**Chapter – 8 Electromagnetic Waves**

Maxwell predicted that an accelerated charge produces a sinusoidal time varying magnetic field, which in turn produces a sinusoidal time varying electric field. The two fields so produced are mutually perpendicular and are sources to each other. The mutually perpendicular time varying electric and magnetic fields constitute electromagnetic waves which can propagate through empty space.

If we assume electric field and magnetic field to vary with distance x and time t in YZ-plane, as follows:

E = Eo sin (wt - kx) B = Bo sin (wt - kx)

then such a combination of electric and magnetic fields in vacuum constitute an electromagnetic wave propagating along X-direction in vacuum.

The velocity of electromagnetic waves in free space is given by: C =1/√(μo∈o)

where, μo = 1.27 x 10-6 TmA-l and ∈o=8.854 x 10-12 C2N-lm-2 respectively the absolute permeability and absolute permittivity of free space. The velocity o[ electromagnetic waves in free space (vacuum) is equal to velocity of light in vacuum,i.e.,3x 108 m/s.

**Maxwell's Displacement Current:**

Maxwell predicted that not only a current flowing in a conductor produces a magnetic field but also a time varying electric field in a vacuum of free space produces a magnetic field. This implies that a changing electric field gives rise to a current which flows through a region so long as electric field is changing there. Maxwell also told that this current generates the same magnetic field as the conduction current can generate. This current is called as **Displacement Current**. Maxwell showed the relation for displacement current as follows:

Id = ∈o dϕE/dt

According to Maxwell, conduction current I and displacement current Id , together have the property of continuity, although individually, they may not be continuous.

This concept led Maxwell to modify Ampere's Circuital law as follows:

**For example** : let us find out how we can establish an instantaneous displacement current of 1.0 ampere in the space between the plates of a 1 μF parallel plate capacitor.

We know that, **Id = ∈o dϕE/dt** and ϕE =EA (where A = Area of the plates of parallel plate capacitor and E is the uniform electric field across the capacitor).



or dV//dt = Id/C = 1/10-6 = 106 V/s

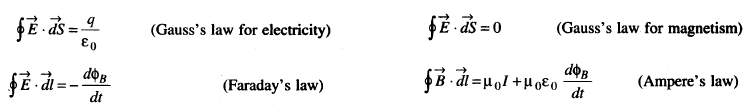
Thus, we find that an instantaneous displacement current of 1 amp can be set up in a capacitor just by changing the potential at the rate of 106 V/s

Also Id = V/XC

**Maxwell's Equations:**

Maxwell formulated the elementary laws of electricity and magnetism in the form of four basic equations, now called **Maxwell's Equations.**

In the absence of any dielectric and magnetic material , the Maxwell's equations, based on experimental observations and followed by all electromagnetic phenomena, can be written in the integral form as follows:

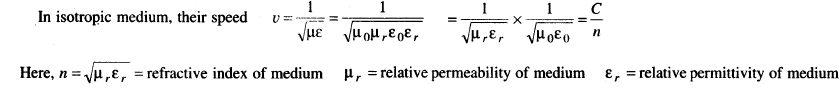


These equations are collectively called Maxwell's Equations.

**Properties of Electromagnetic Waves:**

(i) The electric and magnetic field, **E** and **B** are always perpendicular to the direction of propagation of the wave. These waves travel with the speed of light. The speed of these waves (in vacuum) is:

**C =1/√(μo∈o)**



(ii) The two fields **E** & **B** have the same frequency of oscillation and they are in phase with each other. In keeping with these features in mind, we can assume that if the electromagnetic wave is travelling along positive direction of x-axis, the electric field is oscillating parallel to y-axis and that the magnetic field is then oscillating parallel to z-axis. Then, we can write the electric and magnetic fields as sinusoidal functions of position x and time t.

E = Eo sin (kx -wt) & B = Bo sin (kx -wt) ; where Eo & Bo are the amplitudes of the fields

Further, **C = Eo/Bo =** **1/√(μo∈o)**

(iii) The rate wave is described by the vector **S** called the, **Poynting's** vector, which is defined by the following expression.

**S** =(**E** x **B**)/μo

Its magnitude S is related to the rate at which energy is transported by a wave across a unit area at any instant. The direction of Poynting's vector **S** of an electromagnetic wave at any point give the wave's direction of travel and the direction of energy transport at that point.

Since, **E** and **B** are mutually perpendicular hence, magnitude of (**E** x **B)** = EB ; thus S= EB/μo

But B = E/C therefore S = E2/μoC = CB2/μo The SI unit of Poynting's vector is J/s-m2 or W/m2.

(iv) The time average of S over one cycle is called the wave intensity. When the average is taken, we obtain an expression involving the time average of cos2(kx -wt), which equals 1/2. Thus,



(v) The energy per unit volume is the energy density u.

Energy density associated with electric field is given by: uE = ∈oE2/2

and that with magnetic field is given by: uB = B2/2μo

Using the relation, **C = Eo/Bo =** **1/√(μo∈o)**

We can show that, u = uE + uB = ∈oE2  = B2/μo

When this total instantaneous energy density is averaged over one cycle, we get a factor ½.Hence, for any electromagnetic wave, the total average energy per unit volume is:

uavg. = ∈oE2/2 = B2/2μo

(vi) If a portion of electromagnetic wave of energy U is propagating with speed C, then linear momentum of an electromagnetic wave is given by:

p = U/C

since the pressure exerted on the surface is defined a force per unit area F/A. Thus, pressure,

P = F/A = (dp/dt)/A = (dU/dt)/CA

In this expression (dU/dt) is the rate at which energy is arriving at the surface per unit area, which is the magnitude of the Poynting's vector.

Thus, the radiation pressure P exerted on the perfectly absorbing surface, P = S/C.

If the surface is a perfect reflector and incidence is normal then the momentum transported to the surface in a time t is given by:

p =2U/C and radiation pressure will be P = 2S/C

**Electromagnetic Spectrum**:

The array obtained on arranging all the electromagnetic waves in an order on the basis of their wavelengths is called the electromagnetic spectrum.

In the order of increasing wavelength these waves are: (i) Gamma rays, (ii) X-rays, (iii) Ultraviolet rays, (iv) Visible light, (v) Infrared waves, (vi) Microwaves and (vii) Radio waves.

(i) **Gamma Rays**: They were discovered by Becquerrel and Curies in 1896. Their wavelength is of the order of l0-l4 to l0-10 m, The main sources, are the natural and artificial radioactive substances. These rays affect the photographic plates. These rays are mainly used in the treatment of cancer disease.

(ii) **X-Rays**: Roentgen discovered these rays in 1895. Their wavelength is of the order of 10-12 m to 10-8 m. X-rays are produced when highly energetic cathode rays are stopped by a metal target of high melting point. They affect the photographic plate and can penetrate through transparent materials. They are mainly used in detecting the fracture of bones, hidden bullet, needle, costly material, etc. inside the body and also used in the study of crystal structure.

(iii) **Ultraviolet Rays**: They were discovered by Ritter in 1801. Their wavelength is of the order of 10-9 m to 4x l0-7 m. In the radiations received from the sun, major part is that of ultraviolet radiation. Its other sources are the electric discharge tube, carbon arc, etc. These radiations are mainly used in excitation of photoelectric effect tend to kill the bacteria of many diseases.

(iv) **Visible Light**: This was first studied by Newton in 1666. The radiations in the range of wavelength from 4 x 10-7 m to 7 x l0-7 m fall in the visible region. The wavelength of the light of violet colour is the shortest and that of red colour is the largest. Visible light is obtained from the glowing bodies while they are white hot.

(v) **Thermal or Infrared Waves**: They were discovered by Herschel in 1860. Their wavelength is of the order 7 x l0-7 m to l0-3 m. A body on being heated, emits out the infrared waves. These radiations have the maximum heating effect. The glass absorbs these radiations, therefore, for the study of these radiations, rock salt prism is used instead of a glass prism.

(vi) **Microwaves:** They were discovered by Hertz in 1888. Their wavelength is in the range of near l0-4 m to I m. These waves are produced by the spark discharge or magnetron valve. They are detected by the crystal or semiconductor detector. These waves are used mainly in radar and long distance communication.

(vii) **Radio Waves**: They were first discovered by Marconi in 1895. Their wavelength is in the range of 0.1 m to l05 m. They can be obtained by the flow of high frequency alternating current in an electric conductor. These waves are detected by the tank circuit in a radio receiver or transmitter.

**Home Assignment**

**NCERT Solved/Unsolved**

1. A plane electromagnetic wave of frequency 25 MHz travels in free space along the *x*-direction. At a particular point in space and time, **E** = 6.3 ˆ**j** V/m. What is **B** at this point?

**2.** The magnetic field in a plane electromagnetic wave is given by *By* = 2 × 10–7 sin (0.5×103*x*+1.5×1011*t*) T.

(a) What is the wavelength and frequency of the wave?

(b) Write an expression for the electric field.

3. Light with an energy flux of 18 W/cm2 falls on a non-reflecting surface at normal incidence. If the surface has an area of 20 cm2, find the average force exerted on the surface during a 30 minute time span.

4. Calculate the electric and magnetic fields produced by the radiation coming from a 100 W bulb at a distance of 3 m. Assume that the efficiency of the bulb is 2.5% and it is a point source.



5. Figure 8.6 shows a capacitor made of two circular plates each of radius 12 cm, and separated by 5.0 cm. The capacitor is being charged by an external source (not shown in the figure). The charging current is constant and equal to 0.15A.

(a) Calculate the capacitance and the rate of charge of potential difference between the plates.

(b) Obtain the displacement current across the plates.

(c) Is Kirchhoff’s first rule (junction rule) valid at each plate of the capacitor? Explain.

6. A parallel plate capacitor (Fig. 8.7) made of circular plates each of radius *R* = 6.0 cm has a capacitance *C* = 100 pF. The capacitor is connected to a 230 V ac supply with a (angular) frequency of 300 rad/s.

(a) What is the rms value of the conduction current?

(b) Is the conduction current equal to the displacement current?

(c) Determine the amplitude of **B** at a point 3.0 cm from the axis between the plates.

7. What physical quantity is the same for X-rays of wavelength 10–10 m, red light of wavelength 6800 Å and radiowaves of wavelength 500m?

8. A plane electromagnetic wave travels in vacuum along *z*-direction. What can you say about the directions of its electric and magnetic field vectors? If the frequency of the wave is 30 MHz, what is its wavelength?

9. A radio can tune in to any station in the 7.5 MHz to 12 MHz band. What is the corresponding wavelength band?

10. A charged particle oscillates about its mean equilibrium position with a frequency of 109 Hz. What is the frequency of the electromagnetic waves produced by the oscillator?

11.The amplitude of the magnetic field part of a harmonic electromagnetic wave in vacuum is *B*0 = 510 nT. What is the amplitude of the electric field part of the wave?

12.Suppose that the electric field amplitude of an electromagnetic wave is *E*0 = 120 N/C and that its frequency is ν = 50.0 MHz. (a) Determine *B*0*,*ω, *k,* and λ. (b) Find expressions for **E** and **B**.

13. In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of 2.0 × 1010 Hz and amplitude 48 V m–1.

(a) What is the wavelength of the wave? (b) What is the amplitude of the oscillating magnetic field?

(c) Show that the average energy density of the **E** field equals the average energy density of the **B** field.

14. About 5% of the power of a 100 W light bulb is converted to visible radiation. What is the average intensity of visible radiation

(a) at a distance of 1m from the bulb? (b) at a distance of 10 m?

Assume that the radiation is emitted isotropically and neglect reflection.

**Exemplar**

15. Why is the orientation of the portable radio with respect to broadcasting station important?

16.Why does microwave oven heats up a food item containing water molecules most efficiently?

17.The charge on a parallel plate capacitor varies as *q* = *q0* cos2πν*t*.The plates are very large and close together (area = *A*, separation = *d*). Neglecting the edge effects, find the displacement current through the capacitor?

18.A variable frequency a.c source is connected to a capacitor. How will the displacement current change with decrease in frequency?

19.The magnetic field of a beam emerging from a filter facing a floodlight is given by *B0* = 12 × 10–8 sin (1.20 × 107 *z* – 3.60 × 1015 *t*) T. What is the average intensity of the beam?

20. Electromagnetic waves with wavelength

(i) λ1 is used in satellite communication. (ii) λ2 is used to kill germs in water purifies.

(iii) λ3 is used to detect leakage of oil in underground pipelines.

(iv) λ4 is used to improve visibility in runways during fog and mist conditions.

(a) Identify and name the part of electromagnetic spectrum to which these radiations belong.

(b) Arrange these wavelengths in ascending order of their magnitude.

(c) Write one more application of each.

21.You are given a 2μF parallel plate capacitor. How would you establish an instantaneous displacement current of 1mA in the space between its plates?

22.Show that the radiation pressure exerted by an EM wave of intensity *I* on a surface kept in vacuum is *I*/*c*.

23.What happens to the intensity of light from a bulb if the distance from the bulb is doubled? As a laser beam travels across the length of a room, its intensity essentially remains constant. What geometrical characteristic of LASER beam is responsible for the constant intensity which is missing in the case of light from the bulb?

24. Even though an electric field **E** exerts a force *q***E** on a charged particle yet the electric field of an EM wave does not contribute to the radiation pressure (but transfers energy). Explain

**Objective Questions**

1. Which of the following rays is emitted by a human body?

(a) X-rays (b) Visible rays (c) UV-rays (d) IR-rays (e) None of these

2. An electric charge oscillating with a frequency of I kilo cycle/s can radiate electromagnetic waves of wavelength: (a) 100 km (b) 200 km (c) 300 km (d) 400 km

3. If **E** is an electric field and **B** is the magnetic induction then the energy flow per unit area per unit time in an electromagnetic field is given by: (a) **E** x **B** (b)**E.B** (c) EB/μo (d) E/B

4. The electric field strength in an electromagnetic wave is 104 V/m. The magnitude of magnetic field strength will be: (a) 104 T (b) 3 x 1012 T (c) 3.3 x 10-4 T (d) 3.3 x 10-5 T

5. In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of 2 x l0l0 Hz and amplitude 48 V/m. The wavelength of the wave is:

(a) 1.5 m (b) 1.5x l0-1 m (c) 1.5x 10-2 m (d) l.5x l0-3 m

6. Electromagnetic waves travel in a medium which has relative permeability 1.3 and relative permittivity 2.14.Speed of electromagnetic waves in this medium will be:

(a) 13.6 x 106 m/s (b) 1.8 x 106 m/s (c) 3.6 x 108 m/s (d) l.8 x 108 m/s

7. A brilliant arc lamp delivers a luminous flux of 100 W to a 1cm2 absorber. The force due to radiation pressure is: (a) 3.3 x 10-4 N (b) 16.5 x 10-7 N (c) 3.3 x 10-6 N (d) 3.3 x 10-7 N



8. A cube of edge a has its edges parallel to x, y and z-axis of rectangular co-ordinate system(fig 37.1). A uniform electric field E is parallel to y-axis and a uniform magnetic field is parallel to x-axis. The rate at which energy flows through each face of the cube is:

(a) zero in all faces

(b) a2EB /2μo parallel to XY-plane face and zero in others

(c) a2EB /μo parallel to XY-plane face and zero in others (d) a2EB /2μo in all faces

9. The amplitude of electric field in a parallel light beam of intensity 4 Wm-2 is

(a) 35.5 N/C (b) 45.5 N/C (c) 49.5 N/C (d) 55.5 N/C

10. A plane electromagnetic wave is incident on a material surface. If the wave delivers momentum p and energy E, then: (a) p=0,E=0 (b) p≠ 0,E≠0 (c) p≠0,E=0 (c) p=0,E≠0

11. The nature of electric field in the region between the two plates of a capacitor while charging is:

(a) always constant (b) varying (c) depends on values of C and R (d) depends on emf of battery

12. A radio wave has a maximum magnetic field induction of l0-4 T on arrival at a receiving antenna. The maximum electric field intensity of such a wave is

(a) zero (b) 3 x 104 V/m (c) 5.8x 10-9 V/m (d) 3.3 x 10-13 V/m

13. A radio wave of frequency 90 MHz(FM) enters a ferrite rod. In ferrite, ∈r =103 and μr =10 then the velocity and wavelength of ferrite are: (a) 3 x 106 m/s ,3.33 x 10-2 m (b) 3 x 106 m/s ,3.33 x 10-4 m

(c) 3 x 106 m/s ,3.33 x 10-3 m (d) none of the above

14.In a wave Eo = 100 V/m. Find the magnitude of Poynting's vector:

(a) 13.25 Wm-2 (b) 26.5 Wm-2 (c) 18.25 Wm-2 (d) 19.7 Wm-2

15. A radio station on the surface of the earth radiates 50 kW. If transmitter radiates equally in all directions above the surface of the earth, find the amplitude of electric field detected 100 km away:

(a) 2.45 V/m (b) 2.45 x 10-1 V/m (c) 2.45 x 10-2 V/m (d) 2.45 x 10-3 V/m

16.Find the radiation pressure of solar radiation on the surface of the earth. Solar constant is 1.4 x 103 W/m2: (a) 4.7 x 10-5 Pa (b) 4.7 x 10-6 Pa (c) 2.37 x 10-6 Pa (d) 9.4 x 10-6 Pa

17. The value of magnetic field between the plates of a capacitor at distance of 1m from centre where electric field varies by 103 V/m/s will be: (a) 5.56 T (b) 5.56 μT (c) 5.56 nT (d) 55.6 nT

18. Instantaneous displacement current of 1.0 A in the space between the parallel plates of I μF capacitor can be established by changing potential difference of:

(a) 10-6 V/s (b) 106 V/s (c) 10-8 V/s (d) 108 V/s

19. The magnetic field between the plates of radius 12 cm separated by distance of 4 mm of a parallel plate capacitor of capacitance 100 pF along the axis of plates having conduction current of 0.15 A is:

(a) zero (b) 1.5 T (c) 15T (d) 0.15T

20. An electromagnetic wave going through vacuum is described by E = Eo sin (kx -wt) & B = Bo sin (kx -wt) Which of the following equations is true?

(a) *Eok = Bow* (b) *Eow = Bok* (c) *EoBo = w* *k* (d) none of these

21. A point source of electromagnetic radiation has an average power output of 800 W. The maximum value of electric field at a distance of 4.0 m from the source is:

(a) 64.7 V/m (b) 57.8 V/m (c) 56.72 V/m (d) 54.77 V/m

22. A plane electromagnetic wave, Ez= 100 cos(6x108t +4x) V/m propagates in a medium of dielectric constant : (a) 1.5 (b) 2.0 (c) 2.4 (d) 4.0

23. The average energy density of an electromagnetic wave given by E = (50 N/C) sin (wt - kx) will be nearly :

(a) 10-8 J/m3 (b) 10-7 J/m3 (c) 10-6 J/m3 (d) 10-5 J/m3

24. A circular ring of radius r is placed in a homogeneous magnetic field perpendicular to the plane of the ring. The field B changes with time according to the equation B = kt. (where, k is a constant and t is the time). The electric field in the ring is: (a) kr/4 (b) kr/3 (c) kr/2 (d) k/2r

25. The sun delivers 104 W/m2 of electromagnetic flux to the earth's surface. The total power that is incident on a roof of dimensions (10 x l0) m2 will be: (a) 104 W (b) 105 W (c) 106 W (d) 107 W

26. A plane EM wave of wave intensity l0 W/m2 strikes a small mirror of area 2O cm2 ,held perpendicular to the approaching wave. The radiation force on the mirror will be:

(a) 6.6 x l0-ll N (b) 1.33x l0-11 N (c) 1.33x 10-l0 N (d) 6.6x l0-10 N

27. A large parallel plate capacitor, whose plates have an area of 1m2 and are separated from each other by 1 mm, is being charged at a rate of 25 V/s. If the dielectric between the plates has the dielectric constant 10, then the displacement current at this instant is: (a) 25 μA (b) 11 μA (c) 2.2μA (d) l.l μA

28. A parallel plate capacitor with plate area A and separation between the plates d, is charged by a constant current I. Consider a plane surface of area A/2 parallel to the plates and drawn simultaneously between the plates. The displacement current through this area is: (a) I (b) I/2 (c) I/4 (d) I/8

29. A plane electromagnetic wave propagating in the X-direction has wavelength of 6.0 mm. The electric field is in the Y-direction and its maximum magnitude is 33 Vm-1. The equation for the electric field as a function of x and t is: (a)11sin π (t - x/c) (b) 33sin π x 1011 (t - x/c)

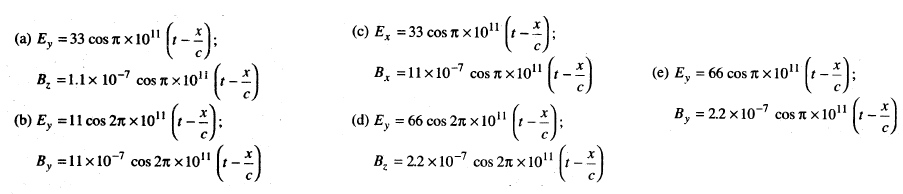
(c) 33sin π (t - x/c) (d) 11sin π x 1011 (t - x/c)

30. The rms value of the electric field of the light coming from the sun is 72O N/C. The average total energy density of the electromagnetic wave is:(a) 4.58 x 10-6 J/m3 (b) 6.37 x 10-9 J/m3

(c) 81.35 x 10-12 J/m3 (d) 3.3 x 10-3 J/m3

31. A plane electromagnetic wave travels in free space along x-axis. At a particular point in space, the electric field along y axis is 9.3 V/m. The magnetic induction is: (a) 3.1 x l0-8 T (b) 3 x l0-5 T

(c) 3 x 10-6 T (d) 9.3 x l0-6 T (e) 3.l x 10-7 T

32. A plane electromagnetic wave travelling along the X-direction has a wavelength of 3 mm. The variation in the electric field occurs in the Y-direction with an amplitude 66 Vm-1. The equation for the electric and magnetic fields as a function of x and t, are respectively:

33. Electromagnetic waves with frequencies greater than the critical frequency of ionosphere cannot be used for communication using sky wave propagation, because:

(a) the refractive index of the ionosphere becomes very light for f > fc

(b) the refractive index of the ionosphere becomes very low for f > fc

(c) the refractive index of the ionosphere becomes very high for f > fc (d) none of the above

34.The characteristic impedance (Zo) of free space is: (a) 377 Ω (b) 357 Ω (c) 100 Ω (d) 1000 Ω

35. In ruby laser, the stimulated emission is due to transition from:

(a) metastable state to any lower state (b) any higher state to lower state

(c) metastable state to ground state (d) any higher state to ground state

36. The electric field part of an electromagnetic wave in a medium is represented by Ex = 0;

Ez = 0.The wave is :

(a) moving along X-direction with frequency 106 Hz and wave length 100 m

(b) moving along X-direction with frequency 106  Hz and wavelength 200 m

(c) moving along - X- direction with frequency 106  Hz and wavelength 200 m

(d) moving along Y-direction with frequency 2π x l06  Hz and wavelength 200 m

37. The refractive index and the permeability of a medium are respectively 1.5 and 5 x 10-7 Hm-1. The relative permittivity of the medium is nearly: (a) 25 (b) 15 (c) 81 (d) 10 (e) 6

38. The magnetic field in the plane electromagnetic field is given by:

By = 2x 10-7 sin (0.5 x l03 z + 1.5 x l0l1 t) T

The expression for the electric field may be given by:

(a) Ey= 2 x 10-7 sin (0.5 x 103 z + l.5 x 10ll t) V/m (b) Ex= 2 x 10-7 sin (0.5 x 103 z + l.5 x 10ll t) V/m

(c) Ey= 60 sin (0.5 x 103 z + l.5 x 10ll t) V/m (d) Ex= 60 sin (0.5 x 103 z + l.5 x 10ll t) V/m

39. Which one of the following is the property of a monochromatic plane electromagnetic wave in free space :

(a) Electric and magnetic fields have a phase difference of π/2.

(b) The energy distribution among both electric and magnetic fields are equal.

(c) The direction of propagation is in the direction of **B x E** ?

(d) The pressure exerted by the wave is the product of its speed and energy density.

(e) The speed of the wave is B/E.

40. The electric field of an electromagnetic wave travelling through vacuum is given by the equation E = Eo sin(kx -wt). The quantity that is independent of wavelength is:

(a) *k/w* (b) *kw* (c) *w* (d) *k* (e) *k2w*

41. The electric field of a plane electromagnetic wave varies with time of amplitude 2V/m propagating along z-axis. The average energy density of the magnetic field is (in J m-3)

(a) 13.29 x 10-12 (b) 8.86 x 10-12 (c) 17.72 x 10-12 (d) 4.43 x 10-12 (e) 2.22 x 10-12

42.The electromagnetic wave having the shortest wavelength is:

(a) X-rays (b) γ-rays (c) infrared rays (d) microwaves (e) radiowaves

**Answers Objective Electromagnetic Waves**

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| 1. D | 1. C | 1. C | 1. D | 1. C | 1. D |
| 1. D | 1. C | 1. D | 1. B | 1. B | 1. B |
| 1. A | 1. B | 1. C | 1. B | 1. D | 1. B |
| 1. A | 1. A | 1. D | 1. B | 1. A | 1. C |
| 1. C | 1. C | 1. C | 1. B | 1. B | 1. A |
| 1. A | 1. D | 1. C | 1. A | 1. C | 1. B |
| 1. E | 1. D | 1. B | 1. A | 1. B | 1. B |

