APPENDIX B

Material Constants of Some Common Materials

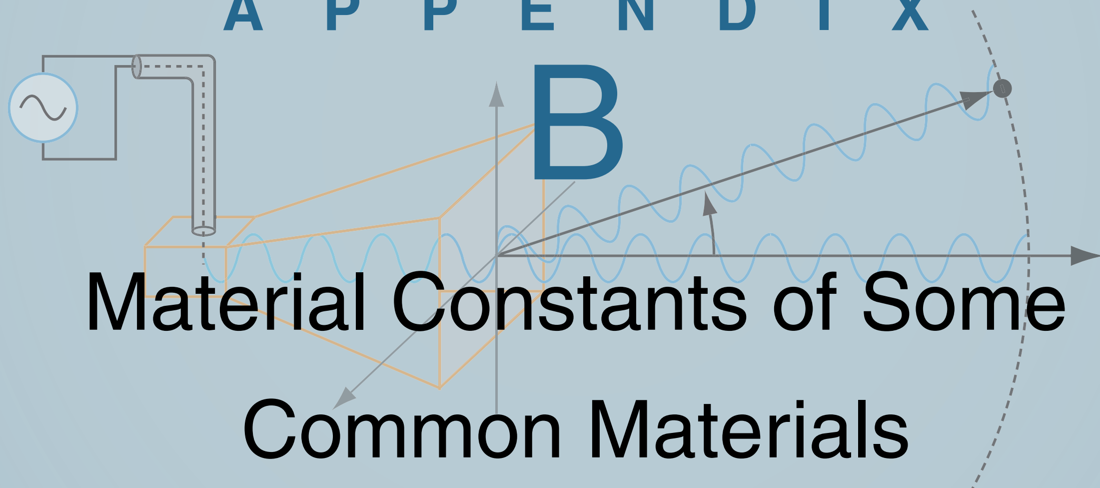


Table B-1 RELATIVE PERMITTIVITY ϵ_r OF COMMON MATERIALS[a]

$\epsilon = \epsilon_r \epsilon_0$ and $\epsilon_0 = 8.854 \times 10^{-12}$ F/m.

Material	Relative Permittivity, ϵ_r	Material	Relative Permittivity, ϵ_r
Vacuum	1	Dry soil	2.5–3.5
Air (at sea level)	1.0006	Plexiglass	3.4
Styrofoam	1.03	Glass	4.5–10
Teflon	2.1	Quartz	3.8–5
Petroleum oil	2.1	Bakelite	5
Wood (dry)	1.5–4	Porcelain	5.7
Paraffin	2.2	Formica	6
Polyethylene	2.25	Mica	5.4–6
Polystyrene	2.6	Ammonia	22
Paper	2–4	Seawater	72–80
Rubber	2.2–4.1	Distilled water	81

[a]These are low-frequency values at room temperature (20° C).

Note: For most metals, $\epsilon_r \simeq 1$.

Table B-2 CONDUCTIVITY σ OF SOME COMMON MATERIALS[a]

Material	Conductivity, σ (S/m)	Material	Conductivity, σ (S/m)
Conductors		**Semiconductors**	
Silver	6.2×10^7	Pure germanium	2.2
Copper	5.8×10^7	Pure silicon	4.4×10^{-4}
Gold	4.1×10^7	**Insulators**	
Aluminum	3.5×10^7	Wet soil	$\sim 10^{-2}$
Tungsten	1.8×10^7	Fresh water	$\sim 10^{-3}$
Zinc	1.7×10^7	Distilled water	$\sim 10^{-4}$
Brass	1.5×10^7	Dry soil	$\sim 10^{-4}$
Iron	10^7	Glass	10^{-12}
Bronze	10^7	Hard rubber	10^{-15}
Tin	9×10^6	Paraffin	10^{-15}
Lead	5×10^6	Mica	10^{-15}
Mercury	10^6	Fused quartz	10^{-17}
Carbon	3×10^4	Wax	10^{-17}
Seawater	4		
Animal body (average)	0.3 (poor cond.)		

[a]These are low-frequency values at room temperature (20° C).

Table B-3 RELATIVE PERMEABILITY μ_r OF SOME COMMON MATERIALS[a]

$\mu = \mu_r \mu_0$ and $\mu_0 = 4\pi \times 10^{-7}$ H/m.

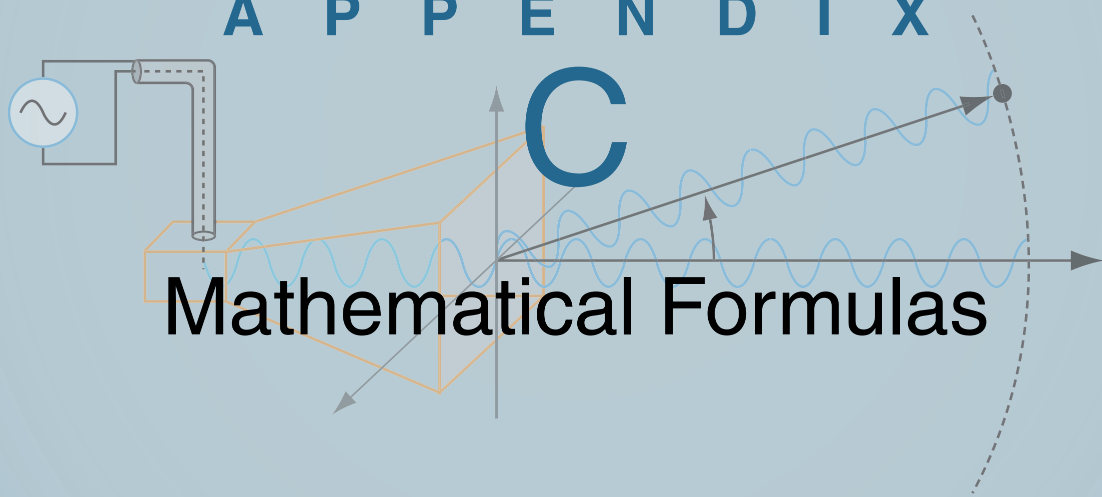
Material	Relative Permeability, μ_r
Diamagnetic	
Bismuth	$0.99983 \simeq 1$
Gold	$0.99996 \simeq 1$
Mercury	$0.99997 \simeq 1$
Silver	$0.99998 \simeq 1$
Copper	$0.99999 \simeq 1$
Water	$0.99999 \simeq 1$
Paramagnetic	
Air	$1.000004 \simeq 1$
Aluminum	$1.00002 \simeq 1$
Tungsten	$1.00008 \simeq 1$
Titanium	$1.0002 \simeq 1$
Platinum	$1.0003 \simeq 1$
Ferromagnetic (nonlinear)	
Cobalt	250
Nickel	600
Mild steel	2,000
Iron (pure)	4,000–5,000
Silicon iron	7,000
Mumetal	$\sim 100,000$
Purified iron	$\sim 200,000$

[a]These are typical values; actual values depend on material variety.

Note: Except for ferromagnetic materials, $\mu_r \simeq 1$ for all dielectrics and conductors.

APPENDIX C

Mathematical Formulas



Trigonometric Relations

$$\sin(x \pm y) = \sin x \cos y \pm \cos x \sin y$$

$$\cos(x \pm y) = \cos x \cos y \mp \sin x \sin y$$

$$2 \sin x \sin y = \cos(x - y) - \cos(x + y)$$

$$2 \sin x \cos y = \sin(x + y) + \sin(x - y)$$

$$2 \cos x \cos y = \cos(x + y) + \cos(x - y)$$

$$\sin 2x = 2 \sin x \cos x$$

$$\cos 2x = 1 - 2 \sin^2 x$$

$$\sin x + \sin y = 2 \sin\left(\frac{x+y}{2}\right) \cos\left(\frac{x-y}{2}\right)$$

$$\sin x - \sin y = 2 \cos\left(\frac{x+y}{2}\right) \sin\left(\frac{x-y}{2}\right)$$

$$\cos x + \cos y = 2 \cos\left(\frac{x+y}{2}\right) \cos\left(\frac{x-y}{2}\right)$$

$$\cos x - \cos y = -2 \sin\left(\frac{x+y}{2}\right) \sin\left(\frac{x-y}{2}\right)$$

$$\cos(x \pm 90^\circ) = \mp \sin x$$

$$\cos(-x) = \cos x$$

$$\sin(x \pm 90^\circ) = \pm \cos x$$

$$\sin(-x) = -\sin x$$

$$e^{jx} = \cos x + j \sin x \qquad \text{(Euler's identity)}$$

$$\sin x = \frac{e^{jx} - e^{-jx}}{2j}$$

$$\cos x = \frac{e^{jx} + e^{-jx}}{2}$$

Approximations for Small Quantities

For $|x| \ll 1$,

$$(1 \pm x)^n \simeq 1 \pm nx$$

$$(1 \pm x)^2 \simeq 1 \pm 2x$$

$$\sqrt{1 \pm x} \simeq 1 \pm \frac{x}{2}$$

$$\frac{1}{\sqrt{1 \pm x}} \simeq 1 \mp \frac{x}{2}$$

$$e^x = 1 + x + \frac{x^2}{2!} + \cdots \simeq 1 + x$$

$$\ln(1 + x) \simeq x$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} + \cdots \simeq x$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} + \cdots \simeq 1 - \frac{x^2}{2}$$

$$\lim_{x \to 0} \frac{\sin x}{x} = 1$$

APPENDIX D

Answers to Selected Problems

Chapter 1

1.1 5 cm

1.3 $p(x, t) = 51.04 \cos(4\pi \times 10^3 t - 12.12\pi x + 36°)$ $(\mathrm{N/m^2})$

1.6 $u_p = 0.83$ (m/s); $\lambda = 10.47$ m

1.8 **(a)** $y_1(x, t)$ is traveling in positive x direction. $y_2(x, t)$ is traveling in negative x direction.

1.10 $y_2(t)$ lags $y_1(t)$ by 54°.

1.12 $T = 1.25$ s; $u_p = 0.28$ m/s; $\lambda = 0.35$ m

1.14 $\alpha = 2 \times 10^{-3}$ (Np/m)

1.16 **(c)** $z_1 z_2 = 18e^{j109.4°}$

1.17 **(b)** $z_2 = \sqrt{3}\, e^{j3\pi/4}$

1.19 **(c)** $|z|^2$,

1.20 **(d)** $t = 0$; $s = 6\, e^{j30°}$

1.22 $\ln(z) = 1.76 + j1.03$

1.25 $v_c(t) = 15.57 \cos(2\pi \times 10^3 t - 81.5°)$ V

1.26 **(d)** $i(t) = 3.61 \cos(\omega t + 146.31°)$ A

1.27 **(d)** $\tilde{I} = 2e^{j\pi/4}$ A

Chapter 2

2.2 **(a)** $l/\lambda = 2 \times 10^{-5}$; transmission line may be ignored.

(c) $l/\lambda = 0.6$; transmission line effects should be included.

2.4 $R' = 0.69$ (Ω/m), $L' = 1.57 \times 10^{-7}$ (H/m), $G' = 0$, $C' = 1.84 \times 10^{-10}$ (F/m)

2.7 $\alpha = 0.109$ Np/m; $\beta = 44.5$ rad/m; $Z_0 = (19.6 + j0.030)\ \Omega$; $u_p = 1.41 \times 10^8$ m/s

2.10 $w = 0.613$ mm, $\lambda = 0.044$ m

2.14 $R' = 0.5$ (Ω/m); $L' = 200$ (nH/m); $G' = 200$ (μS/m); $C' = 80$ (pF/m); $\lambda = 2.5$ m

2.16 $R' = 0.4$ Ω/m, $L' = 38.2$ nH/m, $G' = 0.25$ mS/m, $C' = 23.9$ pF/m

2.17 **(a)** $b = 4.2$ mm

(b) $u_p = 2 \times 10^8$ m/s

2.22 $Z_L = (120.5 - j89.3)$ Ω

2.23 $Z_0 = 70.7$ Ω

2.29 $Z_{in} = (40 + j20)$ Ω

2.31 **(b)** $\Gamma = 0.16\, e^{-j80.54^\circ}$.

2.32 **(a)** $\Gamma = 0.62 e^{-j29.7^\circ}$

2.33 **(a)** $Z_{in_1} = (35.20 - j8.62)$ Ω

2.35 $L = 8.3 \times 10^{-9}$ H

2.36 $l = \lambda/4 + n\lambda/2$

2.39 $Z_{in} = \dfrac{100^2}{33.33} = 300$ Ω

2.41 **(b)** $i_L(t) = 3\cos(6\pi \times 10^8 t - 135^\circ)$ (A)

2.42 **(a)** $Z_{in} = (41.25 - j16.35)$ Ω

2.44 $P^i_{av} = 10.0$ mW; $P^r_{av} = -1.1$ mW; $P^t_{av} = 8.9$ mW

2.45 **(a)** $P_{av} = 0.29$ W

2.48 **(b)** $\Gamma = 0.62 \exp -29.7^\circ$

2.50 $Z_{in} = (66 - j125)$ Ω

2.52 **(b)** $S = 1.64$

2.53 $Z_{01} = 40$ Ω; $Z_{02} = 250$ Ω

2.55 **(a)** $Z_{in} = -j154$ Ω

(b) $0.074\lambda + (n\lambda/2)$, $n = 0, 1, 2, \ldots$

2.57 The reciprocal of point Z is at point Y, which is at $0.55 + j0.26$.

2.61 $Z_L = (41 - j19.5)$ Ω

2.63 $Z_{in} = (95 - j70)$ Ω

2.69 First solution: Stub at $d = 0.199\lambda$ from antenna and stub length $l = 0.125\lambda$. Second solution: $d = 0.375\lambda$ from antenna and stub length $l = 0.375\lambda$.

2.73 $Z_{in} = 100$ Ω

2.78 $V_g = 19.2$ V; $R_g = 30$ Ω; $l = 700$ m

2.80 **(a)** $l = 600$ m

(b) $Z_L = 0$

(c) $R_g = \left(\dfrac{1+\Gamma_g}{1-\Gamma_g}\right) Z_0 = \left(\dfrac{1+0.25}{1-0.25}\right) 50 = 83.3$ Ω

(d) $V_g = 32$ V

Chapter 3

3.2 $\hat{\mathbf{a}} = \hat{\mathbf{x}}\,0.32 - \hat{\mathbf{z}}\,0.95$

3.3 Area $= 36$

3.5 **(a)** $A = \sqrt{14}$; $\hat{\mathbf{a}}_A = (\hat{\mathbf{x}} + \hat{\mathbf{y}}2 - \hat{\mathbf{z}}3)/\sqrt{14}$

(e) $\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) = 20$

(h) $(\mathbf{A} \times \hat{\mathbf{y}}) \cdot \hat{\mathbf{z}} = 1$

3.9 $\hat{\mathbf{a}} = \dfrac{\mathbf{A}}{|\mathbf{A}|} = \dfrac{-\hat{\mathbf{x}} - \hat{\mathbf{y}}y - \hat{\mathbf{z}}2}{\sqrt{5 + y^2}}$

3.10 $\hat{\mathbf{a}} = (\hat{\mathbf{x}}3 - \hat{\mathbf{z}}6)/\sqrt{45}$

3.12 $\mathbf{A} = \hat{\mathbf{x}}\,0.8 + \hat{\mathbf{y}}\,1.6$

3.15 $\hat{\mathbf{c}} = \hat{\mathbf{x}}\,0.37 + \hat{\mathbf{y}}\,0.56 + \hat{\mathbf{z}}\,0.74$

3.17 $\mathbf{G} = \pm\left(-\hat{\mathbf{x}}\,\frac{8}{3} + \hat{\mathbf{y}}\,\frac{8}{3} + \hat{\mathbf{z}}\,\frac{4}{3}\right)$

3.23 **(a)** $P_1 = (2.24,\ 63.4^\circ,\ 0)$ in cylindrical; $P_1 = (2.24,\ 90^\circ,\ 63.4^\circ)$ in spherical

(d) $P_4 = (2.83, 135^\circ, -2)$ in cylindrical; $P_4 = (3.46, 125.3^\circ, 135^\circ)$ in spherical

3.24 **(a)** $P_1 = (0, 0, 5)$

3.25 **(c)** $A = 12$

3.27 **(a)** $V = 21\pi/2$

3.30 **(a)** $\theta_{AB} = 90^\circ$

(b) $\pm(\hat{\mathbf{r}}\,0.487 + \hat{\boldsymbol{\phi}}\,0.228 + \hat{\mathbf{z}}\,0.843)$

3.31 (a) $d = \sqrt{3}$

3.34 (c) $\mathbf{C}(P_3) = \hat{\mathbf{r}}0.707 + \hat{\mathbf{z}}4$

(e) $\mathbf{E}(P_5) = -\hat{\mathbf{r}} + \hat{\boldsymbol{\phi}}$

3.35 (c) $\mathbf{C}(P_3) = \hat{\mathbf{R}}0.854 + \hat{\boldsymbol{\theta}}0.146 - \hat{\boldsymbol{\phi}}0.707$

3.36 (e) $\nabla S = \hat{\mathbf{x}}8xe^{-z} + \hat{\mathbf{y}}3y^2 - \hat{\mathbf{z}}4x^2e^{-z}$

3.37 (b) $\nabla T = \hat{\mathbf{x}}\,2x$

(g) $\nabla T = -\hat{\mathbf{x}}\,\frac{2\pi}{6}\sin\left(\frac{\pi x}{3}\right)$

3.38 $T(z) = 10 + (1 - e^{-4z})/4$

3.39 $\left(\frac{dV}{dl}\right)\Big|_{(1,-1,2)} = 1.34$

3.42 $dU/dl = -0.02$

3.46 $\mathbf{E} = \hat{\mathbf{R}}2R$

3.48 (a) $\oint \mathbf{D} \cdot d\mathbf{s} = 150\pi$

(b) $\iiint \nabla \cdot \mathbf{D}\, d\mathcal{V} = 150\pi$

3.56 (a) **A** is solenoidal, but not conservative.

(d) **D** is conservative, but not solenoidal.

(h) **H** is conservative, but not solenoidal.

3.58 (c) $\nabla^2\left(\frac{3}{x^2+y^2}\right) = \frac{12}{(x^2+y^2)^2}$

Chapter 4

4.2 $Q = 2.62$ (mC)

4.3 $Q = 260$ (mC)

4.7 $I = 314.2$ A

4.8 (a) $\rho_l = -\frac{\pi c a^4}{2}$ (C/m)

4.11 $\mathbf{E} = \hat{\mathbf{z}}\,51.2$ kV/m

4.12 $q_2 \approx -94.69$ (μC)

4.15 (a) $\mathbf{E} = -\hat{\mathbf{x}}\,1.6 - \hat{\mathbf{y}}\,0.66$ (MV/m)

4.17 $\mathbf{E} = \hat{\mathbf{z}}\,(\rho_{s0}h/2\epsilon_0)\left[\sqrt{a^2+h^2} + h^2/\sqrt{a^2+h^2} - 2h\right]$

4.20 $\mathbf{E} = -\hat{\mathbf{y}}\,\frac{\rho_l}{\pi\epsilon_0 R_1}\,\frac{R_1}{R_2} + \hat{\mathbf{y}}\,\frac{\rho_l}{\pi\epsilon_0 R_2} = 0$

4.23 (a) $\rho_v = y^3 z^3$

(b) $Q = 32$ (C)

(c) $Q = 32$ (C)

4.25 $Q = 4\pi\rho_0 a^3$ (C)

4.26 $\mathbf{D} = \hat{\mathbf{r}}\,\frac{\rho_{v0}(r^2-1)}{2r}, \quad 1 \le r \le 2$ m

$\mathbf{D} = \hat{\mathbf{r}}\,D_r = \hat{\mathbf{r}}\,\frac{3\rho_{v0}}{2r}, \quad r \ge 2$ m

4.30 $R_1 = \frac{a}{2},\ R_3 = \frac{a\sqrt{5}}{2},\ V = \frac{0.55Q}{\pi\epsilon_0 a}$

4.33 (b) $\mathbf{E} = \hat{\mathbf{z}}(\rho_l a/2\epsilon_0)[z/(a^2+z^2)^{3/2}]$ (V/m)

4.34 $V(b) = (\rho_l/4\pi\epsilon)$
$\times \ln\left[\frac{l + \sqrt{l^2+4b^2}}{-l + \sqrt{l^2+4b^2}}\right]$ (V)

4.37 $V =$
$\frac{\rho_l}{2\pi\epsilon_0}\left[\ln\left(\frac{a}{\sqrt{(x-a)^2+y^2}}\right) - \ln\left(\frac{a}{\sqrt{(x+a)^2+y^2}}\right)\right]$

4.40 $V_{AB} = -234.18$ V

4.41 (c) $\mathbf{u}_e = -8.125\mathbf{E}/|\mathbf{E}|$ (m/s); $\mathbf{u}_h = 3.125\mathbf{E}/|\mathbf{E}|$ (m/s)

4.45 $R = 4.2$ (mΩ)

4.48 $\theta = 61°$

4.50 $Q = 3\pi\epsilon_0$ (C)

4.52 (a) $|E|$ is maximum at $r = a$.

4.56 $W_e = 4.62 \times 10^{-9}$ (J)

4.57 (a) $C = 3.1$ pF

4.60 (b) $C = 6.07$ pF

4.63 $C' = \frac{\pi\epsilon_0}{\ln[(2d/a) - 1]}$ (C/m)

Chapter 5

5.1 $\mathbf{a} = -\hat{\mathbf{y}}8.44 \times 10^{18}$ (m/s^2)

5.4 $\mathbf{T} = -\hat{\mathbf{z}}1.66$ (N·m); clockwise

5.5 **(a)** $\mathbf{F} = 0$

5.9 $\mathbf{H} = \hat{\mathbf{z}}\dfrac{I\theta\,(b-a)}{4\pi ab}$

5.10 $\mathbf{B} = -\hat{\mathbf{z}}0.6$ (mT)

5.11 $I_2 = \dfrac{2aI_1}{2\pi Nd} = \dfrac{1 \times 50}{\pi \times 20 \times 2} = 0.4$ A

5.14 $I = 100$ A

5.16 $\mathbf{F} = -\hat{\mathbf{x}}0.8$ (mN)

5.18 **(a)** $\mathbf{H}(0, 0, h) = -\hat{\mathbf{x}}\,\dfrac{I}{\pi w}\tan^{-1}\left(\dfrac{w}{2h}\right)$ (A/m)

5.20 $\mathbf{F} = \hat{\mathbf{y}}\,8 \times 10^{-5}$ N

5.24 $\mathbf{J} = \hat{\mathbf{z}}\,9e^{-3r}$ A/m^2

5.26 **(a)** $\mathbf{A} = \hat{\mathbf{z}}\,\dfrac{\mu_0 I}{4\pi}\ln\left(\dfrac{\ell + \sqrt{\ell^2 + 4r^2}}{-\ell + \sqrt{\ell^2 + 4r^2}}\right)$

5.28 **(a)** $\mathbf{B} = \hat{\mathbf{z}}5\pi\,\sin\pi y - \hat{\mathbf{y}}\pi\,\cos\pi x$ (T)

5.29 **(a)** $\mathbf{A} = \hat{\mathbf{z}}\mu_0 IL/(4/pi R)$

(b) $\mathbf{H} = (IL/4\pi)[(-\hat{\mathbf{x}}y + \hat{\mathbf{y}}x)/(x^2 + y^2 + z^2)^{3/2}]$

5.30 $n_\mathrm{e} = 1.5$ electrons/atom

5.33 $\mathbf{H}_2 = \hat{\mathbf{z}}\,7$

5.35 $\vec{B}_2 = \hat{\mathbf{x}}20000 - \hat{\mathbf{y}}30000 + \hat{\mathbf{z}}12$

5.37 $L' = (\mu/\pi)\ln[(d-a)/a]$ (H)

5.40 $\Phi = 1.66 \times 10^{-6}$ (Wb)

Chapter 6

6.1 At $t = 0$, current in top loop is momentarily clockwise. At $t = t_1$, current in top loop is momentarily counterclockwise.

6.4 **(a)** $V_\mathrm{emf} = 750e^{-3t}$ (V)

6.7 $I_\mathrm{ind} = 18.85\sin(200\pi t)$ mA

6.9 $B_0 = 0.4$ (nA/m)

6.10 $V_{12} = -236$ (μV)

6.12 $I = 0.3$ (A)

6.14 $I = 0.82\cos(120\pi t)$ (μA)

6.17 **(b)** 888

6.18 $f = 5$ MHz

6.20 $\rho_\mathrm{v} = (8y/\omega)\sin\omega t + C_0$, where C_0 is a constant of integration.

6.24 $k = (4\pi/30)$ rad/m;
$\mathbf{E} = -\hat{\mathbf{z}}941\cos(2\pi \times 10^7 t + 4\pi y/30)$ (V/m)

6.26 $\mathbf{H}(R, \theta; t) = \hat{\boldsymbol{\phi}}\,(53/R)\sin\theta\cos(6\pi \times 10^8 t - 2\pi R)$ (μA/m)

6.28 **(a)** $k = 20$ (rad/m)

Chapter 7

7.2 **(a)** Positive y-direction

(c) $\lambda = 12.6$ m

7.3 **(a)** $\lambda = 31.42$ m

7.5 $\epsilon_\mathrm{r} = 16$

7.6 **(a)** $\lambda = 10$ m

7.14 **(a)** $\gamma = 73.5°$ and $\chi = -8.73°$

(b) Right-hand elliptically polarized

7.17 **(a)** Low-loss dielectric. $\alpha = 8.42 \times 10^{-11}$ Np/m, $\beta = 468.3$ rad/m, $\lambda = 1.34$ cm, $u_p = 1.34 \times 10^8$ m/s, $\eta_c \approx 168.5\ \Omega$

7.19 **H** lags **E** by 31.72°

7.21 $z = 287.82$ m

7.23 $u_p = 6.28 \times 10^4$ (m/s)

7.25 $\mathbf{H} = -\hat{\mathbf{y}} 0.16\, e^{-30x} \cos(2\pi \times 10^9 t - 40x - 36.85°)$ (A/m)

7.29 $(R_{ac}/R_{dc}) = 287.1$

7.34 $\mathbf{S}_{av} = \hat{\mathbf{y}} 0.48$ (W/m^2)

7.35 **(c)** $z = 23.03$ m

7.36 $u_p = 1 \times 10^8$ (m/s)

7.39 **(b)** $P_{av} = 0$

7.42 **(a)** $(w_e)_{av} = \dfrac{\epsilon E_0^2}{4}$

Chapter 8

8.2 **(a)** $\Gamma = -0.67;\ \tau = 0.33$

(b) $S = 5$

(c) $S^i_{av} = 0.52$ (W/m^2); $S^r_{av} = 0.24$ (W/m^2); $S^t_{av} = 0.28$ (W/m^2)

8.3 **(b)** $\mathbf{S}^i_{av} = \hat{\mathbf{y}}\, 251.34$, $\mathbf{S}^r_{av} = \hat{\mathbf{y}}\, 10.05$, $\mathbf{S}^t_{av} = \hat{\mathbf{y}}\, 241.29$ (W/m^2)

8.6 **(a)** $\Gamma = -0.71$

8.8 $|\widetilde{\mathbf{E}}_1|_{max} = 85.5$ (V/m); $l_{max} = 1.5$ m

8.9 $\epsilon_{r_2} = \sqrt{\epsilon_{r_1}\epsilon_{r_3}}$; $d = c/[4f(\epsilon_{r_1}\epsilon_{r_3})^{1/4}]$

8.11 $Z_{in}(-d) = 0.43\eta_0 \angle{-51.7°}$
$|\Gamma|^2 = 0.24$

8.12 $f = 50$ MHz

8.15 $P' = (3.3 \times 10^{-3})^2 \frac{10^2}{2} \times 1.14\,[1 - e^{-2\times 44.43\times 2\times 10^{-3}}] = 1.01 \times 10^{-4}$ (W/m^2)

8.17 $\theta_{min} = 35.57°$

8.20 $\dfrac{S^t}{S^i} = 0.85$

8.22 $d = 15$ cm

8.25 $d = 68.42$ cm

8.26 $f_p = 166.33$ (Mb/s)

8.27 **(b)** $\theta_i = 36.87°$

8.29 **(a)** $\theta_i = 33.7\circ$

8.30 $\theta_t = 18.44°$

8.37 **(a)** 9.4%

8.39 $a = 2$ cm; $b = 1.6$ cm

8.41 Any one of the first four modes.

8.43 570 Ω (empty); 290 Ω (filled)

8.45 $\theta'_{20} = 43.16°$

8.46 **(a)** $Q = 8367$

Chapter 9

9.2 $S_{max} = 47.5$ (μW/m^2)

9.4 **(a)** Direction of maximum radiation is a circular cone 120° wide, centered around the $+z$ axis.

(b) $D = 4 = 6$ dB

(c) $\Omega_p = \pi$ (sr) $= 3.14$ (sr)

(d) $\beta = 120°$

9.6 **(b)** $G = -3.5$ dB

9.9 $S_{max} = 6 \times 10^{-5}$ (W/m^2)

9.12 $D = 40.11$ dB

9.14 $S = 1.46$

9.15 **(a)** $\widetilde{\mathbf{E}}(R, \theta, \phi) = \hat{\boldsymbol{\theta}} \widetilde{E}_\theta = \hat{\boldsymbol{\theta}} j \dfrac{I_0 l k \eta_0}{8\pi} \left(\dfrac{e^{-jkR}}{R} \right) \sin\theta$ (V/m)

9.17 **(a)** $\theta_{\max_1} = 42.6°, \quad \theta_{\max_2} = 137.4°$

9.20 **(a)** $\theta_{\max_1} = 90°, \quad \theta_{\max_2} = 270°$

(b) $S_{\max} = \dfrac{60 I_0^2}{\pi R^2}$

(c) $F(\theta) = \dfrac{1}{4} \left[\dfrac{\cos(\pi \cos\theta) + 1}{\sin\theta} \right]^2$

9.23 $P_t = 25.9$ (mW)

9.27 **(a)** $P_{\text{rec}} = 3.6 \times 10^{-6}$ W

9.31 $\beta_{\text{null}} = 5.73°$

9.32 $D = 39.96$ dB

9.34 **(a)** $\beta_e = 1.8°$; $\beta_a = 0.18°$

(b) $\Delta y = \beta_a R = 0.96$ m

9.37 **(a)** $F_a(\theta) = 4 \cos^2 \left[\frac{\pi}{8} (4 \cos\theta + 1) \right]$

9.39 $d/\lambda = 1.414$

9.44 $F_a(\theta) = [6 + 8 \cos(\pi \cos\theta) + 2 \cos(2\pi \cos\theta)]^2$

9.47 $\delta = -2.72$ (rad) $= -155.9°$

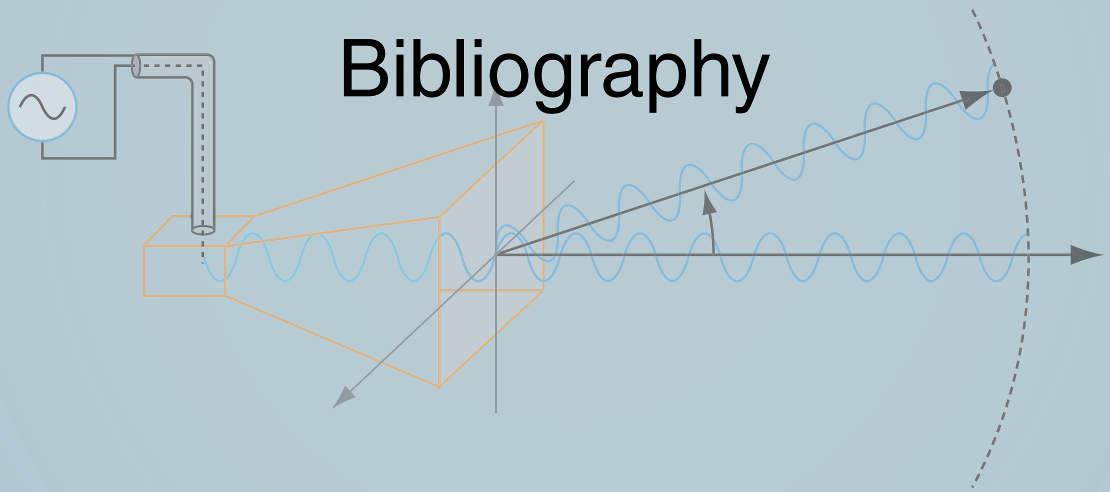
Chapter 10

10.1 $T = 89.72$ minutes

10.3 $133.3 \approx 133$ channels

10.6 $(f_p)_{\max} = 150$ kHz

10.7 $R_{\max} = 4.84$ km



Bibliography

The following list of books, arranged alphabetically by the last name of the first author, provides references for further reading.

Electromagnetics

Balanis, C.A., *Advanced Engineering Electromagnetics,* John Wiley & Sons, Hoboken, NJ, 1989.

Cheng, D.K., *Fundamentals of Engineering Electromagnetics,* Addison Wesley, Reading, MA, 1993.

Hayt, W.H., Jr. and J.A. Buck, *Engineering Electromagnetics,* 7th ed., McGraw-Hill, New York, 2005.

Iskander, M.F., *Electromagnetic Fields & Waves*, Prentice Hall, Upper Saddle River, NJ, 2000.

King, R.W.P. and S. Prasad, *Fundamental Electromagnetic Theory and Applications,* Prentice Hall, Englewood Cliffs, NJ, 1986.

Ramo, S., J.R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics,* 3rd ed., John Wiley & Sons, Hoboken, NJ, 1994.

Rao, N.N., *Elements of Engineering Electromagnetics*, Prentice Hall, Upper Saddle River, NJ, 2004.

Shen, L.C. and J.A. Kong, *Applied Electromagnetism,* 3rd ed., PWS Engineering, Boston, MA, 1995.

Antennas and Radiowave Propagation

Balanis, C.A., *Antenna Theory: Analysis and Design,* John Wiley & Sons, Hoboken, NJ, 2005.

Ishimaru, A., *Electromagnetic Wave Propagation, Radiation, and Scattering,* Prentice Hall, Upper Saddle River, NJ, 1991.

Stutzman, W.L. and G.A. Thiele, *Antenna Theory and Design*, John Wiley & Sons, Hoboken, NJ, 1997.

Optical Engineering

Bohren, C.F. and D.R. Huffman, *Absorption and Scattering of Light by Small Particles*, John Wiley & Sons, Hoboken, NJ, 1998.

Born, M. and E. Wolf, *Principles of Optics*, 7th ed., Pergamon Press, New York, 1999.

Hecht, E., *Optics,* Addison-Wesley, Reading, MA, 2001.

Smith, W.J., *Modern Optical Engineering,* SPIE Press, Bellingham, WA, 2007.

Walker, B.H., *Optical Engineering Fundamentals*, SPIE Press, Bellingham, WA, 2009.

Microwave Engineering

Freeman, J.C., *Fundamentals of Microwave Transmission Lines,* John Wiley & Sons, Hoboken, NJ, 1996.

Pozar, D.M., *Microwave Engineering,* Addison-Wesley, Reading, MA, 2004.

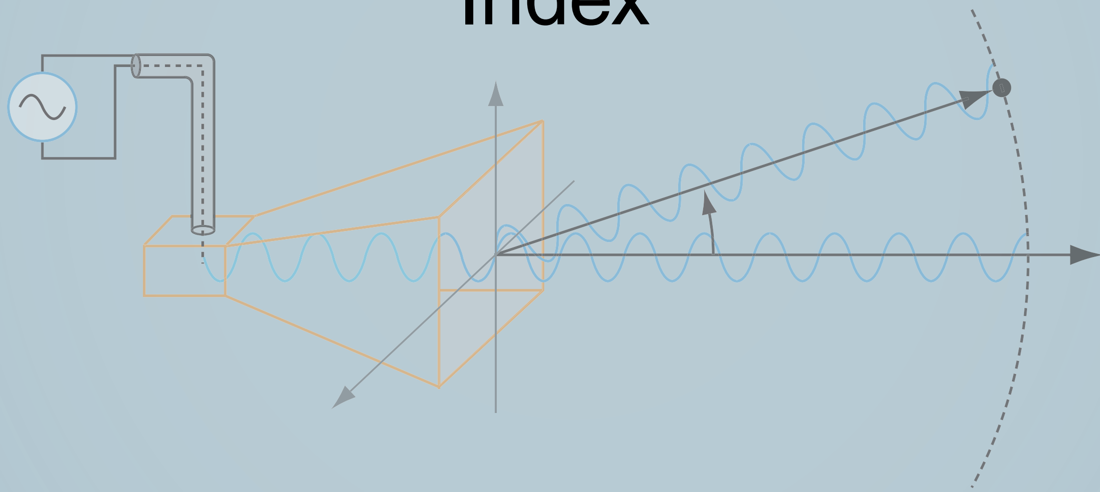
Richharia, M., *Satellite Communication Systems,* McGraw-Hill, New York, 1999.

Scott, A.W., *Understanding Microwaves,* John Wiley & Sons, Hoboken, NJ, 2005.

Skolnik, M.I., *Introduction to Radar Systems,* 3rd ed., McGraw-Hill, New York, 2002.

Stimson, G.W., *Introduction to Airborne Radar,* Hughes Aircraft Company, El Segundo, California, 200l.

Index



B

C

D

E

F

G

H

I

T

U

V

W

X

Z

FUNDAMENTAL PHYSICAL CONSTANTS

CONSTANT	SYMBOL	VALUE
speed of light in vacuum	c	$2.998 \times 10^8 \approx 3 \times 10^8$ m/s
gravitational constant	G	6.67×10^{-11} N·m²/kg²
Boltzmann's constant	K	1.38×10^{-23} J/K
elementary charge	e	1.60×10^{-19} C
permittivity of free space	ε_0	$8.85 \times 10^{-12} \approx \frac{1}{36\pi} \times 10^{-9}$ F/m
permeability of free space	μ_0	$4\pi \times 10^{-7}$ H/m
electron mass	m_e	9.11×10^{-31} kg
proton mass	m_p	1.67×10^{-27} kg
Planck's constant	h	6.63×10^{-34} J·s
intrinsic impedance of free space	η_0	$376.7 \approx 120\pi$ Ω

FUNDAMENTAL SI UNITS

DIMENSION	UNIT	SYMBOL
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous Intensity	candela	cd

MULTIPLE & SUBMULTIPLE PREFIXES

PREFIX	SYMBOL	MAGNITUDE	PREFIX	SYMBOL	MAGNITUDE
exa	E	10^{18}	milli	m	10^{-3}
peta	P	10^{15}	micro	μ	10^{-6}
tera	T	10^{12}	nano	n	10^{-9}
giga	G	10^{9}	pico	p	10^{-12}
mega	M	10^{6}	femto	f	10^{-15}
kilo	k	10^{3}	atto	a	10^{-18}

Book Website: **www.pearsonglobaleditions.com/Ulaby**

GRADIENT, DIVERGENCE, CURL, & LAPLACIAN OPERATORS

CARTESIAN (RECTANGULAR) COORDINATES (x, y, z)

$$\nabla V = \hat{\mathbf{x}}\frac{\partial V}{\partial x} + \hat{\mathbf{y}}\frac{\partial V}{\partial y} + \hat{\mathbf{z}}\frac{\partial V}{\partial z}$$

$$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

$$\nabla \times \mathbf{A} = \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix} = \hat{\mathbf{x}}\left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right) + \hat{\mathbf{y}}\left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right) + \hat{\mathbf{z}}\left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)$$

$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}$$

CYLINDRICAL COORDINATES (r, ϕ, z)

$$\nabla V = \hat{\mathbf{r}}\frac{\partial V}{\partial r} + \hat{\boldsymbol{\phi}}\frac{1}{r}\frac{\partial V}{\partial \phi} + \hat{\mathbf{z}}\frac{\partial V}{\partial z}$$

$$\nabla \cdot \mathbf{A} = \frac{1}{r}\frac{\partial}{\partial r}(rA_r) + \frac{1}{r}\frac{\partial A_\phi}{\partial \phi} + \frac{\partial A_z}{\partial z}$$

$$\nabla \times \mathbf{A} = \frac{1}{r}\begin{vmatrix} \hat{\mathbf{r}} & \hat{\boldsymbol{\phi}}r & \hat{\mathbf{z}} \\ \dfrac{\partial}{\partial r} & \dfrac{\partial}{\partial \phi} & \dfrac{\partial}{\partial z} \\ A_r & rA_\phi & A_z \end{vmatrix} = \hat{\mathbf{r}}\left(\frac{1}{r}\frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z}\right) + \hat{\boldsymbol{\phi}}\left(\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r}\right) + \hat{\mathbf{z}}\frac{1}{r}\left[\frac{\partial}{\partial r}(rA_\phi) - \frac{\partial A_r}{\partial \phi}\right]$$

$$\nabla^2 V = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 V}{\partial \phi^2} + \frac{\partial^2 V}{\partial z^2}$$

SPHERICAL COORDINATES (R, θ, ϕ)

$$\nabla V = \hat{\mathbf{R}}\frac{\partial V}{\partial R} + \hat{\boldsymbol{\theta}}\frac{1}{R}\frac{\partial V}{\partial \theta} + \hat{\boldsymbol{\phi}}\frac{1}{R\sin\theta}\frac{\partial V}{\partial \phi}$$

$$\nabla \cdot \mathbf{A} = \frac{1}{R^2}\frac{\partial}{\partial R}(R^2 A_R) + \frac{1}{R\sin\theta}\frac{\partial}{\partial \theta}(A_\theta \sin\theta) + \frac{1}{R\sin\theta}\frac{\partial A_\phi}{\partial \phi}$$

$$\nabla \times \mathbf{A} = \frac{1}{R^2\sin\theta}\begin{vmatrix} \hat{\mathbf{R}} & \hat{\boldsymbol{\theta}}R & \hat{\boldsymbol{\phi}}R\sin\theta \\ \dfrac{\partial}{\partial R} & \dfrac{\partial}{\partial \theta} & \dfrac{\partial}{\partial \phi} \\ A_R & RA_\theta & (R\sin\theta)A_\phi \end{vmatrix}$$

$$= \hat{\mathbf{R}}\frac{1}{R\sin\theta}\left[\frac{\partial}{\partial \theta}(A_\phi \sin\theta) - \frac{\partial A_\theta}{\partial \phi}\right] + \hat{\boldsymbol{\theta}}\frac{1}{R}\left[\frac{1}{\sin\theta}\frac{\partial A_R}{\partial \phi} - \frac{\partial}{\partial R}(RA_\phi)\right] + \hat{\boldsymbol{\phi}}\frac{1}{R}\left[\frac{\partial}{\partial R}(RA_\theta) - \frac{\partial A_R}{\partial \theta}\right]$$

$$\nabla^2 V = \frac{1}{R^2}\frac{\partial}{\partial R}\left(R^2\frac{\partial V}{\partial R}\right) + \frac{1}{R^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial V}{\partial \theta}\right) + \frac{1}{R^2\sin^2\theta}\frac{\partial^2 V}{\partial \phi^2}$$

SOME USEFUL VECTOR IDENTITIES

$\mathbf{A} \cdot \mathbf{B} = AB \cos \theta_{AB}$ — Scalar (or dot) product

$\mathbf{A} \times \mathbf{B} = \hat{\mathbf{n}} AB \sin \theta_{AB}$ — Vector (or cross) product, $\hat{\mathbf{n}}$ normal to plane containing **A** and **B**

$$\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) = \mathbf{B} \cdot (\mathbf{C} \times \mathbf{A}) = \mathbf{C} \cdot (\mathbf{A} \times \mathbf{B})$$

$$\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = \mathbf{B}(\mathbf{A} \cdot \mathbf{C}) - \mathbf{C}(\mathbf{A} \times \mathbf{B})$$

$$\nabla(U + V) = \nabla U + \nabla V$$

$$\nabla(UV) = U \nabla V + V \nabla U$$

$$\nabla \cdot (\mathbf{A} + \mathbf{B}) = \nabla \cdot \mathbf{A} + \nabla \cdot \mathbf{B}$$

$$\nabla \cdot (U\mathbf{A}) = U \nabla \cdot \mathbf{A} + \mathbf{A} \cdot \nabla U$$

$$\nabla \times (U\mathbf{A}) = U \nabla \times \mathbf{A} + \nabla U \times \mathbf{A}$$

$$\nabla \times (\mathbf{A} + \mathbf{B}) = \nabla \times \mathbf{A} + \nabla \times \mathbf{B}$$

$$\nabla \cdot (\mathbf{A} \times \mathbf{B}) = \mathbf{B} \cdot (\nabla \times \mathbf{A}) - \mathbf{A} \cdot (\nabla \times \mathbf{B})$$

$$\nabla \cdot (\nabla \times \mathbf{A}) = 0$$

$$\nabla \times \nabla V = 0$$

$$\nabla \cdot \nabla V = \nabla^2 V$$

$$\nabla \times \nabla \times \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$$

$\displaystyle\int_{\mathcal{V}} (\nabla \cdot \mathbf{A})\, d\mathcal{V} = \oint_S \mathbf{A} \cdot d\mathbf{s}$ — Divergence theorem (S encloses $\mathcal{V}$)

$\displaystyle\int_S (\nabla \times \mathbf{A}) \cdot d\mathbf{s} = \oint_C \mathbf{A} \cdot d\mathbf{l}$ — Stokes's theorem (S bounded by C)