| UNIT G482 | Module 4 | 2.4.2 | Electromagnetic Waves |
|---|---|---|---|

- ***Candidates should be able to :***

  - *State **typical values for the wavelengths** of the different regions of the electromagnetic spectrum from radio waves to gamma-rays.*

  - *State that all electromagnetic waves travel at the **same speed in a vacuum.***

  - *Describe **differences** and **similarities** between different regions of the electromagnetic spectrum.*

  - *Describe some of the **practical uses** of electromagnetic waves.*

  - *Describe the **characteristics** and **dangers** of **UV-A, UV-B and UV-C radiations** and **explain the use of sunscreen.***

  - *Explain what is meant by **plane-polarised waves** and understand the **polarisation of electromagnetic waves.***

  - *Explain that polarisation is a phenomenon associated with **transverse waves** only.*

  - *State that light is **partially polarised on reflection.***

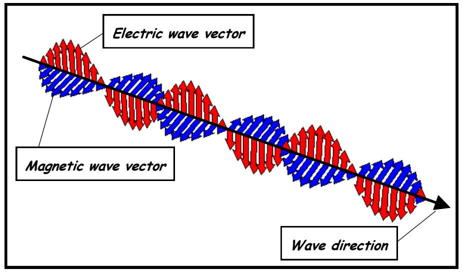
  - ***Recall** and **apply Malus's law** for transmitted intensity of light from a polarising filter.*



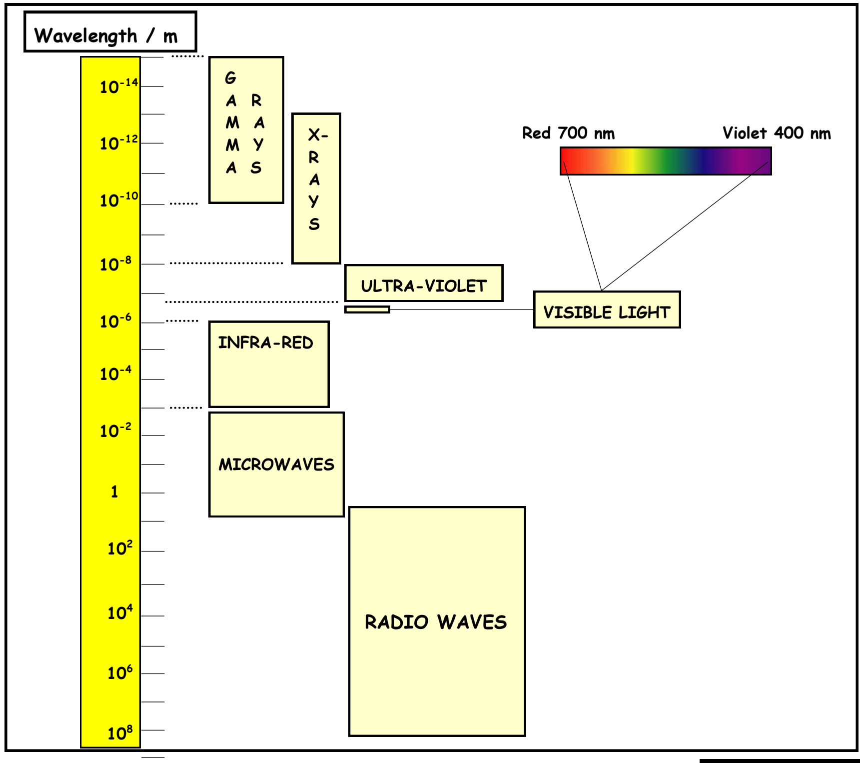
- *An **ELECTROMAGNETIC WAVE** is a disturbance in the form of mutually perpendicular, oscillating electric and magnetic fields.*

  *They are regarded as **TRANSVERSE** waves because the oscillations are at right angles to the direction of travel of the waves.*

  *They do **NOT** require a material medium for their transmission.*




*Gamma-rays, x-rays, ultra-violet radiation, visible light, infra-red radiation, microwaves and radio waves are all part of the **ELECTROMAGNETIC SPECTRUM**, shown below.*



- *The wavelength ranges for each of the radiations shown in the diagram are only approximate and show considerable overlap as there are no hard and fast boundaries between the regions. Visible light is an exception to this, as the visible wavelengths are precisely defined as those which can be seen by the human eye.*

| WAVE TYPE | SOURCES | DETECTORS | PRACTICAL USES |
|---|---|---|---|
| Gamma-rays | Radioactive nuclei | Photographic film<br>Ionisation detectors | Sterilisation<br>Medical imaging<br>Medical treatment |
| X-rays | X-ray tubes | Photographic film<br>Ionisation detectors | Medical imaging<br>Medical treatment |
| Ultra-violet | Energy level changes of electrons in atoms | Fluorescent chemicals<br>Photographic film | Sterilisation<br>Suntanning<br>Security marking |
| Visible light | Energy level changes of electrons in atoms | The eye<br>Photographic film | Signalling<br>Photography |
| Infra-red | Thermal vibrations of atoms in hot bodies | Thermopile, bolometer<br>Photographic film | Night-vision surveil-lance systems<br>Remote controls<br>Cooking |
| Microwaves | Magnetrons and klys-trons | Antennae and tuned circuits | Mobile phones<br>Cooking<br>Radar |
| Radio Waves | Oscillating electrical charges | Antennae and tuned circuits | Broadcasting radio and television<br>Magnetic resonance imaging (MRI) |

## RADIO WAVES

- *These are produced by oscillating electrical charges. When an alternating current flows in a cable, the electrons oscillate and give out radio waves.*
- *When a radio wave interacts with a conductor, the alternating electric and magnetic fields in the radio wave exert forces on the electrons in the conductor, causing them to oscillate. This constitutes an alternating current of the same frequency as the radio wave. Using tuned circuits, particular oscillating frequencies may be selectively amplified.*
- *Most of the bodies in the universe emit radio waves. Radio astronomy is the study of these emissions and it enables a great deal of information about the nature of the emitting bodies to be obtained.*

## MICROWAVES

- *There is considerable overlap between the wavelengths of radio waves, microwaves and infra-red radiation, but even if they have the same wavelength, they can be differentiated by their source. Radio waves are produced by tuned circuits, microwaves by magnetrons and infra-red by hot bodies.*
- *The greatest application of microwaves is in communications and radar, but in recent years microwave cookers have become a regular feature of every kitchen. A magnetron, typically operating at a frequency of 2.45 GHz delivers microwave energy to the cavity containing the food to be cooked. This microwave frequency is the same as the natural frequency of vibration of the water molecules in the food and so causes their amplitude of vibration to increase, resulting in an increase in the internal energy with a consequent rise in temperature.*

## *INFRA-RED (IR) RADIATION*

- *Emitted by all objects at temperatures higher than **absolute zero (0 K ≈ -273°C).** The hotter the object, the higher is the intensity and frequency of the IR emitted.*
- *Because of its longer wavelength, the IR emitted by living creatures can be distinguished from the background IR given out by cooler objects. Burglar alarms, night-vision equipment and thermal imaging cameras (used to locate people buried beneath the rubble of collapsed buildings) all work on the basis of IR wavelength differentiation.*
- *Light-emitting diodes (LEDs) used in TV remote controls work by emitting an IR beam of a specific frequency.*

## *ULTRA-VIOLET (UV) RADIATION*

- *This is e.m. radiation in the wavelength range **10 to 400 nm.** It is given the name ultra-violet because it consists of wavelengths shorter than those which we identify as the colour violet.*
- *There are three main sub-types in the UV which comes from the Sun :*

| UV TYPE | WAVELENGTH RANGE |
| --- | --- |
| UVA (Long wave) | 320 nm to 400 nm |
| UVB (medium wave) | 280 nm to 320 nm |
| UVC | 100 nm to 280 nm |

- *Most of the solar UV incident on Earth is absorbed as it passes through the atmosphere and about 98% of that which reaches ground level is **UVA.** The remaining 2% is mainly **UVB** since most of the **UVC** is absorbed by the ozone layer.*
- *Most people who have suffered sunburn are aware of one of the effects of UV on humans, but there are other effects, both damaging and beneficial.*
    - ***UVA, B and C** cause damage to collagen fibres in the skin which results in premature wrinkling and ageing of the skin.*
    - ***UVB** induces the production of vitamin D in the skin, but it can cause sunburn and it can damage DNA in skin cells which may lead to skin cancer. High intensities of UVB can also lead to the formation of cataracts in the eyes.*
    - ***All UV types** are potentially harmful to the eyes.*
- ***SUNSCREENS** are applied to the skin to protect people from the harmful effects of UV on the skin. Arc welders must protect their skin and eyes against the very intense UV produced in the welding process*

***SUNGLASSES** protect the eyes from the effects of UV which can lead to cataract formation in later life.*

## X-RAYS

- ***X-rays*** *are produced when* ***high-speed electrons*** *collide with a metal target such as* ***tungsten or molybdenum.***

- *These rays are ionising and are therefore harmful to humans.*

- ***X-rays*** *find their greatest use in* ***medical imaging****, especially for the detection of broken and fractured bones.*
  *They are also used in* ***chest x-rays*** *to identify lung diseases such as pneumonia and lung cancer.*

- *In industry, x-rays are used to locate flaws in welds.*

- *Airport security scanners use x-rays to inspect the interior of luggage prior to loading onto the aircraft.*


## GAMMA (γ)-RAYS

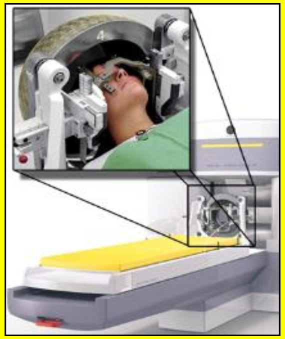
- ***Gamma-rays*** *are* ***high-energy, highly penetrating*** *e.m. radiation which originates in the nuclei of radioactive atoms. They have the shortest wavelength of all the radiations in the e.m spectrum.*

- *As a form of* ***ionising radiation****, γ-rays can cause serious damage to living tissue. High doses kill living cells and lower doses affect the cell DNA and so trigger cancers.*

- *γ-rays are used to* ***sterilise medical equipment*** *(hypodermic syringes, scalpels etc.) and* ***to remove decay-causing bacteria*** *from many foods.*

- *γ-rays are also used in the treatment of some types of cancer.*

  *In gamma-knife surgery (shown in the photograph), multiple, concentrated beams of γ-rays are directed at a tumour in order to kill the cancerous cells.*



## • PROPERTIES OF ELECTROMAGNETIC WAVES

- ***All e.m. radiation travels at the same speed in a vacuum.***
  *This speed,* ***$3.0 \times 10^8$ m s$^{-1}$*** *is one of the universal constants in nature.*

- ***The e.m spectrum is continuous*** *(i.e. there are no gaps in it). The different kinds of radiation merge into one another, with no abrupt change of properties.*

- *Radiations with the* ***same wavelength*** *and* ***frequency*** *have the* ***same properties,*** *but they are differently named according to their* ***origins.***

  *e.g. there is an overlap between the wavelength ranges of* ***x-rays*** *and* ***γ-rays.***

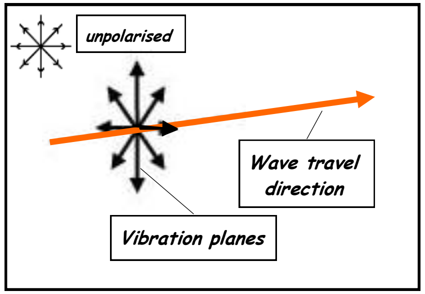
  *x-rays: ~$10^{-13}$ - $10^{-8}$ m* | *γ-rays: ~$10^{-16}$ - $10^{-10}$ m*

  *So although an* ***x-ray*** *of say, λ = $10^{-9}$ m has exactly the* ***same properties*** *as a* ***γ-ray*** *of the same λ, the distinction is the* ***x-rays*** *are produced when high-speed electrons collide with a metal target, whereas the* ***γ-rays*** *are the result of nuclear processes such as radioactive decay.*

- ***<u>ALL</u> ELECTROMAGNETIC WAVES :***
  - ***Transfer energy*** *from one place to another.*
  - *Are* ***transverse*** *and* ***can therefore be polarised.***
  - *Obey the laws of* ***reflection*** *and* ***refraction.***
  - *Can be* ***superposed*** *to produce* ***interference*** *and* ***diffraction*** *effects.*
  - *Have* ***zero electric charge*** *and are unaffected by* ***electric, magnetic*** *and* ***gravitational fields.***

- ***POLARISATION***

- *An* ***<u>UNPOLARISED</u>*** *wave is one which has vibrations in all directions at right angles to the direction of travel of the wave.*
  *(e.g. light from o bulb or the Sun)*

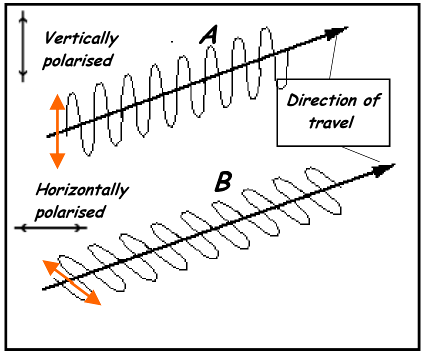



- *A* ***<u>PLANE-POLARISED</u>*** *wave is one in which the vibrations are in one plane only.*

  *In the diagram opposite :*

  ***WAVE A*** *is* ***VERTICALLY*** *polarised*

  ***WAVE B*** *is* ***HORIZONTALLY*** *polarised.*





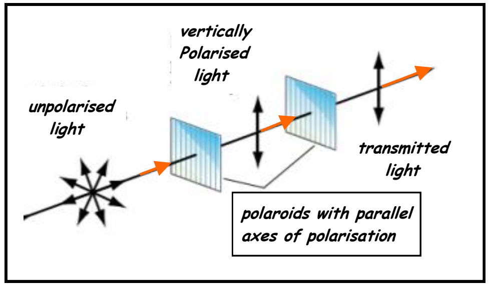

- *The phenomenon of polarisation distinguishes* ***TRANSVERSE*** *waves from* ***LONGITUDINAL*** *waves in that :*

**TRANVERSE WAVES CAN BE POLARISED, BUT LONGITUDINAL WAVES CANNOT BE POLARISED.**

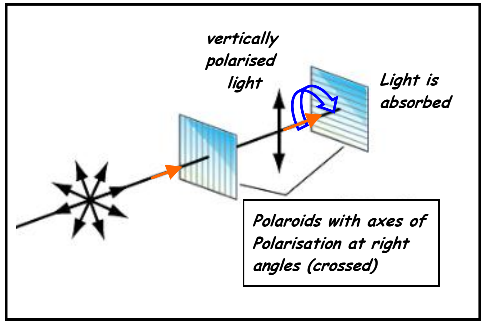
*This is because the vibrations in a longitudinal wave are along the direction of motion of the wave.*

***POLARISATION OF LIGHT USING POLAROID* FILTERS***

***Unpolarised*** *light becomes polarised after it passes through a piece of* ***polaroid.*** *If A second* ***polaroid*** *with its axis of polarisation the same as the first is placed in the path of the polarised light, the* ***light is transmitted.***




*As the second polaroid is slowly rotated so that its polarisation axis moves from* ***vertical*** *to* ***horizontal,*** *less and less light is transmitted. Eventually, when the two polaroids have their axes at* ***right angles (i.e. crossed), no light is transmitted.***




** <u>POLAROID</u> is the trade name of a material which consists of long-chain molecules that absorb the energy from the electric field component of a light wave. A polaroid filter in which the molecules are arranged vertically will absorb vertically polarised light and transmit horizontally polarised light.*

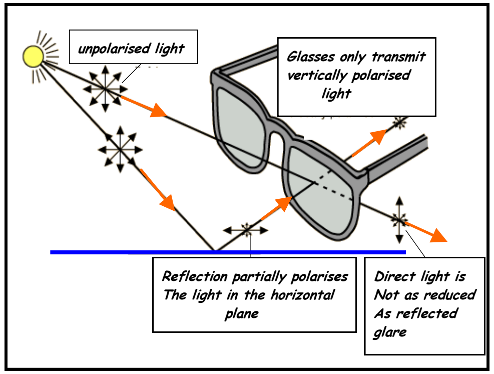
- *Sunlight is scattered as it comes through the Earth's atmosphere and this polarises the light we get from the sky. Although we are unaware of this polarisation, many insects, bees and some birds are thought to make navigational use of it by enabling them to locate the position of the Sun through cloud.*

## *PARTIAL POLARISATION OF REFLECTED LIGHT*

*When light is reflected from any shiny surface, such as water for example, it is* ***partially polarised in the horizontal plane.***

*Reflected sunlight from a wet road surface and other vehicles can create a glare which makes for difficult driving conditions.*

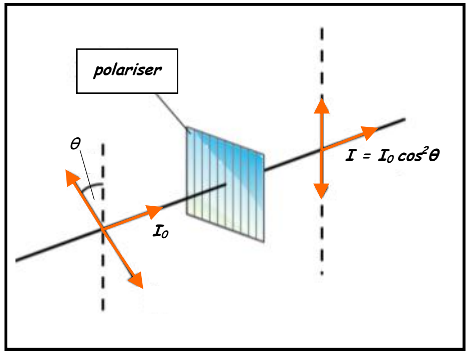
*This is easily remedied by wearing sunglasses. The polaroid in the glasses is arranged so that it will only transmit* ***vertically polarised*** *light and this greatly reduces glare which is light which has been* ***partially polarised in the horizontal plane.***




- ***MALUS'S POLARISATION LAW***



*This law, named after* ***Etienne-Louis Malus****, states that :*




***When a perfect polariser is placed in the path of a polarised light beam, the INTENSITY (I) of the transmitted light is given by :***

$$I = I_0 \cos^2\theta$$

*$I_0$ : initial intensity*

*$\theta$ : angle between the initial polarisation direction and the polariser's axis of polarisation*

*A beam of* ***unpolarised*** *light can be thought of as containing a uniform mixture of linear polarisations at all possible angles.*

*Since the* ***average value of*** $\cos^2\theta = 0.5$ *:*

$$\boxed{\frac{I}{I_0} = 0.5}$$

*( i.e. 50% of the initial intensity is transmitted)*

*In practice, some light is lost in the polariser and so the actual transmission is less than 50% (~40% for polaroid).*

- **HOMEWORK QUESTIONS**

1 Name, in order of **increasing frequency,** the main groups of radiations which form the **electromagnetic spectrum.** For each group, state :

- **A source.**
- **A detector.**
- **A typical wavelength.**

2 Explain why radiations having the **same wavelength** and **properties** are given different names.

3 Give **two similarities** and **two differences** between **visible light** and **radio waves.**

4 **State** the evidence for the assumption that all electromagnetic waves are **transverse.**

5 **Identify the type of electromagnetic radiation** from each of the following descriptions :

(a) Produces fluorescence in chemical dies used in washing powders.

(b) Produced by interactions of high-speed electrons with matter.

(c) Emitted by most astronomical bodies and used in cellular phones.

(d) Have high penetrating power and originate in the nuclei of atoms.

(e) Detectable by the human skin and used in remote controls.

(f) Produces suntan and can cause skin cancer.

6 **Name the type of electromagnetic radiation** which corresponds to each of the following wavelengths measured in a vacuum : 

(a) **$10^{-13}$ m,** (b) **550 nm,** (c) **1500 nm,** (d) **4000 km,** (e) **3 cm.**

7 **Using diagrams** to illustrate your answers, **explain :**

(a) What is meant by : (i) An **unpolarised** wave.

(ii) A **plane-polarised** wave.

(b) The effect of two **'crossed' polaroids** on unpolarised light.

8 **Vertically polarised** light is incident on a piece of polaroid whose axis of polarisation is at **60° to the vertical.** If the incident light intensity is $4.5 \times 10^2$ W m$^{-2}$, use **Malus's law** to calculate the **intensity of the light after it passes through the polaroid.**

Why is your answer likely to be somewhat **greater** than the value which would be obtained in practice ?

9 A polariser is slowly rotated in front of a beam of **horizontally polarised** light. The angle between the axis of the polariser and the horizontal is **'θ'.**

Using **Malus's law,** calculate the **fraction of the incident light intensity transmitted** through the polariser for θ-values taken at **20° intervals** between **0° and 180°.**

Sketch a graph of fraction of light intensity transmitted against angle θ. Show values on both axes.