Electromagnetic waves

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Electromagnetic waves – day to day applications (only few are shown)

(a)

(b)

(a) cell phone and cell phone tower

(b) X-ray photograph of a human being

Summary – Unit I to Unit IV

- From Unit I, Electrostatics (Gauss's law in integral form)

$$\oint \vec{E}.d\vec{A} = \frac{Q_{enclosed}}{\epsilon_0} \qquad \text{(Gauss's law)}$$

- From Unit III, Magnetostatics (similar to Gauss's law – in integral form)

$$\oint \vec{B}.d\vec{A} = 0 \qquad \text{(No name)}$$

The above equation has no name but it is similar to Gauss's law in electrostatics. Hence, this law can be called as Gauss's law in magnetism

Cont...

- From Unit III, Magnetostatics (Ampere's circuital law)

$$\oint \vec{B}.d\vec{l} = \mu_0 I_{enclosed} \quad \left(\begin{array}{c}\text{Ampère's} \\ \text{law}\end{array}\right)$$

- From Unit IV, Electromagnetic induction

$$\oint \vec{E}.d\vec{l} = -\frac{d}{dt}\Phi_B \qquad \text{(Faraday's law)}$$

Displacement current – Maxwell's work

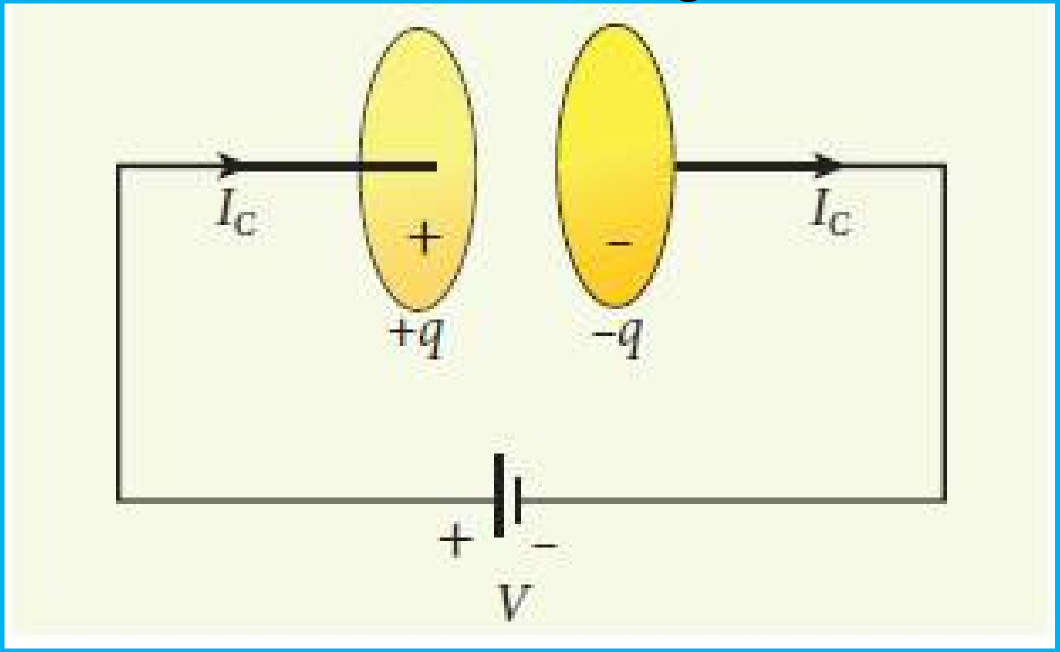
- Faraday's law of electromagnetic induction states that "the change in magnetic field produces electric field"

- The question asked by J.C. Maxwell is ' Is converse of Faraday's law of induction is true?'

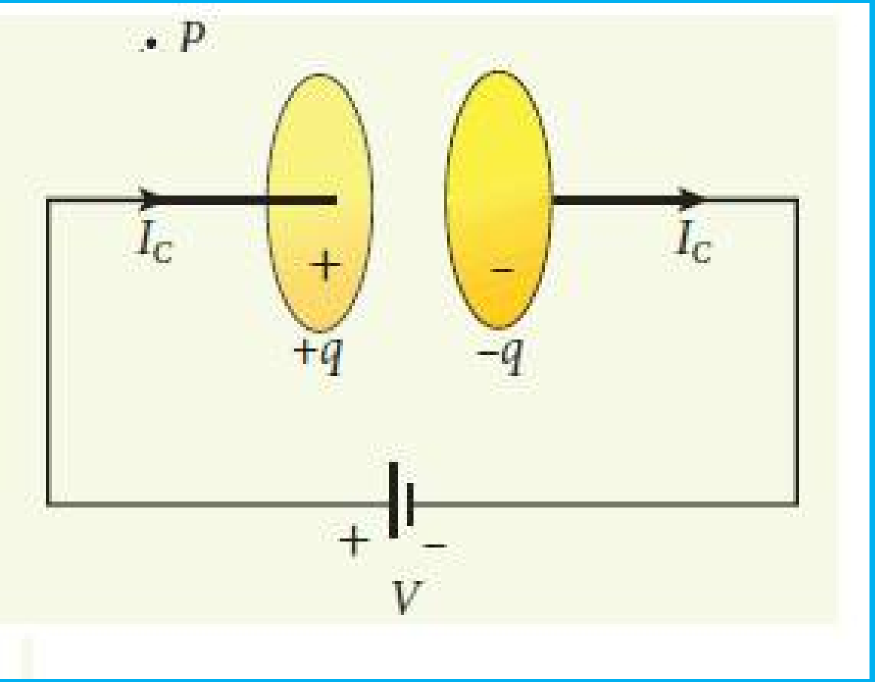
  Yes !, it is true and he showed that 'the change in electric field also produces magnetic field' – Maxwell's law of induction

Illustration – Charging a capacitor

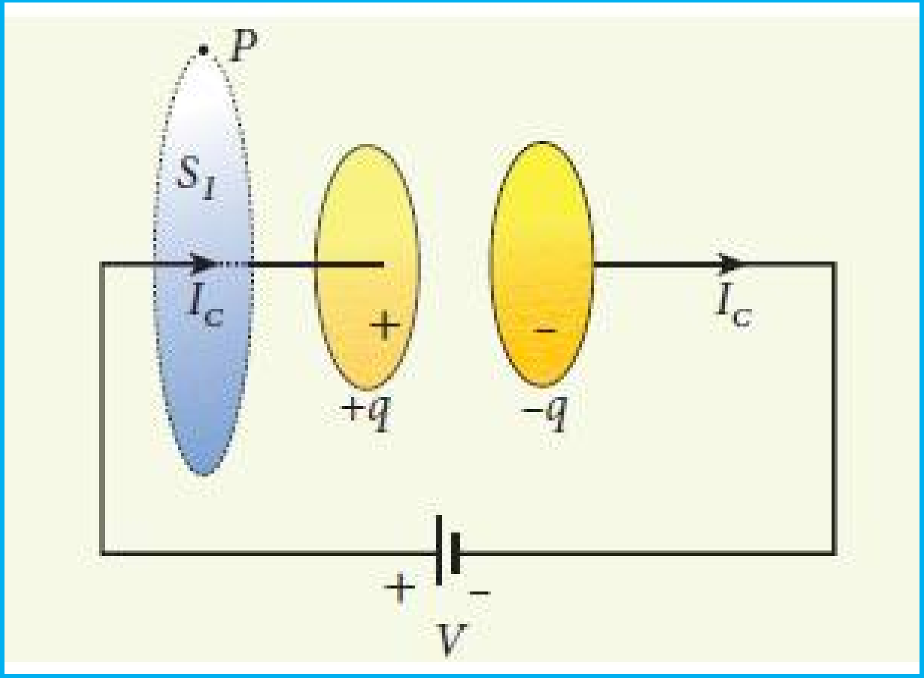
Consider a parallel plate capacitor and assume that the medium in between the capacitor plates is a non-conducting medium.



- Suppose we want to calculate the magnetic field at a point – we use Ampere’s circuital law



- Drawing an amperian loop (circular loop) which encloses the surface S_1 circular surface.



$$\oint_{S_1} \vec{B}\cdot d\vec{l} = \mu_0 I_C$$

where, I_C is the conduction current.

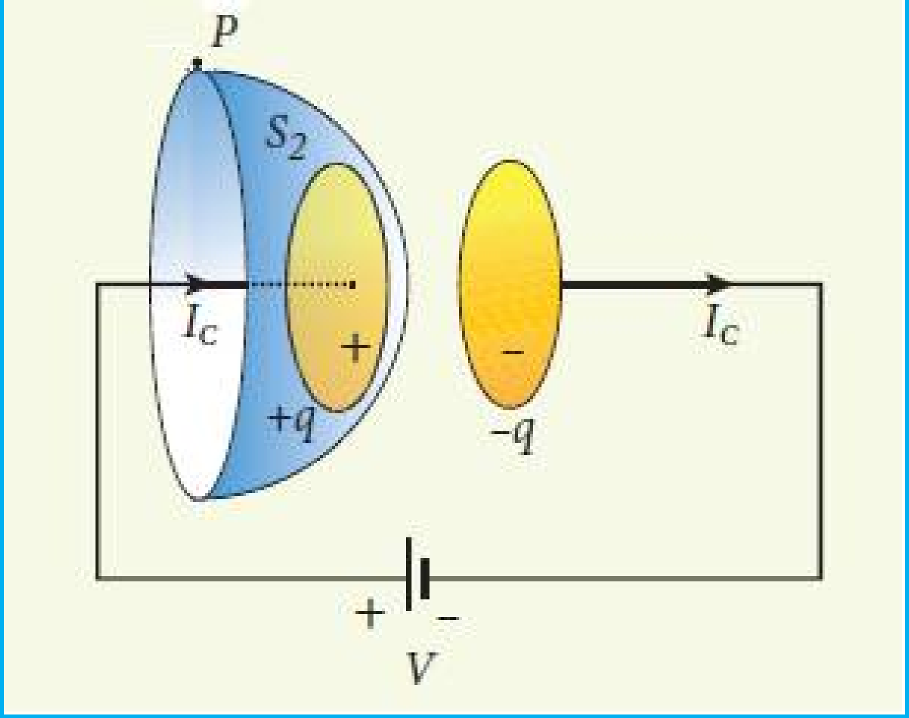
- Is there any unique way to enclose the loop?.

  No

- Why?

  Ampere’s law applied for a given closed loop does not depend on shape of the enclosing surface

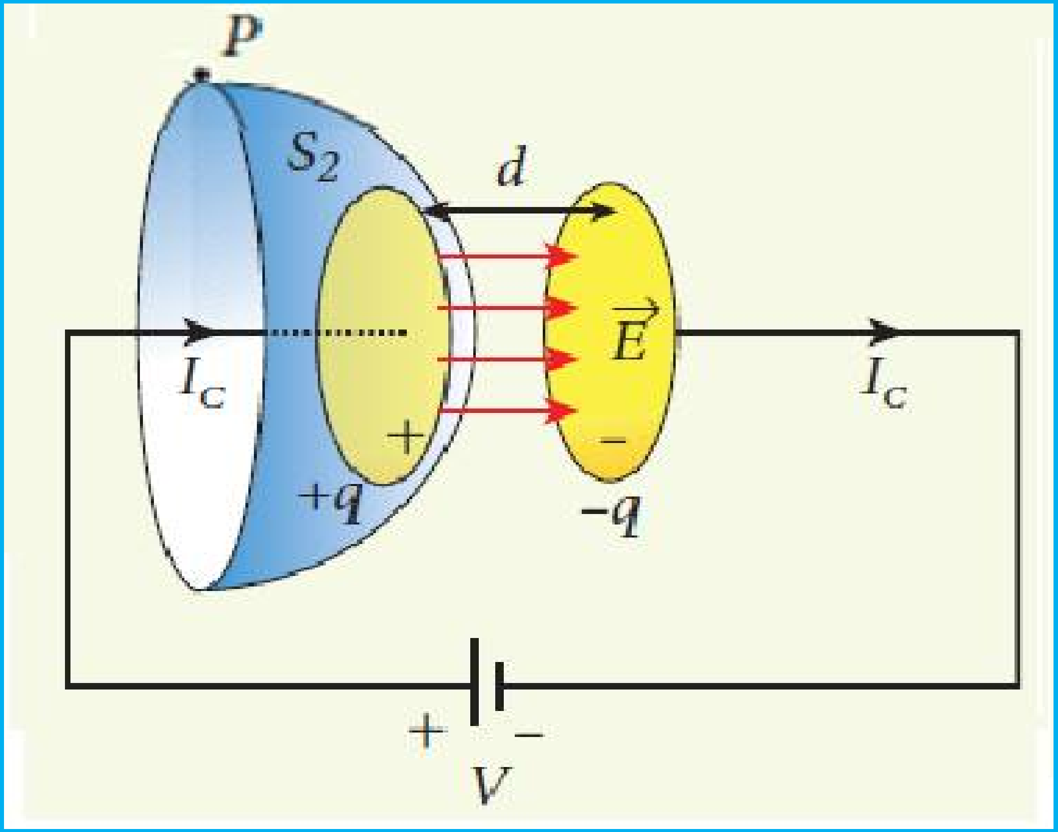
So there is no harm in enclosing the loop by the surface S_2 (Balloon shaped surface). Applying Ampere's circuital law for this case



$$\oint_{\text{enclosing } S_2} \vec{B} \cdot d\vec{l} = 0$$

This implies the magnetic field at the point is zero !
(inconsistency)

Maxwell's contribution



$$\Phi_E = \oiint \vec{E}\cdot d\vec{A} = EA = \frac{q}{\varepsilon_0}$$

where A is the area of the plates of the capacitor

The change in electric flux

$$\frac{d\Phi_E}{dt} = \frac{1}{\varepsilon_0}\frac{dq}{dt} \Rightarrow \frac{dq}{dt} = I_d = \varepsilon_0 \frac{d\Phi_E}{dt}$$

where, I_d is known as displacement current

Displacement (definition)

The current which comes into play in the region in which the electric field and the electric flux are changing with time

↓

whenever the change in electric field takes place, the displacement current is produced

Ampere’s – Maxwell’s law

$$\oint \vec{B}.d\vec{l} = \mu_0 I = \mu_0 (I_c + I_d)$$

where, $I = I_c + I_d$

$$\oint \vec{B}.d\vec{l} = \mu_0 I_{\text{enclosed}} + \mu_0 \epsilon_0 \frac{d}{dt} \int_S \vec{E}.d\vec{A}$$

Maxwell’s equation

- Differential form (also known as point form)
- Integral form

In our discussion, we consider only integral form of Maxwell’s equation.

MAXWELL'S EQUATIONS

Gauss' Law for E Fields

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enclosed}}{\varepsilon_o}$$

Gauss' Law for B Fields

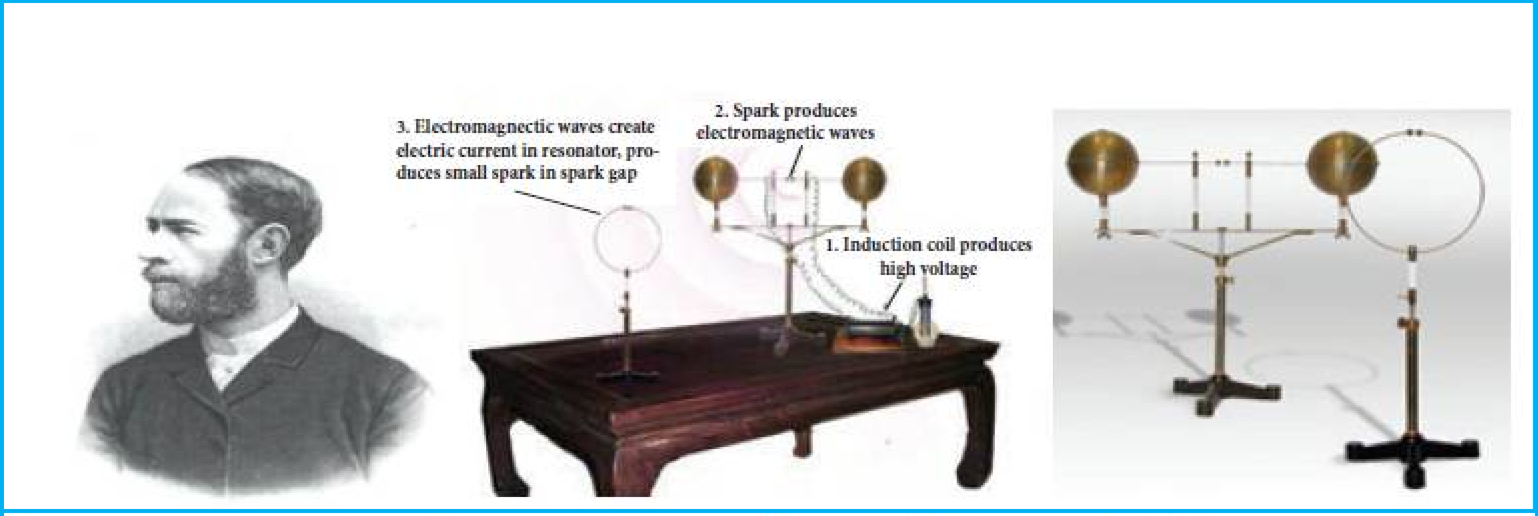
$$\oint \vec{B} \cdot d\vec{A} = 0$$

Faraday's Law

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \int \vec{B} \cdot d\vec{A}$$

Modified Ampere's Law

$$\oint \vec{B} \cdot d\vec{l} = \mu_o I_{enclosed} + \mu_o \varepsilon_o \frac{d}{dt} \int \vec{E} \cdot d\vec{A}$$



Hertz experiment (a) Heinrich Rudolf Hertz (1857 – 1894) (b) Hertz apparatus

- It consists of two metal electrodes which are made of small spherical metals.
- These are connected to larger spheres and the ends of the larger spheres are connected to induction coil which contains very larger number of turns (in order to produce very high emf).
- Due to very high emf, very high potential difference is maintained between the electrodes. Due to this, the air between the electrodes get ionized and spark is observed (between the electrodes).

- These are connected to larger spheres and the ends of the larger spheres are connected to induction coil contains very larger number of turns in order to produce very high electromagnetic waves. Therefore, very high potential difference is maintained between the coils to make the air in between the electrodes (transmitter) to ionize.

- At the receiver (ring electrode – not completely closed and has small gap in between) kept at a distance also show spark.

- This is because the energy is transmitter to receiver as a wave, known as electromagnetic waves.

- If the receiver turned into ninety degrees, the receiver does not receive any spark, which confirm that electromagnetic waves are transverse in nature (as Maxwell predicted theoretically).

- Hertz detected radio wave and speed which is equal to the speed of light (as Maxwell predicted theoretically).

Properties of electromagnetic waves

- It is produced by accelerating charges. It is non-mechanical waves.
- Transverse waves
- In free space, speed is equal to speed of light, c.
- In medium, speed is lesser than speed of light, $v < c$.
- Refractive index of the medium is equal to

$$\mu = \sqrt{\varepsilon_r \mu_r}$$

- Electromagnetic waves shows interference, diffraction and polarization.

- The energy density (energy per unit volume) associated with an electromagnetic wave propagating in vacuum or free space is

$$u = \frac{1}{2}\varepsilon_{\circ}E^{2} + \frac{1}{2\mu_{\circ}}B^{2}$$

Electric field, E = c B, where, B is the magnetic field and c is the speed of light

- The average energy density of electromagnetic field is

$$\langle u \rangle = \frac{1}{2}\varepsilon_{\circ}E^{2} = \frac{1}{2}\frac{1}{\mu_{\circ}}B^{2}$$

- The energy crossing per unit area per unit time and perpendicular to the direction of propagation of electromagnetic wave is called the intensity of the wave.

$$\text{Intensity,} \quad I = \langle u \rangle c$$

$$I = \frac{\text{total electromagnetic energy (U)}}{\text{Surface area (A)} \times \text{time (t)}}$$

$$= \frac{\text{Power (P)}}{\text{Surface area (A)}}$$

- Electromagnetic waves carries energy and momentum, p $= \frac{\text{Energy}}{\text{speed}} = \frac{U}{c}$
- The force exerted by an electromagnetic wave on unit area of a surface is called radiation pressure.

Poynting vector

- The rate of flow of energy crossing a unit area is known as Poynting vector

$$\vec{S} = \frac{1}{\mu_\circ}\left(\vec{E} \times \vec{B}\right) = c^2 \varepsilon_\circ \left(\vec{E} \times \vec{B}\right)$$

- The unit of Poynting vector is watt per square meter.
- The Poynting vector at any point gives the direction of energy transport from that point.

Electromagnetic spectrum

Type of Radiation	Frequency Range (Hz)	Wavelength Range
gamma-rays	10^{20}-10^{24}	$<10^{-12}$m
x-rays	10^{17}-10^{20}	1 nm - 1pm
ultraviolet	10^{15}-10^{17}	400 nm - 1nm
visible	$4 - 7.5 \times 10^{14}$	750 nm - 400nm
near-infrared	1×10^{14}-4×10^{14}	2.5 μm - 750nm
infrared	10^{13}-10^{14}	25 μm - 2.5μm
microwaves	3×10^{11}-10^{13}	1 mm - 25 μm
radio waves	$< 3 \times 10^{11}$	$>$ 1 mm

Uses of electromagnetic waves

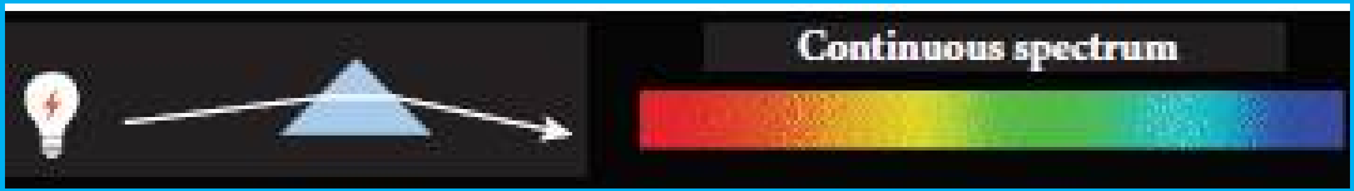
Radiation	Uses
γ-rays	Gives informations on nuclear structure, medical treatment *etc.*
X-rays	Medical diagnosis and treatment study of crystal structure, industrial radiograph.
UV- rays	Preserve food, sterilizing the surgical instruments, detecting the invisible writings, finger prints etc.
Visible light	To see objects
Infrared rays	To treat, muscular strain for taking photography during the fog, haze etc.
Micro wave and radio wave	In radar and telecommunication.

Electromagnetic spectrum

- ➢ Spectrum
- ✓ Absorption spectrum
  - o Continuous spectrum
  - o Line spectrum
  - o Band spectrum
- ✓ Emission spectrum
  - o Continuous spectrum
  - o Line spectrum
  - o Band spectrum

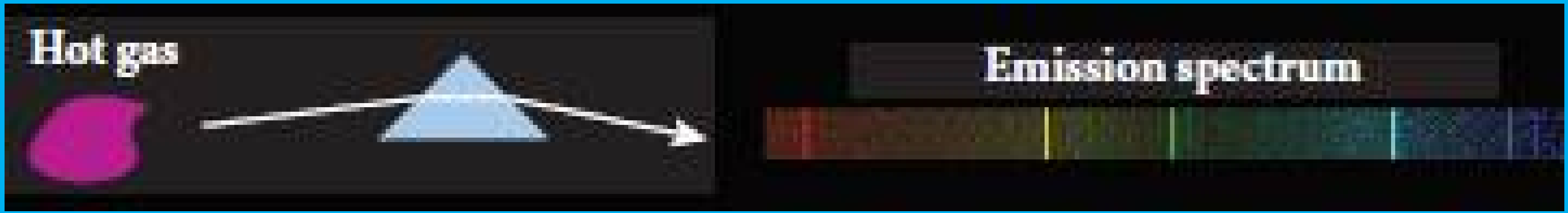
Emission spectrum

- When the spectrum of self luminous source is taken, we get emission spectrum. Each source has its own characteristic emission spectrum.
- Types of emission spectrum
  - Continuous emission spectrum (or continuous spectrum) – light from incandescent lamp (filament bulb)



Examples: spectrum obtained from carbon arc, incandescent solids, liquids gives continuous spectra

- Line emission spectrum or line spectrum



- Light from hot gas – discontinuous spectra. The line spectra are sharp lines of definite wavelengths or frequencies. Such spectra arise due to exicted atoms of elements.
- These lines are the characteristics of the element which means it is different for different elements. Examples: spectra of atomic hydrogen, helium, etc

- Band emission spectrum or band spectrum

- It consists of several number of very closely spaced spectral lines which overlapped together forming specific bands which are separated by dark spaces, known as band spectra.
- This spectrum has a sharp edge at one end and fades out a the other end. Such spectra arise when the molecules are excited.
- Band spectrum is the characteristic of the molecule hence, the structure of the molecules can be studied using their band spectra.

Examples: spectra of hydrogen gas, ammonia gas in the discharge tube, etc.

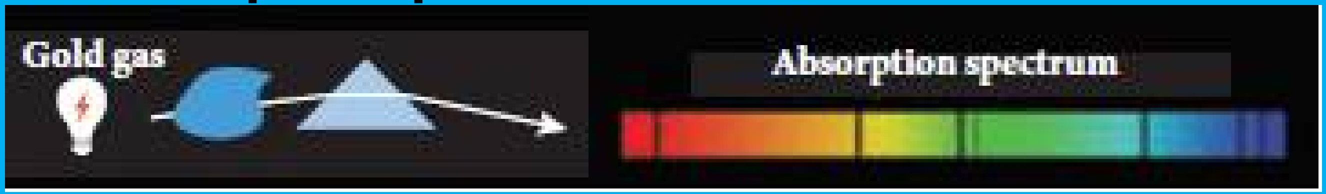
Absorption spectrum

- When light is allowed to pass through a medium or an absorbing substance then the spectrum obtained is known as absorption spectrum.
- It is the characteristic of absorbing substance.
- Types of absorption spectrum

- **Continuous absorption spectrum**

- When the light is passed through a medium, it is dispersed by the prism, we get continuous absorption spectrum.
- Suppose we pass white light through a blue glass plate, it absorbs everything except blue.

- **Line absorption spectrum**



- When light from the incandescent lamp is passed through cold gas (medium), the spectrum obtained through the dispersion due to prism is line absorption spectrum.
- Example: light from carbon arc is made to pass through sodium vapour, a continuous spectrum of carbon arc with two dark lines in the yellow region of sodium vapour is obtained

- **Band absorption spectrum:**
  - When the white light is passed through the iodine vapour, dark bands on continuous bright background is obtained.
  - Examples: When white light is passed through diluted solution of blood or chlorophyll or through certain solutions of organic and inorganic compounds.

Fraunhofer lines – Solar spectrum

- When the spectrum from the Sun is examined, it consists of large number of dark lines (line absorption spectrum). These dark lines in the solar spectrum are known as Fraunhofer lines.
- It is used to identify elements present in the Sun’s atmosphere.