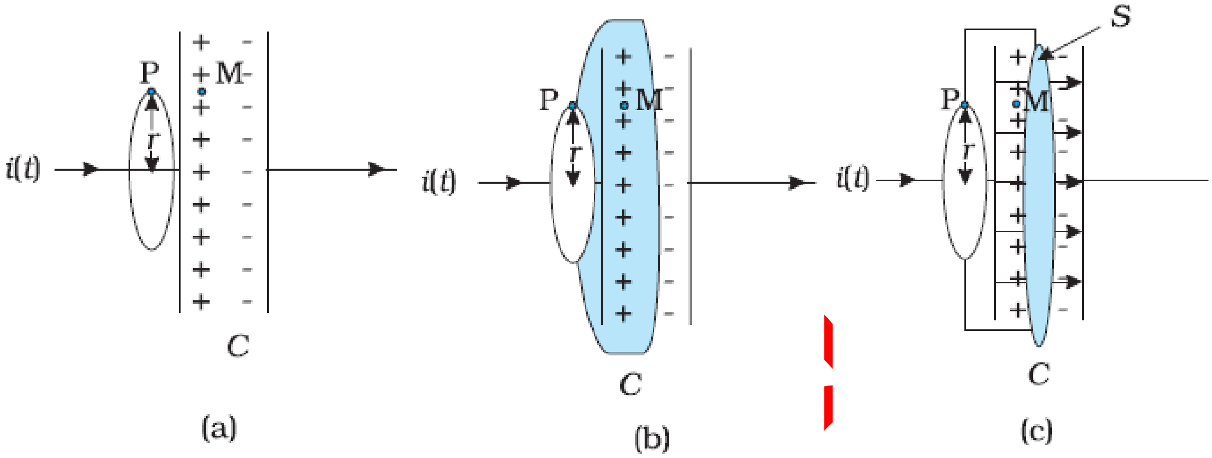
Electro-magnetic waves

➢ Displacement current



- Consider a parallel plate capacitor *C* which is a part of circuit through which a time-dependent current *i* (*t*) flows and P be a point in a region outside the capacitor.
- Consider a plane circular loop of radius *r* whose plane is perpendicular to the direction of the current-carrying wire, and which is centred symmetrically with respect to the wire [Fig. (a)].

Magnetic field at P, $\oint \vec{B}.\vec{dl} = \mu_0 i(t)$ → (1)

- Now, consider a different surface, which has the same boundary for example a pot like surface [Fig. (b)] or tiffin box (without the lid) [Fig. (c)] which nowhere touches the current, but has its bottom between the capacitor plates.
- On applying Ampere's circuital law to such surfaces with the *same* perimeter,

Magnetic field at P, $\oint \vec{B}.\vec{dl} = 0$ → (2)

(As *no* current passes through the surface of Fig.(b) and (c).)

- From (1) and (2) we have a *contradiction*; as calculated one way, there is a magnetic field at a point P; calculated another way, the magnetic field at P is zero.
- Maxwell proposed that as a changing magnetic field induces an electric field so a changing electric field must induce a magnetic field.
- The current associated with a changing electric field is called displacement current.
- Let E be electric field between the plates of the capacitor having area *A*, and a total charge

$\mathbf{E} = \frac{QA}{\varepsilon_0}$ (Perpendicular to the surface *S* of Fig. (c))

- Using Gauss law electric flux through surface S

$$\phi_E = EA = \frac{Q}{\varepsilon_0 A} A = \frac{Q}{\varepsilon_0}$$

Differentiating both sides

$$\frac{d\phi_E}{dt} = \frac{d}{dt}\frac{Q}{\varepsilon_0}$$

$$\frac{d\phi_E}{dt} = \frac{1}{\varepsilon_0}\frac{dQ}{dt}$$

$$\frac{d\phi_E}{dt} = \frac{1}{\varepsilon_0} i_d$$

- So for consistency in ampere circuital law, $i_d = \varepsilon_0 \frac{d\phi_E}{dt}$ (missing term in Ampere's circuital law)
- On generalizing Ampere's circuital law by adding $i_d = \varepsilon_0 \frac{d\phi_E}{dt}$ to the total current carried by conductors through the surface, we find that *total* has the same value of current *i* for all surfaces and there is no contradiction in the value of *B* obtained anywhere.
[B at the point P is non-zero no matter which surface is used for calculating it. *B* at a point P outside the plates [Fig.(a)] is the same as at a point M just inside, as it should be.]
- Current carried by conductors due to flow of charges is called **conduction current** and Current due to changing electric field is called **displacement current** $i_d = \varepsilon_0 \frac{d\phi_E}{dt}$.
- Total current 'i' is sum of the conduction current denoted by i_c, and displacement current i_d.

$$i = i_c + i_d = i_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

i.e. outside the capacitor plates, $i_c = i$, and $i_d = 0$.

inside the capacitor plates, $i_c = 0$, and $i_d = i$.

➢ <u>Generalisation Ampere circuital law</u>

"The total current passing through any surface of which the closed loop is the perimeter" is the sum of the conduction current and the displacement current.

$$\oint \vec{B}.\vec{dl} = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}$$

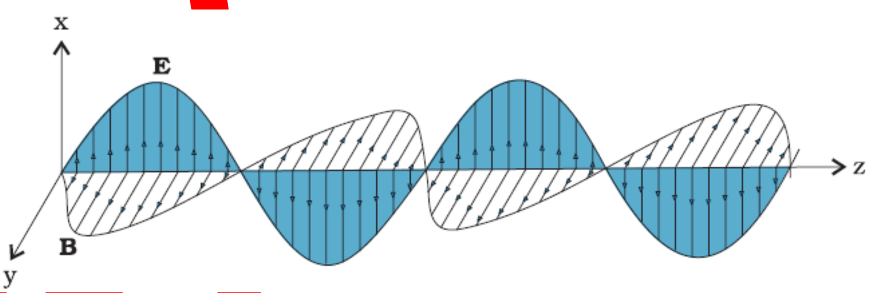
∗ This is also called as Ampere-Maxwell law.

Source of electromagnetic waves

- Neither stationary charges nor charges in uniform motion (steady currents) can be sources of electromagnetic waves. The former produces only electrostatic fields, while the latter produces magnetic fields that do not vary with time.
- Consider a charge oscillating (i.e. accelerating charge) with some frequency. This produces an oscillating electric field in space, which produces an oscillating magnetic field, which in turn, is a source of oscillating electric field, and so on.
- The oscillating electric and magnetic fields thus regenerate each other as the wave propagates through the space.
- The frequency of the electromagnetic wave equals the frequency of oscillation of the charge.
- The energy associated with the propagating wave comes at the expense of the energy of accelerated charge (source).

Propagation of e-m waves

- Electric and magnetic fields in an electromagnetic wave are perpendicular to each other, *and* to the direction of propagation.
- The electric field E_x is along the *x*-axis, and varies sinusoidally with *z*, at a given time. The magnetic field B_y is along the *y*-axis, and again varies sinusoidally with *z*. The electric and magnetic fields E_x and B_y are perpendicular to each other, and to the direction *z* of propagation.
- $E_x = E_0 \sin(kz - wt)$ $\qquad$ $B_y = B_0 \sin(kz - wt)$



Properties of e-m waves

1. They are self-sustaining oscillations of electric and magnetic fields in free space, or vacuum.
2. They do not require any material medium for propagation.
3. They travel with velocity $v = \dfrac{1}{\sqrt{\mu\varepsilon}}$
4. They can be polarized
5. They carry energy and momentum.
6. They exert pressure called as radiation pressure.

Some Important Questions

1. Why the experimental demonstration (performed by Hertz) of electromagnetic wave had to come in the low frequency region?

Ans. Because even the frequency of visible light, say, yellow light frequency(6×10^{14} Hz) is 10^{14} Hz, while the frequency that we get even with modern electronic circuits is hardly about 10^{11} Hz.

2. How can you show that electromagnetic waves carry energy and momentum.

Ans.
- Energy density in electric field : $\frac{1}{2}\varepsilon_0 E^2$

  Energy density in magnetic field : $\frac{B^2}{2\mu_0}$
- As electromagnetic wave contains both electric and magnetic fields, there is a non-zero energy density associated with it.
- Consider a plane perpendicular to the direction of propagation of the electromagnetic wave. The electric charges on the plane will be set and sustained in motion by the electric and magnetic fields of the electromagnetic wave.

  The charges thus acquire energy and momentum from the waves.

3. Show that electromagnetic waves exert pressure.

Ans. As it carries momentum, an electromagnetic wave also exerts pressure, called radiation pressure.

4. Electro-magnetic waves exert pressure called radiation pressure but we don't feel it. Why?

Ans.
- If the total energy transferred to a surface in time t is U, then the magnitude of the total momentum delivered to this surface (*for complete absorption*) is,p=U/c
- When the sun shines on your hand, you feel the energy being absorbed from the electromagnetic waves (your hands get warm).
- Electromagnetic waves also transfer momentum to your hand but because c is very large, the amount of momentum transferred is extremely small and you do not feel the pressure.

5. Name the animal which can detect infrared waves

Ans. Snake

Electro-magnetic Spectrum

S.No.	Type of wave	Frequency(Hz)	Wavelength(m)	Production	Detection	Uses
1.	Radio waves	$5 \times 10^9 - 10^9$	> 0.1 m	By the accelerated motion of charges in conducting wires.	Receiver's aerials	• Cellular phones use radio waves. • Radio and TV comm.
2.	Microwaves (short wavelength radio waves)	$10^9 - 10^{11}$	0.1m to 1 mm	Produced by special vacuum tubes (called klystrons, magnetrons and Gunn diodes).	Point contact diodes	• for radar systems used in aircraft navigation
3.	Infrared waves (heat waves)	$10^{11} - 10^{14}$	1mm - 700 nm	Produced by hot bodies and molecules.	Infrared photographic film	• Infrared lamps for physical therapy. • Maintaining the earth's average temperature. • Electronic appliance remotes.
4.	Visible rays	$4 \times 10^{14} - 8 \times 10^{14}$	700nm-400nm	Electrons in atoms emit light when they move from one energy level to another	• The eye • Photographic film	• To see objects
5.	Ultraviolet rays	$10^{14} - 10^{16}$	$10^{-7} - 10^{-10}$	Produced by special lamps and very hot bodies.	Photographic film	• LASIK eye surgery. • To kill germs in water purifiers.
6.	X-rays	$10^{16} - 10^{21}$	$10^{-8} - 10^{-13}$	bombard a metal target by high energy electrons	Photographic film	• diagnostic tool in medicine • Treatment for certain forms of cancer.
7.	Gamma rays	$10^{18} - 10^{22}$	$10^{-10} - 10^{-14}$	• Produced in nuclear reactions. • Emitted by radioactive nuclei.	Photographic film	• Used in medicine to destroy cancer cells.

Some Important Questions

1. Why are radio waves suitable for radar systems

Ans. Due to their short wavelengths, they are suitable for the radar systems used in aircraft navigation.

2. Give other applications of radar system.

Ans. It provides the basis for the speed guns used to time fast balls, tennis serves, and automobiles.

3. How is food cooked in a microwave oven?

Ans.
- The frequency of microwaves is selected to match the resonant frequency of water molecules so that energy from the waves is transferred efficiently to the kinetic energy of the molecules.
- This raises the temperature of any food containing water.

4. Why are infrared waves referred as heat waves?

Ans.
- This is because water molecules present in most materials readily absorb infrared waves.
- After absorption, their thermal motion increases, i.e., they heat up and heat their surroundings.

5. How does infrared waves plays an important role in maintaining earth's warmth or average tem?

Ans.
- Infrared plays an important role in maintaining earth's warmth through the greenhouse effect.
- Incoming visible light is absorbed by the earth's surface and reradiated as infrared (longer wavelength) radiations.
- This radiation is trapped by greenhouse gases such as carbon dioxide and water vapour.

6. Why care must be taken to avoid unnecessary or over exposure of X-rays?

Ans. Because X-rays damage or destroy living tissues and organisms.

7. How are ordinary glass windows helpful against UV rays?

Ans. Exposure to UV radiation induces production of more melanin, causing tanning of the skin. UV rays are absorbed by ordinary glass. So, one can't get tanned/ sunburn through glass windows.

8. Why welders wear special glass goggles or face masks with glass windows?

Ans. To protect their eyes from large amount of UV produced by welding arcs.

9. Why are UV rays used in high precision applications such as LASIK eye surgery?

Ans. Due to its shorter wavelengths, UV radiations can be focused into very narrow beams for high precision applications such as LASIK.

10. Why infrared detectors are used in Earth satellites?

Ans. For military purposes and to observe growth of crops.

11. Write the frequency range for AM,TV and FM.

Ans. AM (530 kHz – 1710 kHz), TV (54 MHz - 890 MHz), FM (88 MHz - 108 MHz)