CHAPTER 4+7 ELECTROMAGNETIC SPECTRUM AND LIGHT WAVE

1 Introduction

**Electromagnetic nature of light**

- Electric field
- Magnetic field

**Speed of electromagnetic wave**

\[ c = 3 \times 10^8 \text{ m/s} \]

\[ c = f \lambda \]

(\text{const})

- \( c, \lambda \) may vary

**The electromagnetic spectrum**

- **Radiowave**
- **Microwave**
- **Infrared**
- **Visible light**
- **Ultraviolet**
- **X-ray**
- **Gamma ray**

**SI unit prefixes**

- 1 km
- 1 m
- 1 cm
- 1 mm
- 1 \( \mu \)m
- 1 nm

- 10^3 m
- 10^{-1} m
- 10^{-3} m
- 10^{-6} m
- 10^{-9} m

About the size of...

- Buildings
- Humans
- Honey Bee
- Pinhead
- Protozoans
- Molecules
- Atoms
- Atomic Nuclei

\( 10^{-11} \text{ m} \)
<table>
<thead>
<tr>
<th>Member</th>
<th>Wavelength</th>
<th>Generation</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Waves</td>
<td>&gt; 0.1m</td>
<td>Reception</td>
<td>Communication</td>
</tr>
<tr>
<td>X-Rays</td>
<td>0.01m - 10m</td>
<td>Imaging</td>
<td>Medical</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>10nm - 400nm</td>
<td>Fluorescent</td>
<td></td>
</tr>
<tr>
<td>Visible</td>
<td>390nm - 750nm</td>
<td>Lamp</td>
<td>400nm - 700nm</td>
</tr>
<tr>
<td>Infrared</td>
<td>750nm - 1mm</td>
<td>Thermometer</td>
<td>Night-vision, skin, heat,</td>
</tr>
<tr>
<td>Microwave</td>
<td>1mm - 1m</td>
<td>Radar</td>
<td>Control, transmission, microwave</td>
</tr>
<tr>
<td>Microwaves</td>
<td>1m - 1m</td>
<td>Antenna</td>
<td>Portable, radio, communication, radio</td>
</tr>
<tr>
<td>Radio Waves</td>
<td>&lt; 1m</td>
<td>Transmitter</td>
<td>Antenna, wireless, radio,</td>
</tr>
<tr>
<td>Gamma</td>
<td>&lt; 0.01nm</td>
<td>Detection</td>
<td>400nm - 750nm</td>
</tr>
</tbody>
</table>

2. Members of Electromagnetic Spectrum

Chapter 4.7: Electromagnetic Spectrum and Light Wave
Which of the following statements concerning infra-red radiation is correct?

A. Infra-red is red in colour  
B. Infra-red can be detected by a Geiger-Muller counter  
C. Infra-red can be used to sterilize drinking water  
D. Infra-red is a longitudinal wave  
E. Warm objects emit infra-red

Part of the electromagnetic spectrum is shown above. Which of the following statements is/are correct?

(1) P is ultra-violet and Q is infra-red
(2) The wavelength of P is shorter than that of Q
(3) The speed of P in vacuum is higher than that of Q

A. (1) only   B. (3) only  C. (1) and (2) only  D. (2) and (3) only  E. (1),(2) and (3)

Which of the following is not an application of the corresponding electromagnetic wave?

<table>
<thead>
<tr>
<th>Electromagnetic wave</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Ultra-violet</td>
<td>Camera autofocus</td>
</tr>
<tr>
<td>B. Infra-red</td>
<td>Detecting survivors buried in landslides</td>
</tr>
<tr>
<td>C. Microwaves</td>
<td>Satellite communication</td>
</tr>
<tr>
<td>D. X-rays</td>
<td>Detecting weapons hidden in suitcases</td>
</tr>
<tr>
<td>E. Radio waves</td>
<td>TV broadcasting</td>
</tr>
</tbody>
</table>

Scientist have discovered that ozone molecules in the earth’s atmosphere are being destroyed. Which of the flowing electromagnetic waves is mainly responsible for causing hazard to human health as a result of the damaging of the ozone layer?

A. gamma radiation  B. visible light  C. infra-red  D. microwaves  E. ultra-violet
3 Colour and Visible Spectrum

**Visible Spectrum**
[Concept]

Name the colours of the visible spectrum.

- red
- orange
- yellow
- green
- blue
- indigo
- violet

What is white light?

white light = mixture of light in visible spectrum.

**Why object has colours?**
[Concept]

Explain why a leaf appears green under sunlight.

Upon incidence of white light, the leaf absorbs light of all colours except green light being reflected to different directions.

**Dispersion**
[Concept]

Explain why white light separates into different colours after refracted by a prism.

Different colours of lights correspond to slightly different frequencies, which have slightly different refractive indices inside a prism. Hence they are refracted to different positions.

- red being refracted least
- violet being refracted most.
4 Evidence of Wave Nature of Light

[Concept]
What properties differentiate wave from particles?

interference & diffraction

### Interference of light (Young’s double slit experiment)

**Setup:**

![Diagram of Young's double slit experiment]

**Observation:**
Alternating bright and dark fringes on the screen

**Parameter controlling fringe separation:**
\[
\frac{\lambda}{a} \propto \text{slit separation}
\]

**Precautions for the experiment:**
- Small slit
- Far screen
- Strong light
- Use monochromatic light
Interference of light (Young’s double slit experiment)

[Further question]

1. Describe the change in the interference pattern if the following change is made.
   (a) Red light is replaced by green light.

   \[ \lambda \downarrow \frac{\lambda}{a} \downarrow \text{the fringe separation will decrease} \]

   (b) Use another double slit with a smaller slit separation.

   \[ \frac{\lambda}{a} \uparrow \text{wider} \]

   (c) The experiment is performed in water.

   \[ \downarrow V = f \lambda \downarrow \frac{\lambda}{a} \downarrow \text{narrower} \]

2. Describe and explain the interference pattern formed by directing white light through a double slit.
   - **Central white fringe**
   - Other fringes multi-coloured
     - inner edge violet
     - outer edge red
   - White light is a mixture of different colours, they produce patterns.

3. What is the importance of Young’s double slit experiment in the development of science?

   It provided direct evidence to support light as a wave, as it demonstrated interference of light separation, which is a phenomenon unique to wave.

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Interference of light (Single slit experiment)

Describe the observation when red laser passes through a narrow slit.

- Alternating bright & dark fringes.
5 Mathematical Background

Small angle approximation
[Concept]
(a) Express $AC$ in terms of $r$ and $\theta$.

$$AC = rs \sin \theta$$

(b) Express $BD$ in terms of $r$ and $\theta$.

$$BD = r \tan \theta$$

(c) If we made the prediction that as $\theta \to 0$, $AC \approx BD$. What conclusion can be drawn?

$$A \text{ as } \theta \to 0, \quad AC \approx BD$$

Parallel ray approximation
[Concept]
(a) Express $\tan \theta_1$ and $\tan \theta_2$ in terms of $a, D$ and $h$.

$$\tan \theta_1 = \frac{h + \frac{a}{2}}{D}$$

$$\tan \theta_2 = \frac{h - \frac{a}{2}}{D}$$

(b) Now if $D \gg h$ and $D \gg a$, show that

(i) $\theta_1 \approx \theta_2 \approx \theta$, and
(ii) $PB - PA \approx a \sin \theta$.

(i) $\tan \theta_1 = \frac{h + \frac{a}{2}}{D} \approx 0$

(ii) $\tan \theta_1 = \frac{h - \frac{a}{2}}{D} \approx 0$

$\therefore \theta_1 \approx \theta_2 \approx \theta$

call it as $\theta$
6 Young’s Double Slit Calculation

**Fringe position and fringe separation**

![Diagram of Young's Double Slit Experiment]

**Constructive interference (bright spots)**

Path difference: \( n \lambda \)

\[ |Z_B - Z_A| = n \lambda \]

\[ a \sin \theta = n \lambda \]

For screen approx.:

To find \( y_n \),

\( \tan \theta = \frac{y_n}{D} \)

\[ \frac{n \lambda}{a} \approx \frac{y_n}{D} \]

\[ y_n \approx \frac{D \lambda}{a} \]

Example:

Put \( n = 3 \), red light

\( \lambda = 7 \times 10^{-7} \text{m} \)

\( a = 0.1 \text{mm} \)

\( \theta \approx 1.2 \times 10^{-3} \text{°} \)

From the result, fringe separation \( \Delta y \)

\[ \Delta y = y_{n+1} - y_n \]

\[ = \frac{D(n+1) \lambda}{a} - \frac{Dn \lambda}{a} \]

\[ = \frac{D \lambda}{a} \text{ (fixed number)} \]

Fringe separation is fixed.
A laser beam is directed at a double slit of slit separation 0.2mm. The interference pattern is projected on a screen 5m from the slit. The 6th order maximum is measured to be 8cm from the central maximum. Find the wavelength of the laser beam.

\[
\tan \theta = \frac{8 \text{ cm}}{5 \text{ m}} = \frac{0.08}{5}
\]

\[
\theta = 0.9166^\circ
\]

\[
(0.2 \times 10^{-3}) \sin (0.9166^\circ) = 6 \lambda
\]

\[
\lambda = 5.33 \times 10^{-7} \text{ m}
\]

In Young’s double-slit experiment, which of the following combinations of monochromatic light, the slit-separation and the slit-to-screen distance would produce the widest fringe separation on the screen?

<table>
<thead>
<tr>
<th>Monochromatic light</th>
<th>slit-separation</th>
<th>slit-to-screen distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red light</td>
<td>1 mm</td>
<td>1 m</td>
</tr>
<tr>
<td>Red light</td>
<td>1 mm</td>
<td>2 m</td>
</tr>
<tr>
<td>Red light</td>
<td>2 mm</td>
<td>1 m</td>
</tr>
<tr>
<td>Green light</td>
<td>1 mm</td>
<td>1 m</td>
</tr>
<tr>
<td>Green light</td>
<td>2 mm</td>
<td>1 m</td>
</tr>
</tbody>
</table>

In a Young’s double-slit experiment, light of wavelength 400 nm is used. If the path difference between the light from the two slits X and Y to a point P on the screen is 3000 nm, which of the following is/are correct?

(1) P is the 7th fringe.
(2) The fringe separation on the screen increases if the light source is moved closer to the slits.
(3) P becomes a bright fringe if light of wavelength 500 nm is used.

A. (1) only
B. (3) only
C. (1) and (2) only
D. (2) and (3) only
E. (1), (2) and (3)
Multiple Slit Diffraction: Diffraction Grating

**Diffraction grating**

A diffraction grating has a specification 500 lines/mm.

(a) Describe what a diffraction grating is.

A diffraction grating is a series of densely spaced parallel slits.

(b) Find the slit separation of two adjacent lines.

\[
\frac{1\text{ mm}}{500}
\]

**Diffraction grating calculation and maximum order**

Let \( d \) be the slit separation of the diffraction grating, \( \lambda \) be the wave length of the incoming light. Derive the angular position \( \theta \) of the \( n \)th bright fringe, in terms of \( d \), \( n \) and \( \lambda \).

\[
\text{path diff} = a \sin \theta = n \lambda
\]

**Example:** 80 lines/mm

\[
a = \frac{1\text{ mm}}{80} = 0.0125 \text{ m}
\]

\[
\lambda = 7 \times 10^{-7} \text{ m}
\]

\[
n = 3
\]

\[
\theta = 9.67^\circ
\]

Why a maximum order of bright fringe exists?

\[
\sin \theta = \frac{n \lambda}{a} \leq 1 \quad \text{\( \therefore \frac{\lambda}{a} \) not small and \( \frac{n \lambda}{a} \) cannot greater than 1}
\]

\[
\Rightarrow \exists \text{ a max } n
\]

[Further question]

Does we have a similar maximum order in the case of double slit?

Theoretically yes, but \( \frac{\lambda}{a} \) is too small in that case. The max is unrealistically large.
A plane transmission grating is placed at the centre of a circular 0° - 360° protractor. A beam of monochromatic light is incident normally on the grating. The zeroth-order maximum occurs at a scale reading of 90° and a first-order maximum occurs at a scale reading of 65°. At what scale reading would a second-order maximum be observed?

A. 148°  B. 140°  C. 130°  D. 58°  E. 40°

When a diffraction grating is replaced by another with more lines per mm, which of the following quantities is/are increased?

1) The angle of diffraction for every spectral line
2) The angular separation of red and blue lines in the first order spectrum
3) The number of orders which can be observed

A. (1), (2) and (3)  B. (1) and (2) only  C. (2) and (3) only  D. (1) only  E. (3) only
Light of wavelength \( \lambda \) is incident normally on a diffraction grating with \( p \) lines per millimetre. The second-order diffraction maximum is at angle \( \theta \) from the central position. For a second grating with \( 3p \) lines per millimetre illuminated normally by light of wavelength \( 5\lambda / 4 \), the angle between the first order diffraction maximum and the central position is \( \phi \). Which of the following relations is correct?

A. \( \sin \phi = \frac{5 \sin \theta}{12} \) 
B. \( \sin \phi = \sin \left( \frac{5\theta}{12} \right) \) 
C. \( \sin \phi = \sin \left( \frac{15\theta}{4} \right) \) 
D. \( \sin \phi = \frac{15 \sin \theta}{8} \) 
E. \( \sin \phi = \sin \left( \frac{15\theta}{8} \right) \)

A beam of white light is shone normally on a diffraction grating. The diagram shows the spectra of the first two orders, which may not be drawn to scale. The first-order spectrum starts at angle of 20° from the zeroth order. The respective angular separations between the two ends (red and violet) of a spectrum are \( \alpha \) and \( \beta \) for the first- and second-order spectra. Which of the following statements is/are correct?

1) In the first-order spectrum, \( P \) is the violet end.
2) \( \beta \) is greater than \( \alpha \).
3) There is no third-order spectrum.

A. (1) only  
B. (3) only  
C. (1) and (2) only  
D. (2) and (3) only  
E. (1), (2) and (3)
Student A views a line filament lamp covered with a yellow filter through diffraction grating with its lines parallel to the filament as shown in the figure above. The grating is held at one end of a metre rule which is aimed at the lamp. At the other end of the metre rule, a second rule is placed at right angles to the first rule.

(a) Student A asks student B to move a pencil held vertically along the second rule and tells him to stop when it coincides with the yellow hand in the first image of the lamp as seen through the grating. If the distance between the first rule and the pencil is \(x = 0.37\) m as shown in the figure above, and the diffraction grating has \(6.0 \times 10^5\) lines per metre, calculate the wavelength of the yellow light.

\[
\tan \theta = \frac{x}{\lambda} = \frac{0.37}{\lambda}
\]

\[
\theta = 20.3^\circ
\]

\[
a \sin \theta = \lambda
\]

\[
\left( \frac{1}{6.0 \times 10^5} \right) \sin (20.3^\circ) = \lambda
\]

\[
\lambda = 5.78 \times 10^{-7} \text{ m}
\]

(b) If student B keeps moving the pencil along the second metre rule in the same direction, how many more yellow bands will be encountered? Explain.

\[
\sin \theta = \frac{n \lambda}{a} \leq 1
\]

\[
n \leq \frac{a}{\lambda} = \left( \frac{6.0 \times 10^5}{5.78 \times 10^{-7}} \right) = 2.88 \text{ max. } n = 2
\]

One more band will be encountered.

(c) If the filter is removed, sketch the full pattern seen by student A on both sides of the filament, in the space below.

Label significant features.

Position of zero order
(a) A student views a green light source through a multiple-slit set-up which can be considered as a diffraction grating with a few slits. The pattern observed is shown in Figure 1.

How would the pattern be affected if red light is used instead? (1 mark)

(b) (i) To observe the spectrum of the sodium lamp, a student places a diffraction grating on the platform of a spectrometer such that the incident light falls normally on the grating. The sodium lamp produces yellow light of two slightly different wavelengths. The student uses the second-order images and records the angular position readings of the two yellow lines on each side of the central image as follows:

<table>
<thead>
<tr>
<th></th>
<th>Left-hand side (second order)</th>
<th>Right-hand side (second order)</th>
</tr>
</thead>
<tbody>
<tr>
<td>angular position reading</td>
<td>second line</td>
<td>first line</td>
</tr>
<tr>
<td></td>
<td>45°36’</td>
<td>45°40’</td>
</tr>
<tr>
<td></td>
<td>45°67’</td>
<td>134°36’</td>
</tr>
</tbody>
</table>

Give the grating constant (i.e. the slit separation) to be 1684 nm, calculate the two wavelengths of the yellow light produced by the sodium lamp. (4 marks)

\[
\begin{align*}
\text{1st line:} & \quad \theta_1 = \frac{134.36° - 45.67°}{2} = \frac{184.36°}{2} \overset{\text{a}}{\sin \theta} = 2\lambda_1, \\
\text{2nd line:} & \quad \theta_2 = \frac{134.43° - 45.6°}{2} = \frac{184.43°}{2} \overset{\text{a}}{\sin \theta} = 2\lambda_2
\end{align*}
\]

(ii) Suggest ONE reason for making measurements by using the second-order images instead of the first-order ones. (1 mark)

To obtain better measurement by separating the two light wider.
FINAL REMARKS

The first half of the chapter introduces the electromagnetic spectrum. Students should be able to recall the members of the spectrum and arrange them in order of wavelength and frequency. For each member, students are expected to give at least one usage and know their characteristics. This part is covered in Book 3A Chapter 4 in your textbook series.

The second half corresponds to Chapter 7 in Book 3B. Students should know the importance of Young’s double slit experiment as a confirmation of wave property of light in the development of science, and the observations and precautions of the experiment. The calculation of double slit and diffraction is quite difficult and was previously an A-Level topic. Students should at least understand and be able to follow the calculation, understanding it is a calculation on interference based on path difference. The use of the formula $a \sin \theta = n\lambda$ is expected and should be fairly straightforward.