5 Optics

5.1 Refraction of Light

- In a diagram, **light rays** represent the direction of travel of wavefronts.
- The **normal** is an imaginary line perpendicular to a surface.

Refraction is the **change of direction** that occurs when light passes at an angle across a boundary between two transparent materials.

A **ray box** can be used to direct a light ray into a glass block.

- Bend **towards the normal** when it passes from air into glass.
- Bend **away from the normal** when it passes from glass into air.

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

- **Angle of refraction** r is always less than **angle of incident** i.
- The radio $\sin i / \sin r$ is the same for each ray, this known as **Snell's law**.

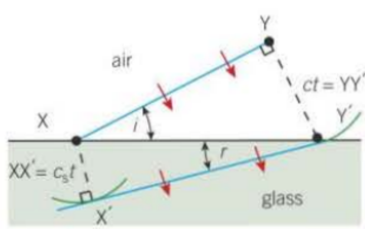
$$\text{the refractive index of the substance}\, n = \frac{\sin i}{\sin r}$$

Partial reflection occurs when a light ray enters a refractive substance.

5.2 More about Refraction

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

1. Consider a wavefront of light wave when it **passes across a straight boundary** into a transparent substance.



2. The **wavefront** moves from XY to $X'Y'$ in time t. The wavefront moves
   - A distance ct from Y to Y'
   - A distance $c_s t$ from X to X'

This gives up equations

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

Rearranging gives **Snell's law -** the smaller the speed of light is in a substance, the greater the refractive index of the substance.

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

For refraction at a boundary between two transparent substances:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Refraction of White Light

We can use a **prism** to split a beam of white light into colours of the spectrum

- Light is composed of light with a **continuous range of wavelengths**.
- The shorter the wavelength, the greater the amount of refraction.
- So each colour of light is refracted by a different amounts.

5.3 Total Internal Reflection

When light ray travels <u>from glass into air</u>, it refracts away from the normal.

- The **critical angle** is the angle of incidence where the light ray refracts <u>along the boundary</u>.
- The ray undergoes **total internal reflection** if the angle of incidence is increased further.

Conditions for TIR:

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

The critical angle satisfies

$$\sin \theta_c = \frac{n_2}{n_1}$$

Diamonds sparkle with different colours when white light is directed at them

- Very high refractive index **separate the colours** more than any other substance.
- A light ray may **totally internally reflect many times** before it emerges so the colours spread out more and more.

Optic Fibres

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

- The light ray is totally internally reflected each time it reaches the fibre boundary.
- Even when the fabric bends, unless the radius of the bend is too small.

The fibres are **highly transparent** to minimised the absorption of light, as **light loss** would reduce the amplitude of the pulses.

- TIR takes place at the **core-cladding boundary**.
  - If there were no cladding, two fibres would be in direct contact and light would **cross from one fibre to the other**.
  - And the signal would reach the wrong destination.
- The core must be narrow to prevent **modal dispersion**.
  - This occurs in a **wide core** as light travelling along the axis travels a **shorter distance per metre of fabric** than light that repeatedly undergoes TIR.
  - If a pulse of light becomes too long, it would **merge with the next pulse**.

Material dispersion occurs if white light is used instead of **monochromatic light**, as the speed of light in glass depends on the wavelength of the light.

5.4 Double Slit Interference

1. Two closely spaced parallel slits acts as **coherent sources of waves** - they emit light waves with a **constant phase difference** and the **same frequency**.
   - A **laser beam** could be used instead of a light bulb and a single slit.
2. **Young's fringes - evenly spaced**, alternative bright and dark fringes can be seen on a white screen where the diffracted light from the double slits **overlap**.

The fringes are formed due to the **interference of light** from the slits.

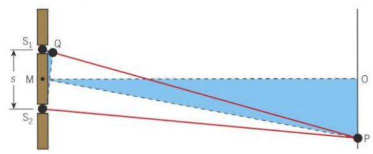
- Bright fringe is formed where light from one slit **reinforces light from the other slit**.
  - The light waves from each slit arrive **in phase** with each other.
- Dark fringe is formed where light from one slit **cancels light from the other slit**.
  - The light waves from each slit arrive **180 deg out of phase**.

Fringe separation is the distance from the centre of the of the bright fringe to the centre of the next bright fringe.

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

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

Theory of Double Slit Equation



- **Reinforcement** at P if the **path difference** $S_1P - S_2P = m\lambda$
- **Cancellation** at P if the **path difference** $S_1P - S_2P = \left(m + \frac{1}{2}\right)\lambda$

where $m = 0, 1, 2, \ldots$

From the diagram

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

5.5 More about Interference

Double slits are **coherent sources** because they emit light waves

- Of the **same frequency**, and
- With a **constant phase difference**.

Each wave crest from the single slit always passes trough one of the double slits a fixed time after it passes through the other slit. Therefore emits wavefronts with a **constant phase difference**.

Light from two filament lamps do not form an interference pattern because the 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

- **Discharge tubes** produce light with a **dominant colour**.
  - A **sodium vapour lamp** is in effect a monochromatic light source.

- Light from a **filament lamp** is composed of colours of the spectrum and therefore covers a **continuous range** of wavelengths.
- **Laser light** is
  - Monochromatic
  - Coherent

Each component of white light produces its own fringe pattern.

- The **central fringe** is white
  - 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.
  - Red fringes are more spaced out, than blue fringes.
  - The two fringe patterns <u>do not overlap directly</u>.

5.6 Diffraction

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

Diffraction of water waves through a gap shows that diffracted waves spread out more if

- The gap is made narrower, or
- 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 pattern show a **central fringe** <u>twice as wide</u> as the outer fringes.
- Each **outer fringe** is the <u>same width</u>.
- **Peak intensity** of each fringe <u>decreases with distance</u> from the centre.

$$\text{Width of the central fringe } w = \frac{2\lambda D}{a}$$

where a is the width of the single slit.

5.7 The Diffraction Grating

A diffraction grating is a plate with **many closely spaced parallel slits** ruled on it. When a beam of **monochromatic light** is directed a diffraction grating, light is transmitted in <u>certain directions only</u>.

- The light passing through each slit is **diffracted**.

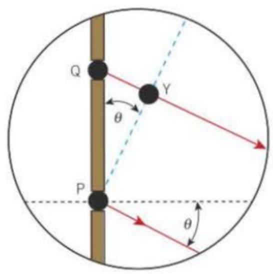
- The diffracted waves from adjacent slits reinforce each other in **certain directions only**.

The **zero order beam** is in the same direction as the incident beam.

The **angle of diffraction** between each transmitted beam and the central beam increases if

- Light with a **longer wavelength** is used.
- Grating with **closer slits** is used.

Each diffracted wavefront emerges from a slit and **reinforces a wavefront** from a slit adjacent to it.



- The distance QY from the slit to the wavefront is equal to $n\lambda$.
- The **angle of diffraction** of the beam θ is equal to the angle between the wavefront and the plate of the slits.
- So $\sin\theta = n\lambda/d$ where d is the **grating spacing**.

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

for the nth order beam.

The **maximum number of orders** is given by the value d/λ rounded down to the nearest whole number.

Types of Spectra

- **Continuous spectra** - the hotter the light source, the shorter the wavelength of the brightest part of the spectrum.
- **Line emission spectra** - consists of **narrow vertical lines** of different colour. The wavelengths of the lines are **characteristic of the chemical element** that produced the light.
- **Line absorptions spectra** - a continuous spectrum with **narrow dark lines** at certain wavelengths. Atoms of glowing gas absorb light then emit light subsequently, but not necessarily in the same direction as the transmitted light.