Section 4.1.7 – Young's Double Slit Experiment

Young's Double Slit Experiment – Set Up

Thomas Young was a supporter of the wave model of light. He had observed interference between two synchronised water waves and wondered if light would do the same.

Young constructed the following apparatus:

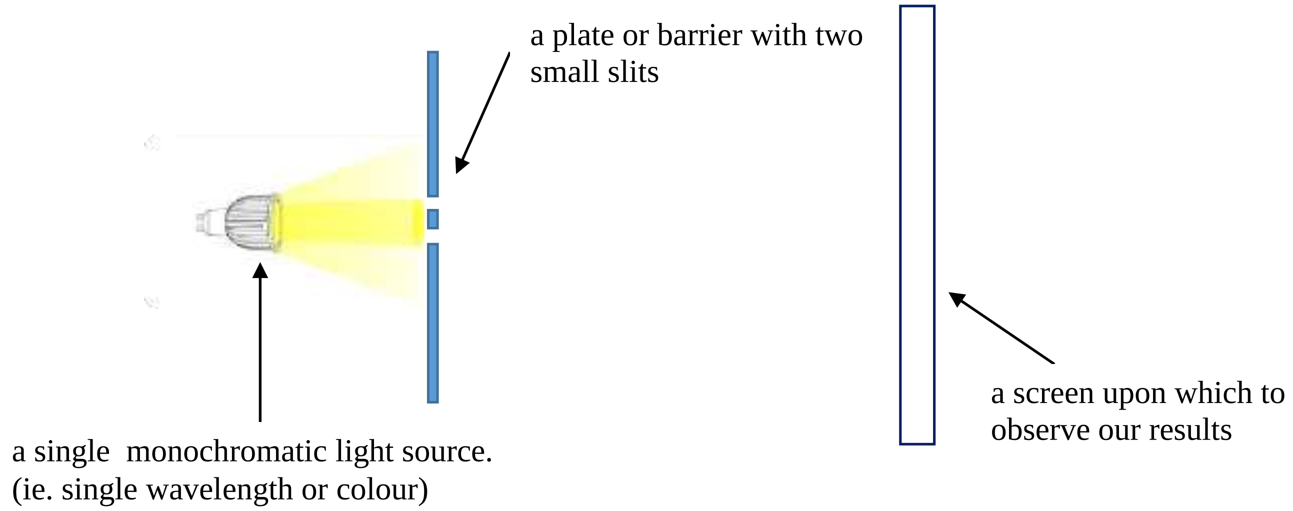


Figure.1 *Birds eye view of Young's Double Slit apparatus*

Young's Double Slit – Predictions

If, as Sir Isaac Newton had predicted, light was a stream of particles, then it was expected that light would be blocked at the plate, and only allowed to pass in a straight line via the two small slits.

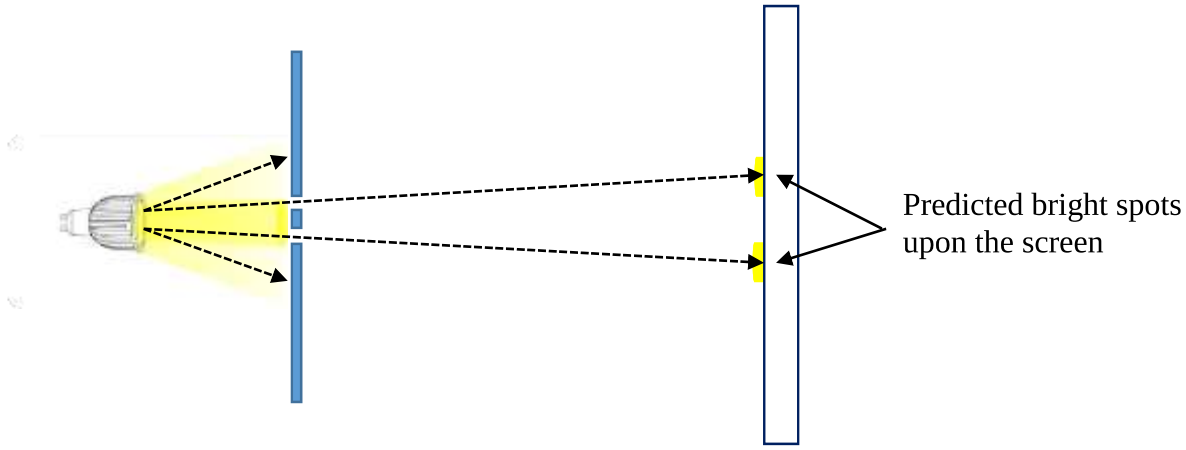


Figure.2 *Prediction if light were a particle*

If light were a particle you would expect to find two bright spots upon the screen.

Whereas, if light was in fact a wave, as Thomas Young had predicted, then it was expected that light waves would diffract through the two slits causing the two resulting waves to interfere with one another, just as water waves do. Thereby creating an interference pattern on the distant screen.

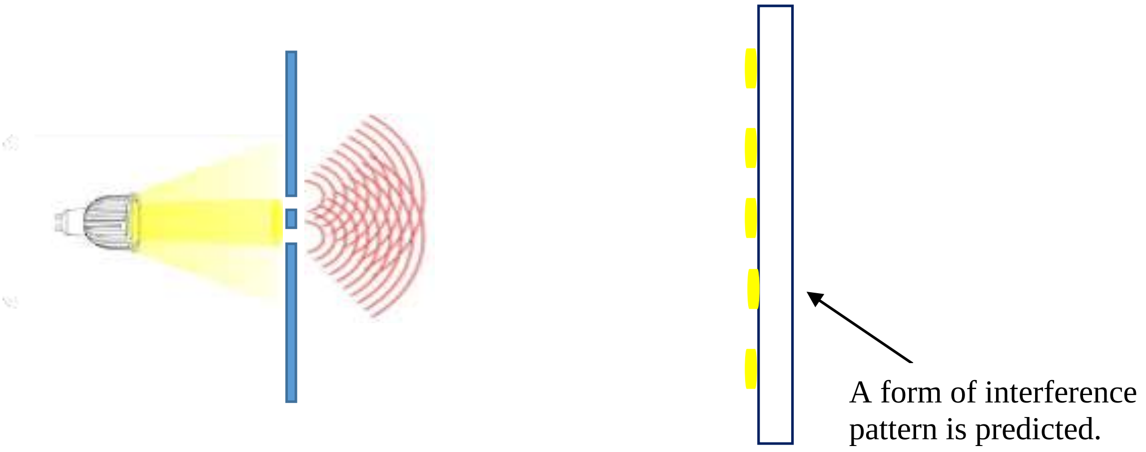


Figure.3 *Prediction if light were a wave*

If light were a wave you would expect to find bright and dark fringes representing regions of constructive and destructive interference.

Young's Double Slit - Observations

When Young's double slit experiment is carried out using a red laser the following image is captured upon the screen

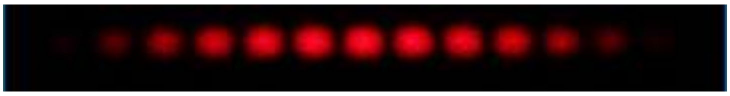


Figure.4 *Image of Young's double slit screen*

As can be seen from Figure.4 above the image upon the screen displays a sequence of bright and dark bands or fringes that decrease in intensity as they spread further away from the central bright spot.

This looks nothing like the two bright spots expected via the particle model. However, it does offer support to the wave model prediction as this image supports a wave like interference pattern.

Young's Double Slit - Explained

To explain the results of Young's double-slit experiment:

Recall that the original single light source is monochromatic.
Diffraction occurs at each slit so that they act like two coherent point sources of waves.
Constructive interference occurs where two crests or two troughs overlap which results in bright light and destructive interference occurs where a crest meets a trough which results in darkness. This creates the interference pattern. Both diffraction and interference are wave like properties.

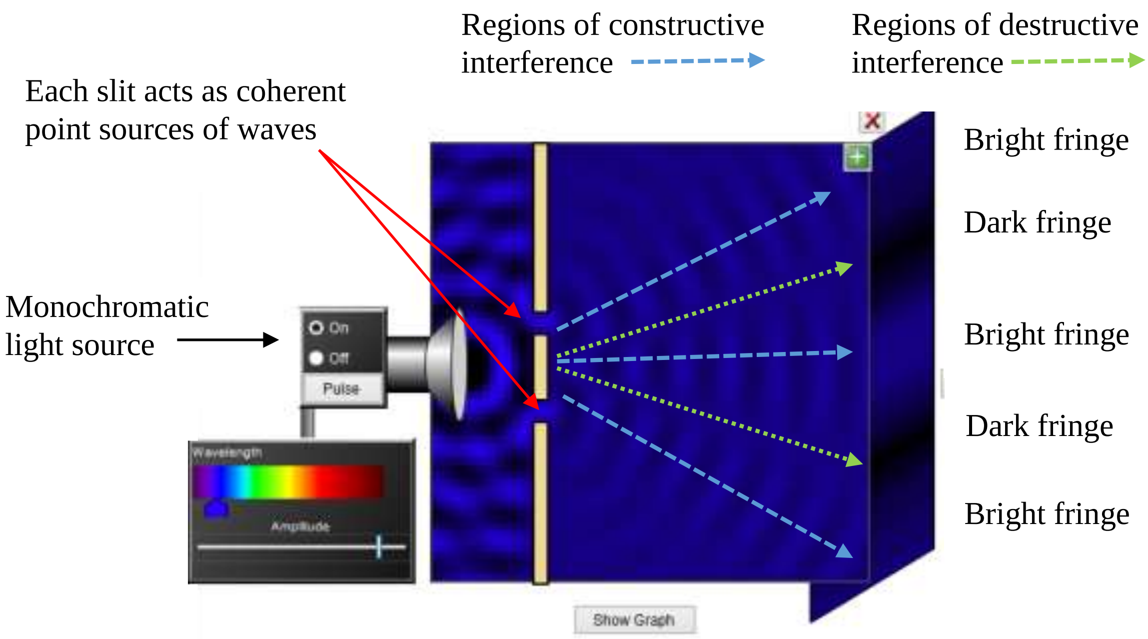


Figure.5 *Young's double slit explained*

Example.1

At the time of Young's double-slit experiment there were two competing models of the nature of light.

a) Which of the two competing models does the experiment support?
b) Why do the results of the experiment support this model?
c) Why do the results of the experiment not support the competing model?

Answers

a) The wave model
b) Interference pattern is caused by:
   - Alternating constructive and destructive interference
   - Diffraction through the two slits

   Interference and diffraction are wave behaviours
c) If light behaved as a particle, we would expect only two bright spots on the screen rather than an interference pattern.

Young's Double Slit - Path difference

You would recall from Notes 4.1.2 that:
"For constructive interference to occur the crest of the first wave must meet the crest of the second wave. This condition can only occur when the path difference between both waves to a point is either 0 or an exact multiple of the wavelength (λ) of each wave."

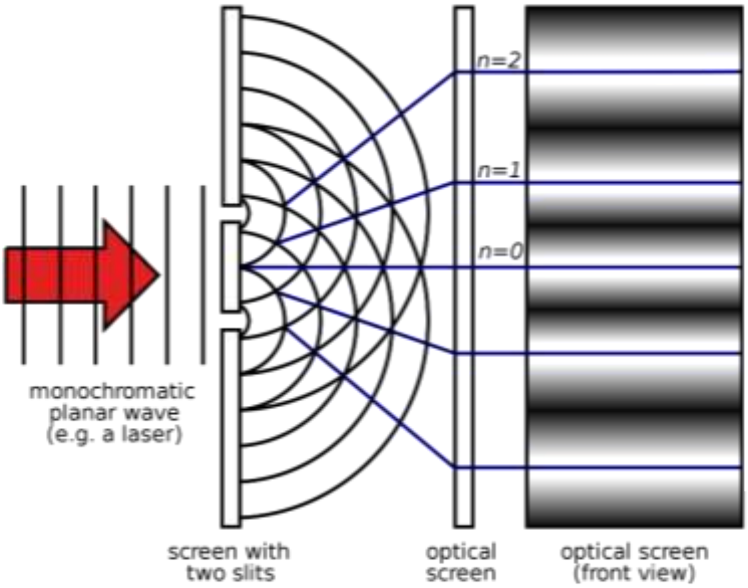
Constructive interference will occur for;

- *path differences of 0, λ, 2λ, 3λ, 4λ, 5λ etc.*
- *Path Difference (PD) = $n\lambda$ Where n = 0, 1, 2, 3 …*

For destructive interference to occur the crest of the first wave must meet the trough of the second wave. This condition can only occur when the path difference between both waves to a point is an odd multiple of half the wavelength ($\frac{\lambda}{2}$) of each wave.

Destructive interference will occur for'

- *path differences of $\frac{\lambda}{2}$, $\frac{3\lambda}{2}$, $\frac{5\lambda}{2}$, $\frac{7\lambda}{2}$ etc.*
- *Path Difference (PD) = $(n - \frac{1}{2})\lambda$. Where n = 1, 2, 3 …*



Description	Path Diff
3rd dark fringe	$5\lambda/2$
2nd bright fringe	2λ
2nd dark fringe	$3\lambda/2$
1st bright fringe	λ
1st dark fringe	$\lambda/2$
Central bright fringe	0

Figure.6 *Young's double slit in terms if path difference*

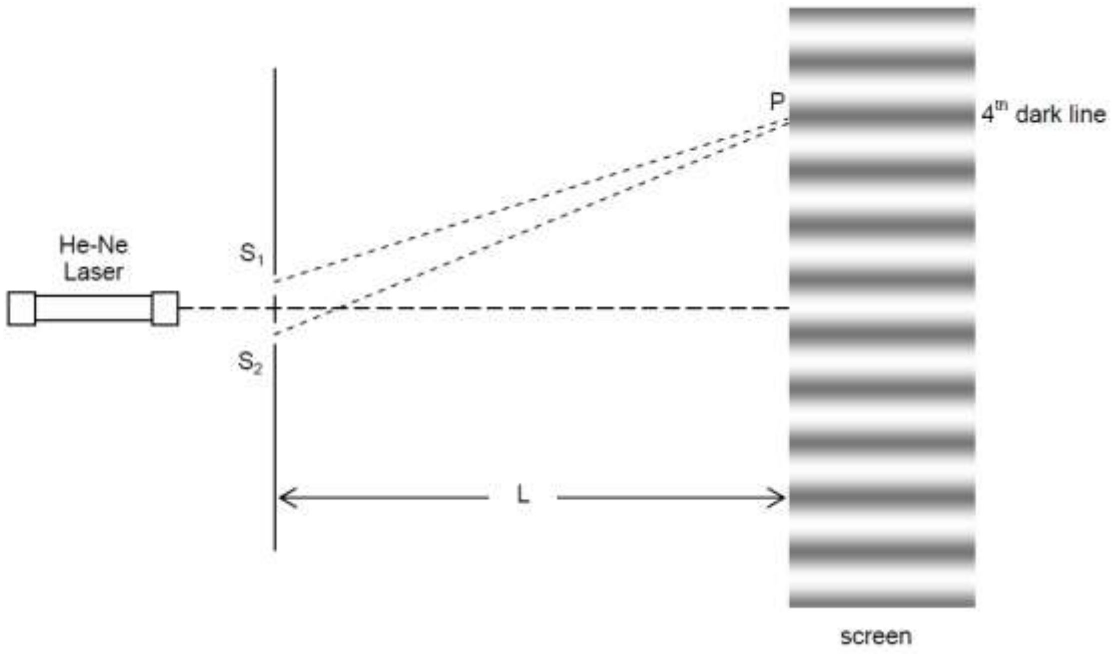
There is a simple pattern for each bright and dark fringe.

The central fringe is symmetrically located between the two slits and so has a path difference of 0 and is a bright (constructive) fringe.

The 1st dark fringe has a path difference of $\lambda/2$ and is a dark (destructive) fringe.
The 1st bright fringe has a path difference of λ and is a bright (constructive) fringe.
The 2nd dark fringe has a path difference of $3\lambda/2$ and is a dark (destructive) fringe.
The 2nd bright fringe has a path difference of 2λ and is a bright (constructive) fringe.

Example.2

A student sets up a Young's Double Slit experiment in the laboratory. A series of light and dark bands are seen on the screen. The experimental set up is shown below. The light source used in this experiment is a He-Ne laser of wavelength 632 nm.



Question 1

Explain why there is a series of bright and dark lines on the screen.

The pattern of bright and dark lines are produced by the constructive and destructive interference of the light coming through the two slits.

Question 2

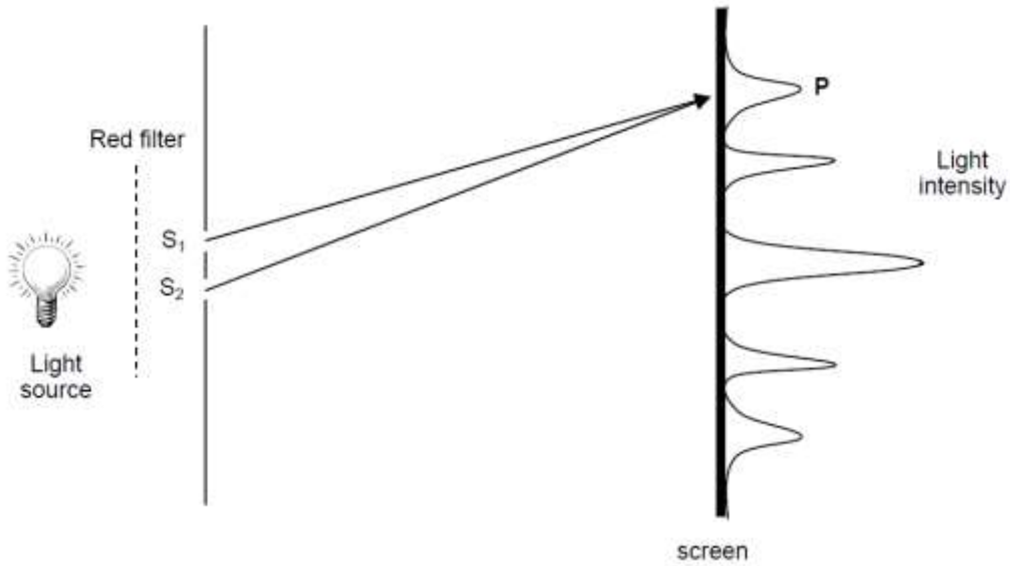
Estimate the path difference for the 4th dark line on the screen.

$\lambda = 632 \times 10^{-9}$ *m*
n = 4 for 4th dark line
pd = ?

pd = $(n - 1/2)\lambda$ *for a dark (destructive) line*
$\therefore pd = (4 - 1/2)\lambda$
$= 3.5 \times 632 \times 10^{-9}$
$= 2.21 \times 10^{-6}$ *m* (2.21 μm)

Example.3

A Young's double slit interference experiment is shown in the diagram below.
The red filter allows light of wavelength 680 nm to pass and blocks all other wavelengths.



Question 1.
What is the frequency of a photon of wavelength of 680 nm?

f = ?
$\lambda = 680 \times 10^{-9}$ m
$c = 3.0 \times 10^{8}\ ms^{-1}$

$c = \lambda f$

$\therefore f = \frac{c}{\lambda} = \frac{3.0 \times 10^8}{680 \times 10^{-9}} = 4.4 \times 10^{14}$

$\boxed{4.4 \times 10^{14}\ \text{Hz}}$

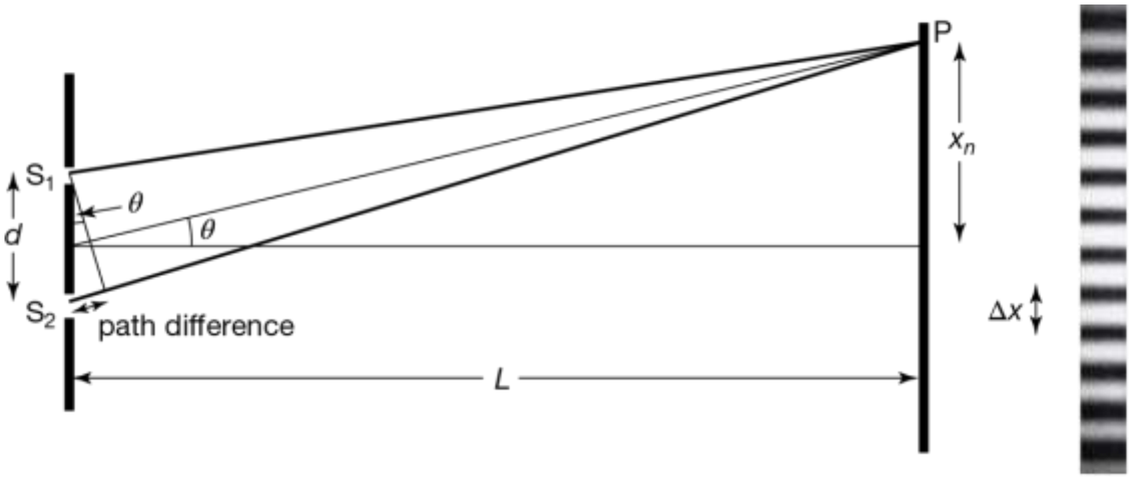
Question 2.
What is the path difference $PS_1 - PS_2$?

P is the second bright band so n=2
$\therefore$ path difference (pd) = $2 \times \lambda = 2 \times 680$ nm = 1360 nm

$\boxed{1360\ \text{nm}}$

Young’s Double Slit – Fringe Spacing

Fringe spacing (Δx) is the distance between adjacent bright bands (or between adjacent dark bands) of an interference pattern.



Pattern on screen

$$\boxed{\Delta x = \frac{\lambda L}{d}}$$

Path difference (pd) = dsin(θ)
For bright fringes nλ = dsin(θ)

Where Δx = fringe spacing (metres)
λ = wavelength of light source (metres)
L = perpendicular distance between slits and screen (metres)
d = distance between two slits (metres)

Table.1 *Fringe spacing comparison*

Change	↑λ	↓λ	**↑L**	**↓L**	**↑d**	**↓d**
Δx	↑Δx	↓Δx	↑Δx	↓Δx	↓Δx	↑Δx

Example.4

A double slit experiment was performed with light of wavelength 550 nm, a slit spacing of 0.20mm and a screen 2.0 m from the slit. Calculate the spacing of the light fringes on the screen.

Δx = ?
λ = 550 nm
= 550×10^{-9} m
d = .20 mm
= $.20 \times 10^{-3}$ m
L = 2.0 m

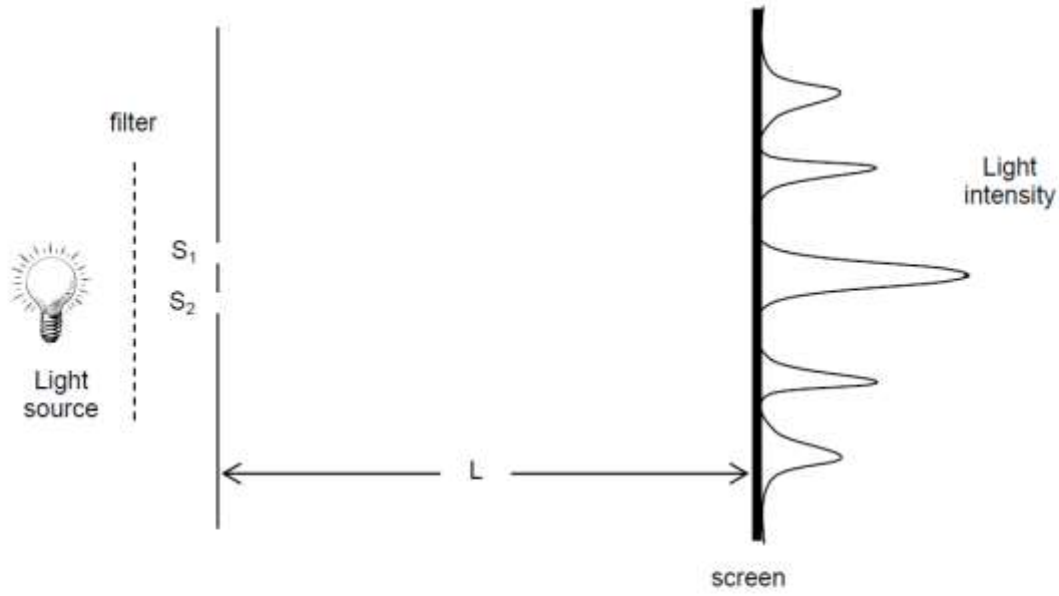
$$\Delta x = \frac{\lambda L}{d}$$

$$= \frac{550 \times 10^{-9} \times 2.0}{0.20 \times 10^{-3}}$$

= 0.0055 m (5.5×10^{-3} m or 5.5 mm)

Example.5

A student sets up a Young's Double Slit experiment in the laboratory. A series of light and dark bands are seen on the screen. The experimental set up is shown below. The light source used in this experiment is filtered to provide monochromatic light.



Question 1

Explain why there is a bright band in the middle of the screen.

In the middle of the screen, the path difference is zero and constructive interference has occurred.

Question 2

Predict what will happen to the light intensity pattern seen on the screen when the distance between the slits S1 and S2 is halved.

The light intensity pattern will increase OR the pattern will be more spread out.
($\Delta x \propto 1/d$, $\therefore$ if $d\downarrow$ then $\Delta x\uparrow$)

Question 3

Predict what will happen to the light intensity pattern seen on the screen when the distance L between the slits to the screen is doubled.

The light intensity pattern will increase OR the pattern will be more spread out.
($\Delta x \propto L$, $\therefore$ if $L\uparrow$ then $\Delta x\uparrow$)

Question 4

Predict what will happen to the light intensity pattern seen on the screen when the filter is changed so that the wavelength of the light passing through the slits is decreased.

The light intensity pattern will decrease OR the pattern will be narrower or closer together.
($\Delta x \propto \lambda$, $\therefore$ if $\lambda\downarrow$ then $\Delta x\downarrow$)

Exam Styled Questions

Question 1

At the time of Young's double-slit experiment there were two competing models of the nature of light. Explain how Young's experiment supported one of these models compared with the other.

Supported wave model (1).
Waves interfere (1).
Young's expt: light and dark lines (1)

The two competing models of light were the particle model, initially proposed by Newton and the wave model proposed by Huygens. The wave model predicted that if light behaved as a wave it should show the wave-like properties of diffraction (spreading through a narrow gap or bending around a sharp edge) and interference (points of reinforcement and cancellation on the other side of a double slit).

Young passed light through a pair of very narrow slits and produced an interference pattern, evidence of constructive and destructive interference. This supported the wave model.

The following information relates to Questions 2 and 3.

Louise and Thelma set up the apparatus shown in Figure 1. It consists of a laser providing light of a single wavelength, which passes through two narrow slits and produces a pattern of bright and dark bands on a screen some distance away.

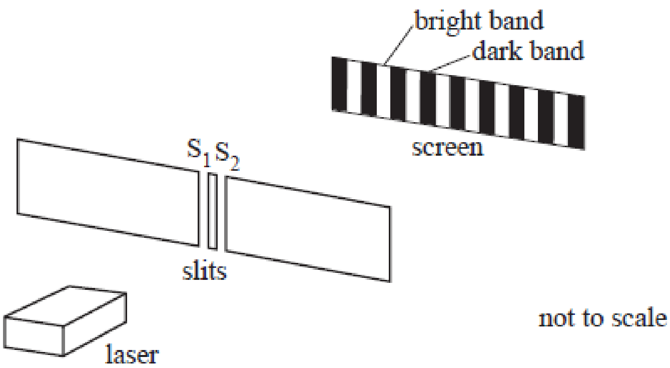


Figure 1

Question 2

Before doing the experiment, Louise believes that the central band (the one exactly opposite the centre point between the two slits) is a dark band. Thelma believes that this is a bright band. Who is correct? Outline your reasoning clearly.

Thelma (1)
The path difference is zero (1) as the centre point is the same distance from S_1 and S_2.
The point is a maximum (1) because waves from S_1 and S_2 will constructively interfere.

Question 3

The pattern of bright and dark bands is shown in Figure 2 below.

Figure 2

Precision measurement shows that the **path difference** to the middle of dark band A (that is, the distance AS2–AS1) is greater than the path difference to the middle of dark band B by 496 nm. From this information, determine the wavelength of the laser. You may include a diagram.

A and B are adjacent positions of destructive interference. So, the path difference for A is one wavelength longer than that for B (1).

The wavelength = 496 nm. (1)

496 nm

The following information relates to Question 4.

Two students are studying interference of light. They use a laser of wavelength 580 nm.

The students set up the laser, two slits, S_1 and S_2, and a screen on which an interference pattern is observed, as shown in Figure 3a.
The pattern they observe on the screen is also shown in Figure 3b.
C indicates the centre of the pattern.

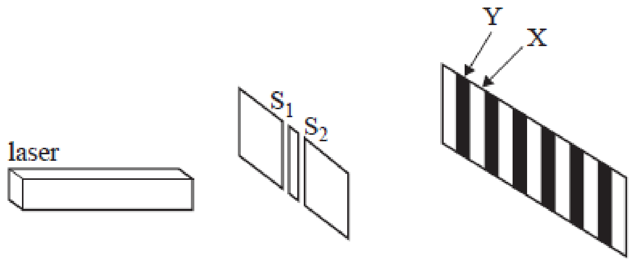


Figure 3a

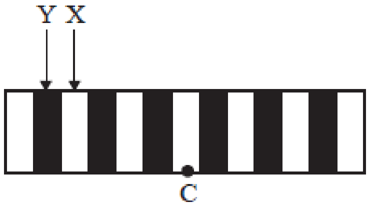


Figure 3b

X is at the centre of a bright band. Y is at the centre of the dark band next to X and further away from the centre of the pattern. The path difference $S_2X–S_1X$ is 1160 nm.

Question 4
What is the path difference $S_2Y–S_1Y$? Show your working.

The path difference to Y is an extra half wavelength, so it is 1160 + 290 nm (1)
∴ Path diff to Y = 1450 nm (1)

1450 nm

Use the following information to answer Questions 5–8.

Students set up the apparatus shown in Figure 4 to repeat Young's double –slit experiment.
They used a laser of λ = 560 nm as the light source.
In the first experiment, the separation d, of the two narrow slits, S_1 and S_2, is 0.32 mm.
P is a point on the interference pattern at the centre of the second dark band out from the centre of the pattern, C.

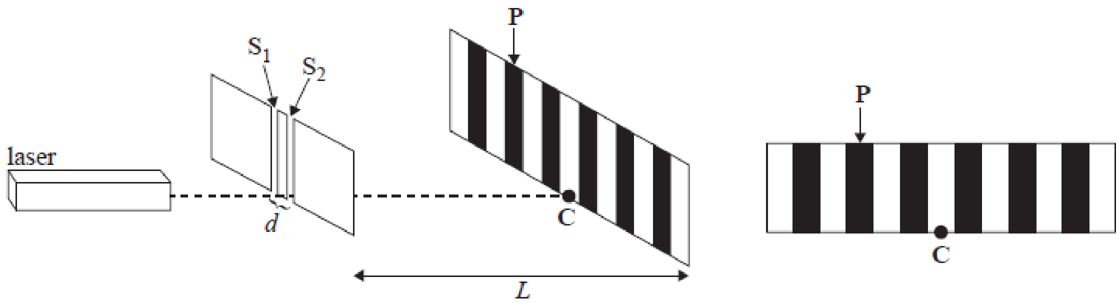


Figure 4

Question 5
Calculate the path difference $S_2P - S_1P$. Show your workings.

P is second dark band from C, so path diff = 1.5 x wavelengths (1) = 1.5 x 560 = 840 nm.

840 nm

Question 6
The distance, L, is now increased.
Describe the effect of this change on the spacing of the observed interference pattern.

Increased
As the screen is moved further away, the image, that is, the bands and the spaces between them will get larger and so further apart.

Question 7
L is reset to its original value.
The separation of the slits, d, is then decreased.
Describe the effect of this change on the spacing of the observed interference pattern.

Increased
As the slits get closer, the dark band at point P will need to move further out to keep the path difference the same.

Question 8
Explain how the observations in Young's experiment led to his conclusion about wave-like nature of light.

Young observed an interference pattern (1), which consists of light and dark lines due to constructive and destructive superposition respectively (1). The spacing of these lines depended on the wavelength of the light (1).

Two students set up a two-slit interference experiment with a source of laser light, as shown in Figure 5.

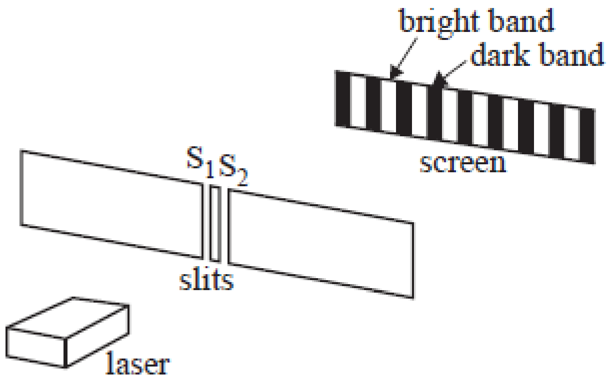


Figure 5

The wavelength of the light from the laser is 612 nm. Figure 6 shows a sketch of the central section of the interference pattern that they obtain. The central band **C**, which is a bright band, is labelled.

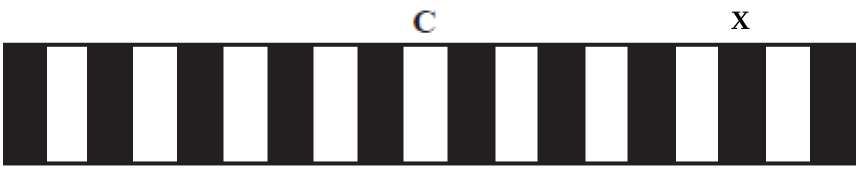


Figure 6

Question 9

Explain why the central band of the pattern at point C is a bright band and not a dark band.

Lights arriving at C from S_1 and S_2 are in phase because the path difference is zero. This results in constructive interference of the two light waves to produce a bright band.

Question 10

Another point on the pattern is further from slit S_1 than from slit S_2 by a distance of 2.142×10^{-6} m. Its position is to the right of point C in Figure 6, above.
Indicate where this point is in Figure 6 by writing the letter X above the point. You must show your working.

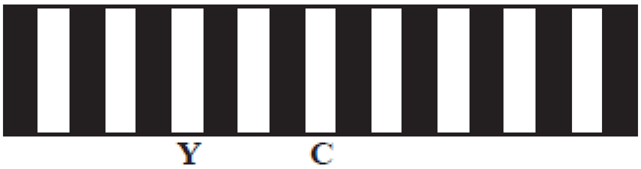
Path difference = 2.142×10^{-6} m
How many wavelengths fit into this path difference?

$$\text{No. of } \lambda = \frac{path\ difference}{\lambda}$$
$$= \frac{2.142 \times 10^{-6}}{612 \times 10^{-9}}$$
$$= 3.5$$

.: it is the fourth dark band on the right of C.

Question 11

Another laser that produces light of a different wavelength is now used. The pattern is now spaced more closely.
Figure 7a shows the new pattern and Figure 7b shows the original pattern.
The second bright band to the left of C in the new pattern is at the position labelled Y in Figure 7a. In the original pattern (Figure 7b), this was the position of the second dark band to the left of C.



new pattern

Figure 7a

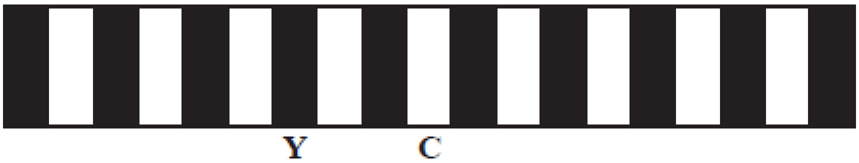


Figure 7b

Question 10

Calculate the wavelength of the light produced by this new laser.

Original path difference (Figure 7b) $= 1.5\lambda_{original}$
$= 1.5 \times 612 \times 10^{-9}$
$= 918 \times 10^{-9}$ m

NB: *The 2 points physically have the same path difference (ie. same difference from centre)*

New path difference (Figure 7a) = Old path difference
$= 918 \times 10^{-9}$ m
$= 2\lambda_{new}$

$$\therefore \lambda_{new} = \frac{918 \times 10^{-9}}{2}$$
$$= 459 \times 10^{-9} \text{ m}$$

459 nm