UNIT 5

ELECTROMAGNETIC WAVES

"One scientific epoch ended and another began with James Clerk Maxwell"

– Albert Einstein

LEARNING OBJECTIVES

In this unit, the student is exposed to

- the displacement current
- Maxwell's correction to Ampere's circuital law
- Maxwell's equation in integral form
- production and properties of electromagnetic waves – Hertz's experiment
- sources of electromagnetic waves
- electromagnetic spectrum

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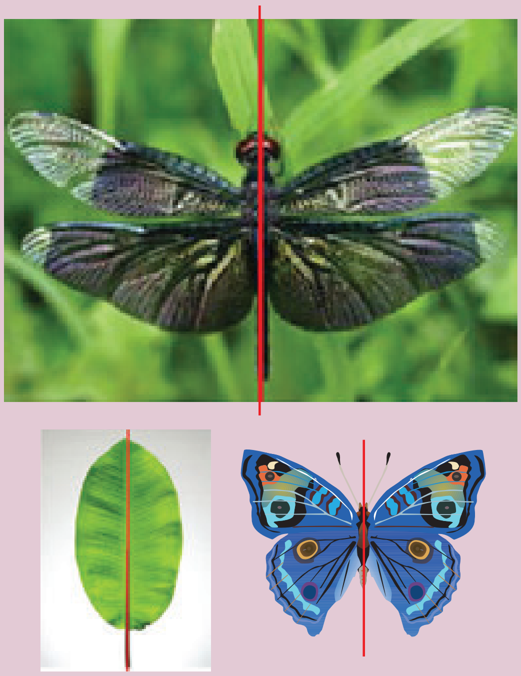
5.1 INTRODUCTION

Figure 5.1 Visible spectrum – rainbow and lightning

We see the world around us through light. Light from the Sun is one of the sources of energy without which we human beings cannot survive in this planet. Light plays crucial role in understanding the structure and properties of various things from atom to universe. Without light, even our eyes cannot see objects. What is light?. This puzzle made many physicists sleepless until middle of 19^{th} century. Earlier, many scientists thought that optics and electromagnetism are two different branches of physics. But from the work of James Clerk Maxwell, who actually enlightened the concept of light from his theoretical prediction is that light is an electromagnetic wave which moves with the speed equal to 3×10^8 m/s (in free space or vacuum). Later, it was confirmed that light is just only small portion of electromagnetic spectrum, which ranges from gamma rays to radio waves.

In the unit 4, we studied that time varying magnetic field produces an electric field (Faraday's law of electromagnetic induction). Maxwell strongly believed that nature must possess symmetry and he asked the following question, "when the time varying magnetic field produces an electric field, why not the time varying electric field produce a magnetic field?"



Symmetry in nature

Later he proved that indeed it exists, which is often known as Maxwell's law of induction. In 1888, H. Hertz experimentally verified Maxwell's predication and hence, this understanding resulted in new technological invention, especially in wireless communication, LASER (Light Amplification by Stimulated Emission of Radiation) technology, RADAR (**Ra**dio **D**etection **A**nd **R**anging), etc.

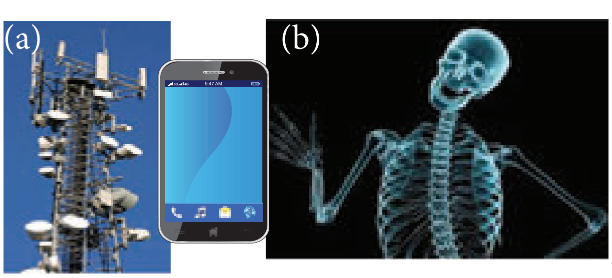


Figure 5.2 (a) cell phone and cell phone tower (b) X-ray radiograph of a human being

In today's digital world, cell phones (Figure 5.2 (a)) have greater influence in our day to day life. It is a faster and more effective mode of transferring information from one place to another. It works on the basis that light is an electromagnetic wave. In hospitals, the location of bone fracture can be detected using X-rays as shown in Figure 5.2 (b), which is also an electromagnetic wave. For cooking microwave oven is used. The microwave is also an electromagnetic wave. There are plenty of applications of electromagnetic waves in engineering, medical (example LASER surgery, etc), defence (example, RADAR signals) and also in fundamental scientific research. In this unit, basics of electromagnetic waves are covered.

5.1.1 Displacement current and Maxwell's correction to Ampere's circuital law

In unit 4, we studied Faraday's law of electromagnetic induction which states that the change in magnetic field produces an electric field. Mathematically

$$\oint_l \vec{E}\cdot\vec{dl} = -\frac{\partial}{\partial t}\Phi_B = -\frac{\partial}{\partial t}\oint_S \vec{B}\cdot\vec{dS} \qquad (5.1)$$

$$\underbrace{\oint_l \vec{E}\cdot\vec{dl}}_{\text{Electric field induced along a closed loop}} = \underbrace{-\frac{\partial}{\partial t}\Phi_B}_{\text{Variation of magnetic flux with time}} = \underbrace{-\frac{\partial}{\partial t}\oint_S \vec{B}\cdot\vec{dS}}_{\text{Changing magnetic flux } \Phi_B \text{ in the region enclosed by the loop}}$$

where Φ_B is the magnetic flux and $\frac{\partial}{\partial t}$ is the partial derivative with respect to time. Equation (5.1) means that the electric field $\vec{E}$ is induced along a closed loop by the changing magnetic flux Φ_B in the region encircled by the loop. Now the question asked by James Clerk Maxwell is 'Is converse of this statement true?' Answer is 'yes'. He showed that the change in electric field also produces magnetic field which is

$$\oint_l \vec{B}\cdot\vec{dl} = -\frac{\partial}{\partial t}\Phi_E = -\frac{\partial}{\partial t}\oint_S \vec{B}\cdot\vec{dS} \qquad (5.2)$$

$$\underbrace{\oint_l \vec{E}\cdot\vec{dl}}_{\text{Magnetic field induced along a closed loop}} = \underbrace{-\frac{\partial}{\partial t}\Phi_E}_{\text{Variation of electric flux with time}} = \underbrace{-\frac{\partial}{\partial t}\oint_S \vec{B}\cdot\vec{dS}}_{\text{Changing electric flux } \Phi_E \text{ in the region enclosed by the loop}}$$

where Φ_B is the electric flux. This is known as Maxwell's law of induction, which explains that the magnetic field $\vec{B}$ induced along a closed loop by the changing electric flux Φ_E in the region encircled by that loop. This in turn, explains the existence of radio waves, gamma rays, infrared rays, etc.

In order to understand how the changing electric field produces magnetic field, let us consider a situation of 'charging a parallel plate capacitor' shown in Figure 5.3 Assume that the medium in between the capacitor plates is a non-conducting medium.

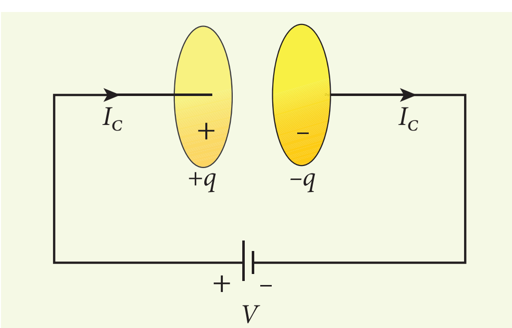


Figure 5.3 charging of capacitor

The electric current passing through the wire is the conduction current I_C. This current generates magnetic field around the wire (refer Unit 3) connected across the capacitor. Therefore, when a magnetic needle is kept near the wire, deflection is observed. In order to compute the strength of magnetic field at a point, we use Ampere's circuital law (from Unit 3) which states that 'the line integral of the magnetic field $\vec{B}$ around any closed loop is equal to μ_o times the net current I threading through the area enclosed by the loop'. Ampere's law in equation form is

$$\oint_l \vec{B}\cdot d\vec{l} = \mu_o I(t) \qquad (5.3)$$

where μ_o is the permeability of free space.

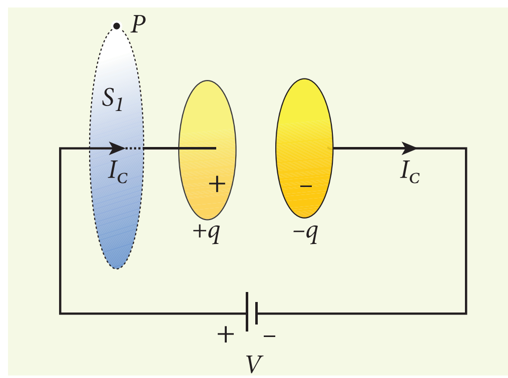


Figure 5.4 Applying Ampere's circuital law - loop enclosing surface

To calculate the magnetic field at a point P near the wire as shown in Figure 5.4, let us draw an amperian loop (circular loop) which encloses the surface S_1 (circular surface). Therefore, using Ampere's circuital law (equation 5.3), we get

$$\oint_{S_1} \vec{B}\cdot d\vec{l} = \mu_0 I_C \qquad (5.4)$$

where I_c is the conduction current.

Suppose the same loop is enclosed by balloon shaped surface S_2 as shown in Figure 5.5. This means that the boundaries of two surfaces S_1 and S_2 are same but shape of the enclosing surfaces are different (first surface (S_1) is circular in shape and second one is balloon shaped surface (S_2)). As the Ampere's law applied for a given closed loop does not depend on shape of the enclosing surface, the integrals will give the same answer. But by applying Ampere's circuital law (equation 5.3), we get

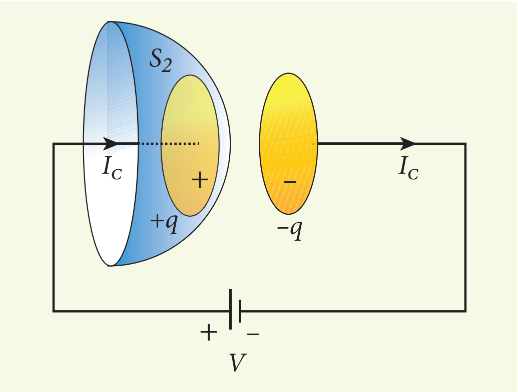


Figure 5.5 Applying Ampere's circuital law - loop enclosing surface S2

$$\oint_{\text{enclosing } S_2} \vec{B}\cdot d\vec{l} = 0 \qquad (5.5)$$

The right hand side of equation is zero because the surface S_2 no where touches the wire carrying conduction current and further, there is no current in between the plates of the capacitor (there is a discontinuity). So the magnetic field at a point P is zero. Hence there is an inconsistency between equation (5.4) and equation (5.5). J. C.Maxwell resolved this inconsistency as follows:

Due to external source (battery or cell), the capacitor gets charged up because of current flowing through the capacitor. This produces an increasing electric field between the capacitor plates. So, there must be a current associated with the changing electric field in between the capacitor plates. In other words, the time varying electric flux (or time varying electric field) existing between the plates of the capacitor also produces a current known as displacement current.

Note

Displacement current

The name stuck because Maxwell named it. The word displacement is poorly chosen because nothing is being displaced here.

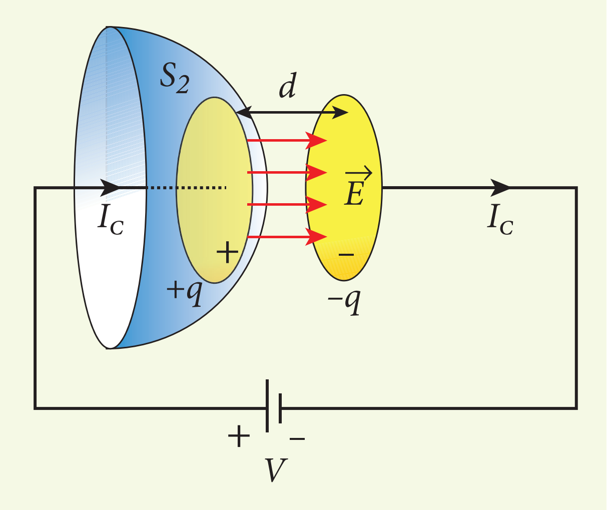


Figure 5.6 Applying Gauss's law between the plates of the capacitor

From Gauss's law (refer Unit 1), the electric flux between the plates of the capacitor (Figure 5.6) is

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

where A is the area of the plates of capacitor.

The change in electric flux is

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

where I_d is known as displacement current. The **displacement current can be defined as the current which comes into play in the region in which the electric field and the electric flux are changing with time**. In other words, whenever the change in electric field takes place, displacement current is produced. Maxwell modified Ampere's law as

$$\oint \vec{B}\cdot d\vec{S} = \mu_\circ I = \mu_\circ (I_C + I_d) \qquad (5.6)$$

where $I = I_c + I_d$ which means the total current enclosed by the surface is sum of conduction current and displacement current. When a constant current is applied, displacement current $I_d = 0$ and hence $I_c = I$. Between the plates, the conduction current $I_c = 0$ and hence $I_d = I$.

EXAMPLE 5.1

Consider a parallel plate capacitor which is maintained at potential of 200 V. If the separation distance between the plates of the capacitor and area of the plates are 1 mm and 20 cm². Calculate the displacement current for the time in μs.

Solution

Potential difference between the plates of the capacitor, V = 200 V

The distance between the plates,

$$d = 1 \text{ mm} = 1 \times 10^{-3} \text{ m}$$

Area of the plates of the capacitor,

$$A = 20 \text{ cm}^2 = 20 \times 10^{-4} \text{ m}^2$$

Time is given in micro-second, μs = 10^{-6} s

Displacement current

$$I_d = \varepsilon_\circ \frac{d\Phi_B}{dt} \Rightarrow I_d = \varepsilon_\circ \frac{EA}{t}$$

But electric field, $E = \frac{V}{d}$

Therefore,

$$I = \frac{V}{d} I_d = \varepsilon_\circ \frac{VA}{td} = 8.85 \times 10^{-12} \times \frac{200 \times 20 \times 10^{-4}}{10^{-6} \times 1 \times 10^{-3}}$$

$$= 35400 \times 10^{-7} = 3.5\ mA$$

5.1.3 Maxwell's equations in integral form

Electrodynamics can be summarized into four basic equations, known as Maxwell's equations. These equations are analogous to Newton's equations in mechanics. Maxwell's equations completely explain the behaviour of charges, currents and properties of electric and magnetic fields. These equations can be written in integral form (or integration form) or derivative form (or differentiation form). The differential form of Maxwell's equation is beyond higher secondary level because we need to learn additional mathematical operations like curl of vector fields and divergence of vector fields. So we focus here only in integral form of Maxwell's equations:

1. First equation is nothing but the Gauss's law. It relates the net electric flux to net electric charge enclosed in a surface. Mathematically, it is expressed as

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enclosed}}{\varepsilon_\circ} \quad \text{(Gauss's law)} \quad (5.7)$$

   where $\vec{E}$ is the electric field and $Q_{enclosed}$ is the charge enclosed. This equation is true for both discrete or continuous distribution of charges. It also indicates that the electric field lines start from positive charge and terminate at negative charge. This implies that the electric field lines do not form a continuous closed path. In other words, it means that isolated positive charge or negative charge can exist.

2. Second equation has no name. But this law is similar to Gauss's law in electrostatics. So this law can also be called as Gauss's law in magnetism. The

surface integral of magnetic field over a closed surface is zero. Mathematically,

$$\oint \vec{B}\cdot d\vec{A} = 0 \qquad \text{(No name)} \qquad (5.8)$$

where $\vec{B}$ is the magnetic field. This equation implies that the magnetic lines of force form a continuous closed path. In other words, it means that no isolated magnetic monopole exists.

3. Third equation is Faraday's law of electromagnetic induction. This law relates electric field with the changing magnetic flux which is mathematically written as

$$\oint \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\Phi_B \text{(Faraday's law)} \qquad (5.9)$$

where $\vec{E}$ is the electric field. This equation implies that the line integral of the electric field around any closed path is equal to the rate of change of magnetic flux through the closed path bounded by the surface. Our modern technological revolution is due to Faraday's laws of electromagnetic induction. The electrical energy supplied to our houses from electricity board by using Faraday's law of induction.

4. Fourth equation is modified Ampere's circuital law. This is also known as Ampere – Maxwell's law. This law relates the magnetic field around any closed path to the conduction current and displacement current through that path.

$$\oint \vec{B}.d\vec{l} = \mu_0 I_{enclosed} + \mu_0\varepsilon_0 \frac{d}{dt}\int_s \vec{E}.d\vec{A} \qquad (5.10)$$

(Ampere-Maxwell's law)

where $\vec{B}$ is the magnetic field. This equation shows that both conduction and also displacement current produces magnetic field. These four equations are known as Maxwell's equations in electrodynamics. This equation ensures the existence of electromagnetic waves. The entire communication system in the world depends on electromagnetic waves. In fact our understanding of stars, galaxy, planets etc come by analysing the electromagnetic waves emitted by these astronomical objects.

5.2 ELECTROMAGNETIC WAVES

Electromagnetic waves are non-mechanical waves which move with speed equals to the speed of light (in vacuum). It is a transverse wave. In the following subsections, we discuss the production of electromagnetic waves and its properties, sources of electromagnetic waves and also classification of electromagnetic spectrum.

5.2.1 Production and properties of electromagnetic waves - Hertz experiment

Maxwell's prediction was experimentally confirmed by Heinrich Rudolf Hertz (Figure 5.7 (a)) in 1888. The experimental set up used is shown in Figure 5.7 (b).

It consists of two metal electrodes which are made of small spherical metals as shown in Figure 5.7. These are connected to larger spheres and the ends of them are connected to induction coil with very large number of turns. This is to produce very high electromotive force (emf). Since the

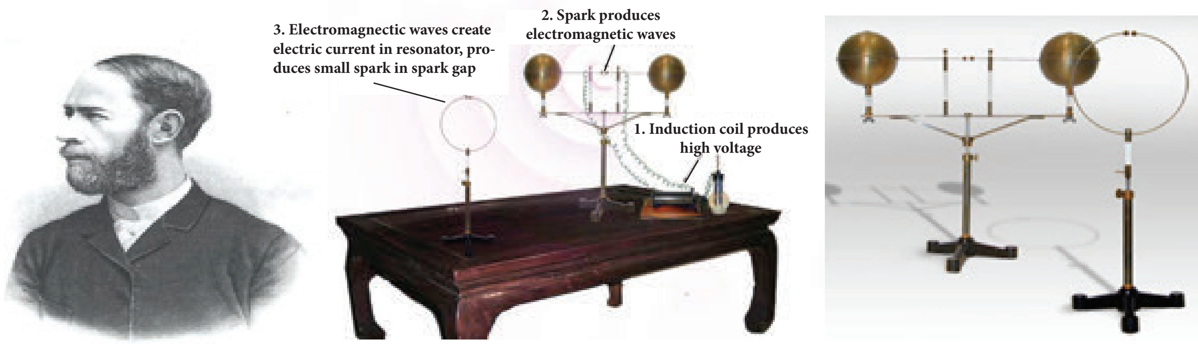


Figure 5.7 Hertz experiment (a) Heinrich Rudolf Hertz (1857 – 1894) (b) Hertz apparatus

coil is maintained at very high potential, air between the electrodes gets ionized and spark (spark means discharge of electricity) is produced. The gap between electrode (ring type – not completely closed and has a small gap in between) kept at a distance also gets spark. This implies that the energy is transmitted from electrode to the receiver (ring electrode) as a wave, known as electromagnetic waves. If the receiver is rotated by 90° - then no spark is observed by the receiver. This confirms that electromagnetic waves are transverse waves as predicted by Maxwell. Hertz detected radio waves and also computed the speed of radio waves which is equal to the speed of light (3×10^8 m s^{-1}).

Properties of electromagnetic waves

1. Electromagnetic waves are produced by any accelerated charge.
2. Electromagnetic waves do not require any medium for propagation. So electromagnetic wave is a non-mechanical wave.
3. Electromagnetic waves are transverse in nature. This means that the oscillating electric field vector, oscillating magnetic field vector and propagation vector (gives direction of propagation) are mutually perpendicular to each other. The electric and magnetic fields are in the y and z directions respectively and the direction of propagation is along x direction. This is shown in Figure 5.8.
4. Electromagnetic waves travel with speed which is equal to the speed of light in vacuum or free space, $c = \frac{1}{\sqrt{\varepsilon_\circ \mu_\circ}} = 3 \times 10^8 \, \mathrm{m\,s^{-1}}$, where ε_o is the permittivity of free space or vacuum and μ_o is the permeability of free space or vacuum (refer Unit 1 for permittivity and Unit 3 for permeability).
5. In a medium with permittivity ε and permeability μ, the speed of electromagnetic wave is less than speed in free space or vacuum, that is, $v < c$. In a medium of refractive index,
$$\mu = \frac{c}{v} = \frac{\frac{1}{\sqrt{\varepsilon_\circ \mu_\circ}}}{\frac{1}{\sqrt{\varepsilon \mu}}} \Rightarrow \mu = \sqrt{\varepsilon_r \mu_r}$$, where ε_r is the relative permittivity of the medium (also known as dielectric constant) and μ_r is the relative permeability of the medium.
6. Electromagnetic waves are not deflected by electric field or magnetic field.

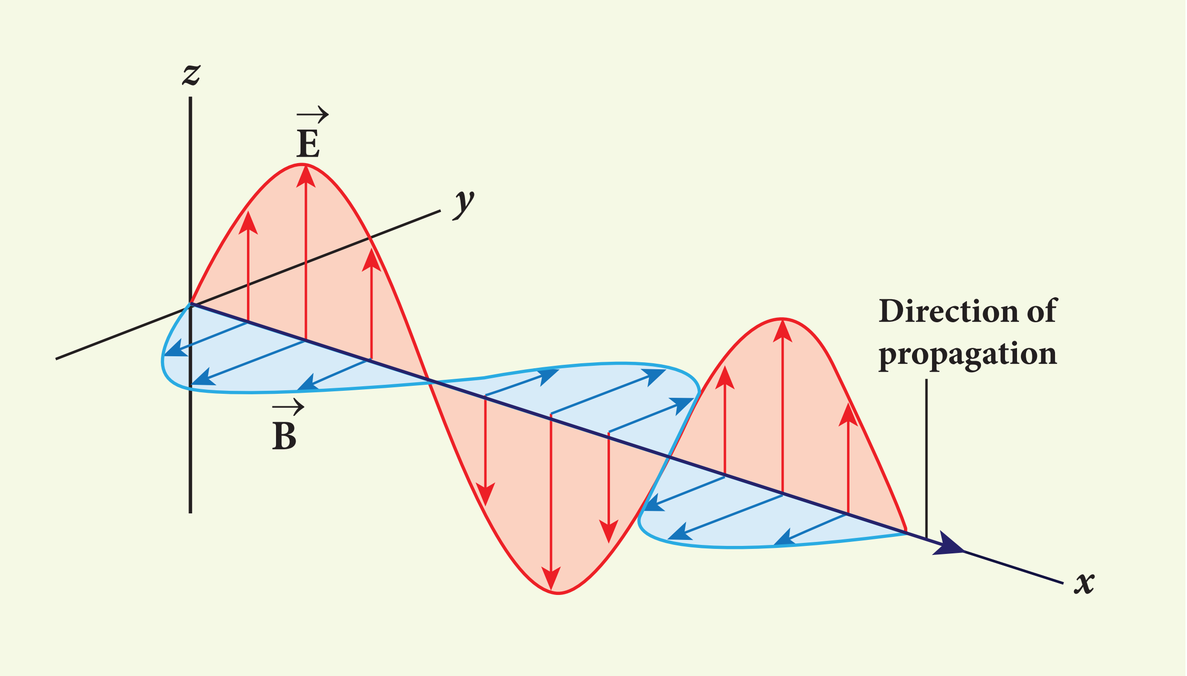


Figure 5.8 Electromagnetic waves – transverse wave

7. Electromagnetic waves can show interference, diffraction and can also be polarized.
8. The energy density (energy per unit volume) associated with an electromagnetic wave propagating in vacuum or free space is

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

where, $\frac{1}{2}\varepsilon_{\circ}E^2 = u_E$ is the energy density in an electric field and $\frac{1}{2\mu_0}B^2 = u_B$ is the energy density in a magnetic field.

Since, $E = Bc \Rightarrow u_B = u_E$.

The energy density of the electromagnetic wave is

$$u = \varepsilon_0 E^2 = \frac{1}{\mu_0}B^2$$

9. The average energy density for electromagnetic wave,

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

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

Intensity, $I = \langle u \rangle c$ or

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

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

Note

For a point source, $I = \frac{P}{4\pi r^2} \Rightarrow I \propto \frac{1}{r^2}$

For a line source, $I \propto \frac{1}{r}$

For a plane source, I is independent of r

11. Like other waves, electromagnetic waves also carry energy and momentum. For the electromagnetic wave of energy U propagating with speed c has linear momentum which

is given by $= \frac{\text{Energy}}{\text{speed}} = \frac{U}{c}$. The force exerted by an electromagnetic wave on unit area of a surface is called radiation pressure.

12. If the electromagnetic wave incident on a material surface is completely absorbed, then the energy delivered is U and momentum imparted on the surface is $p = \frac{U}{c}$.
13. If the incident electromagnetic wave of energy U is totally reflected from the surface, then the momentum delivered to the surface is $\Delta p = \frac{U}{c} - \left(-\frac{U}{c}\right) = 2\frac{U}{c}$.
14. The rate of flow of energy crossing a unit area is known as pointing vector for electromagnetic waves, which is $\vec{S} = \frac{1}{\mu_\circ}\left(\vec{E}\times\vec{B}\right) = c^2\varepsilon_\circ\left(\vec{E}\times\vec{B}\right)$. The unit for pointing vector is W m^{-2}. The pointing vector at any point gives the direction of energy transport from that point.
15. Electromagnetic waves carries not only energy and momentum but also angular momentum.

EXAMPLE 5.2

The relative magnetic permeability of the medium is 2.5 and the relative electrical permittivity of the medium is 2.25. Compute the refractive index of the medium.

Solution

Dielectric constant (relative permeability of the medium) is $\varepsilon_r = 2.25$

Magnetic permeability is $\mu_r = 2.5$

Refractive index of the medium,

$$n = \sqrt{\varepsilon_r \mu_r} = \sqrt{2.25 \times 2.5} = 2.37$$

5.2.2 Sources of electromagnetic waves

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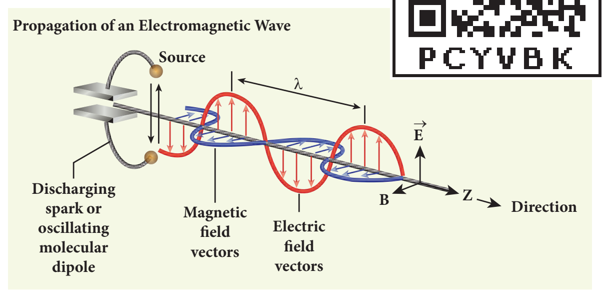


Figure 5.9 Oscillating charges - sources of electromagnetic waves

Any stationary source charge produces only electric field (refer Unit 1). When the charge moves with uniform velocity, it produces steady current which gives rise to magnetic field (not time dependent, only space dependent) around the conductor in which charge flows. If the charged particle accelerates, in addition to electric field it also produces magnetic field. Both electric and magnetic fields are time varying fields. Since the electromagnetic waves are transverse waves, the direction of propagation of electromagnetic waves is perpendicular to the plane containing electric and magnetic field vectors.

Any oscillatory motion is also an accelerating motion, so, when the charge oscillates (oscillating molecular dipole) about their mean position as shown in Figure 5.9, it produces electromagnetic waves. Suppose the electromagnetic field in free space propagates along z direction, and if the electric field vector points along y axis then the magnetic field vector will be mutually perpendicular to both electric field and the propagation vector direction, which means

$$E_y = E_\circ \sin\left(kz - \omega t\right)$$

$$B_x = B_\circ \sin\left(kz - \omega t\right)$$

where, E_o and B_o are amplitude of oscillating electric and magnetic field, k is a wave number, ω is the angular frequency of the wave and $\hat{k}$ (unit vector, here it is called propagation vector) denotes the direction of propagation of electromagnetic wave.

Note that both electric field and magnetic field oscillate with a frequency (frequency of electromagnetic wave) which is equal to the frequency of the source (here, oscillating charge is the source for the production of electromagnetic waves). In free space or in vacuum, the ratio between E_o and B_o is equal to the speed of electromagnetic wave, which is equal to speed of light c.

$$c = \frac{E_o}{B_o}$$

In any medium, the ratio of E_o and B_o is equal to the speed of electromagnetic wave in that medium, mathematically, it can be written as

$$v = \frac{E_o}{B_o} < c$$

Further, the energy of electromagnetic waves comes from the energy of the oscillating charge.

EXAMPLE 5.3

Compute the speed of the electromagnetic wave in a medium if the amplitude of electric and magnetic fields are 3×10^4 N C^{-1} and 2×10^{-4} T, respectively.

Solution

The amplitude of the electric field, $E_o = 3 \times 10^4$ N C^{-1}

The amplitude of the magnetic field, $B_o = 2 \times 10^{-4}$ T. Therefore, speed of the electromagnetic wave in a medium is

$$v = \frac{3\times10^4}{2\times10^{-4}} = 1.5\times10^8\, ms^{-1}$$

5.2.3 Electromagnetic spectrum

ELECTROMAGNETIC SPECTRUM

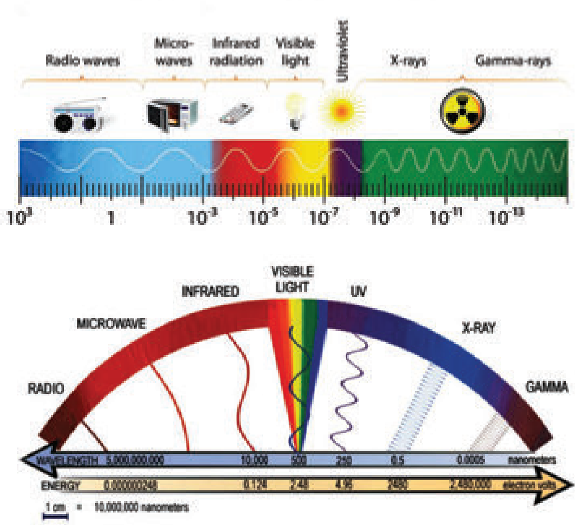


Figure 5.10 Electromagnetic spectrum -

Electromagnetic spectrum is an orderly distribution of electromagnetic waves in terms of wavelength or frequency as shown in Figure 5.10.

Radio waves

It is produced by oscillators in electric circuits. The wavelength range is 1×10^{-1} m to 1×10^4 m and frequency range is 3×10^9 Hz to 3×10^4 Hz. It obeys reflection and diffraction. It is used in radio and television communication systems and also in cellular phones to transmit voice communication in the ultra high frequency band.

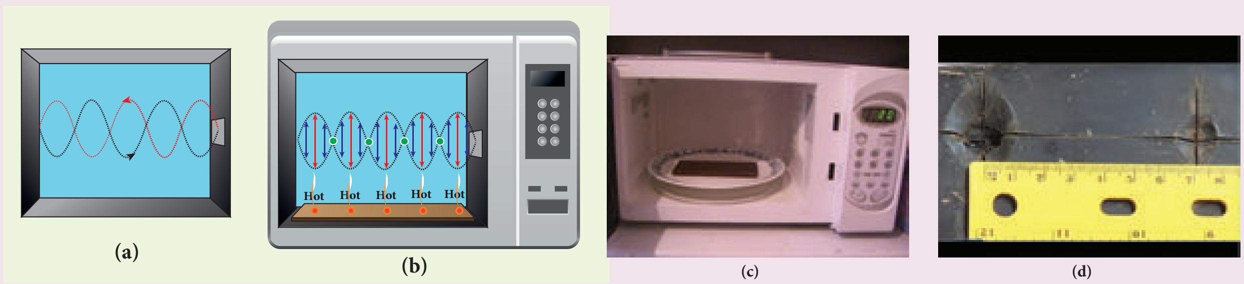
Microwaves

It is produced by electromagnetic oscillators in electric circuits. The wavelength range is 1×10^{-3} m to 3×10^{-1} m and frequency range is 3×10^{11} Hz to 1×10^9 Hz. It obeys reflection and polarization. It is used in radar system for aircraft navigation, speed of the vehicle, microwave oven for cooking and very long distance wireless communication through satellites.

ACTIVITY

Measuring the speed of light using the microwave oven

Nowadays the microwave oven is very commonly used to heat the food items. Micro waves of wavelengths 1 mm to 30 cm are produced in these ovens. Such waves form the standing waves between the interior walls of the oven. It is interesting to note that the speed of light can be measured using micro wave oven.



(a) (b) (c) (d)

We studied about the standing waves in XI physics, Volume 2, Unit 11. The standing waves have nodes and antinodes at fixed points. At node point, the amplitude of the wave is zero and at antinodes point, the amplitude is maximum. In other words, the maximal energy of microwaves is located at antinode points. When we keep some food items like chappathi or choclate (after removing the rotating platform) inside the oven, we can notice that at antinode locations, chappathi will be burnt more than other locations. It is shown in the Figure (c) and (d). The distance between two successive burnt spots will give the wavelength of microwave. The frequency of microwave is printed in the panel of oven. By knowing wavelength and frequency of microwaves, using the formula $\nu\lambda = c$, we can calculate the speed of light *c*.

Infrared radiation

It is produced from hot bodies (also known as heat waves) and also when the molecules undergo rotational and vibrational transitions. The wavelength range is 8×10^{-7} m to 5×10^{-3} m and frequency range are 4×10^{14} Hz to 6×10^{10} Hz. It provides electrical energy to satellites by means of solar cells. It is used to produce dehydrated fruits, in green houses to keep the plants warm, heat therapy for muscular pain or sprain, TV remote as a signal carrier, to look through haze fog or mist and used in night vision or infrared photography.

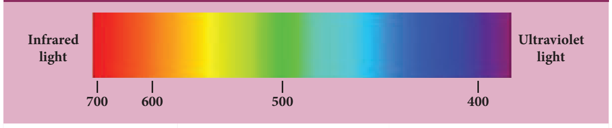
Visible light

It is produced by incandescent bodies and also it is radiated by excited atoms in gases. The wavelength range is 4×10^{-7} m to 7×10^{-7} m and frequency range are 7×10^{14} Hz to 4×10^{14} Hz. It obeys the laws of reflection, refraction, interference, diffraction, polarization, photo-electric effect and photographic action. It can be used to study the structure of molecules, arrangement of electrons in external shells of atoms and sensation of our eyes.

Ultraviolet radiation

It is produced by Sun, arc and ionized gases. The wavelength range is 6×10^{-10} m to 4×10^{-7} m and frequency range are 5×10^{17} Hz to 7×10^{14} Hz. It has less penetrating power. It can be absorbed by atmospheric ozone and harmful to human body. It is used to destroy bacteria, sterilizing the surgical instruments, burglar alarm, detect the invisible writing, finger prints and also in the study of molecular structure.

Table 5.1 visible region, frequency and wavelength of different types of radiation



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

X-rays

It is produced when there is a sudden deceleration of high speed electrons at high-atomic number target, and also by electronic transitions among the innermost orbits of atoms. The wavelength range 10^{-13} m to 10^{-8} m and frequency range are 3×10^{21} Hz to 1×10^{16} Hz. X-rays have more penetrating power than ultraviolet radiation. X-rays are used extensively in studying structures of inner atomic electron shells and crystal structures. It is used in detecting fractures, diseased organs, formation of bones and stones, observing the progress of healing bones. Further, in a finished metal product, it is used to detect faults, cracks, flaws and holes.

Gamma rays

It is produced by transitions of atomic nuclei and decay of certain elementary particles. They produce chemical reactions on photographic plates, fluorescence, ionisation, diffraction. The wavelength range is 1×10^{-14} m to 1×10^{-10} m and frequency range are 3×10^{22} Hz to 3×10^{18} Hz. Gamma rays have high penetrating power than X-rays and ultraviolet radiations; it has no charge but harmful to human body. Gamma rays provide information about the structure of atomic nuclei. It is used in radio therapy for the treatment of cancer and tumour, in food industry to kill pathogenic microorganism.

EXAMPLE 5.4

A magnetron in a microwave oven emits electromagnetic waves (em waves) with frequency f = 2450 MHz. What magnetic field strength is required for electrons to move in circular paths with this frequency?.

Solution

Frequency of the electromagnetic waves given is f = 2450 MHz

The corresponding angular frequency is

$\omega = 2\pi f = 2 \text{ x } 3.14 \text{ x } 2450 \text{ x } 10^6$

$= 15,386 \text{ x } 10^6$ Hz

$= 1.54 \times 10^{10} \text{ s}^{-1}$

The magnetic field $B = \dfrac{m_e \omega}{|q|}$

Mass of the electron, $m_e = 9.22 \text{ x } 10^{-31}$ kg

Charge of the electron

$$q = -1.60 \times 10^{-19} C \Rightarrow |q| = 1.60 \times 10^{-19} C$$

$$B = \frac{\left(9.22 \times 10^{-31}\right)\left(1.54 \times 10^{10}\right)}{\left(1.60 \times 10^{-19}\right)} = 8.87425 \times 10^{-2} T$$

B = 0.0887 T

This magnetic field can be easily produced with a permanent magnet. So, electromagnetic waves of frequency 2450 MHz can be used for heating and cooking food because they are strongly absorbed by water molecules.

5.3 TYPES OF SPECTRUM- EMISSION AND ABSORPTION SPECTRUM- FRAUNHOFER LINES

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Blackbody radiation curves

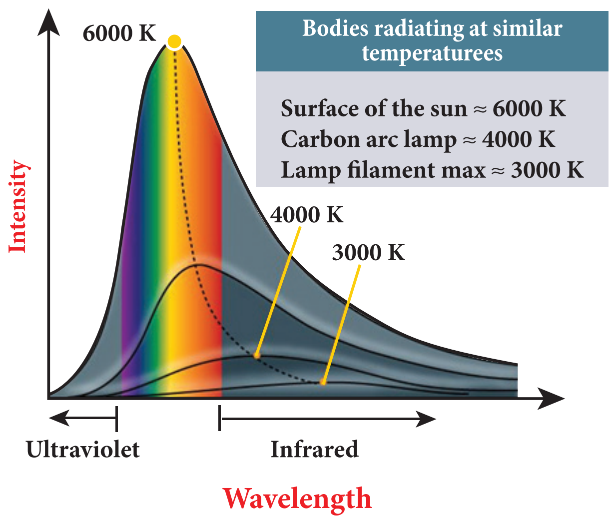


Figure 5.11 Black body radiation spectrum – variation with temperature

When an object burns, it emits colours. That is, it emits electromagnetic radiation which depends on temperature. If the object becomes hot then it glows in red colour. If the temperature of the object is further increased then it glows in reddish-orange colour and becomes white when it is hottest. The spectrum in Figure 5.11 usually called as black body spectrum (refer plus one volume two Unit 8). It is a continuous frequency (or wavelength) curve and depends on the body's temperature.

Suppose we allow a beam of white light to pass through the prism as shown in Figure 5.12, it is split into its seven constituent colours which can be viewed on the screen as continuous spectrum. This phenomenon is known as dispersion of light and the definite

Figure 5.12 White light passed through prism – dispersion

pattern of colours obtained on the screen after dispersion is called as spectrum. The plural for spectrum is spectra. The spectra can be broadly classified into two catagories:

(a)Emission spectra

When the spectrum of self luminous source is taken, we get emission spectrum. Each source has its own characteristic emission spectrum. The emission spectrum can be divided into three types:

(i) Continuous emission spectra (or continuous spectra)

Figure 5.13 continuous emission spectra

If the light from incandescent lamp (filament bulb) is allowed to pass through prism (simplest spectroscope), it splits into seven colours. Thus, it consists of wavelengths containing all the visible colours ranging from violet to red (Figure 5.13). Examples: spectrum obtained from carbon arc, incandescent solids, liquids gives continuous spectra.

(ii) Line emission spectrum (or line spectrum):

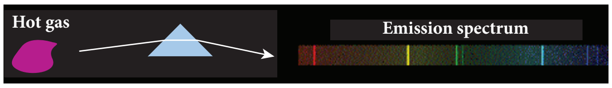


Figure 5.14 line emission spectra

Suppose light from hot gas is allowed to pass through prism, line spectrum is observed (Figure 5.14). Line spectra are also known as discontinuous spectra. The line spectra are sharp lines of definite wavelengths or frequencies. Such spectra arise due to excited 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.

(3) Band emission spectrum (or band spectrum)

Band spectrum 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 at 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.

(b) Absorption spectra

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. Absorption spectrum is classified into three types:

(i) Continuous absorption spectrum

When the light is passed through a medium, it is dispersed by the prism, we get continuous absorption spectrum. For instance, when we pass white light through a blue glass plate, it absorbs everything except blue. This is an example of continuous absorption spectrum.

(ii) Line absorption spectrum

Figure 5.15 line absorption spectra

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 (Figure 5.15). Similarly, if the light from the 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.

(iii) Band absorption spectrum

When the white light is passed through the iodine vapour, dark bands on continuous bright background is obtained. This type of band is also obtained when white light is passed through diluted solution of blood or chlorophyll or through certain solutions of organic and inorganic compounds.

Fraunhofer lines

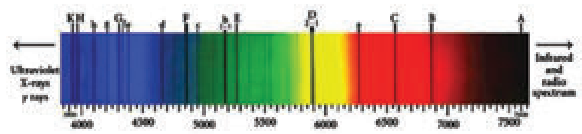


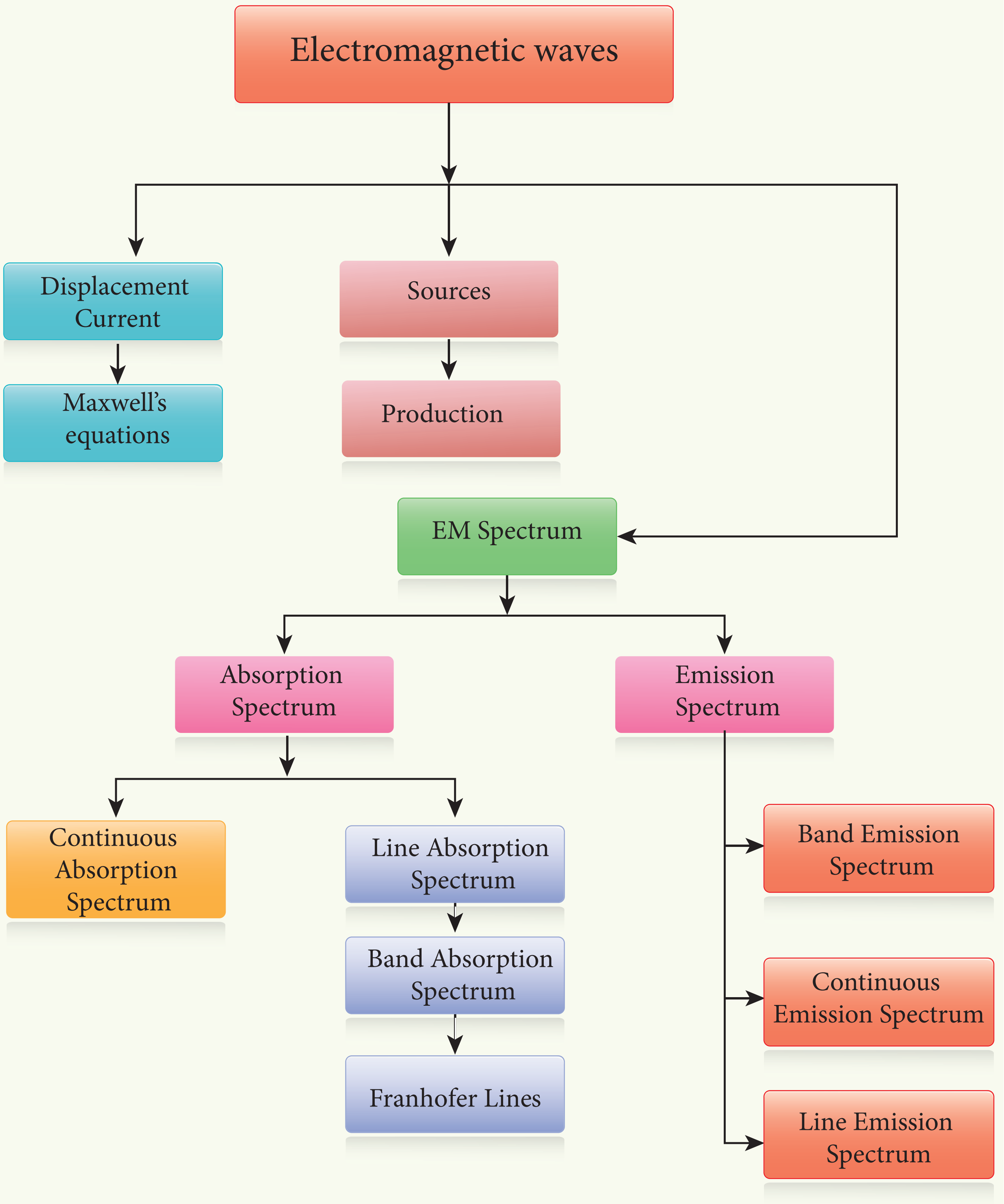
Figure 5.16 Solar spectrum - Fraunhofer lines

When the spectrum obtained 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 (Figure 5.16). The absorption spectra for various materials are compared with the Fraunhofer lines in the solar spectrum, which helps in identifying elements present in the Sun's atmosphere.

SUMMARY

- Displacement current can be defined as 'the current which comes into play in the region in which the electric field and the electric flux are changing with time'
- Maxwell modified Ampere's law as
  $\oint \vec{B}\cdot d\vec{S} = \mu_o I = \mu_o (I_c + I_d)$
- An electromagnetic wave is radiated by an accelerated charge which propagates through space as coupled electric and magnetic fields, oscillating perpendicular to each other and to the direction of propagation of the wave
- Electromagnetic wave is a transverse wave. They are non-mechanical wave and do not require any medium for propagation
- The instantaneous magnitude of the electric and magnetic field vectors in electromagnetic wave are related by E = Bc
- Electromagnetic waves are transverse in nature. This means that the oscillating electric field vector, oscillating magnetic field vector and propagation vector are (gives direction of propagation) mutually perpendicular to each other
- Electromagnetic waves can show interference, diffraction and also can be polarized
- The average energy density $\langle u \rangle = 2u_e = 2u_m = \varepsilon_\circ E^2 = \frac{1}{\mu_\circ} B^2$
- The energy crossing per unit area per unit time and perpendicular to the direction of propagation of electromagnetic wave is called the intensity, which is $I = \langle u \rangle c$
- If the electromagnetic wave incident on a material surface is completely absorbed, then the energy delivered is U and momentum imparted on the surface is $p = \frac{U}{c}$
- If the incident electromagnetic wave of energy U is totally reflected from the surface, then the momentum delivered to the surface is $\Delta p = \frac{U}{c} - \left(-\frac{U}{c}\right) = 2\frac{U}{c}$
- The rate of flow of energy crossing a unit area is known as poynting vector for electromagnetic waves, which is $\vec{S} = \frac{1}{\mu_\circ}(\vec{E}\times\vec{B}) = c^2\varepsilon_\circ(\vec{E}\times\vec{B})$.
- Electromagnetic waves carry not only energy and momentum but also angular momentum.
- Types of spectrum – emission and absorption
- When the spectrum of self luminous source is taken, we get emission spectrum. Each source has its own characteristic emission spectrum. The emission spectrum can be divided into three types: continuous, line and band.
- The spectrum obtained 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.

CONCEPT MAP



Electromagnetic waves
Displacement Current
Maxwell's equations
Sources
Production
EM Spectrum
Absorption Spectrum
Emission Spectrum
Continuous Absorption Spectrum
Line Absorption Spectrum
Band Absorption Spectrum
Franhofer Lines
Band Emission Spectrum
Continuous Emission Spectrum
Line Emission Spectrum

EVALUATION

I Multiple choice questions

1. The dimension of $\frac{1}{\mu_o \varepsilon_\circ}$ is

(a) $[L T^{-1}]$ (b) $[L^2 T^{-2}]$

(c) $[L^{-1} T]$ (d) $[L^{-2} T^2]$

2. If the amplitude of the magnetic field is 3×10^{-6} T, then amplitude of the electric field for a electromagnetic waves is

(a) 100 V m^{-1} (b) 300 V m^{-1}

(c) 600 V m^{-1} (d) 900 V m^{-1}

3. Which of the following electromagnetic radiation is used for viewing objects through fog

(a) microwave (b) gamma rays

(c) X- rays (d) infrared

4. Which of the following are false for electromagnetic waves

E67JQC

(a) transverse

(b) mechanical waves

(c) longitudinal

(d) produced by accelerating charges

5. Consider an oscillator which has a charged particle and oscillates about its mean position with a frequency of 300 MHz. The wavelength of electromagnetic waves produced by this oscillator is

(a) 1 m (b) 10 m

(c) 100 m (d) 1000 m

6. The electric and the magnetic field, associated with an electromagnetic wave, propagating along X axis can be represented by

(a) $\vec{E} = E_\circ \hat{j}$ and $\vec{B} = B_\circ \hat{k}$

(b) $\vec{E} = E_\circ \hat{k}$ and $\vec{B} = B_\circ \hat{j}$

(c) $\vec{E} = E_\circ \hat{i}$ and $\vec{B} = B_\circ \hat{j}$

(d) $\vec{E} = E_\circ \hat{j}$ and $\vec{B} = B_\circ \hat{i}$

7. In an electromagnetic wave in free space the rms value of the electric field is 3 V m^{-1}. The peak value of the magnetic field is

(a) 1.414×10^{-8} T (b) 1.0×10^{-8} T

(c) 2.828×10^{-8} T (d) 2.0×10^{-8} T

8. During the propagation of electromagnetic waves in a medium:

(a) electric energy density is double of the magnetic energy density

(b) electric energy density is half of the magnetic energy density

(c) electric energy density is equal to the magnetic energy density

(d) both electric and magnetic energy densities are zero

9. If the magnetic monopole exists, then which of the Maxwell's equation to be modified?.

(a) $\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enclosed}}{\epsilon_\circ}$

(b) $\oint \vec{E} \cdot d\vec{A} = 0$

(c) $\oint \vec{E} \cdot d\vec{A} = \mu_\circ I_{enclosed} + \mu_\circ \epsilon_\circ \frac{d}{dt} \int \vec{E} \cdot d\vec{A}$

(d) $\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \Phi_B$

10. A radiation of energy E falls normally on a perfectly reflecting surface. The momentum transferred to the surface is

(a) $\frac{E}{c}$ (b) $2\frac{E}{c}$

(c) Ec (d) $\frac{E}{c^2}$

11. Which of the following is an electromagnetic wave?

(a) α - rays (b) β - rays

(c) γ - rays (d) all of them

12. Which one of them is used to produce a propagating electromagnetic wave?.

(a) an accelerating charge

(b) a charge moving at constant velocity

(c) a stationary charge

(d) an uncharged particle

13. Let $E = E_o \sin[10^6 x - \omega t]$ be the electric field of plane electromagnetic wave, the value of ω is

(a) 0.3×10^{-14} rad s^{-1}

(b) 3×10^{-14} rad s^{-1}

(c) 0.3×10^{14} rad s^{-1}

(d) 3×10^{14} rad s^{-1}

14. Which of the following is NOT true for electromagnetic waves?.

(a) it transport energy

(b) it transport momentum

(c) it transport angular momentum

(d) in vacuum, it travels with different speeds which depend on their frequency

15. The electric and magnetic fields of an electromagnetic wave are

(a) in phase and perpendicular to each other

(b) out of phase and not perpendicular to each other

(c) in phase and not perpendicular to each other

(d) out of phase and perpendicular to each other

Answers

1) b	**2)** d	**3)** d	**4)** c	**5)** a
6) b	**7)** a	**8)** c	**9)** b	**10)** b
11) c	**12)** a	**13)** d	**14)** d	**15)** a

II Short answer questions

1. What is displacement current?

2. What are electromagnetic waves?

3. Write down the integral form of modified Ampere's circuital law.

4. Explain the concept of intensity of electromagnetic waves.

5. What is meant by Fraunhofer lines?

III Long answer questions

1. Write down Maxwell equations in integral form.

2. Write short notes on (a) microwave (b) X-ray (c) radio waves (d) visible spectrum

3. Discuss briefly the experiment conducted by Hertz to produce and detect electromagnetic spectrum.

4. Explain the Maxwell's modification of Ampere's circuital law.

5. Write down the properties of electromagnetic waves.

6. Discuss the source of electromagnetic waves.

7. What is emission spectra?. Give their types.

8. What is absorption spectra?. Give their types.

IV Numerical problems

1. Consider a parallel plate capacitor whose plates are closely spaced. Let R be the radius of the plates and the current in the wire connected to the plates is 5 A, calculate the displacement current through the surface passing between the plates by directly calculating the rate of change of flux of electric field through the surface.

   Answer: $I_d = I_c = 5$ A

2. A transmitter consists of LC circuit with an inductance of 1 μH and a capacitance of 1 μF. What is the wavelength of the electromagnetic waves it emits?

   Answer: 18.84×10^{-6} m

3. A pulse of light of duration 10^{-6} s is absorbed completely by a small object initially at rest. If the power of the pulse is 60×10^{-3} W, calculate the final momentum of the object.

   Answer: 20×10^{-17} kg m s^{-1}

4. Let an electromagnetic wave propagate along the x direction, the magnetic field oscillates at a frequency of 10^{10} Hz and has an amplitude of 10^{-5} T, acting along the y - direction. Then, compute the wavelength of the wave. Also write down the expression for electric field in this case.

   Answer: $\lambda = 3 \times 10^{-18}$ m and

   $$\vec{E}(x,t) = 3\times10^{3} \sin\left(2.09\times10^{18} x - 6.28\times10^{10} t\right)\hat{i} \;\; NC^{-1}$$

5. If the relative permeability and relative permittivity of the medium is 1.0 and 2.25, respectively. Find the speed of the electromagnetic wave in this medium.

   Answer: $v = 2$ m s^{-1}

BOOKS FOR REFERENCE:

1. H. C. Verma, *Concepts of Physics – Volume 2*, Bharati Bhawan Publisher
2. Halliday, Resnick and Walker, *Fundamentals of Physics*, Wiley Publishers, 10th edition
3. Serway and Jewett, *Physics for scientist and engineers with modern physics*, Brook/Coole publishers, Eighth edition
4. David J. Griffiths, *Introduction to electrodynamics*, Pearson publishers
5. Paul Tipler and Gene Mosca, *Physics for scientist and engineers with modern physics*, Sixth edition, W.H.Freeman and Company

ICT CORNER

Electromagnetic waves

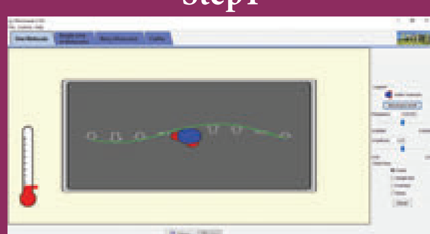
In this activity you will be able to how do microwaves heat food?

Physics of microwaves and heating food

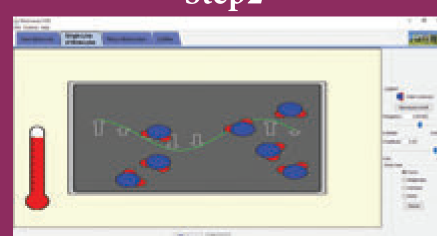
STEPS:

- Open the browser and type "phet.colorado.edu/en/simulation/microwaves" in the address bar. Run the simulation.
- select 'one molecule' tab. Turn on the microwave using the button in the right control panel. The arrows indicate the strength and direction of the force that would be exerted by the micro wave on the water molecules present in food. Observe the response of water molecule in response to this force?
- Observe how do microwaves heat food by rotating water molecule?
- Change amplitude and frequency of microwave and discuss how fast the water molecules are rotating?

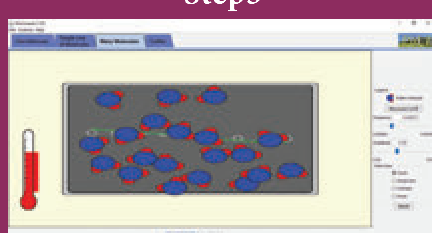
Step1



Step2



Step3



Step4

Discuss the relationship between rotating speed of the molecule with cooking time.

Note:

Install Java application if it is not in your system. You can download all the phet simulation and works in off line from https://phet.colorado.edu/en/offline-access.

URL:

https://phet.colorado.edu/en/simulation/microwaves

* Pictures are indicative only.

* If browser requires, allow **Flash Player** or **Java Script** to load the page.

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