Section 3: Light and Matter

The study of charges at rest and charges moving with uniform velocity is extended to accelerating charges, which radiate electromagnetic waves. When the acceleration is in the form of a continuous oscillation, the frequency of the electromagnetic waves is equal to the frequency of oscillation of the charges. The behaviour of these waves is described, and interference patterns are explained, using the principle of superposition.

The behaviour of light at relatively low intensity is used to introduce photons. The photoelectric effect and X-ray production are explained in terms of photons.

The interference of electrons reflected by crystal lattices is used to introduce matter waves.

Topic 1: Electromagnetic Waves

Accelerating electric charges radiate electromagnetic waves, which propagate at the speed of light. The link between electromagnetism and light is discussed. Orders of magnitude of the wavelengths of waves in the various sections of the electromagnetic spectrum are considered.

The frequency of television and radio waves is related to the frequency of oscillation of the electrons in an antenna.

These key ideas are applied to the laser airborne depth sounder.

Key Ideas

Students should know and understand the following:

Characteristics of Electromagnetic Waves

Accelerating charged particles radiate electromagnetic waves.

Electromagnetic waves exist because the accelerating charges produce changing electric and magnetic fields.

An electromagnetic wave in a vacuum consists of oscillating mutually perpendicular electric and magnetic fields.

The electric and magnetic fields oscillate at right angles to the direction of travel of the electromagnetic wave. The wave is therefore transverse.

The plane of polarisation of an electromagnetic wave is the plane defined by the direction of travel and the oscillating electric field.

The frequency of the radiated electromagnetic waves is the same as the frequency of oscillation of the source charges.

Intended Student Learning

Students should be able to do the following:

Describe the relation between the oscillating electric and magnetic fields and the direction of travel of an electromagnetic wave.

Relate the frequency of radio or television waves to the frequency of oscillation of the electrons in the transmitting antenna.

Relate the orientation of the receiving antenna to the plane of polarisation of radio or television waves.

Explain why transmissions from some country television channels are polarised at right angles to city channels.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Speed, Frequency, and Wavelength	
Electromagnetic waves in a vacuum travel at a constant speed $c = 3.00 \times 10^8 \, \mathrm{m\,s^{-1}}$, which is the speed of light.	Solve problems involving the use of $v = f\lambda$.
Electromagnetic waves in a transparent medium travel at a speed v less than c.	
The speed of a wave v is related to its frequency f and its wavelength λ by $v = f\lambda$.	
Application: Laser Airborne Depth Sounder (LADS)	
	Explain how the depth of a body of water can be determined by the detection of reflections of laser light from the surface and the bottom of the water.
	Calculate the depth of water from given reflection times at normal incidence and the given speed of the light in water.
	Justify the use of powerful lasers because of light losses due to factors such as scattering by suspended sediment and absorption.

Topic 2: The Interference of Light

Interference and diffraction are two phenomena most easily understood in terms of the propagation of light as a wave. Interference of light occurs when two or more light sources are superimposed. Diffraction of light occurs when part of its wave-front is obstructed (e.g. by a narrow slit). Diffraction is treated qualitatively as a precursor to a more extended quantitative treatment of the interference of light from two slits. This is extended to the transmission diffraction grating.

The topic ends with an overview of some aspects of the optical systems of compact disc players as an application.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Coherent Wave Sources	
'Coherent' wave sources are wave sources that maintain a constant phase relationship with each other. They must therefore have the same frequency. 'Monochromatic' light is light composed of a single frequency.	Describe what is meant by two wave sources being in phase or out of phase. Give a qualitative explanation of why light from an incandescent source is neither coherent nor monochromatic.
Interference	
In the region where two or more electromagnetic waves overlap, the resultant electric and magnetic fields at a point are the vector sums of their separate fields. This is an example of the principle of superposition. When the waves at a point are in phase, the resultant amplitude is the sum of the individual amplitudes. This is referred to as 'constructive interference'. When the waves at a point are out of phase, the resultant amplitude is the difference between the individual amplitudes. This is referred to as 'destructive interference'.	Describe constructive and destructive interference in terms of the principle of superposition.
Two-source Interference	
For two monochromatic sources in phase, the waves at a point some distance away in a vacuum: • constructively interfere when the path difference from the sources to the point is $m\lambda$ • destructively interfere when the path difference from the sources to the point is $(m+1/2)\lambda$ where m is an integer and λ is the wavelength.	Perform a geometrical construction to identify the locations in two dimensions of the lines of maximum and minimum amplitude due to the interference of light from two wave sources of the same frequency. Explain the maximum and minimum amplitudes in terms of constructive and destructive interference. Identify the path difference associated with each line of maximum and minimum amplitude.

Key Ideas

Students should know and understand the following:

Diffraction

The spreading out of plane waves as they pass through an opening is an example of diffraction. This is most noticeable when the opening is comparable in size with the wavelength of the waves.

Two-slit Interference

Interference between light diffracted by two narrow slits can be produced by illuminating the slits with light from a laser or by passing light from a monochromatic source through a single slit before illuminating the double slits.

Intended Student Learning

Students should be able to do the following:

Describe without detailed explanation the main feature of the diffraction of light by a narrow slit, where the width of the slit is about the same size as the wavelength.

Explain why a single slit is used before a double slit for two-slit interference when the light source used is not coherent.

Describe how two-slit interference is produced in the laboratory.

Describe how diffraction of the light by the slits in a two-slit interference apparatus allows the light to overlap and hence interfere.

Sketch a graph of the intensity distribution for two-slit interference of monochromatic light.

(Consider only cases where the slit separation is much greater than the width of the slits.)

Explain the bright fringes of a two-slit interference pattern in terms of constructive interference, and the dark fringes in terms of destructive interference.

Derive $d\sin\theta = m\lambda$ for two-slit interference, where d is the distance between the slits and θ is the angular position of the mth maximum.

Solve problems involving the use of $d\sin\theta = m\lambda$ and $\Delta y = \lambda L/d$. Δy is the distance between adjacent minima or maxima on the screen and L is the slit-to-screen distance.

Determine the wavelength of monochromatic light from measurements of the two-slit interference pattern.

Key Ideas

Students should know and understand the following:

Transmission Diffraction Gratings

A transmission diffraction grating consists of many very thin, equally spaced parallel slits.

The interference of light from a grating results in a pattern consisting of very narrow intensity maxima separated by regions of negligible intensity.

Speckle

Speckle is produced whenever a laser beam is reflected by a rough surface.

Speckle is due to the interference between light reflected in different directions by the rough surface.

Application: Compact Discs and DVDs

Intended Student Learning

Students should be able to do the following:

Transmission Diffraction Gratings

Describe how diffraction by the very thin slits in a grating allows the light from the slits to overlap and hence interfere to produce significant intensity maxima at large angles.

Derive $d \sin\theta = m\lambda$ for the intensity maxima in the pattern produced by a transmission diffraction grating, where d is the distance between the slits in the grating and θ is the angular position of the $m\text{th}$ maximum (m specifies the order of the maximum).

Solve problems involving the use of $d \sin\theta = m\lambda,$ where $d = 1/N$ for a grating with N slits per metre.

Sketch a graph of the intensity distribution of the maxima produced by a grating, for monochromatic light.

Determine, from the distance between the slits in the grating, the maximum number of orders possible for a given grating and wavelength.

Give a qualitative explanation of the negligible intensity between the maxima.

Describe how a grating can be used to measure the wavelength of light from a monochromatic source.

Describe and explain the white-light pattern produced by a grating.

Identify the properties of a grating which make it useful in spectroscopy.

Speckle

Explain the speckle effect in terms of interference.

Application: Compact Discs and DVDs

Explain how the interference of light can be used to read the information stored on a compact disc or a DVD.

Explain how a diffraction grating is used in the three-beam method to keep the laser on the correct track of a compact disc or a DVD.

Topic 3: Photons

Although the propagation of light can most simply be described in terms of waves, when light interacts with matter it does so in a manner characteristic of particles. Some of the properties of photons are introduced. Two phenomena — the photoelectric effect and X-rays — are then examined and explained in terms of photons.

The key ideas are applied to the use of X-rays in medicine.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Photons	
In interacting with matter, light behaves like particles (called 'photons'), with energy given by $E = hf$ and momentum given by $p = h/\lambda$, where h is Planck's constant, f is the frequency of the light, and λ is its wavelength.	Describe how microscopic observations of the building up of an image produced by light of very low intensity demonstrate the arrival of localised bundles of energy and momentum called 'photons'. Calculate the energy and momentum of the photons in various regions of the electromagnetic spectrum. Describe how two-slit interference patterns build up over time when light of very low intensity is used.
The Photoelectric Effect	
When light of sufficiently high frequency is incident on matter, it may be absorbed by the matter, from which electrons are then emitted. This is called the 'photoelectric effect'. The intensity of the incident light affects the number, but not the energy, of emitted electrons. The minimum frequency f_o at which electrons are emitted varies with the type of material and is called the 'threshold frequency'. The work function W of a surface is the minimum energy required to remove an electron from it. The work function W is related to the threshold frequency by $W = hf_o$.	Describe an experimental method for investigating the relation between the maximum kinetic energy of the emitted electrons (calculated from the measured stopping voltage) and the frequency of the light incident on a metal surface. Describe how Einstein used the concept of photons and the conservation of energy to explain the photoelectric effect. Deduce the equation $K_{max} = hf - W$, where K_{max} is the maximum kinetic energy of the emitted electrons. Plot experimental values of maximum kinetic energy versus frequency, and relate the slope and horizontal and vertical intercepts to the equation $K_{max} = hf - W$. Using graphical and algebraic methods, solve problems that require the use of $K_{max} = hf - W$.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*

X-rays

X-ray photons can be produced when electrons that have been accelerated to high speed collide with a target.

The three main features of the spectrum of the X-rays produced in this way are:

- a continuous range of frequencies (bremsstrahlung)
- a maximum frequency
- high-intensity peaks at particular frequencies.

The intensity of X-rays is decreased (i.e. attenuated) as they pass through matter by scattering and absorption.

Describe the following features of a simple X-ray tube: filament, target, high voltage supply, evacuated tube, and a means of cooling the target.

Explain how the electrons are accelerated in an X-ray tube, the choice of target material, and why the target needs to be cooled.

Sketch a graph of the spectrum from an X-ray tube, showing the three main features of the spectrum.

Explain the continuous range of frequencies and the maximum frequency in the spectrum of the X-rays.

Derive the equation for the maximum frequency, $f_{\max} = e\Delta V/h$, where ΔV is the potential difference across the X-ray tube.

Solve problems involving the use of $f_{\max} = e\Delta V/h$.

Application: The Use of X-rays in Medicine

Relate the attenuation of X-rays to the types of tissue through which they pass (e.g. soft tissue or bone).

Relate the penetrating power (hardness) of X-rays required to pass through a particular type of tissue to the energy and frequency of the X-rays, and hence to the potential difference across the X-ray tube.

Relate the minimum exposure time for X-ray photographs of a given hardness to the intensity of the X-rays, and hence to the tube current, which is determined by the filament current.

Topic 4: Wave Behaviour of Particles

In some circumstances (associated with its propagation), light exhibits the behaviour of waves, and in other circumstances (associated with its interaction with matter) it exhibits the behaviour of particles, prompting the question that forms the subject of this topic: do electrons and other particles exhibit wave behaviour in similar circumstances?

A classic experiment in which the interference effects of electrons were observed is examined.

The use of electrons as an alternative to light in microscopy is discussed as an application.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Wave Behaviour of Particles	
Particles exhibit wave behaviour with a wavelength determined by the equation $\lambda = h/p$ (de Broglie relation), where h is Planck's constant and p is the momentum of the particles.	Solve problems involving the use of the equation $\lambda = h/p$ for electrons and other particles.
Experimental Evidence for Wave Behaviour of Particles	
The spacing of the atoms in crystals is such that interference effects are observed when low-energy electrons are used.	Describe the Davisson–Germer experiment, in which the diffraction of electrons by the surface layers of a crystal lattice was observed. Using the grating equation $d\sin\theta = m\lambda$ and the measured angle θ of the first-order maximum from the Davisson–Germer experiment, calculate the wavelength of the electrons used in the experiment. Calculate the momentum of the electrons used in the Davisson–Germer experiment, and hence verify that $\lambda = h/p$.
Application: Electron Microscopes	
	Explain how the very short wavelength of electrons and the ability to use electric or magnetic fields to focus them allow electron microscopes to achieve very high resolution.