $\Delta y = L\lambda/d$, so it grows with λ ; the other three changes all make it smaller.

MCQ 15.3 Using monochromatic light, interference fringes are produced on a screen placed at a distance L from a pair of slits of separation d . The separation of the fringes is y . Both d and L are now doubled. What is the new fringe separation?

- | | |
|---------|--------|
| A $y/2$ | B y |
| C $2y$ | D $4y$ |

SOLUTION: In $\Delta y = L\lambda/d$ the two factors of 2 cancel, so the spacing is unchanged.

MCQ 15.4 Which of the following is not a necessary condition for two waves to produce interference?

- | | |
|---|--|
| A Waves must be of same type | B Waves must be coherent |
| C Waves must have same amplitude | D Waves must be moving in same direction |

SOLUTION: Waves of different amplitudes still interfere; the dark fringes are simply not completely dark.

MCQ 15.5 The colours observed on a soap bubble are due to which phenomenon of light?

- | | |
|------------------------------------|---------------|
| A Reflection | B Refraction |
| C Interference in thin film | D Diffraction |

SOLUTION: Light reflected from the two surfaces of the soap film interferes, and each colour is reinforced at a different thickness.

MCQ 15.6 Continuous water waves are diffracted through a gap in a barrier in a ripple tank. Which change will cause the diffraction of the waves to increase?

- | | |
|---|--|
| A Increasing the frequency of the waves | B Increasing the width of the gap |
| C Reducing the wavelength of the waves | D Reducing the width of the gap |

SOLUTION: Diffraction is greatest when the gap is comparable to the wavelength, so a narrower gap spreads the waves more.

MCQ 15.7 Which property of a light wave can be determined using a diffraction grating?

- | | |
|-------------|-------------|
| A Amplitude | B Intensity |
|-------------|-------------|

C Speed

D Wavelength

SOLUTION: Measuring the angle of an order gives $\lambda = d \sin \theta / n$.

MCQ 15.8 The central maximum in a diffraction grating is called:

A zero order

B first order

C second order

D higher order

SOLUTION: It is the maximum for $n = 0$, straight ahead, where the path difference is zero.

Numerical 15.1 Coherent light of wavelength 500 nm is incident on two very narrow and closely spaced slits. The interference pattern is observed on a very tall screen that is 2.00 m from the slits. Near the center of the screen the separation between two adjacent interference maxima is 3.53 cm. What is the distance on the screen between the $m = 49$ and $m = 50$ maxima? (Ans: 3.53 cm)

Given Data

$$\lambda = 500 \text{ nm} = 5.00 \times 10^{-7} \text{ m}$$

$$L = 2.00 \text{ m}$$

$$\Delta y = 3.53 \text{ cm} = 3.53 \times 10^{-2} \text{ m}$$

To Find

Distance between the 49th and 50th maxima

$$y_{50} - y_{49} = ?$$

Formula

$$\Delta y = \frac{L\lambda}{d}$$

$$d \sin \theta = m\lambda$$

$$y_m = L \tan \theta$$

Solution

The spacing near the centre gives the slit separation.

$$d = \frac{L\lambda}{\Delta y} = \frac{2.00 \times 5.00 \times 10^{-7}}{3.53 \times 10^{-2}} = 2.833 \times 10^{-5} \text{ m}$$

For the 49th maximum

$$\sin \theta_{49} = \frac{49 \times 5.00 \times 10^{-7}}{2.833 \times 10^{-5}} = 0.8648$$

$$\theta_{49} = 59.87^\circ$$

$$y_{49} = 2.00 \times \tan 59.87^\circ = 3.445 \text{ m}$$

For the 50th maximum

$$\sin \theta_{50} = \frac{50 \times 5.00 \times 10^{-7}}{2.833 \times 10^{-5}} = 0.8825$$

$$\theta_{50} = 61.94^\circ$$

$$y_{50} = 2.00 \times \tan 61.94^\circ = 3.753 \text{ m}$$

Result

$$y_{50} - y_{49} = 0.307 \text{ m} = 30.7 \text{ cm}$$

Note

The book prints 3.53 cm, the spacing near the centre. At these orders the angle is about 60° , so the small-angle result no longer holds and the maxima are much farther apart.

Numerical 15.2

Young's experiment is performed with light from excited helium atoms $\lambda = 502 \text{ nm}$. Fringes are measured carefully on a screen 1.20 m away from the double slit, and the center of the 20th fringe (not counting the central bright fringe) is found to be 10.6 mm from the center of the central bright fringe. What is the separation of the two slits? (Ans: $1.14 \times 10^{-3} \text{ m}$)

Given Data

$$\lambda = 502 \text{ nm} = 502 \times 10^{-9} \text{ m}$$

$$L = 1.20 \text{ m}$$

$$m = 20$$

$$y_{20} = 10.6 \text{ mm} = 10.6 \times 10^{-3} \text{ m}$$

To Find

Slit separation $d = ?$

Formula

$$y_m = \frac{mL\lambda}{d}$$

$$d = \frac{mL\lambda}{y_m}$$

Solution

Putting the values in the formula

$$d = \frac{20 \times 1.20 \text{ m} \times 502 \times 10^{-9} \text{ m}}{10.6 \times 10^{-3} \text{ m}} = 1.14 \times 10^{-3} \text{ m}$$

Result

$$d = 1.14 \times 10^{-3} \text{ m}$$

Numerical 15.3

Coherent light with wavelength 450 nm falls on a pair of slits. On a screen 1.80 m away, the distance between dark fringes is 3.90 mm. What is the slit separation? (Ans: $2.08 \times 10^{-4} \text{ m}$)

Given Data

$$\lambda = 450 \text{ nm} = 450 \times 10^{-9} \text{ m}$$

$$L = 1.80 \text{ m}$$

$$\Delta y = 3.90 \text{ mm} = 3.90 \times 10^{-3} \text{ m}$$

To Find

Slit separation $d = ?$

Formula

Adjacent dark fringes are one fringe spacing apart.

$$\Delta y = \frac{L\lambda}{d}$$

$$d = \frac{L\lambda}{\Delta y}$$

Solution

Putting the values in the formula

$$d = \frac{1.80 \text{ m} \times 450 \times 10^{-9} \text{ m}}{3.90 \times 10^{-3} \text{ m}} = 2.08 \times 10^{-4} \text{ m}$$

Result

$$d = 2.08 \times 10^{-4} \text{ m}$$

Numerical 15.4 Two slits spaced 0.450 mm apart are placed 75.0 cm from a screen. What is the distance between the second and third dark lines of the interference pattern on the screen when the slits are illuminated with coherent light with a wavelength of 500 nm? (Ans: 8.33×10^{-4} cm)

Given Data

$$d = 0.450 \text{ mm} = 0.450 \times 10^{-3} \text{ m}$$

$$L = 75.0 \text{ cm} = 0.750 \text{ m}$$

$$\lambda = 500 \text{ nm} = 500 \times 10^{-9} \text{ m}$$

To Find

Distance between the second and third dark lines

$$\Delta y = ?$$

Formula

The second and third dark lines have m of 1 and 2.

$$y_m = \left(m + \frac{1}{2}\right) \frac{L\lambda}{d}$$

$$\Delta y = y_2 - y_1 = \frac{L\lambda}{d}$$

Solution

Putting the values in the formula

$$\Delta y = \frac{0.750 \text{ m} \times 500 \times 10^{-9} \text{ m}}{0.450 \times 10^{-3} \text{ m}} = 8.33 \times 10^{-4} \text{ m}$$

Result

$$\Delta y = 8.33 \times 10^{-4} \text{ m} = 0.0833 \text{ cm}$$

Note

The book prints the answer as 8.33×10^{-4} cm; the value is in metres.

Numerical 15.5 Two very narrow slits are spaced 1.80 mm apart and are placed 35.0 cm from a screen. What is the distance between the first and second dark lines of the interference pattern when the slits are illuminated with coherent light of wavelength 550 nm? (Ans: 1.07×10^{-4} m)

Given Data

$$d = 1.80 \text{ mm} = 1.80 \times 10^{-3} \text{ m}$$

$$L = 35.0 \text{ cm} = 0.350 \text{ m}$$

$$\lambda = 550 \text{ nm} = 550 \times 10^{-9} \text{ m}$$

To Find

Distance between the first and second dark lines

$$\Delta y = ?$$

Formula

Adjacent dark lines are one fringe spacing apart.

$$\Delta y = \frac{L\lambda}{d}$$

Solution

Putting the values in the formula

$$\Delta y = \frac{0.350 \text{ m} \times 550 \times 10^{-9} \text{ m}}{1.80 \times 10^{-3} \text{ m}} = 1.07 \times 10^{-4} \text{ m}$$

Result

$$\Delta y = 1.07 \times 10^{-4} \text{ m}$$

Numerical 15.6 Monochromatic light is at normal incidence on a plane transmission grating. The first-order maximum in the interference pattern is at an angle of 11.3° . What is the angular position of the fourth-order maximum? (Ans: 51.7°)

Given Data

$$\theta_1 = 11.3^\circ$$

$$n = 4$$

To Find

Angle of the fourth order $\theta_4 = ?$

Formula

$$d \sin \theta = n\lambda$$

For the same grating and light

$$\frac{\lambda}{d} = \text{constant}$$

$$\sin \theta \propto n$$

$$\sin \theta_4 = 4 \sin \theta_1$$

Solution

Putting the value of the first-order angle

$$\sin \theta_4 = 4 \times \sin 11.3^\circ = 4 \times 0.196 = 0.784$$

$$\theta_4 = \sin^{-1}(0.784) = 51.6^\circ$$

Result

$$\theta_4 = 51.6^\circ$$

Note

The book prints 51.7° ; the working gives 51.6° .

Numerical 15.7 If a diffraction grating produces a third-order bright spot for red light of wavelength 700 nm at 65° from the central maximum, at what angle will the second-order bright spot be for violet light of wavelength 400 nm? (Ans: 20.2°)

Given Data

$$n_r = 3$$

$$\lambda_r = 700 \text{ nm} = 700 \times 10^{-9} \text{ m}$$

$$\theta_r = 65^\circ$$

$$n_v = 2$$

$$\lambda_v = 400 \text{ nm} = 400 \times 10^{-9} \text{ m}$$

To Find

Angle of the second-order violet spot $\theta_v = ?$

Formula

$$d \sin \theta = n\lambda$$

$$d = \frac{n_r \lambda_r}{\sin \theta_r}$$

$$\sin \theta_v = \frac{n_v \lambda_v}{d}$$

Solution

The grating spacing is

$$d = \frac{3 \times 700 \times 10^{-9} \text{ m}}{\sin 65^\circ} = \frac{2.10 \times 10^{-6} \text{ m}}{0.9063} = 2.317 \times 10^{-6} \text{ m}$$

For the violet light

$$\sin \theta_v = \frac{2 \times 400 \times 10^{-9} \text{ m}}{2.317 \times 10^{-6} \text{ m}} = 0.3453$$

$$\theta_v = \sin^{-1}(0.3453) = 20.2^\circ$$

Result

$$\theta_v = 20.2^\circ$$

Self Test

Seventeen questions across the whole chapter. Work through them without the notes, then check the answers keyed at the foot of the page.

Q 1 Light from the Sun reaches the Earth with wavefronts that are nearly:

A	spherical	B	circular
C	plane	D	cylindrical

Q 2 Huygens proposed the wave theory of light in about:

A	1801	B	1860
C	1914	D	1678

Q 3 Maxwell proposed that light consists of:

A	longitudinal waves	B	electromagnetic waves
C	particles only	D	sound waves

Q 4 Light propagates as a wave but interacts with matter as massless particles called:

A	photons	B	electrons
C	protons	D	neutrons

Q 5 Waves of amplitudes 3 units and 1 unit meet in antiphase. The resultant amplitude is:

A	4 units	B	zero
C	2 units	D	3 units

Q 6 The phase difference between two coherent sources:

A	changes randomly	B	stays constant
C	is always 90°	D	increases steadily

Q 7 The two slits of Young's experiment are lit by a single laser so that they are:

A	of different wavelengths	B	far apart
C	of different amplitudes	D	coherent

Q 8 If the slit separation in Young's experiment is halved, the fringe spacing becomes:

A	double	B	half
C	four times	D	unchanged

Q 9 Light of wavelength 500 nm passes through slits 0.5 mm apart onto a screen 2 m away. The fringe spacing is:

A	2 mm	B	0.2 mm
C	1 mm	D	4 mm

Q 10 For the second dark fringe in Young's experiment the path difference is:

A	$\lambda/2$	B	$3\lambda/2$
C	λ	D	2λ

Q 11 The colours of an oil film on water come from interference between light reflected at:

A	two separate lamps	B	the bed of the water
C	the top and bottom surfaces of the film	D	the air above the film

Q 12 Ignoring the phase shift, the first bright fringe of an air wedge in light of 600 nm forms where the film is:

A	600 nm thick	B	150 nm thick
C	1200 nm thick	D	300 nm thick

Q 13 Newton's rings are viewed with:

A	X-rays	B	sound waves
C	monochromatic light	D	microwaves

Q 14 A grating with 5000 lines per cm has a grating spacing of:

A	5×10^{-5} m	B	2×10^{-6} m
C	2×10^{-4} m	D	5×10^{-7} m

Q 15 A grating of spacing 1.67×10^{-6} m gives a first-order line at 20.7° . The wavelength of the light is about:

A	295 nm	B	1180 nm
C	450 nm	D	590 nm

Q 16 In Bragg's equation, θ is the angle between the incident X-rays and the:

A	atomic planes	B	normal to the planes
C	reflected X-rays	D	vertical

Q 17 X-rays of wavelength 0.154 nm reflect in the first order from planes 0.154 nm apart. The Bragg angle is:

A	60°	B	15°
C	30°	D	45°

Answers 1 (c) 2 (d) 3 (b) 4 (a) 5 (c) 6 (b) 7 (d) 8 (a) 9 (a) 10 (b) 11 (c) 12 (d) 13 (c) 14 (b) 15 (d) 16 (a) 17 (c)