

EXAMPLE 1:

Verify that $E_y = f_1(x - v_0 t)$ is a solution of $\frac{\partial^2 E_y}{\partial x^2} = \mu\epsilon \frac{\partial^2 E_y}{\partial t^2}$.

Solution

Given, $E_y = f_1(x - v_0 t)$

$$\frac{\partial E_y}{\partial x} = \frac{\partial f_1(x - v_0 t)}{\partial x}; \quad \frac{\partial^2 E_y}{\partial x^2} = \frac{\partial^2 f_1(x - v_0 t)}{\partial x^2} \quad \text{(i)}$$

$$\frac{\partial E_y}{\partial t} = -v_0 \frac{\partial f_1(x - v_0 t)}{\partial t}; \quad \frac{\partial^2 E_y}{\partial t^2} = v_0^2 \frac{\partial^2 f_1(x - v_0 t)}{\partial t^2} \quad \text{(ii)}$$

From (i) and (ii), we get,

$$\frac{\partial^2 E_y}{\partial t^2} = v_0^2 \frac{\partial^2 E_y}{\partial x^2} = \frac{1}{\mu\epsilon} \frac{\partial^2 E_y}{\partial x^2}$$

$$\boxed{\frac{\partial^2 E_y}{\partial x^2} = \mu\epsilon \frac{\partial^2 E_y}{\partial t^2}}$$

EXAMPLE 2:

The electric field intensity associated with a plane wave travelling in a perfect dielectric medium having $\mu = \mu_0$ is given by,

$$\vec{E} = 10 \cos(6\pi \times 10^7 t - 0.4\pi z) \hat{i} \text{ V/m}$$

Find the phase velocity, the permittivity of the medium and associated magnetic field vector \vec{H} . Velocity in free space = 3×10^8 m/s.

Solution

Here, $\omega = 6\pi \times 10^7$ rad/s, $\beta = 0.4\pi$

$$\text{phase velocity, } v = \frac{\omega}{\beta} = \frac{6\pi \times 10^7}{0.4\pi} = 1.5 \times 10^8 \text{ m/s}$$

$$\text{Now, } v = \frac{1}{\sqrt{\mu\epsilon}} = \frac{1}{\sqrt{\mu_0\epsilon_0}} \times \frac{1}{\sqrt{\mu_r\epsilon_r}} = \frac{c}{\sqrt{\epsilon_r}} \quad (\because \mu_r = 1)$$

$$\epsilon_r = \left(\frac{c}{v}\right)^2 = \left(\frac{3 \times 10^8}{1.5 \times 10^8}\right)^2 = 4$$

By Maxwell's equation,

$$\text{or, } \frac{\partial E_x}{\partial z} \hat{j} - \frac{\partial E_x}{\partial y} \hat{k} = -\mu_0 \left[\frac{\partial H_x}{\partial t} \hat{i} + \frac{\partial H_y}{\partial t} \hat{j} + \frac{\partial H_z}{\partial t} \hat{k} \right]$$

Comparing both sides, we get,

$$H_x = 0, H_z = 0$$

and

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} = -\mu_0 \frac{\partial \vec{H}}{\partial t}$$

$$\text{or, } \begin{vmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \\ \hat{i} & \hat{j} & \hat{k} \end{vmatrix} = -\mu_0 \left[\frac{\partial H_x}{\partial t} \hat{i} + \frac{\partial H_y}{\partial t} \hat{j} + \frac{\partial H_z}{\partial t} \hat{k} \right]$$

$$\text{or, } \begin{vmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & 0 & 0 \\ \hat{i} & \hat{j} & \hat{k} \end{vmatrix} = -\mu_0 \left[\frac{\partial H_x}{\partial t} \hat{i} + \frac{\partial H_y}{\partial t} \hat{j} + \frac{\partial H_z}{\partial t} \hat{k} \right]$$

$$\begin{aligned}
\frac{\partial H_y}{\partial t} &= -\frac{1}{\mu_0} \frac{\partial E_x}{\partial z} = -\frac{1}{\mu_0} \frac{\partial}{\partial z} [10 \cos(6\pi \times 10^7 t - 0.4\pi z)] \\
&= -\frac{1}{\mu_0} [-0.4\pi \times 10 \sin(6\pi \times 10^7 t - 0.4\pi z)] \\
&= \frac{4\pi}{\mu_0} \sin(6\pi \times 10^7 t - 0.4\pi z) \\
H_y &= \frac{4\pi}{\mu_0} \int \sin(6\pi \times 10^7 t - 0.4\pi z) dt \\
&= -\frac{4\pi}{\mu_0} \frac{1}{6\pi \times 10^7} \cos(6\pi \times 10^7 t - 0.4\pi z) \\
&= -\frac{1}{6\pi} \cos(6\pi \times 10^7 t - 0.4\pi z)
\end{aligned}$$

Hence, the magnetic field is given as,

$$\vec{H} = -\frac{1}{6\pi} \cos(6\pi \times 10^7 t - 0.4\pi z) \hat{j} \text{ A/m}$$

EXAMPLE 3:

The electric field of a uniform plane wave propagating in the positive z-direction is given by,

$$\vec{E} = E_0 \cos(\omega t - \beta z) \hat{i} + E_0 \sin(\omega t - \beta z) \hat{j}$$

where, E_0 is a constant. Find (a) the corresponding magnetic field \vec{H} , and (b) the Poynting vector. Evaluate the Poynting vector if $E_0 = 10$ V/m.

Solution

(a) By Maxwell's equation,

$$\nabla \times \vec{E} = -\mu j \omega$$

$$\text{or, } \vec{H} = -\frac{1}{j\omega\mu} \begin{vmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & 0 \\ \hat{i} & \hat{j} & \hat{k} \end{vmatrix} = -\frac{1}{j\omega\mu} \left[-\frac{\partial E_y}{\partial z} \hat{i} + \frac{\partial E_x}{\partial z} \hat{j} \right]$$

$$= -\frac{1}{j\omega\mu} \left[-\{-E_0\beta \cos(\omega t - \beta z)\} \hat{i} + \{E_0\beta \sin(\omega t - \beta z)\} \hat{j} \right]$$

$$= \frac{E_0\beta}{j\omega\mu} \left[\cos(\omega t - \beta z) \hat{i} + \sin(\omega t - \beta z) \hat{j} \right]$$

Hence, the magnetic field is given as,

$$\hat{i} \vec{H} = \frac{E_0\beta}{j\omega\mu} \left[\cos(\omega t - \beta z) \hat{i} + \sin(\omega t - \beta z) \hat{j} \right]$$

(b) The Poynting vector,

$$\vec{P} = \vec{E} \times \vec{H} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ E_x & E_y & 0 \\ H_x & H_y & 0 \end{vmatrix} = (E_x H_y - E_y H_x) \hat{k}$$

$$= \left[E_0 \cos(\omega t - \beta z) \frac{E_0\beta}{j\omega\mu} \sin(\omega t - \beta z) - E_0 \sin(\omega t - \beta z) \frac{E_0\beta}{j\omega\mu} \cos(\omega t - \beta z) \right] \hat{k}$$

$$= \frac{E_0^2\beta}{\omega\mu} \left\{ \cos^2(\omega t - \beta z) + \sin^2(\omega t - \beta z) \right\} \hat{k} \quad (\because j = 90^\circ)$$

$$\begin{aligned}
&= \frac{E_0^2 \beta}{\omega \mu} \hat{k} \\
&= E_0^2 \sqrt{\frac{\epsilon}{\mu}} \hat{k} \\
&= \frac{E_0^2}{\eta} \hat{k} \quad \eta \text{ is the intrinsic impedance}
\end{aligned}$$

$$\boxed{\bar{P} = \frac{E_0^2}{\eta} \hat{k}}$$

EXAMPLE 4:

Consider a monochromatic plane wave, where the electric field is given by

$$\vec{E} = E_0 e^{j(\omega t - kz)} \hat{i}$$

where E_0 is an arbitrary constant vector and other symbols have their usual meanings.

- Show that the electric field vector lies in a direction perpendicular to the propagation.
- Determine the corresponding magnetic field.
- Calculate the wave impedance and show that this is equal to the intrinsic impedance of the medium.

Solution

Here, $\vec{E} = E_0 e^{j(\omega t - kz)} \hat{i}$

By Maxwell's equation,

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} = -\mu_0 \frac{\partial \vec{H}}{\partial t}$$

$$\text{or, } \begin{vmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & 0 & 0 \\ \hat{i} & \hat{j} & \hat{k} \end{vmatrix} = -\mu_0 \left[\frac{\partial H_x}{\partial t} \hat{i} + \frac{\partial H_y}{\partial t} \hat{j} + \frac{\partial H_z}{\partial t} \hat{k} \right]$$

$$\text{or, } \frac{\partial E_x}{\partial z} \hat{j} = -\mu_0 \left[\frac{\partial H_x}{\partial t} \hat{i} + \frac{\partial H_y}{\partial t} \hat{j} + \frac{\partial H_z}{\partial t} \hat{k} \right] \quad (\because E_x = f(t, z))$$

Comparing both sides, we get,

$$H_x = 0, H_z = 0$$

and

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_x}{\partial z} = -\frac{1}{\mu_0} \frac{\partial}{\partial z} [E_0 e^{j(\omega t - kz)}] = j \frac{E_0 k}{\mu_0} e^{j(\omega t - kz)}$$
$$H_y = j \frac{E_0 k}{\mu_0} \int e^{j(\omega t - kz)} dt = j \frac{E_0 k}{\mu_0} \frac{1}{j\omega} e^{j(\omega t - kz)} = \frac{E_0 k}{\mu_0 \omega} e^{j(\omega t - kz)}$$

(a) Here, the electric field propagates in the x -direction and the magnetic field propagates in the y -direction whereas the wave propagates in the z -direction. Thus, we can say that the electric field vector lies in a direction perpendicular to the propagation.

Since the electric field is directed across unit vector \hat{i} and the magnetic field is directed across the unit vector \hat{j} , we conclude that the two fields are perpendicular to each other.

(b) The corresponding magnetic field is given as,

$$\vec{H} = \frac{E_0 k}{\mu_0 \omega} e^{j(\omega t - kz)} \hat{j}$$

(c) The wave impedance is given as,

$$\eta = \left| \frac{\vec{E}}{\vec{H}} \right| = \frac{\mu_0 \omega}{k} = \frac{\mu_0 2\pi f}{2\pi/\lambda} = \mu_0 f \lambda = \mu_0 c = \mu_0 \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi$$

This is equal to the intrinsic impedance of the medium.

EXAMPLE 5:

Find the depth of penetration of a megacycle wave into copper which has a conductivity of $\sigma = 5.8 \times 10^7$ mho/m and a permeability approximately equal to that of free space.

Solution

Given, $\sigma = 5.8 \times 10^7$ mho/m, $f = 1$ MHz, $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m
depth of penetration is,

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{1}{\sqrt{f\pi\mu\sigma}} = \frac{1}{\sqrt{1 \times 10^6 \times \pi \times 4\pi \times 10^{-7} \times 5.8 \times 10^7}} = 6.602 \times 10^{-5} \text{ m}$$

EXAMPLE 6:

For sea water with $\sigma = 5$ mho/m and $\epsilon_r = 80$, $\mu = \mu_0$, find the distance a radio signal can be transmitted at 25 kcps and 25 Mcps, if the range is taken to be the distance at which 90% of the wave amplitude is attenuated.

Solution

The wave is attenuated by the factor $e^{-\alpha x}$. In this case, the wave is attenuated to 90%.

$$e^{-\alpha x} = 0.1 \Rightarrow -\alpha x = \ln(0.1) \Rightarrow x = \frac{2.302}{\alpha}$$

$$\text{Also, } \alpha = \omega \sqrt{\frac{\mu\epsilon}{2} \left(\sqrt{1 + \frac{\sigma^2}{\omega^2\epsilon^2}} - 1 \right)}$$

Substituting the given values, we have the following results.

For 25 kcps,

$$\alpha = 2\pi \times 25 \times 10^3 \sqrt{\frac{4\pi \times 10^{-7} \times 80 \times 8.854 \times 10^{-12}}{2} \left(\sqrt{1 + \frac{5^2}{(2\pi \times 25 \times 10^3)^2 (8.854 \times 10^{-12})^2}} - 1 \right)}$$
$$= 0.7025$$

$$x = \frac{2.302}{0.7025} = 3.278 \text{ m}$$

For 25 Mcps,

$$\alpha = 2\pi \times 25 \times 10^6 \sqrt{\frac{4\pi \times 10^{-7} \times 80 \times 8.854 \times 10^{-12}}{2} \left(\sqrt{1 + \frac{5^2}{(2\pi \times 25 \times 10^6)^2 (8.854 \times 10^{-12})^2}} - 1 \right)}$$
$$= 21.969$$

$$x = 21.969 = 0.105 \text{ m}$$

EXAMPLE 7:

(a) A plane wave $\vec{E} = E_0 \cos(\omega t - \beta z) \hat{i}$ is incident on a good conductor at $z = 0$. Find the current density in the conductor.

(b) Due to this current density, find the magnitude of the total current through a strip of the conductor of infinite depth along z and width w along y .

Solution

(a) we get,

$$\nabla^2 E_S - \gamma^2 E_S = 0$$

Using Ohm's law, $\mathbf{J} = \sigma \mathbf{E}$, we get in time-harmonic form,

$$\nabla^2 \mathbf{J}_S - \gamma^2 \mathbf{J}_S = 0$$

Since \mathbf{E} has only the x -component which is a function of z only the above equation reduces to an ordinary differential equation given as,

$$\frac{d^2}{dz^2} \mathbf{J}_S - \gamma^2 \mathbf{J}_S = 0$$

Solving,

$$J = K_1 e^{-\gamma z} + K_2 e^{\gamma z}$$

Since the current is finite as $z \rightarrow \infty$, $K_2 = 0$

$$J = K_1 e^{-\gamma z}$$

Also, for a good conductor, $\gamma = \alpha + j\beta = \alpha(1 + j) = \frac{1 + j}{\delta}$

where δ is the skin depth.

$$J = K_1 e^{-\left(\frac{1+j}{\delta}\right)z}$$

This current density can be written as,

$$J = J(0) e^{-\left(\frac{1+j}{\delta}\right)z}$$

where $J(0)$ is the current density at $z = 0$, i.e., on the surface of the conductor.

(b) Total current is given as,

$$I = \int_S \vec{J} \cdot d\vec{s} = \int_{y=0}^w \int_{z=0}^{\infty} J(0) e^{-\left(\frac{1+j}{\delta}\right)z} dy dz = J(0)w \int_{z=0}^{\infty} e^{-\left(\frac{1+j}{\delta}\right)z} dz = \frac{J(0)w}{-\frac{1+j}{\delta}} \left[e^{-\left(\frac{1+j}{\delta}\right)z} \right]_0^{\infty}$$

$$= \frac{J(0)w\delta}{-(1+j)} (e^{-\infty} - e^0)$$

$$= \frac{J(0)w\delta}{(1+j)}$$

The magnitude of the current is

$$I = \frac{J(0)w\delta}{\sqrt{2}}$$

EXAMPLE 8:

The x - and y -components of a circularly polarised electromagnetic wave in free space are,

$$E_x = 2 \sin(\omega t - \beta z)$$

$$E_y = 2 \cos(\omega t - \beta z)$$

Find the expression for the displacement current density and draw a neat sketch showing the fields.

Solution

Here, the magnitude of the electric field having circular Polarisation and components as given is,

$$|E| = \sqrt{E_x^2 + E_y^2} = \sqrt{2^2 \cos^2(\omega t - \beta z) + 2^2 \sin^2(\omega t - \beta z)} = 2$$

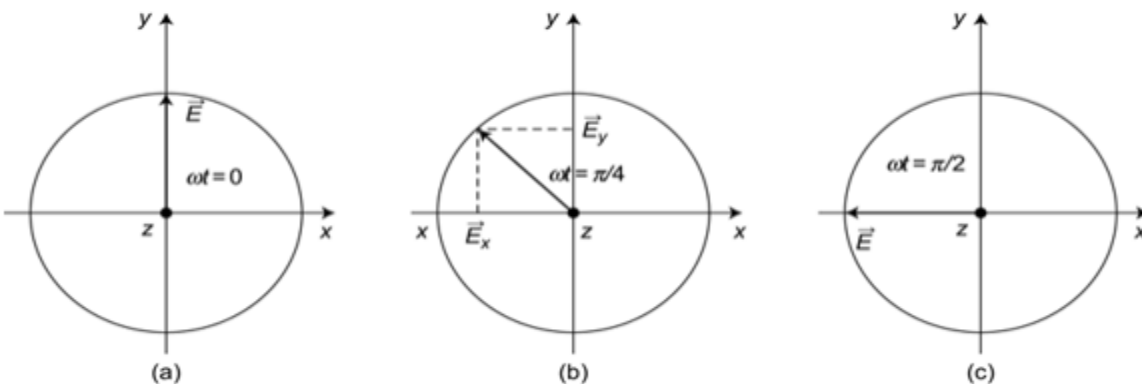
The displacement current density is,

$$\vec{J}_d = \frac{\partial \vec{D}}{\partial t} = \frac{\partial}{\partial t}(\epsilon \vec{E}) = j\omega \epsilon \vec{E}$$

$$J_d = |\vec{J}_d| = |j\omega \epsilon \vec{E}| = 2\omega \epsilon E$$

$$\boxed{J_d = 2\omega \epsilon E}$$

The electric field is plotted in the $z = 0$ plane for different values of ωt as shown in the figure.



Electric field in $z = 0$ plane with three conditions: (a) $\omega t = 0$ (b) $\omega t = \frac{\pi}{4}$

(c) $\omega t = \frac{\pi}{2}$

EXAMPLE 9:

Calculate the power flow for a plane wave using the Poynting theorem.

Solution

Velocity of a uniform plane wave, $v = \frac{1}{\sqrt{\mu\epsilon}}$

The total energy density due to electric and magnetic fields is given by $\frac{1}{2}(\epsilon E^2 + \mu H^2)$

Rate of flow of energy per unit area,

$$\begin{aligned}
 P &= \frac{1}{2}(\epsilon E^2 + \mu H^2)v = \frac{1}{2}\left(\epsilon\sqrt{\frac{\mu}{\epsilon}}EH + \mu\sqrt{\frac{\epsilon}{\mu}}EH\right)v \quad \left\{ \because \frac{E}{H} = \sqrt{\frac{\mu}{\epsilon}} \right\} \\
 &= \frac{1}{2}EH(2\sqrt{\epsilon\mu})v \\
 &= vEH\sqrt{\epsilon\mu} \\
 &= vEH\frac{1}{v} \\
 &= EH
 \end{aligned}$$

Since the angle between \vec{E} and \vec{H} is 90° , the power flow can be written as,

$$\boxed{\vec{P} = \vec{E} \times \vec{H}}$$

EXAMPLE 10:

A sinusoidal plane wave is transmitted through a medium whose breakdown strength is 30 kV/m (rms) and whose relative permittivity is 4. Determine the mean possible power flow density and the peak value of the associated magnetic field intensity.

Solution

The mean power density is,

$$P_{av} = \frac{1}{2} \frac{E^2}{\eta} = \frac{E_{rms}^2}{\eta}$$

$$\text{Here, } \eta = \sqrt{\frac{\mu}{\epsilon}} = \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}} = \sqrt{\frac{\mu_0}{\epsilon_0}} \sqrt{\frac{\mu_r}{\epsilon_r}} = 120\pi \times \sqrt{\frac{1}{4}} = 60\pi \Omega$$

$$P_{av} = \frac{(30 \times 10^3)^2}{60\pi} = 4774.65 \text{ kW/m}^2$$

$$\text{Also, } H_{rms} = \frac{E_{rms}}{\eta} = \frac{P_{av}}{E_{rms}}$$

peak value of the magnetic field is,

$$H_0 = \sqrt{2} \times \frac{P_{av}}{E_{rms}} = \sqrt{2} \times \frac{4774.65 \times 10^3}{30 \times 10^3} = 225 \text{ A/m}$$

EXAMPLE 11:

Assume a plane wave with $E = 1 \text{ V/m}$ and a frequency of $300 \times 10^6 \text{ cps}$ moving in free space, impinges on a thick copper plate located perpendicularly to the direction of propagation. Find

- E at the plane surface
- H at the same location
- δ , depth of penetration
- Conduction current density at the surface
- J , the conduction current density, at the depth of 10-2 mm
- Surface current density
- Surface impedance
- Power loss per square metre of surface area

Assume $\sigma = 5.8 \times 10^7 \text{ mho/m}$. $\epsilon = \epsilon_0$, $\mu = \mu_0$.

Solution

Given: $E_i = 1 \text{ V/m}$, $f = 300 \times 10^6 \text{ cps}$

(a) Here, $\eta_1 = 377 \Omega$

$$\eta_2 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} = \sqrt{\frac{j \times 2\pi \times 300 \times 10^6 \times 4\pi \times 10^{-7}}{5.8 \times 10^7 + j \times 2\pi \times 300 \times 10^6 \times 8.854 \times 10^{-12}}}$$
$$= 6.39 \times 10^{-3} \angle 45^\circ$$

\therefore transmission coefficient is,

$$\frac{E_t}{E_i} = \frac{2\eta_2}{\eta_2 + \eta_1} = \frac{2 \times 6.39 \times 10^{-3} \angle 45^\circ}{6.39 \times 10^{-3} \angle 45^\circ + 377} = 3.39 \times 10^{-5} \angle 45^\circ$$
$$\frac{E_t}{1} = 3.39 \times 10^{-5} \angle 45^\circ \quad \Rightarrow \quad E_t = 3.39 \times 10^{-5} \angle 45^\circ \text{ V/m}$$

(b)

$$\frac{H_t}{H_i} = \frac{2\eta_1}{\eta_2 + \eta_1} = \frac{2 \times 377}{6.39 \times 10^{-3} \angle 45^\circ + 377} = 2$$
$$H_t = 2H_i = 2 \frac{E_i}{\eta_1} = \frac{2 \times 1}{377} = 5.3 \times 10^{-3} \text{ A/m}$$

(c) Depth of penetration,

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{2}{2\pi \times 300 \times 10^6 \times 4\pi \times 10^{-7} \times 5.8 \times 10^7}} = 3.81 \times 10^{-6} \text{ m} = 3.81 \mu\text{m}$$

(d) Conduction current density at the surface is,

$$J_0 = \sigma E_t = 5.8 \times 10^7 \times 3.39 \times 10^{-5} \angle 45^\circ = 1966 \angle 45^\circ \text{ A/m}^2$$

(e) At a distance x below the surface, the conduction current density is given as,

$$J = J_0 e^{-\gamma x}$$

where,

$$\gamma = \sqrt{j\omega\mu\sigma} = \sqrt{2\pi \times 300 \times 10^6 \times 4\pi \times 10^{-7} \times 5.8 \times 10^7} \angle 45^\circ = 3.7 \times 10^5 \angle 45^\circ$$
$$\text{Re}[\gamma] = 3.7 \times 10^5 \cos 45^\circ = 2.62 \times 10^5$$

So, at a distance, $x = 0.01 \times 10^{-3}$ m, the conduction current density is,

$$J = 1966 e^{-2.62 \times 10^5 \times 10^{-3}} \angle 45^\circ = 144 \angle 45^\circ \text{ A/m}^2$$

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(f) According to the boundary condition, the surface current density is equal to the tangential component of the magnetic field. From the result of (b), we have the surface current density given as,

$$K = 5.3 \times 10^{-3} \text{ A/m}$$

(g) Surface impedance is given as,

$$Z_s = \sqrt{\frac{\omega\mu}{\sigma}} \angle 45^\circ = \sqrt{\frac{2\pi \times 300 \times 10^6 \times 4\pi \times 10^{-7}}{5.8 \times 10^7}} \angle 45^\circ = 6.39 \times 10^{-3} \angle 45^\circ \Omega$$

(h) Power loss per square metre of surface area is,

$$p_{ave} = \frac{1}{4} E^2 \sigma \delta = \frac{1}{4} (3.39 \times 10^{-5})^2 \times 5.8 \times 10^7 \times 3.81 \times 10^{-6} = 6.35 \times 10^{-8} \text{ W/m}^2$$