UNIT G482	Module 4	2.4.3	Interference

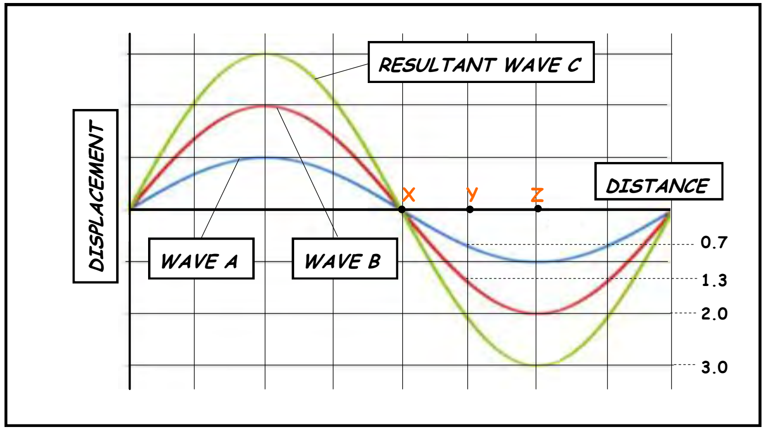
- *Candidates should be able to* :
  - *State and use the **principle of superposition of waves.***
  - *Apply **graphical methods** to illustrate the principle of superposition.*
  - *Explain the terms **interference, coherence, path difference and phase difference.***
  - *State what is meant by **constructive** interference and **destructive** interference.*
  - *Describe experiments that demonstrate **two-source interference** using **sound, light and microwaves.***
  - *Describe constructive interference and destructive interference in terms of **path difference and phase difference.***
  - *Use the relationships :*

Intensity = power/cross-sectional area

Intensity a amplitude ^{2}

- *Describe the **Young double-slit experiment** and explain how it is a classical confirmation of the wave nature of light.*
- *Select and use the equation* $\boxed{\lambda = ax/D}$ *for electromagnetic waves.*
- *Describe an experiment to determine the **wavelength** of monochromatic light **using a laser and a double slit.***
- *Describe the use of a **diffraction grating to determine the wavelength of light** (structure and use of a spectrometer not required).*
- *Select and use the equation* $\boxed{d \sin\theta = n\lambda.}$
- *Explain the **advantages of using multiple slits** in an experiment to find the wavelength of light.*

• SUPERPOSITION OF WAVES



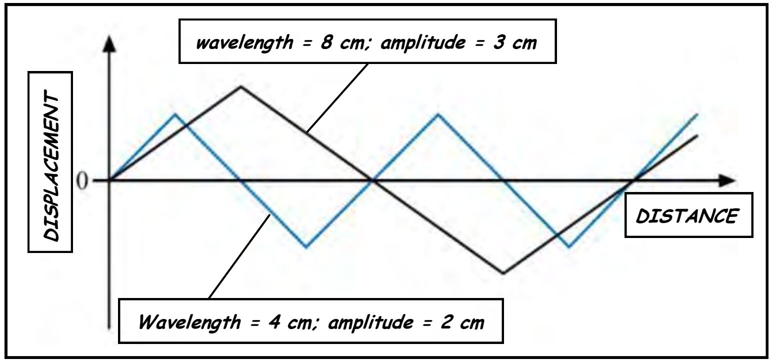
*The **PRINCIPLE OF SUPERPOSITION** of waves states that when two or more waves meet at a point, the resultant displacement is the sum of the displacements of the individual waves.*

*Consider the diagram shown above. Applying the principle to the two **WAVES A and B** produces the **RESULTANT WAVE C**, whose shape is worked out by adding the displacements of A and B at any given point. For example :*

- *At point **X*** — *Both A and B have zero displacement, and so* **Resultant displacement = zero.**
- *At point **Y*** — *Both A and B have a negative displacement, and so,* **Resultant displacement = A + B = 0.7 + 1.3 = 2.0**
- *At point **Z*** — **Resultant displacement = A + B = 1.0 + 2.0 = 3.0**

- PRACTICE QUESTIONS (1)

1

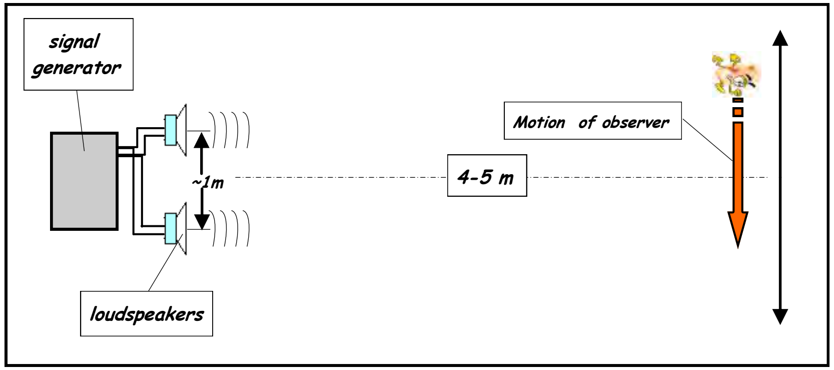


The diagram above shows two triangular waves. One of the waves has a wavelength of **8 cm** and an amplitude of **3 cm**, while the other has a wavelength of **4 cm** and an amplitude of **2 cm**.

Draw these waves on graph paper and use the **principle of superposition** to determine the resultant displacement at several points in order to **draw the complete resultant wave.**

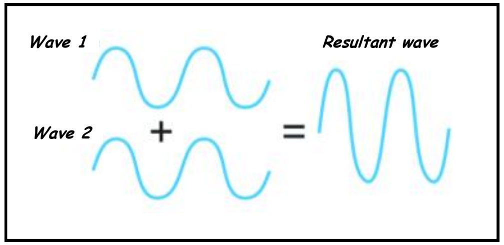
- ***INTERFERENCE***

SOUND WAVES

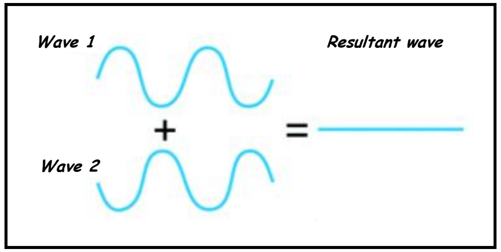


Two loudspeakers are connected to a single signal generator as shown in the diagram. The sound waves emitted by each speaker are then of equal frequency, wavelength and amplitude. An interference effect due to the superposition of the sound waves is observed in the region in front of the speakers.

At some points the waves arrive ***IN PHASE*** *with each other and so a resultant wave having twice the amplitude of each wave is produced. At such points a* ***LOUD*** *sound is heard.*



At other points the waves arrive in ***ANTIPHASE*** *with each other and so a resultant wave having zero or a very small amplitude is produced. At such points a very* ***QUIET*** *sound is heard.*

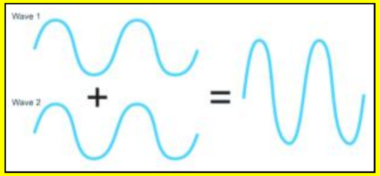


At points in between, the waves are somewhere in between being ***IN PHASE*** *and* ***ANTIPHASE*** *and so the sound level heard is somewhere between* ***LOUD*** *and* ***QUIET****.*

CONSTRUCTIVE AND DESTRUCTIVE INTERFERENCE

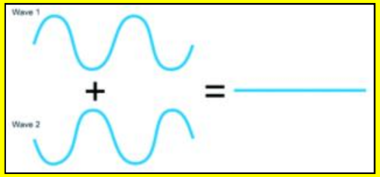
CONSTRUCTIVE

At points where waves arrive ***IN PHASE*** *with each other, the waves reinforce each other to give a resultant wave of* ***larger amplitude****.*



DESTRUCTIVE

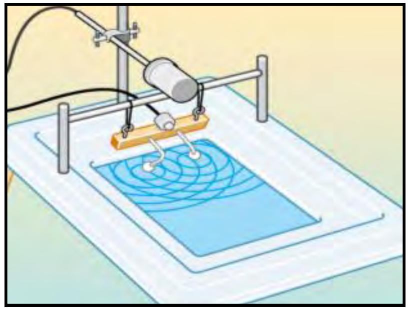
At points where waves arrive in ***ANTIPHASE*** *with each other, the waves cancel each other to give a resultant wave of* ***zero amplitude****.*

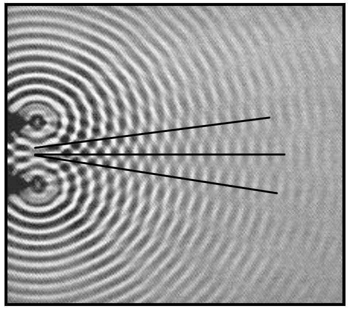


WATER WAVES

Interference of water waves can be observed using a ripple tank.

*Two ball-ended dippers are made to vibrate on the water surface so as two produce two sets of circular waves having the **same frequency and amplitude**.*

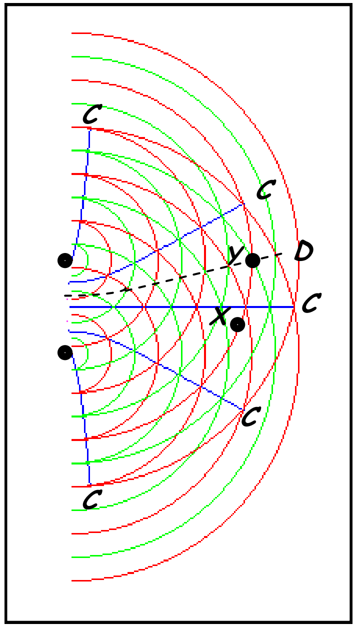




The resulting wave pattern which is seen on the water shows interference effects.

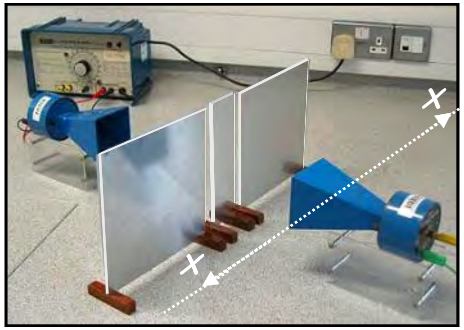
- *There are regions (e.g. **X**) where the interfering waves are **in phase** (i.e. a **crest** is superposed with a **crest**). **CONSTRUCTIVE** interference occurs producing a large amplitude wave. These regions occur along lines **C**.*

- *There are regions (e.g. **Y**) where the interfering waves are **in antiphase** (i.e. a **crest** is superposed with a **trough**). **DESTRUCTIVE** interference occurs producing almost complete cancellation. These regions occur along lines **D**.*



MICROWAVES

*A **microwave transmitter** is directed towards the double gap in a metal barrier, as shown in the photo opposite.*



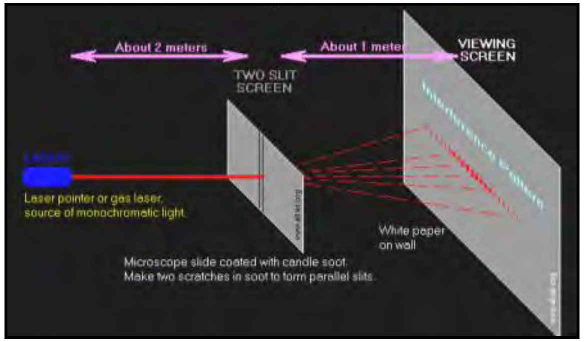
*The waves diffract through the two gaps into the region beyond the barrier, where they **superpose and produce interference effects**.*

*A **microwave receiver** connected to a **microammeter** is moved along a line **XX**, parallel to the metal barrier. As the receiver is moved, the meter registers **HIGH** readings as it passes through regions where **CONSTRUCTIVE** interference is occurring and **LOW** readings where **DESTRUCTIVE** interference is occurring.*

If the receiver is at a point which gives a low meter reading and one of the gaps in the barrier is closed, the meter reading will increase, showing that the low reading is due destructive interference of the microwaves.

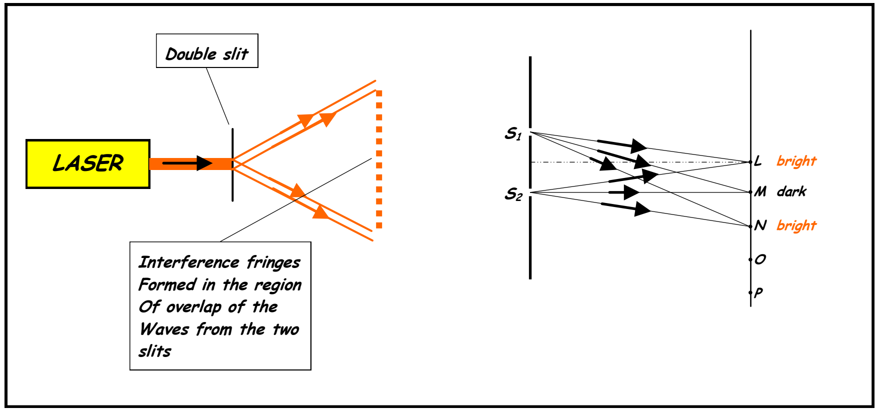
LIGHT WAVES

When a beam of laser light is directed onto a double slit (two clear slits on a black slide), an interference pattern of equally spaced light dots is seen on a screen placed ~1 m from the slits.



*The light dots are called **INTERFERENCE FRINGES**. They are points where light waves are arriving **in phase** with each other to give **CONSTRUCTIVE** interference. The **dark regions** in between the dots are the result of **DESTRUCTIVE** interference caused by light waves arriving in **antiphase**.*

- ***EXPLAINING THE INTERFERENCE FRINGES***



POINT L

- *Is directly opposite the midpoint of the slits and equidistant from **S_1** and **S_2**, so the **PATH DIFFERENCE (PD)** between light waves from **S_1** and **S_2** = **0**.*

  *Then, assuming that they are **IN PHASE** with each other when they leave **S_1** and **S_2**, the light waves will be **IN PHASE** when they arrive at **L**. So **CONSTRUCTIVE INTERFERENCE** occurs and a **BRIGHT** fringe is formed at **L**.*

POINT M

- *The light waves arriving at **M** from **S_1** and **S_2** are in **ANTIPHASE** with each other because the **PD** between the waves is exactly **$\frac{1}{2}$ a wavelength ($\frac{1}{2}\lambda$)**. So **DESTRUCTIVE INTERFERENCE** occurs and a **DARK** fringe is formed. Point **M** is the midpoint of the **first dark fringe**.*

POINT N

- *The light waves arriving at **N** from **S_1** and **S_2** are **IN PHASE** because the **PD** between them is exactly **1 wavelength (λ)** and so **CONSTRUCTIVE INTERFERENCE** occurs. Point **N** is the midpoint of the **second bright fringe**.*

*In this way the interference pattern formed may be explained in terms of **PHASE** or **PATH DIFFERENCE** between the light waves from each slit arriving at a given point.*

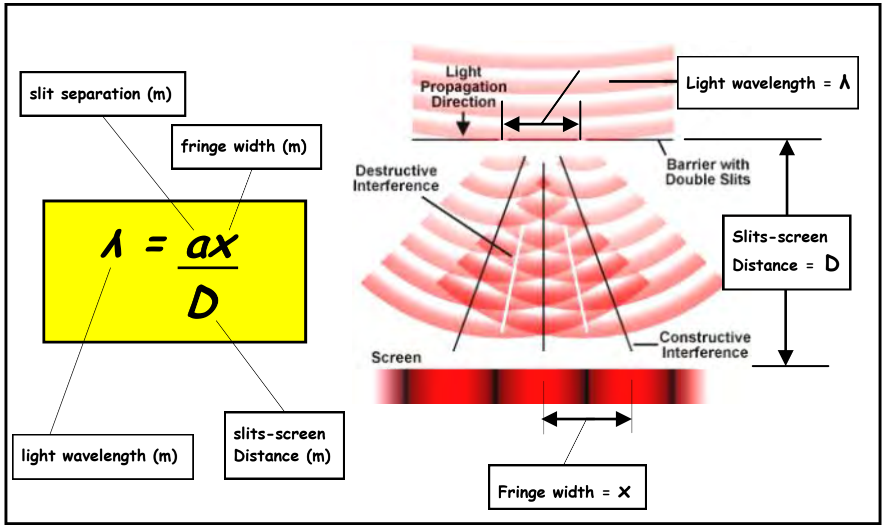
SUMMARY

path difference = $n\lambda$	***waves arrive in phase***	***constructive interference bright fringe***
path difference = $(n + \frac{1}{2})\lambda$	***waves arrive in antiphase***	***destructive interference dark fringe***

Where n = 0, 1, 2, 3, etc..

***State** what you would expect to observe at points **O** and **P** and use the rules outlined in the summary above to **explain** why.*

DOUBLE-SLIT INTERFERENCE EQUATION



$$\lambda = \frac{ax}{D}$$

COHERENT SOURCES

For interference effects to be observable, the interference pattern must be steady (i.e. it must not change with time).

*This only happens if the wave sources are **IN PHASE** or if they have a **CONSTANT PHASE DIFFERENCE**. Such wave sources are said to be **COHERENT**.*

*Two wave sources are said to be **COHERENT** if the waves emitted from them are **IN PHASE** or if they have a **CONSTANT PHASE DIFFERENCE**. This implies that the sources have the **SAME FREQUENCY**.*

EXAMPLES OF COHERENCE

- *The vibrating dippers in a ripple tank are **IN PHASE** because they are driven by the same source.*
- *In the case of the microwave interference, the two slits emit waves derived from the same source.*
- *Laser light is coherent.*

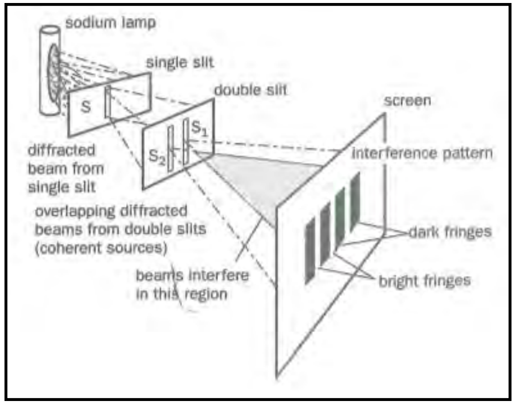
CONDITIONS FOR OBSERVABLE INTERFERENCE

- ***COHERENT** wave sources, which means that they must have the **SAME FREQUENCY**. Otherwise the interference pattern is continually changing.*
- *The interfering waves should be of about the **SAME AMPLITUDE** so as to ensure good contrast between the bright and dark fringes.*

YOUNG'S DOUBLE-SLIT EXPERIMENT - EVIDENCE IN FAVOUR OF THE WAVE THEORY OF LIGHT

*The first widely accepted evidence in favour of the wave theory of light was provided by **Thomas Young** when he demonstrated interference of light in 1801.*

A diagram of a more modern version of his apparatus is shown opposite.



*The sodium lamp acts as a monochromatic (single wavelength) light source and it illuminates the narrow slit (**S**). Diffraction at **S** causes a diverging beam of light to fall on the two narrow slits S_1 and S_2 which are very close together and parallel to **S**. Since they are derived from a single source **S**, the two slits act as **coherent** light sources.*

*The diffracted light beams emerging from S_1 and S_2 overlap in the region beyond the slits and superposition of the light waves produces an **interference pattern of bright and dark fringes** which can be seen on a white screen placed 1-2 m from the double slits.*

NOTE

- *The slits need to be extremely narrow and as a result very little light is transmitted, so the interference pattern is very faint and can only be seen in a darkened room.*
- *A travelling microscope can be used instead of the screen and this makes the pattern easier to observe.*
- *A modern version of the apparatus uses a laser whose coherent light is shone directly at the double slit, producing an interference pattern which is bright enough to be viewed in daylight.*

EVIDENCE FOR WAVE THEORY OF LIGHT

- *Young's double-slit experiment was a classical confirmation of the **WAVE THEORY OF LIGHT** because the interference pattern could only be explained in terms of the superposition of light waves from the two slits.*

- *The **BRIGHT** fringes were explained by stating that at such points the light waves arrive **IN PHASE** and so reinforce each other (i.e. **CONSTRUCTIVE INTERFERENCE** occurs).*

  *At points where the light waves arrive in **ANTIPHASE**, cancellation occurs (i.e. **DESTRUCTIVE INTERFERENCE**) and so a **DARK** fringe is formed.*

- *If one of the slits is covered, the interference fringes disappear and the screen is then uniformly illuminated. This shows that the interference pattern is produced as a result of superposition between the light waves coming from both slits.*

- *INTENSITY (I)*

The INTENSITY (I) of a wave motion at a point is the rate at which energy is transmitted (i.e. the power) per unit area perpendicular to the wave direction.

$$\text{intensity} = \frac{\text{power}}{\text{cross-sectional area}}$$

$$I = \frac{P}{A}$$

(W)

(W m^{-2})

(m^2)

- *The **intensity of a wave decreases with distance** because its energy is spread out over a larger area and also because some of it may be absorbed.*

- *The **amplitude of a wave decreases with distance** because it is proportional to **intensity** $^{\frac{1}{2}}$.*

$$I \ a \ a^2$$

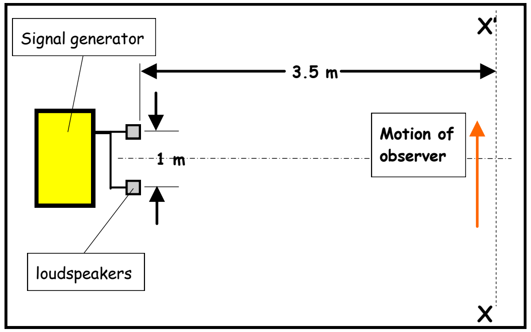
$$I = ka^2$$

So, $$\frac{I}{a^2} = K$$

*This means that a wave which has **twice the amplitude** of another has **four times the intensity** (i.e. it is carrying energy at four times the rate).*

- **PRACTICE QUESTIONS (2)**

1 Two loudspeakers are connected to the same signal generator as shown in the diagram opposite.



An observer moving slowly along the line **XX'** hears alternate loud and quiet sounds when the speakers are continuously emitting sound waves of frequency **680 Hz**.

Given that sound travels at **340 m s^{-1}** in air, calculate **the distance moved by the observer from one loud sound to the next.**

2 In a double slits interference experiment using monochromatic light from a laser, a pattern of red fringes is seen on a white screen placed at a distance of 3 m from the double slit.

State and **explain** how the fringe pattern would change if :

(a) The screen is **moved further away from the double slit.**

(b) The double slit is replaced by one in which **the slits separation is smaller.**

(c) Laser light of a **shorter wavelength** is used.

(d) One of the double slits is completely covered so that no light can pass through it.

3 In a double slits experiment, a laser beam is directed normally at a pair of slits which are **0.45 mm** apart. A fringe pattern is seen on a screen placed at a distance of 1400 mm from the double slit and perpendicular to the centre line from the slits to the screen. The distance between two **BRIGHT** fringes on the screen is found to be **1.64 mm.**

(a) Calculate the **wavelength** of the laser light used.

(b) How **far and in which direction** must the screen be moved in order to increase the fringe spacing to **2.00 mm ?**

4 A **60 W** light bulb emits electromagnetic radiation in all directions. Assuming the bulb to be a point source, calculate the **INTENSITY** :

(a) At a distance of **2.0 m** from the bulb.

(b) At a distance of **4.0 m** from the bulb.

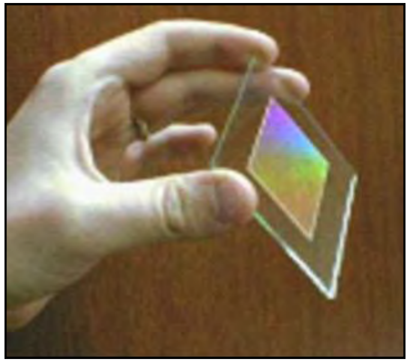
5 Waves from a point source have an intensity of **600 W m^{-2}** and an amplitude of **80 mm.**

(a) What is the **new intensity** when the wave amplitude has increased to 160 mm ?

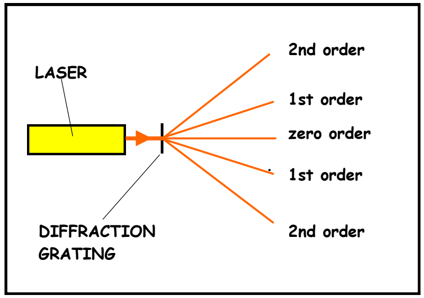
(b) What is the wave **amplitude** when the intensity is decreased to **150 W m^{-2}** ?

• *THE DIFFRACTION GRATING*

- *A **DIFFRACTION GRATING** consists of a small glass plate with a very large number (e.g. 600 lines mm-1) of closely spaced, parallel lines scratched onto it.*

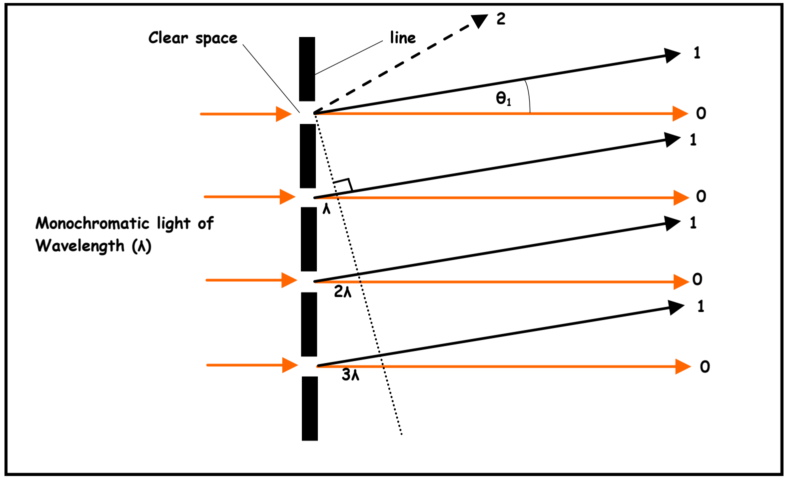


*When a beam of monochromatic light is directed at a diffraction grating, it passes through the clear spaces between the lines and it is transmitted in certain, clearly defined directions only. This is because as they pass through the slits, the light waves are diffracted and those from adjacent slits interfere **constructively** in certain directions (maximas) and **destructively** in others (minimas).*



*The diffraction images observed include the **ZERO ORDER** image which is along the straight-through position, with further images on either side which are referred to as the **1st ORDER**, **2nd ORDER** and so on.*

EXPLAINING THE DIFFRACTION GRATING IMAGES



The above diagram shows a small section of a diffraction grating on which monochromatic light of wavelength (λ) is normally incident. Consider what happens after the light passes through the grating.

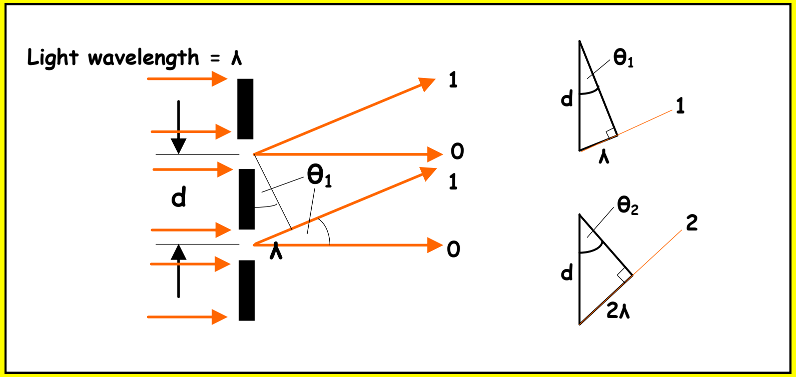
- ***DIRECTION 0*** *is that of light waves which have passed perpendicularly through the grating. The **PATH DIFFERENCE (PD)** between light waves from adjacent slits is **ZERO** and so they are **IN PHASE** with each other and **CONSTRUCTIVE** interference occurs. These light waves then give the **ZERO (0) ORDER MAXIMUM.***

- ***DIRECTION 1*** *is that of light waves from adjacent slits having a **PD = 1λ**. So in this direction the light waves are also **IN PHASE** and **CONSTRUCTIVE** interference occurs. This gives the **1st ORDER MAXIMA** at an angle (**θ_1**) on either side of the central zero order maximum.*

- ***DIRECTION 2*** *is that for the **2nd ORDER MAXIMA**. The light waves from adjacent slits have a **PD = 2λ**, so they are **IN PHASE** and **CONSTRUCTIVE** interference occurs at another angle (**θ_2**) to the central 0 order maximum. Further maxima can be observed on either side of the central maximum for values of θ up the a maximum of 90°.*

- ***MINIMA** are obtained between the maxima positions and in these cases the light waves from adjacent slits have a **PD = $(n - \frac{1}{2})\lambda$** (n = 1, 2, 3 etc), so **DESTRUCTIVE** interference occurs.*

DIFFRACTION GRATING EQUATION



The light waves travelling along direction 1 interfere constructively to give the ***!st ORDER MAXIMUM.*** *For this to happen, the PD for light waves from adjacent slits =* ***1 λ.***

Therefore : $d \sin\theta_1 = 1\,\lambda$

Applying the same analysis for the ***2nd ORDER MAXIMUM*** *gives :*

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

Thus, for the ***nth ORDER MAXIMUM*** *:*

diffraction angle

light wavelength

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

grating spacing

d = 1/N

Number of lines per mm

diffraction order

n = 0,1,2,3 ....etc

USE OF DIFFRACTION GRATING TO MEASURE LIGHT WAVELENGTH

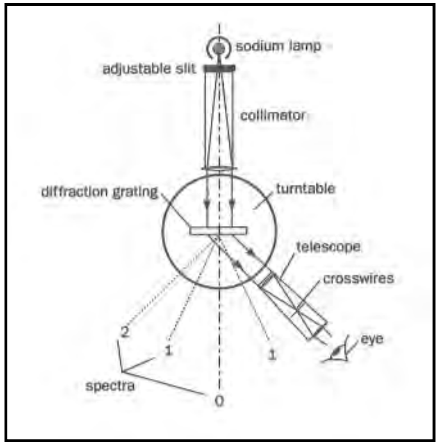
A monochromatic beam of light is directed at a diffraction grating of known grating spacing (d).

The diffraction angles (θ_1, θ_2, θ_3, etc) for the 1st, 2nd and 3rd order diffraction images of the slit are measured using a spectrometer.

These results are used in the equation :

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

To determine the wavelength of the light used.



ADVANTAGES OF USING MULTIPLE SLITS

- *The interference fringes obtained with the double-slit apparatus are :*
  - ***FAINT*** *(unless a laser is used).*
  - ***BLURRED*** *(they don't have a definite edge).*

  This makes it difficult to measure the fringe width accurately.

- *Using a diffraction grating with many slits overcomes these problems because :*
  - *The maxima are* ***MUCH BRIGHTER*** *(the larger number of slits allows much more light to be transmitted).*
  - *The maxima are* ***VERY SHARP*** *(since constructive interference only happens in certain precise directions).*

- **PRACTICE QUESTIONS (3)**

1 Light of wavelength **640 nm** is directed normally at a diffraction grating having **500 lines per mm.** Calculate :

(a) The **angle of diffraction for 1st and 2nd order images.**

(b) The **maximum number of diffraction orders possible.**

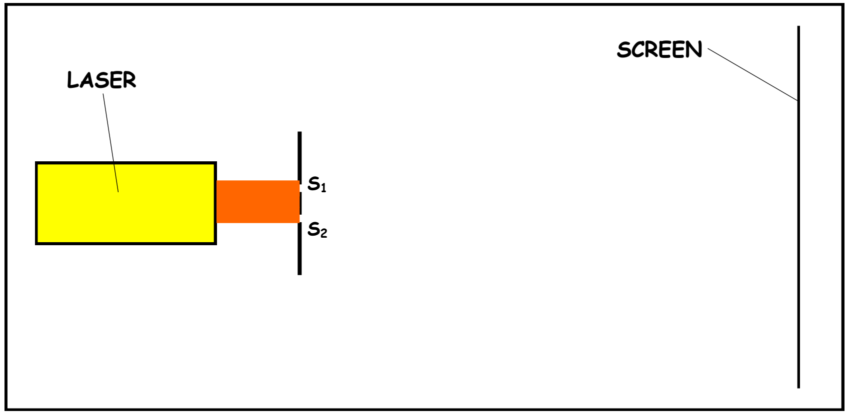
2 Light of wavelength **430 nm** is directed normally at a diffraction grating. The first order transmitted beams are at **28° to the zero order beam.** Calculate :

(a) The **number of lines per mm** on the grating.

(b) The **angle of diffraction** for each of the other diffracted orders of the transmitted light.

- **HOMEWORK QUESTIONS**

1 The diagram below shows an arrangement to demonstrate the interference of light. A double-slit, consisting of two narrow slits very close together, is placed in the path of a laser beam.



(a) Light spreads out as it passes through each slit. **State** the term used to describe this.

(b) The slits **S_1** and **S_2** can be regarded as coherent light sources. State what is meant by **COHERENT.**

(c) Light emerging from **S_1** and **S_2** produces an interference pattern consisting of bright and dark lines on the screen. **Explain in terms of the path difference** why bright and dark lines are formed on the screen.

(d) The wavelength of the laser light is **6.5×10^{-7} m** and the separation between **S_1** and **S_2** is **0.25 mm.** Calculate the **distance between neighbouring dark lines** on the screen when it is placed **1.5 m** from the double-slit.

(OCR AS Physics - Module 2823 - June 2005)