Electromagnetic Spectrum

When Maxwell predicted the existence of electromagnetic waves, the visible light waves were the only ones familiar to us. People barely knew about ultraviolet and infrared rays. However, by the end of the nineteenth century, X-rays and gamma-rays were also discovered. Today, we know that electromagnetic waves include different types of waves. Electromagnetic Spectrum is the classification of these waves according to their frequency.

Remember: There is no demarked division between the waves. They are classified based on how they are produced and/or detected.

Electromagnetic Spectrum

Here is a quick look at the electromagnetic spectrum with common names for various regions.

Let's look at each of these electromagnetic waves in the order of decreasing wavelengths.

Waves in the Electromagnetic Spectrum

Waves in the electromagnetic spectrum are broadly classified as follows:

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1. Radio waves

2. Microwaves

3. Infrared rays

4. Visible rays

5. Ultraviolet rays

6. X-rays

7. Gamma rays

Radio Waves

- Radio waves are usually in the frequency range from 500 kHz to 1000 MHz.

- Also, the range of the AM (amplitude modulated) band is between 530 kHz and 1710 kHz.

- Further, shortwave bands use higher frequencies of up to 54 MHz.

- TV waves range from 54 MHz to 890 MHz.

- The FM (frequency modulated) radio band is from 88 MHz to 108 MHz.

- Cellular phones also use radio waves to transmit voice communication in an ultra-high frequency (UHF) band.

Generation of Radio Waves

The accelerated motion of charges in conducting wires generates Radio waves. Radio and television communication systems widely use these waves.

Microwaves

- Microwaves are short-wavelength radio waves with frequencies in the Gigahertz (GHz) range
- Best suited for the radar systems in aircraft navigation
- Another use of Radars is as speed-guns. These speed guns help time fastballs, tennis serves and automobiles.
- These waves form the basis of microwave ovens. In microwave ovens, the frequency of the microwaves is selected to match the resonant frequency of water molecules. This results in a direct transfer of energy from the waves to the kinetic energy of the water molecules raising the temperature of any food containing water.

Generation of Microwaves

Special vacuum tubes called klystrons, magnetrons and Gunn diodes generate microwaves.

Infrared Rays

- 'Heat Waves' is another name for Infrared rays.
- Water molecules present in most materials readily absorb these rays.
- After absorption, their thermal motion increases which increases their heat and that of their surroundings.
- Many physical therapy treatments use Infrared lamps.
- These rays also play an important role in maintaining the earth's average temperature through the greenhouse effect.
  - *Greenhouse effect: The earth's surface absorbs the incoming visible light. Then, it re-radiates it as infrared radiations. The greenhouse gases like carbon dioxide and water vapour trap these radiations.*
- Earth Satellites deploy Infrared detectors for military purposes and to observe the growth of crops.

- Remote switches of household appliances like TV, video recorders, etc. use infrared rays.

Generation of Infrared Rays

Hot bodies and molecules generate Infrared rays. Also, the band lies next to the low-frequency or long-wavelength end of the electromagnetic spectrum.

Visible Rays

- Visible rays are the most familiar form of electromagnetic waves.
- Most importantly, it is that part of the electromagnetic spectrum that is detected by the human eye.
- Frequency range is between 4×10^{14} Hz and 7×10^{14}
- Wavelength range is from 700-400 nm.

Ultraviolet Rays

- Ultraviolet rays have wavelengths ranging from 4×10^{-7} m (400 nm) to 6×10^{-10} m (0.6 nm).

- These rays can have harmful effects on humans if exposed to in large quantities.
- Ordinary glass absorbs UV rays. In other words, sit behind a glass window and avoid suntans and sunburns.
- Welding arcs produce a large number of UV rays. Hence, welders wear special goggles or masks with glass to protect their eyes.
- Now, UV rays have shorter wavelengths. Hence, they are focused into very narrow beams and used in high-precision applications like LASIK eye surgery.
- Many water purifiers use UV lamps to kill germs in water.

Generation of Ultraviolet Rays

Special lamps and very hot bodies generate Ultraviolet rays. Also, the sun is an important source of ultraviolet rays.

X-rays

- In the electromagnetic spectrum, X-rays lie beyond the ultraviolet region.

- X-rays have wavelengths ranging from about 10^{-8} m or 10 nm to 10^{-13} m or 10^{-4}

- X-rays are particularly well known due to their use as a diagnostic tool in medicine.

- Also, the treatment for certain types of cancer involves the use of X-rays.

- X-rays can damage or destroy living tissues. Hence, you must take care and avoid unnecessary over-exposure to these rays.

Generation of X-rays

X-rays are commonly generated by bombarding a metal target with high energy electrons.

Gamma Rays

- Gamma rays lie in the upper-frequency region of the electromagnetic spectrum

- The wavelengths of these waves range from about 10^{-10} m to less than 10^{-14}

- An important application of Gamma rays is their extensive use in medicine to destroy cancer cells

Generation of Gamma Rays

Gamma rays are produced in nuclear reactions. Some radioactive nuclei also emit gamma rays.

Solved Examples for You

Question: List down the different types of waves in the electromagnetic spectrum. Also, specify the method of generation of each of these waves.

Solution: The waves in the electromagnetic spectrum can be broadly classified as:

1. Radio waves – produced by the accelerated motion of charges in conducting wires
2. Microwaves – produced by special vacuum tubes called klystrons, magnetrons and Gunn diodes.
3. Infrared rays – produced by hot bodies and molecules.
4. Visible rays – visible light emitted or reflected by objects

5. Ultraviolet rays – produced by special lamps and very hot bodies, like the sun.

6. X-rays – produced by bombarding a metal target with high energy electrons.

7. Gamma rays – produced in nuclear reactions and also emitted by radioactive nuclei.

Displacement Current

We know that an electric current produces a magnetic field around it. J.C. Maxwell showed that for logical consistency, a changing electric field must also produce a magnetic field. Further, since magnetic fields have always been associated with currents, Maxwell postulated that this current was proportional to the rate of change of the electric field and called it displacement current. In this article, we will look at displacement current in detail.

How a changing electric field produces a magnetic field?

To determine this, let's look at the process of charging a capacitor. Further, we will apply Ampere's circuital law to find a magnetic point outside the capacitor.
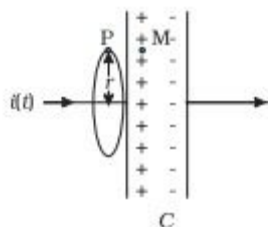
The figure above shows a parallel plate capacitor connected in a circuit through which a time-dependent current i(t) flows. We will try to find the magnetic field at a point P, in the region outside the capacitor.

Consider a plane circular loop of radius r centred symmetrically with the wire. Also, the plane of the loop is perpendicular to the direction of the current carrying wire. Due to the symmetry, the magnetic field is directed along the circumference of the loop and has similar magnitude at all points on the loop.

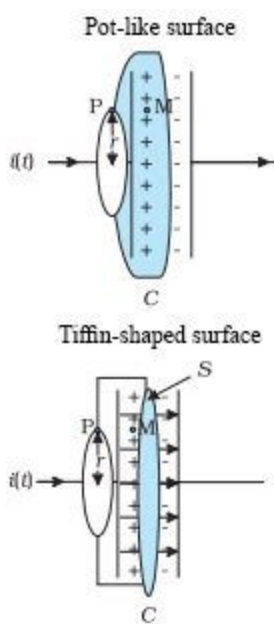Pot-like surface

Tiffin-shaped surface

Figure 2

However, as shown in the Figure(2) above, when the surface is replaced by a pot-like surface where it doesn't touch the current but has its bottom between the capacitor plates or a tiffin-shaped surface (without the lid) and Ampere's circuital law is applied, certain contradictions arise.

These contradictions arise since no current passes through the surface and Ampere's law does not take that scenario into consideration. This leads us to understand that there is something missing in the Ampere's circuital law. Also, the missing term is such which enables us to get the same magnetic field at point P regardless of the surface used.

Maxwell's Displacement Current

If we look at the last figure again, we can observe that the common thing that passes through the surface and between the capacitor plates is an electric field. This field is perpendicular to the surface, has the same magnitude over the area of the capacitor plats and vanishes outside it.

Hence, the electric flux through the surface is Q/ε_0 (using Gauss's law). Further, since the charge on the capacitor plates changes with time, for consistency we can calculate the current as follows:

$$i = \varepsilon_0 \, (dQ/dt)$$

This is the missing term in Ampere's circuital law. In simple words, when we add a term which is ε_0 times the rate of change of electric flux to the total current carried by the conductors, through the same surface, then the total has the same value of current 'i' for all surfaces. Therefore, no contradiction is observed if we use the Generalized Ampere's Law.

Hence, the magnitude of B at a point P outside the plates is the same at a point just inside. Now, the current carried by conductors due to the flow of charge is called 'Conduction current'. The new term added is the current that flows due to the changing electric field and is called 'Displacement current' or Maxwell's Displacement current'.

Displacement Current Explained

By now we understand that there are two sources of a magnetic field:

1. Conduction electric current due to the flow of charges
2. Displacement current due to the rate of change of the electric field

Hence, the total current (i) is calculated as follows: (where i_c – conduction current and i_d – displacement current)

$$i = i_c + i_d$$

$$= i_c + \varepsilon_0(dQ/dt)$$

This means that –

- Outside the capacitor plates: $i_c=i$ and $i_d=0$
- Inside the capacitor plates: $i_c=0$ and $i_d=i$

So, the generalized Ampere's law states:

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.

This is also known as – Ampere-Maxwell Law. It is important to remember that the displacement and conduction currents have the same physical effects. Here are some points to remember:

- In cases where the electric field does not change with time, like steady electric fields in a conducting wire, the displacement current may be zero.
- In cases like the one explained above, both currents are present in different regions of the space.
- Since a perfectly conducting or insulating medium does not exist, in most cases both the currents can be present in the same region.
- In cases where there is no conduction current but a time-varying electric field, only displacement current is present. In such a scenario we have a magnetic field even when there is no conduction current source nearby.

Faraday's Law of Induction and Ampere-Maxwell Law

According to Faraday's law of induction, there is an induced emf which is equal to the rate of change of magnetic flux. Since emf

between two points is the work done per unit charge to take it from one point to the other, its existence simply implies the existence of an electric field. Rephrasing Faraday's law:

A magnetic field that changes with time gives rise to an electric field.

Hence, an electric field changing with time gives rise to a magnetic field. This is a consequence of the displacement current being the source of the magnetic field. Hence, it is fair to say that time-dependent magnetic and electric fields give rise to each other.

Solved Examples for You

Question: Explain the missing term in Ampere's circuital law

Solution: According to Ampere's circuital law, the integral of magnetic field density (B) along an imaginary closed path is equal to the product of current enclosed by the path and permeability of the medium. However, upon passing a time-dependent current and changing the surface which does not touch the current, certain contradictions arise since Ampere's law does not take these parameters into consideration. The inability of the law to determine

the magnetic field at a point outside the region of the capacitor explains the missing term in the equation.