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VCE Physics Unit 4

Area Of Study 2, Interactions Of Light And Matter, Study Notes 1

Waves

Waves **transfer energy** in straight lines away from a source.

Mechanical waves require a medium through which to travel. As it is energy, and not mass, that's transferred by a wave, the medium through which a wave travels is left undisturbed after a wave has travelled through it, exactly as it was previous to the wave. The particles of a medium return to their original locations after a wave has passed through. Waves travel along, carrying energy; the media (and hence the mass) through which they travel remain where they already were.

In **longitudinal**, or "**one dimensional**", mechanical waves, particles of the medium through which the waves travel are displaced along the same axis ("**back and forth**") as the wave's direction of motion, before returning to their original positions. **Sound** is an example of energy that's transferred as a longitudinal mechanical wave.

In **transverse**, or "**two dimensional**", mechanical waves, particles of the medium through which the waves travel are displaced along an axis at a right angle ("**up and down**") to the wave's direction of motion, before returning to their original positions. **Water** waves are an example of transverse mechanical waves.

Electromagnetic waves do not require a medium through which to travel. They can travel through a vacuum. They can be considered as two waves occurring simultaneously:

- one which is an **electric field**, oscillating between a positive and negative charge, and
- another which is a **magnetic field**, oscillating between a North and South polarity, at the same frequency and wavelength, but on a plane at a right angle to that of the electric field.

Light, along with the entire "electromagnetic spectrum" (consisting of radio waves, microwaves, infrared radiation, ultraviolet radiation, x-rays and gamma rays) can be considered as electromagnetic waves.

Waves have these components:

- **Displacement**, or "amplitude", which is the extent to which matter is shifted from its original location as a wave passes through it. Referred to as "intensity" when considering electromagnetic waves.

- **Crests**; points of maximum displacement.

- **Troughs**; points of minimum displacement.

- **Antinodes** (Peaks); crests or troughs.

- **Nodes**; points of zero displacement, midway between antinodes.

- **Period, T**; the time taken for one single and complete cycle of the wave to occur (the time difference between two crests, two troughs, three antinodes or three nodes), measured in seconds, s.

- **Frequency, f**; the number of waves occurring per second of time, measured in Hertz, Hz. Frequency and period are given by each other's inverse.

$$f = \frac{1}{T} = T^{-1} \rightarrow T = \frac{1}{f} = f^{-1}$$

- **Wavelength, λ**; the distance covered by one single and complete cycle of the wave, measured in metres, m.

- **Velocity, v**; the straight line speed of a wave, given by dividing λ by T, or the product of f and λ. Measured in metres per second, ms^{-1}.

$$v = \frac{\lambda}{T} = f\lambda$$

Reflection Of Waves

Waves reflect from barriers such that the angle of reflection is equal to the angle of incidence. The angles of reflection and incidence are measured between the direction of the wave's motion and "the normal", and imaginary line at a right angle to the barrier, originating from the point of incidence and reflection; **not** between the direction of the wave's motion and the barrier.

$$r^\circ = i^\circ$$

Electromagnetic radiation, and hence light, is demonstrated to be a wave by reflecting in this way (however particles reflect in the same way as well...).

Waves that are **fixed** to the barrier from which they reflect (such as a transverse wave sent along a rope tied firmly to a post) are reflected such that the reflected wave is "**out of phase**" by half a wavelength; crests of the incident wave become troughs of the reflected wave, and troughs of the incident wave become crests of the reflected wave.

Waves that are **not fixed** to the barrier from which they reflect (such as water waves reflected from the edge of a pool) are reflected such that the reflected wave is "**in phase**"; crests of the incident wave become crests of the reflected wave, and troughs of the incident wave become troughs of the reflected wave. Electromagnetic radiation, and hence light, is reflected in this way (which makes sense, as light can't be attached to a mirror).

Refraction Of Waves

Waves change direction as they move between media of different densities. This occurs because a wave's velocity changes as it moves from a medium of one density to a medium of another. As the velocity changes, so does the wavelength, causing the change in direction.

A transparent material's **Refractive Index**, $\boldsymbol{n}$, indicates the extent to which a light wave's velocity, and hence direction, will change as it passes into the material.

Again (as in reflection), angles of refraction and incidence are measured between the direction of the wave's motion and "the normal", and imaginary line at a right angle to the surface of the medium, intersecting the point of incidence and refraction; **not** between the direction of the wave's motion and the surface.

The higher a material's refractive index, the more a light wave will decrease in velocity (slow down).

"Snell's Law" mathematically relates refractive indices, angles of incidence and refraction, and initial and final velocities:

$$\frac{\sin i^\circ}{\sin r^\circ} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

- If $n_2>n_1$, light waves **decrease in velocity** ($v_2<v_1$), and refract **towards** the normal ($r^\circ<i^\circ$).
- If $n_2<n_1$, light waves **increase in velocity** ($v_2>v_1$), and refract **away from** the normal ($r^\circ>i^\circ$).

Electromagnetic radiation, and hence light, is demonstrated to be a wave by refracting according to Snell's Law. Particles refract too, but not according to Snell's Law.

Diffraction Of Waves

Waves change direction as they pass by the edge of barriers, and therefore as they pass through slits between barriers.

Wavefronts are the crests of waves as viewed from above, rather than from the side. If many waves, of equal v, f and λ, travel side by side, in synchronicity, the wavefronts are lines crossing all the corresponding crests. A wavefront, therefore, is at a right angle to the direction of a wave's motion. Wavefronts are what's seen of waves when looking at water from above, rather then from the side.

If a barrier does not oppose an entire wavefront, the section of the wavefront opposed by the barrier is reflected, and the remaining section of the wavefront mostly passes the barrier unobstructed, but the section of the wavefront at the edge of the barrier can be considered as being "held back", slowing the wave down at this point. Just as with refraction, a change in a wave's velocity (a reduction, in the situation of diffraction) results in a change in its wavelength (a shortening, in the situation of diffraction), which results in a change in the direction of its motion. Through diffraction, waves can move around barriers, such that they appear on the other side.

The extent of diffraction is proportional to wavelength:
- **short wavelength; less diffraction, and**
- **long wavelength; more diffraction.**

By diffracting through a "slit", a gap in a barrier, a straight wavefront can be transformed into a circular wavefront, such as that formed by a "point source", like a small stone dropped into a still pond.

The extent of diffraction is inversely proportion to the slit width, w:
- **wide slit; less diffraction, and**
- **narrow slit; more diffraction.**
- **Slit width must be equal to or less than wavelength to form circular wavefronts.**

Interference Of Waves

Constructive interference is where the **crest of one wave meets the crest of another**, or when the **trough of one wave meets the trough of another**. The waves cumulate at the point where they meet, such that the resulting displacement is equal to the sum of the displacements that met, so there's **greater displacement** at points of constructive interference, or **double displacement** if the cumulating waves have equal displacement. After constructive interference has occurred, each wave continues as though nothing ever happened.

Destructive interference is where the **crest of one wave meets the trough of another**, or when the **trough of one wave meets the crest of another**. The waves cumulate at the point where they meet, such that the resulting displacement is equal to the sum of the displacements that met, so there's **less displacement** at points of destructive interference, or **zero displacement** if the cumulating waves have equal (although opposite in phase) displacement. After destructive interference has occurred, each wave continues as though nothing ever happened.

By diffracting through a barrier with two slits (a "double slit"), a single straight wavefront can be transformed into two, synchronised circular wavefronts (or "point sources") of equal v, f and λ.

These wavefronts interfere with each other to produce fixed lines of constructive and destructive interference.
- Lines of **constructive interference** are called **antinodal lines**, as they're **lines of maximum displacement**.
- Lines of **destructive interference** are called **nodal lines**, as they're **lines of zero displacement**.

In both directions out from the centre (as the lines formed are symmetrical), **antinodal lines are numbered as m_0, m_1, m_2, m_3** and so on, and **nodal lines are numbered n_1, n_2, n_3** and so on.

Path difference is the difference in the distance travelled between waves from each of the two slits at one single point. Path difference along antinodal lines is equal to the product of wavelength and the antinodal line number. Path difference along nodal lines is equal to the product of wavelength and the nodal line number minus a half:

$$pd_{\text{antinodal lines}} = m\lambda$$

$$pd_{\text{nodal lines}} = (n - \frac{1}{2})\lambda$$

Where pd = path difference, in m
m = antinodal line number
n = nodal line number
λ = wavelength, in m

Interference Patterns

Electromagnetic radiation, and hence light, is demonstrated to be a wave by diffracting through a double slit to form antinodal and nodal lines. Particles of tangible mass cannot be observed to diffract.

The antinodal and nodal lines formed by refracting light through a double slit can be projected on to a screen and observed as **interference patterns**. Bright bands of light are seen where there's antinodal lines, and dark bands (or "fringes") are seen where there's nodal lines between the bright bands.

The light needs to be monochromatic (consisting of only one constant wavelength) and coherent (synchronised waves to form wavefronts) for diffraction to be effective.

The wavelength of the light is given by the relationship between the distance between the slits, the distance between the fringes, and the distance between the barrier and the screen:

$$\lambda = \frac{xd}{L}$$

Where λ = wavelength, in m
x = distance between fringes (dark bands), or width of bright bands, in m
d = distance between slits, in m
L = distance between barrier and screen

This procedure is known as "Young's Double Slit Experiment".

Single Slit Interference

Electromagnetic radiation, and hence light, also forms antinodal and nodal lines, and hence interference patterns, when diffracted through a **single slit**. The edges of the slit act as the two point sources.

The interference pattern formed by single slit diffraction is similar to that formed by double slit diffraction, in that there's the same distance between the dark fringes (except for those either side of the central bright band (see below), and assuming that all other variables are equal [L and λ, and d equal to slit width]).

The interference pattern formed by single slit diffraction is different to that formed by double slit diffraction, in that:

- The central bright band is twice as wide as the others, and
- The other bright bands decrease in intensity with their distance from the central bright band.

The below formula relating the variables involved with single slit interference does not function in consideration of the central bright band, because it's double the width of the others.

$$\lambda = \frac{xw}{L}$$

Where λ = wavelength, in m
x = distance between fringes (dark bands), or width of bright bands; **not at the centre**, in m
w = slit width, in m
L = distance between barrier and screen

Comparison Of Interference Patterns

If the interference pattern of a known wavelength of light is compared with that of another of unknown wavelength, the unknown wavelength can be determined by the ratio between the spacing of the bright bands in the two patterns.

For example, if the pattern of the unknown wavelength has X bright bands **across the same width** (such that the fringes at outside edges of each pattern are separated by equal distances) as the known wavelength's Y, the unknown wavelength is Y/X that of the known wavelength.

$$\lambda_{unknown} = \frac{\text{Number of bright bands in pattern of } \lambda_{known}}{\text{Number of bright bands in pattern of } \lambda_{unknown}} \times \lambda_{known}$$