5 Optics

5.1 Refraction of Light

When considering the effect of lenses or mirrors on the path of light, we draw diagrams using **light rays** and **normals**.

- **Light rays** represent the direction of travel of wavefronts.
- The **normals** is an imaginary line perpendicular to a boundary between two materials or a surface.

Refraction is the change of direction that occur when light **passes at an angle** across a boundary between two **transparent substances**. When entering a glass block from air, the light ray bends

- **Towards the normal** when it passes from air into glass.
- **Away from the normal** when it passes from glass into air.

No refraction takes place if the incident light ray is along the normal.

At a boundary between two transparent substances, the ray bends towards the normal if it passes into a **more dense substance**.

Investigating Refraction by Glass

1. Use a **ray box** to direct a light ray into a **rectangular glass block** at different angles of incident at point P on one of the sides.
2. For each angle of incidence, mark point Q where the light leaves the block.

The **angle of incidence** is the angle between the incident light ray and the **normal** at the point of incident. The **angle of reflection** is the angle between the refracted light ray and the normal at the point of incident.

- The angle of diffraction r is always less than the angle of incident i.
- **Snell's law**: the ratio $\sin i/\sin r$ is the same for each light ray.
  - The ratio is referred to as the **refractive index** n of glass.

$$\text{refractive index of the substance } n = \frac{\sin i}{\sin r}$$

Partial reflection also occur when a light ray in air enters any refractive substance.

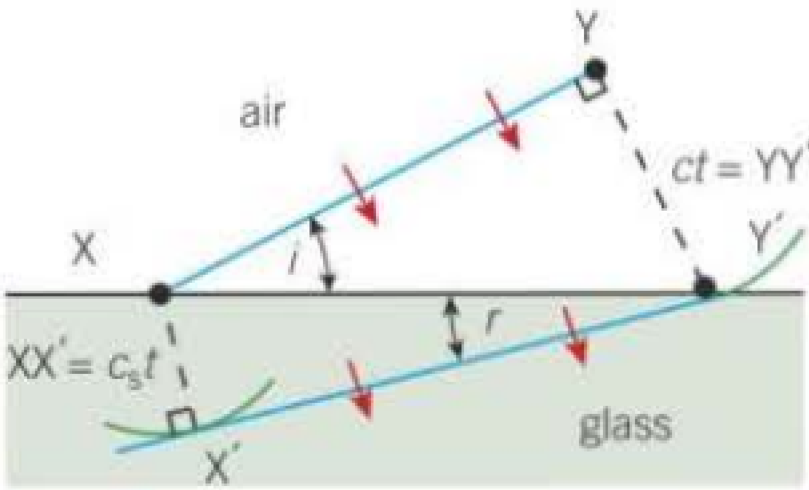
The angle of refraction of the light ray emerging from a rectangular glass block is the same as the **angle of incidence** of the ray entering the block.

- The two side of the block are **parallel to each other**.
- Refractive index when entering the glass is n, when leaving the glass is $1/n$, so the combined effect is $n = 1$.

5.2 More about Refraction

Refraction occurs because the **speed of light waves** is different in each substance. The amount of refraction that takes place depends on the **speed of the waves in each substance**.

Consider a wavefront of light waves when it passes across a **straight boundary** from a vacuum into a transparent substance.



The wave front moves

- A distance ct at speed c in vacuum from Y to Y'.
- A distance $c_s t$ at speed c_s in the substance from X to X'.

This gives us equations

$$\begin{cases} ct & = XY' \sin i \\ c_s t & = XY' \sin r \end{cases}$$

Combining the equations give

$$\frac{\sin i}{\sin r} = \frac{c}{c_s}$$

This shows the **smaller the speed of light** is in a substance, the **greater the refractive index** of the substance.

Since the **frequency does not change** when refraction occurs

$$n_s = \frac{c}{c_s} = \frac{\lambda}{\lambda_s}$$

Refraction at a Boundary between Two Transparent Substances

Consider light crossing a boundary from a substance which the speed of light is c_1 to one that the speed of light is c_2.

$$
\begin{aligned}
\frac{\sin i}{\sin r} &= \frac{c_1}{c_2} \\
\frac{1}{c_1}\sin i &= \frac{1}{c_2}\sin r \\
\frac{c}{c_1}\sin i &= \frac{c}{c_2}\sin r \\
n_1 \sin\theta_1 &= n_2 \sin\theta_2
\end{aligned}
$$

which is the equation form of **Snell's law**.

Note that the refractive index of air is 1.0003, for most purposes can be assumed to be 1.

White Light Spectrum

A **glass prism** can be used to split a **beam of white light** from a filament lamp into the colours of the spectrum. The dispersive effect occur because the speed of light in glass **depends on wavelength**.

- White light is composed of light with a **continuous range of wavelengths**.
- The shorter the wavelength in air, the greater the amount of diffraction.
- So each colour in the white light beam is **refracted by a different amount**.

5.3 Total Internal Reflection

- If the **angle of incidence** is increased to a certain value known as the **critical angle**, the light ray travels along the boundary.
- If the angle of incidence is increased beyond the critical angle, the light ray undergoes **total internal reflection**.

Total internal reflection takes place if

- The incidence substance has a **larger refractive index** than the other substance.
- The angle of incidence **exceeds the critical angle**.

When light enters a diamond

1. It is **split into the colours of the spectrum** as diamond's very high refractive index separates the colours more than any other substance does.
2. The high refractive index gives a **small critical angle**
   - So a light ray entering a diamond may be **totally internally reflected many times** before it emerges.
   - So its colours **spreads out more and more**.

Optical Fibres

Optical fibres are used in **medical endoscopes** to see inside the body, and communications to **carry light signals**.

- The light ray is **totally internally reflected** each time it reaches the fibre boundary.
- At each point where the light ray reaches the boundary, the angle of incidence **exceeds the critical angle** of the fibre.

Unless the radius of the bend is too small, then the light will not totally internally reflect.

A **communications optical fibre** allows **pulses of light** that enter at one end from a transmitter to reach a receiver at the other end.

- Fibres are **highly transparent** to minimise absorption of light
  - Otherwise would reduce the amplitude of the pulses the further they travel in the fibre.

Each fibre consists of a **core surrounded by a layer of cladding**.

- Total internal reflection takes place at the **core-cladding boundary**
  - If there were no cladding, such crossover would mean the signal **would not be secure** - they would **reach the wrong destination**.

The core must be **very narrow** to prevent **modal dispersion**.

- This occurs in a **wide core** as light travelling along the axis of the core **travels a shorter distance per metre of fibre** than light that repeatedly undergoes TIR.
  - A pulse of light sent would be **longer than it ought to be**.
  - If it is too long, it would merge with the next pulse.

Material dispersion occurs if white light is used instead of **monochromatic light**, because the speed of light in glass of the optical fibre depends on the wavelength of light travelling through it.

5.4 Double Slit Interference

Illuminate two **closely spaced parallel slits**, the two slits acts as **coherent sources of waves**.

- They emit light waves with a **constant phase difference** and the **same frequency**.
- E.g. use a bulb to illuminate a **narrow single slit**, then double slit arrangement is illuminated by light from the narrow single slit.
- Or just use a low power laser beam.

Young's fringes - alternate bright and dark fringes can be seen on a white screen where the diffracted light from the double slits **overlaps**. They are **evenly spaced** and **parallel to the double slits**.

The fringes are formed due to the **Interference of light** from the two slits

- Where a **bright fringe** is formed, light from one slit **reinforces the light from the other slit**.

  - The light waves from each slit **arrive in phase** with each other.
- Where a **dark fringe** is formed, light from one slit **cancels the light from the other slit**.
  - The light waves from each slit **arrive 180° out of phase**.

Fringes separation is the distance between the centre of a bright fringe to the next bright fringe.

$$\text{fringe separation } w = \frac{\lambda D}{s}$$

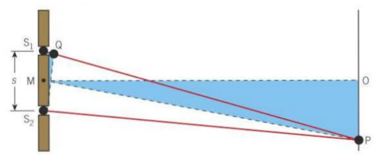
where s is the **slit spacing** and D the distance from the silts to the screen.

The fringe becomes more widely spaced if

- Distance D from the slits to the screen is increased.
- Wavelength λ of the light used is increased.
- The slit spacing s is reduced.

The slit spacing is the distance between the centre of the slits.

Theory of the Double Slit Equation



- For **reinforcement** at P, the path difference $S_1P - S_2P = m\lambda$.
- For **cancellation** at P, the path difference $S_1P - S_2P = \left(m + \frac{1}{2}\right)\lambda$.

where $m = 0, 1, 2$

Consider similar triangles

$$\begin{aligned} \frac{S_1Q}{S_1S_2} &= \frac{OP}{OM} \\ \frac{m\lambda}{s} &= \frac{mw}{D} \\ w &= \frac{\lambda D}{s} \end{aligned}$$

The formula is only valid if the fringe separation w is **much less than the distance** D from the slits to the screen.

5.5 More about Interference

For a double slit illuminated by light from a single slit, each wave crest always pass through one of the double slits a **fixed time after it passes through the other slit**. The double slits therefore emit wavefronts with a **constant phase difference**.

Light from two nearby lamp bulbs does not form an interference pattern because the two light sources emit light waves at random, the points of cancellation and reinforcement would **change at random**, so no interference pattern is possible.

Light sources

- **Vapour lamps and discharge tubes** produce light with a dominant colour. They are in effect a **monochromatic light source** because its spectrum is dominated by light of a certain colour.
- **Light from a filament lamp or the Sun** is composed of the colours of the spectrum and covers a **continuous range of wavelengths**.
  - Light from a filter is a particular colour because it contains a **much narrower range of wavelengths**.
- **Laser** is almost **perfectly parallel** and **highly monochromatic -** its wavelength can be specified to within a nanometre.
  - A laser is a convenient source of **coherent light**.

White Light Fringes

As we know blue light fringes are much closer together than the red light fringes.

- The **central fringe** is white because every colour contributes at the centre of the pattern.
- The **inner fringes** are tinged with blue on the inner side and red on the outer side, this is because the two fringe patterns do not overlap exactly.

5.6 Diffraction

Diffraction is the **spreading of waves** when they pass through a gap or by an edge.

- **Diffraction of water waves** through a gap can be observed using a **ripple tank**. The diffracted waves spread out more if
  - The gap is made narrower.
  - The wavelength is made larger.
- **Diffraction of light** by a single slit can be demonstrated by directing a **parallel beam of light** at the slit.

The diffracted light forms a pattern that can be observed on a white screen.

- A **central fringe** with further fringes either side of the central fringe.
- The **intensity** of the fringes is greatest at the centre of the central fringe.
- The central fringe is **twice as wide** as each of the other fringes.
- The **peak intensity** of each fringe decreases with distance from the centre.
- Each outer fringe is the **same width**.

- The outer fringe is much **less intense** than the central fringe.

The width is measured from **minimum to minimum intensity**.

For a **monochromatic light** with wavelength λ

$$w = \frac{2D \times \lambda}{a}$$

where a is the width of the single slit.

- The greater the **wavelength**, the wider the fringes.
- The narrower the **slit**, the wider the fringes.