$$e = 1.6 \times 10^{-19} \quad \text{(C)}. \qquad (1.6)$$

$$\mathbf{F}_{e_{21}} = \hat{\mathbf{R}}_{12} \frac{q_1 q_2}{4\pi\varepsilon_0 R_{12}^2} \quad \text{(N)} \quad \text{(in free space)}, \qquad (1.7)$$

$$\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi\varepsilon_0 R^2} \quad \text{(V/m)} \quad \text{(in free space)}, \qquad (1.8)$$

$$\mathbf{D} = \varepsilon \mathbf{E} \quad \text{(C/m}^2\text{)}, \qquad (1.12)$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \quad \text{(m/s)}. \qquad (1.14)$$

$$\mathbf{B} = \mu \mathbf{H}. \qquad (1.16)$$

$$u_\text{p} = \frac{dx}{dt} = \frac{\lambda}{T} \quad \text{(m/s)}. \qquad (1.25)$$

$$f = \frac{1}{T} \quad \text{(Hz)}. \qquad (1.26)$$

$$u_\text{p} = f\lambda \quad \text{(m/s)}. \qquad (1.27)$$

$$\omega = 2\pi f \quad \text{(rad/s)}, \qquad (1.29a)$$

$$\beta = \frac{2\pi}{\lambda} \quad \text{(rad/m)}. \qquad (1.29b)$$

$$\lambda = \frac{c}{f}. \qquad (1.34)$$

$$e^{j\theta} = \cos\theta + j\sin\theta, \qquad (1.38)$$

$$x = |z|\cos\theta, \qquad y = |z|\sin\theta, \qquad (1.40)$$

$$|z| = \sqrt[+]{x^2 + y^2}, \qquad \theta = \tan^{-1}(y/x). \qquad (1.41)$$

$$\begin{aligned} z^* = (x + jy)^* = x - jy &= |z|e^{-j\theta} \\ &= |z|\angle{-\theta}. \qquad (1.42) \end{aligned}$$

$$|z| = \sqrt[+]{zz^*}. \qquad (1.43)$$

$$R\,i(t) + \frac{1}{C}\int i(t)\,dt = \upsilon_s(t) \quad \text{(time domain)}. \quad (1.56)$$

$$\tilde{I}\left(R + \frac{1}{j\omega C}\right) = \widetilde{V}_s \qquad \text{(phasor domain)}. \quad (1.66)$$

$$L'C' = \mu\varepsilon \qquad \text{(all TEM lines)}, \tag{2.10}$$

$$\frac{G'}{C'} = \frac{\sigma}{\varepsilon} \qquad \text{(all TEM lines)}. \tag{2.11}$$

$$-\frac{\partial \upsilon(z,t)}{\partial z} = R'\, i(z,t) + L' \frac{\partial i(z,t)}{\partial t}. \tag{2.14}$$

$$-\frac{\partial i(z,t)}{\partial z} = G'\, \upsilon(z,t) + C' \frac{\partial \upsilon(z,t)}{\partial t}. \tag{2.16}$$

$$-\frac{d\widetilde{V}(z)}{dz} = (R' + j\omega L')\,\tilde{I}(z), \tag{2.18a}$$

$$-\frac{d\tilde{I}(z)}{dz} = (G' + j\omega C')\,\widetilde{V}(z). \tag{2.18b}$$

$$\frac{d^2\widetilde{V}(z)}{dz^2} - \gamma^2\,\widetilde{V}(z) = 0, \tag{2.21}$$

$$\gamma = \sqrt{(R' + j\omega L')(G' + j\omega C')}. \tag{2.22}$$

$$\frac{d^2\tilde{I}(z)}{dz^2} - \gamma^2\,\tilde{I}(z) = 0. \tag{2.23}$$

$$\begin{aligned}\alpha &= \mathfrak{Re}(\gamma) \\ &= \mathfrak{Re}\left(\sqrt{(R' + j\omega L')(G' + j\omega C')}\right) \quad \text{(Np/m)}, \end{aligned} \tag{2.25a}$$

$$\begin{aligned}\beta &= \mathfrak{Im}(\gamma) \\ &= \mathfrak{Im}\left(\sqrt{(R' + j\omega L')(G' + j\omega C')}\right) \quad \text{(rad/m)}. \end{aligned} \tag{2.25b}$$

$$Z_0 = \frac{R' + j\omega L'}{\gamma} = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \quad (\Omega), \tag{2.29}$$

$$\begin{aligned}\alpha &= 0 && \text{(lossless line)}, \\ \beta &= \omega\sqrt{L'C'} && \text{(lossless line)}. \end{aligned} \tag{2.45}$$

$$Z_0 = \sqrt{\frac{L'}{C'}} \quad \text{(lossless line)}, \tag{2.46}$$

$$\beta = \omega\sqrt{\mu\varepsilon} \quad \text{(rad/m)}, \tag{2.29}$$

$$u_p = \frac{1}{\sqrt{\mu\varepsilon}} \quad \text{(m/s)}, \tag{2.30}$$

$$\lambda = \frac{u_p}{f} = \frac{c}{f}\frac{1}{\sqrt{\varepsilon_r}} = \frac{\lambda_0}{\sqrt{\varepsilon_r}}, \tag{2.53}$$

$$\begin{aligned}\Gamma = \frac{V_0^-}{V_0^+} &= \frac{Z_L - Z_0}{Z_L + Z_0} \\ &= \frac{Z_L/Z_0 - 1}{Z_L/Z_0 + 1} \\ &= \frac{z_L - 1}{z_L + 1} \quad \text{(dimensionless)}, \end{aligned} \tag{2.59}$$

$$\frac{I_0^-}{I_0^+} = -\frac{V_0^-}{V_0^+} = -\Gamma. \qquad (2.61)$$

$$\Gamma = |\Gamma| e^{j\theta_r}, \qquad (2.62)$$

$$d_{\max} = \frac{\theta_r + 2n\pi}{2\beta} = \frac{\theta_r \lambda}{4\pi} + \frac{n\lambda}{2}\,, \quad \begin{cases} n = 1,2,\ldots & \text{if } \theta_r < 0, \\ n = 0,1,2,\ldots & \text{if } \theta_r \geq 0, \end{cases} \qquad (2.70)$$

$$d_{\min} = \begin{cases} d_{\max} + \lambda/4, & \text{if } d_{\max} < \lambda/4, \\ d_{\max} - \lambda/4, & \text{if } d_{\max} \geq \lambda/4. \end{cases} \qquad (2.72)$$

$$S = \frac{|\widetilde{V}|_{\max}}{|\widetilde{V}|_{\min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (\text{dimensionless}). \qquad (2.73)$$

$$Z_{\text{in}} = Z_0 \left(\frac{z_L \cos\beta l + j \sin\beta l}{\cos\beta l + j z_L \sin\beta l} \right) = Z_0 \left(\frac{z_L + j \tan\beta l}{1 + j z_L \tan\beta l} \right). \qquad (2.79)$$

$$V_0^+ = \left(\frac{\widetilde{V}_g Z_{\text{in}}}{Z_g + Z_{\text{in}}} \right) \left(\frac{1}{e^{j\beta l} + \Gamma e^{-j\beta l}} \right). \qquad (2.82)$$

$$Z_{\text{in}}^{\text{sc}} = \frac{\widetilde{V}_{\text{sc}}(l)}{\widetilde{I}_{\text{sc}}(l)} = j Z_0 \tan\beta l. \qquad (2.84)$$

$$Z_{\text{in}}^{\text{oc}} = \frac{\widetilde{V}_{\text{oc}}(l)}{\widetilde{I}_{\text{oc}}(l)} = -j Z_0 \cot\beta l. \qquad (2.93)$$

$$Z_0 = \sqrt[+]{Z_{\rm in}^{\rm sc}\, Z_{\rm in}^{\rm oc}}\,, \qquad (2.94)$$

$$\tan\beta l = \sqrt{\frac{-Z_{\rm in}^{\rm sc}}{Z_{\rm in}^{\rm oc}}}\,. \qquad (2.95)$$

$$Z_{\rm in} = Z_{\rm L}, \qquad \text{for } l = n\lambda/2, \qquad (2.96)$$

$$Z_{\rm in} = \frac{Z_0^2}{Z_{\rm L}}\,, \qquad \text{for } l = \lambda/4 + n\lambda/2. \qquad (2.97)$$

$$P_{\rm av}^{\rm i} = \frac{|V_0^+|^2}{2Z_0} \qquad \text{(W)}, \qquad (2.104)$$

$$P_{\rm av}^{\rm r} = -|\Gamma|^2 \frac{|V_0^+|^2}{2Z_0} = -|\Gamma|^2 P_{\rm av}^{\rm i}. \qquad (2.105)$$

$$\begin{aligned} P_{\rm av} &= P_{\rm av}^{\rm i} + P_{\rm av}^{\rm r} \\ &= \frac{|V_0^+|^2}{2Z_0}\left[1 - |\Gamma|^2\right] \qquad \text{(W)}. \end{aligned} \qquad (2.106)$$

$$P_{\rm av} = \tfrac{1}{2}\mathfrak{Re}\left[\widetilde{V} \cdot \widetilde{I}^*\right], \qquad (2.107)$$

$$z_{\rm L} = \frac{1+\Gamma}{1-\Gamma}\,. \qquad (2.112)$$

$$y_{\rm L} = \frac{1}{z_{\rm L}} = \frac{1-\Gamma}{1+\Gamma} \qquad \text{(dimensionless)}. \qquad (2.135)$$

$$g_{\mathrm{d}} = 1 \quad \text{(real-part condition)}, \tag{2.141a}$$

$$b_{\mathrm{s}} = -b_{\mathrm{d}} \quad \text{(imaginary-part condition)}. \tag{2.141b}$$

$$V_{\infty} = \frac{V_{\mathrm{g}} R_{\mathrm{L}}}{R_{\mathrm{g}} + R_{\mathrm{L}}}\,. \tag{2.159}$$

$$I_{\infty} = \frac{V_{\infty}}{R_{\mathrm{L}}} = \frac{V_{\mathrm{g}}}{R_{\mathrm{g}} + R_{\mathrm{L}}}\,. \tag{2.160}$$

$$\mathbf{A}\cdot\mathbf{B} = AB\cos\theta_{AB}, \qquad (3.14)$$

$$\hat{\mathbf{x}}\cdot\hat{\mathbf{x}} = \hat{\mathbf{y}}\cdot\hat{\mathbf{y}} = \hat{\mathbf{z}}\cdot\hat{\mathbf{z}} = 1, \qquad (3.19a)$$

$$\hat{\mathbf{x}}\cdot\hat{\mathbf{y}} = \hat{\mathbf{y}}\cdot\hat{\mathbf{z}} = \hat{\mathbf{z}}\cdot\hat{\mathbf{x}} = 0. \qquad (3.19b)$$

$$\mathbf{A}\times\mathbf{B} = \hat{\mathbf{n}}\,AB\sin\theta_{AB}, \qquad (3.22)$$

$$\hat{\mathbf{x}}\times\hat{\mathbf{y}} = \hat{\mathbf{z}}, \qquad \hat{\mathbf{y}}\times\hat{\mathbf{z}} = \hat{\mathbf{x}}, \qquad \hat{\mathbf{z}}\times\hat{\mathbf{x}} = \hat{\mathbf{y}}. \qquad (3.25)$$

$$\hat{\mathbf{x}}\times\hat{\mathbf{x}} = \hat{\mathbf{y}}\times\hat{\mathbf{y}} = \hat{\mathbf{z}}\times\hat{\mathbf{z}} = 0. \qquad (3.26)$$

$$\mathbf{A}\times\mathbf{B} = \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}. \qquad (3.28)$$

$$\mathbf{A}\cdot(\mathbf{B}\times\mathbf{C}) = \mathbf{B}\cdot(\mathbf{C}\times\mathbf{A}) = \mathbf{C}\cdot(\mathbf{A}\times\mathbf{B}). \qquad (3.29)$$

$$\mathbf{A}\times(\mathbf{B}\times\mathbf{C}) = \mathbf{B}(\mathbf{A}\cdot\mathbf{C}) - \mathbf{C}(\mathbf{A}\cdot\mathbf{B}), \qquad (3.33)$$

$$\hat{\mathbf{r}}\times\hat{\boldsymbol{\phi}} = \hat{\mathbf{z}}, \qquad \hat{\boldsymbol{\phi}}\times\hat{\mathbf{z}} = \hat{\mathbf{r}}, \qquad \hat{\mathbf{z}}\times\hat{\mathbf{r}} = \hat{\boldsymbol{\phi}}, \qquad (3.37)$$

$$\hat{\mathbf{R}}\times\hat{\boldsymbol{\theta}} = \hat{\boldsymbol{\phi}}, \quad \hat{\boldsymbol{\theta}}\times\hat{\boldsymbol{\phi}} = \hat{\mathbf{R}}, \quad \hat{\boldsymbol{\phi}}\times\hat{\mathbf{R}} = \hat{\boldsymbol{\theta}}. \qquad (3.45)$$

$$\hat{\mathbf{r}} = \hat{\mathbf{x}}\cos\phi + \hat{\mathbf{y}}\sin\phi. \qquad (3.56a)$$

$$\hat{\boldsymbol{\phi}} = -\hat{\mathbf{x}}\sin\phi + \hat{\mathbf{y}}\cos\phi. \qquad (3.56b)$$

$$\hat{\mathbf{x}} = \hat{\mathbf{r}}\cos\phi - \hat{\boldsymbol{\phi}}\sin\phi, \qquad (3.57a)$$
$$\hat{\mathbf{y}} = \hat{\mathbf{r}}\sin\phi + \hat{\boldsymbol{\phi}}\cos\phi. \qquad (3.57b)$$

$$A_r = A_x\cos\phi + A_y\sin\phi, \qquad (3.58a)$$
$$A_\phi = -A_x\sin\phi + A_y\cos\phi, \qquad (3.58b)$$

$$A_x = A_r\cos\phi - A_\phi\sin\phi, \qquad (3.59a)$$
$$A_y = A_r\sin\phi + A_\phi\cos\phi. \qquad (3.59b)$$

$$\hat{\mathbf{R}} = \hat{\mathbf{x}}\sin\theta\cos\phi + \hat{\mathbf{y}}\sin\theta\sin\phi + \hat{\mathbf{z}}\cos\theta. \qquad (3.64a)$$

$$\hat{\boldsymbol{\theta}} = \hat{\mathbf{x}}\cos\theta\cos\phi + \hat{\mathbf{y}}\cos\theta\sin\phi - \hat{\mathbf{z}}\sin\theta. \qquad (3.64b)$$

$$\hat{\boldsymbol{\phi}} = -\hat{\mathbf{x}}\sin\phi + \hat{\mathbf{y}}\cos\phi. \qquad (3.64c)$$

$$\hat{\mathbf{x}} = \hat{\mathbf{R}}\sin\theta\cos\phi + \hat{\boldsymbol{\theta}}\cos\theta\cos\phi - \hat{\boldsymbol{\phi}}\sin\phi, \qquad (3.65a)$$
$$\hat{\mathbf{y}} = \hat{\mathbf{R}}\sin\theta\sin\phi + \hat{\boldsymbol{\theta}}\cos\theta\sin\phi + \hat{\boldsymbol{\phi}}\cos\phi, \qquad (3.65b)$$
$$\hat{\mathbf{z}} = \hat{\mathbf{R}}\cos\theta - \hat{\boldsymbol{\theta}}\sin\theta. \qquad (3.65c)$$

$$\begin{aligned} d &= |\mathbf{R}_{12}| \\ &= [(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2]^{1/2}. \qquad (3.66) \end{aligned}$$

$$\begin{aligned} d &= \big[(r_2\cos\phi_2 - r_1\cos\phi_1)^2 \\ &\qquad + (r_2\sin\phi_2 - r_1\sin\phi_1)^2 + (z_2 - z_1)^2\big]^{1/2} \\ &= \big[r_2^2 + r_1^2 - 2r_1r_2\cos(\phi_2 - \phi_1) + (z_2 - z_1)^2\big]^{1/2} \\ &\qquad\qquad \text{(cylindrical).} \qquad (3.67) \end{aligned}$$

$$d = \left\{R_2^2 + R_1^2 - 2R_1R_2[\cos\theta_2\cos\theta_1 + \sin\theta_1\sin\theta_2\cos(\phi_2 - \phi_1)]\right\}^{1/2} \quad \text{(spherical).} \tag{3.68}$$

$$\nabla T = \text{grad } T = \hat{\mathbf{x}}\frac{\partial T}{\partial x} + \hat{\mathbf{y}}\frac{\partial T}{\partial y} + \hat{\mathbf{z}}\frac{\partial T}{\partial z}\ . \tag{3.72}$$

$$\nabla = \hat{\mathbf{x}}\frac{\partial}{\partial x} + \hat{\mathbf{y}}\frac{\partial}{\partial y} + \hat{\mathbf{z}}\frac{\partial}{\partial z} \qquad \text{(Cartesian).} \tag{3.74}$$

$$\frac{dT}{dl} = \nabla T \cdot \hat{\mathbf{a}}_l. \tag{3.75}$$

$$\nabla = \hat{\mathbf{r}}\frac{\partial}{\partial r} + \hat{\boldsymbol{\phi}}\frac{1}{r}\frac{\partial}{\partial \phi} + \hat{\mathbf{z}}\frac{\partial}{\partial z} \qquad \text{(cylindrical).} \tag{3.82}$$

$$\nabla = \hat{\mathbf{R}}\frac{\partial}{\partial R} + \hat{\boldsymbol{\theta}}\frac{1}{R}\frac{\partial}{\partial \theta} + \hat{\boldsymbol{\phi}}\frac{1}{R\sin\theta}\frac{\partial}{\partial \phi} \qquad \text{(spherical).} \tag{3.83}$$

$$\nabla \cdot \mathbf{E} = \text{div } \mathbf{E} = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} \tag{3.96}$$

$$\int_{\mathcal{V}} \nabla \cdot \mathbf{E}\, d\mathcal{V} = \oint_S \mathbf{E} \cdot d\mathbf{s} \qquad \text{(divergence theorem).} \tag{3.98}$$

$$\nabla \times \mathbf{B} = \text{curl } \mathbf{B} = \lim_{\Delta s \to 0} \frac{1}{\Delta s}\left[\hat{\mathbf{n}} \oint_C \mathbf{B} \cdot d\mathbf{l}\right]_{\max}. \tag{3.103}$$

$$\int_S (\nabla \times \mathbf{B}) \cdot d\mathbf{s} = \oint_C \mathbf{B} \cdot d\mathbf{l} \qquad \text{(Stokes's theorem)}, \tag{3.107}$$

$$\nabla^2 V = \nabla \cdot (\nabla V) = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \, . \tag{3.110}$$

$$\nabla^2 \mathbf{E} = \nabla(\nabla \cdot \mathbf{E}) - \nabla \times (\nabla \times \mathbf{E}). \tag{3.113}$$

$$\nabla \cdot \mathbf{D} = \rho_{\mathrm{v}}, \tag{4.1a}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{4.1b}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{4.1c}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}. \tag{4.1d}$$

$$\nabla \cdot \mathbf{D} = \rho_{\mathrm{v}}, \tag{4.2a}$$

$$\nabla \times \mathbf{E} = 0. \tag{4.2b}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{4.3a}$$

$$\nabla \times \mathbf{H} = \mathbf{J}. \tag{4.3b}$$

$$\mathbf{J} = \rho_{\mathrm{v}} \mathbf{u} \qquad (\mathrm{A/m^2}) \tag{4.11}$$

$$I = \int_S \mathbf{J} \cdot d\mathbf{s} \qquad (\mathrm{A}). \tag{4.12}$$

$$\mathbf{E} = \frac{1}{4\pi\varepsilon} \sum_{i=1}^{N} \frac{q_i (\mathbf{R} - \mathbf{R}_i)}{|\mathbf{R} - \mathbf{R}_i|^3} \qquad (\mathrm{V/m}). \tag{4.19}$$

$$\mathbf{E} = \int_{\mathcal{V}'} d\mathbf{E} = \frac{1}{4\pi\varepsilon} \int_{\mathcal{V}'} \hat{\mathbf{R}}' \frac{\rho_{\mathrm{v}}\, d\mathcal{V}'}{R'^2} \qquad \text{(volume distribution).} \tag{4.21a}$$

$$\mathbf{E} = \frac{1}{4\pi\varepsilon} \int_{S'} \hat{\mathbf{R}}' \frac{\rho_{\mathrm{s}}\, ds'}{R'^2} \qquad \text{(surface distribution),} \tag{4.21b}$$

$$\mathbf{E} = \frac{1}{4\pi\varepsilon} \int_{l'} \hat{\mathbf{R}}' \frac{\rho_{\ell}\, dl'}{R'^2} \qquad \text{(line distribution).} \tag{4.21c}$$

$$\mathbf{E} = \pm\hat{\mathbf{z}}\,\frac{\rho_s}{2\varepsilon_0} \qquad \text{(infinite sheet of charge).} \qquad (4.25)$$

$$\nabla\cdot\mathbf{D} = \rho_v \qquad (4.26)$$

(Differential form of Gauss's law),

$$\oint_S \mathbf{D}\cdot d\mathbf{s} = Q \qquad (4.29)$$

(Integral form of Gauss's law).

$$\mathbf{E} = \frac{\mathbf{D}}{\varepsilon_0} = \hat{\mathbf{r}}\,\frac{D_r}{\varepsilon_0} = \hat{\mathbf{r}}\,\frac{\rho_\ell}{2\pi\varepsilon_0 r} \qquad (4.33)$$

(infinite line charge).

$$V_{21} = V_2 - V_1 = -\int_{P_1}^{P_2} \mathbf{E}\cdot d\mathbf{l}, \qquad (4.39)$$

$$\oint_C \mathbf{E}\cdot d\mathbf{l} = 0 \qquad \text{(Electrostatics).} \qquad (4.40)$$

$$V = -\int_{\infty}^{P} \mathbf{E}\cdot d\mathbf{l} \qquad \text{(V).} \qquad (4.43)$$

$$V = \frac{1}{4\pi\varepsilon}\sum_{i=1}^{N}\frac{q_i}{|\mathbf{R}-\mathbf{R}_i|} \qquad \text{(V).} \qquad (4.47)$$

$$V = \frac{1}{4\pi\varepsilon} \int_{\mathcal{V}'} \frac{\rho_{\mathrm{v}}}{R'}\, d\mathcal{V}' \quad \text{(volume distribution)}, \tag{4.48a}$$

$$V = \frac{1}{4\pi\varepsilon} \int_{S'} \frac{\rho_{\mathrm{s}}}{R'}\, ds' \quad \text{(surface distribution)}, \tag{4.48b}$$

$$V = \frac{1}{4\pi\varepsilon} \int_{l'} \frac{\rho_{\ell}}{R'}\, dl' \quad \text{(line distribution)}. \tag{4.48c}$$

$$\mathbf{E} = -\nabla V. \tag{4.51}$$

$$V = \frac{\mathbf{p} \cdot \hat{\mathbf{R}}}{4\pi\varepsilon_0 R^2} \quad \text{(electric dipole)}. \tag{4.54}$$

$$\mathbf{E} = \frac{qd}{4\pi\varepsilon_0 R^3} \left(\hat{\mathbf{R}}\, 2\cos\theta + \hat{\boldsymbol{\theta}} \sin\theta\right) \quad \text{(V/m)}. \tag{4.56}$$

$$\nabla^2 V = -\frac{\rho_{\mathrm{v}}}{\varepsilon} \quad \text{(Poisson's equation)}. \tag{4.60}$$

$$\nabla^2 V = 0 \quad \text{(Laplace's equation)}, \tag{4.62}$$

$$\mathbf{J} = \sigma \mathbf{E} \quad (\mathrm{A/m^2}) \quad \text{(Ohm's law)}, \tag{4.63}$$

$$\begin{aligned} \sigma &= -\rho_{\mathrm{ve}}\mu_{\mathrm{e}} + \rho_{\mathrm{vh}}\mu_{\mathrm{h}} \\ &= (N_{\mathrm{e}}\mu_{\mathrm{e}} + N_{\mathrm{h}}\mu_{\mathrm{h}})e \quad \text{(S/m)} \quad \text{(semiconductor)}, \end{aligned} \tag{4.67a}$$

$$\sigma = -\rho_{\mathrm{ve}}\mu_{\mathrm{e}} = N_{\mathrm{e}}\mu_{\mathrm{e}} e \quad \text{(S/m)} \quad \text{(conductor)}. \tag{4.67b}$$

$$\text{Perfect dielectric:} \quad \mathbf{J} = 0,$$
$$\text{Perfect conductor:} \quad \mathbf{E} = 0.$$

$$R = \frac{V}{I} = \frac{-\int_l \mathbf{E} \cdot d\mathbf{l}}{\int_S \mathbf{J} \cdot d\mathbf{s}} = \frac{-\int_l \mathbf{E} \cdot d\mathbf{l}}{\int_S \sigma \mathbf{E} \cdot d\mathbf{s}} . \qquad (4.71)$$

$$P = \int_{\mathcal{V}} \mathbf{E} \cdot \mathbf{J} \, d\mathcal{V} \qquad \text{(W)} \quad \text{(Joule's law)}, \qquad (4.79)$$

$$\mathbf{E}_{1\mathrm{t}} = \mathbf{E}_{2\mathrm{t}} \qquad \text{(V/m)}. \qquad (4.90)$$

$$\frac{\mathbf{D}_{1\mathrm{t}}}{\varepsilon_1} = \frac{\mathbf{D}_{2\mathrm{t}}}{\varepsilon_2} . \qquad (4.91)$$

$$\hat{\mathbf{n}}_2 \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_{\mathrm{s}} \qquad (\text{C/m}^2). \qquad (4.93)$$

$$D_{1\mathrm{n}} - D_{2\mathrm{n}} = \rho_{\mathrm{s}} \qquad (\text{C/m}^2). \qquad (4.94)$$

$$\hat{\mathbf{n}}_2 \cdot (\varepsilon_1 \mathbf{E}_1 - \varepsilon_2 \mathbf{E}_2) = \rho_{\mathrm{s}}, \qquad (4.95\text{a})$$

$$\varepsilon_1 E_{1\mathrm{n}} - \varepsilon_2 E_{2\mathrm{n}} = \rho_{\mathrm{s}}. \qquad (4.95\text{b})$$

$$\mathbf{D}_1 = \varepsilon_1 \mathbf{E}_1 = \hat{\mathbf{n}} \rho_{\mathrm{s}} \quad (\text{at conductor surface}), \quad (4.101)$$

$$J_{1\mathrm{n}} \left(\frac{\varepsilon_1}{\sigma_1} - \frac{\varepsilon_2}{\sigma_2} \right) = \rho_{\mathrm{s}} \quad (\text{electrostatics}). \qquad (4.104)$$

$$C = \frac{\int_S \varepsilon \mathbf{E} \cdot d\mathbf{s}}{-\int_l \mathbf{E} \cdot d\mathbf{l}} \qquad \text{(F)}, \qquad (4.109)$$

$$RC = \frac{\varepsilon}{\sigma}. \qquad (4.111)$$

$$C = \frac{Q}{V} = \frac{Q}{Ed} = \frac{\varepsilon A}{d}, \qquad (4.113)$$

$$C = \frac{Q}{V} = \frac{2\pi\varepsilon l}{\ln(b/a)}, \qquad (4.116)$$

$$W_\mathrm{e} = \tfrac{1}{2} C V^2 \qquad \text{(J)}. \qquad (4.121)$$

$$w_\mathrm{e} = \frac{W_\mathrm{e}}{v} = \frac{1}{2} \varepsilon E^2 \qquad (\text{J/m}^3). \qquad (4.123)$$

$$\mathbf{F} = -\nabla W_\mathrm{e} \qquad \text{(N)}. \qquad (4.128)$$

$$\nabla \cdot \mathbf{B} = 0, \qquad (5.1a)$$

$$\nabla \times \mathbf{H} = \mathbf{J}, \qquad (5.1b)$$

$$\mathbf{F} = \mathbf{F}_\text{e} + \mathbf{F}_\text{m} = q\mathbf{E} + q\mathbf{u} \times \mathbf{B} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}). \quad (5.5)$$

$$\mathbf{F}_\text{m} = I \oint_C d\mathbf{l} \times \mathbf{B} \qquad \text{(N)}. \qquad (5.10)$$

$$\mathbf{m} = \hat{\mathbf{n}} NIA = \hat{\mathbf{n}} m \qquad (\text{A}\cdot\text{m}^2), \qquad (5.19)$$

$$\mathbf{T} = \mathbf{m} \times \mathbf{B} \qquad (\text{N}\cdot\text{m}). \qquad (5.20)$$

$$\mathbf{H} = \frac{I}{4\pi} \int_l \frac{d\mathbf{l} \times \hat{\mathbf{R}}}{R^2} \qquad \text{(A/m)}, \qquad (5.22)$$

$$\mathbf{H} = \frac{1}{4\pi} \int_S \frac{\mathbf{J}_\text{s} \times \hat{\mathbf{R}}}{R^2}\, ds \quad \text{(surface current)}, \qquad (5.24a)$$

$$\mathbf{H} = \frac{1}{4\pi} \int_V \frac{\mathbf{J} \times \hat{\mathbf{R}}}{R^2}\, d\mathcal{V} \quad \text{(volume current)}. \qquad (5.24b)$$

$$\mathbf{B} = \hat{\boldsymbol{\phi}} \frac{\mu_0 I}{2\pi r} \qquad \text{(infinitely long wire)}. \qquad (5.30)$$

$$\mathbf{H} = \hat{\mathbf{z}} \frac{Ia^2}{2(a^2 + z^2)^{3/2}} \qquad \text{(A/m)}. \qquad (5.34)$$

$$\mathbf{H} = \frac{m}{4\pi R^3} (\hat{\mathbf{R}}\, 2\cos\theta + \hat{\boldsymbol{\theta}} \sin\theta) \quad (\text{for } R \gg a). \qquad (5.38)$$

$$\nabla \cdot \mathbf{B} = 0 \quad \leftrightarrow \quad \oint_S \mathbf{B} \cdot d\mathbf{s} = 0. \qquad (5.44)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad (\text{Wb/m}^2), \qquad (5.53)$$

$$\nabla^2 \mathbf{A} = -\mu \mathbf{J}. \qquad (5.60)$$

$$\mathbf{A} = \frac{\mu}{4\pi} \int_{\mathcal{V}'} \frac{\mathbf{J}}{R'}\, d\mathcal{V}' \qquad (\text{Wb/m}). \qquad (5.65)$$

$$\mu = \mu_0(1 + \chi_\text{m}) \qquad (\text{H/m}). \qquad (5.76)$$

$$\mu_\text{r} = \frac{\mu}{\mu_0} = 1 + \chi_\text{m}. \qquad (5.77)$$

$$\oint_S \mathbf{D} \cdot d\mathbf{s} = Q \quad \rightarrow \quad D_{1\text{n}} - D_{2\text{n}} = \rho_\text{s}. \qquad (5.78)$$

$$\oint_S \mathbf{B} \cdot d\mathbf{s} = 0 \quad \rightarrow \quad B_{1\text{n}} = B_{2\text{n}}. \qquad (5.79)$$

$$\mu_1 H_{1\text{n}} = \mu_2 H_{2\text{n}}. \qquad (5.80)$$

$$\hat{\mathbf{n}}_2 \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{J}_\text{s}. \qquad (5.84)$$

$$H_{1\text{t}} = H_{2\text{t}}. \qquad (5.85)$$

$$\mathbf{B} \simeq \hat{\mathbf{z}}\mu n I = \frac{\hat{\mathbf{z}}\mu N I}{l} \qquad (\text{long solenoid with } l/a \gg 1). \qquad (5.90)$$

$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{s} \qquad \text{(Wb)}. \qquad (5.91)$$

$$L = \frac{\Lambda}{I} \qquad \text{(H)}. \qquad (5.94)$$

$$L = \mu \frac{N^2}{l} S \qquad \text{(solenoid)}, \qquad (5.95)$$

$$L = \frac{\Lambda}{I} = \frac{\Phi}{I} = \frac{1}{I} \int_S \mathbf{B} \cdot d\mathbf{s}. \qquad (5.96)$$

$$L' = \frac{L}{l} = \frac{\Phi}{lI} = \frac{\mu}{2\pi} \ln\left(\frac{b}{a}\right). \qquad (5.99)$$

$$L_{12} = \frac{\Lambda_{12}}{I_1} = \frac{N_2}{I_1} \int_{S_2} \mathbf{B}_1 \cdot d\mathbf{s} \qquad \text{(H)}. \qquad (5.102)$$

$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{s} \qquad \text{(Wb)}. \qquad (6.5)$$

$$V_{\text{emf}}^{\text{tr}} = -N \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{s} \quad \text{(transformer emf)}, \qquad (6.8)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \text{(Faraday's law)}. \qquad (6.13)$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}. \qquad (6.16)$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}. \qquad (6.18)$$

$$Z_{\text{in}} = \left(\frac{N_1}{N_2}\right)^2 Z_{\text{L}}. \qquad (6.21)$$

$$V_{\text{emf}}^{\text{m}} = \oint_C (\mathbf{u} \times \mathbf{B}) \cdot d\mathbf{l} \qquad \text{(motional emf)}. \qquad (6.26)$$

$$V_{\text{emf}} = -\frac{d\Phi}{dt} = -\frac{d}{dt} \int_S \mathbf{B} \cdot d\mathbf{s} \quad \text{(total emf)}. \qquad (6.40)$$

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = I_{\text{c}} + \int_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{s} \quad \text{(Ampère's law)}. \quad (6.43)$$

$$I_{\text{d}} = \int_S \mathbf{J}_{\text{d}} \cdot d\mathbf{s} = \int_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{s}, \qquad (6.44)$$

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho_v}{\partial t}\,, \qquad (6.54)$$

$$\oint_S \mathbf{J} \cdot d\mathbf{s} = 0 \quad \text{(Kirchhoff's current law).} \qquad (6.56)$$

$$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t} \qquad \text{(dynamic case).} \qquad (6.70)$$

$$\mathbf{B} = \nabla \times \mathbf{A}. \qquad (6.71)$$

$$V(\mathbf{R},t) = \frac{1}{4\pi\varepsilon} \int_{\mathcal{V}'} \frac{\rho_v(\mathbf{R}_i,\, t - R'/u_p)}{R'}\, d\mathcal{V}' \quad \text{(V)}, \qquad (6.74)$$

$$\mathbf{A}(\mathbf{R},t) = \frac{\mu}{4\pi} \int_{\mathcal{V}'} \frac{\mathbf{J}(\mathbf{R}_i,\, t - R'/u_p)}{R'}\, d\mathcal{V}' \qquad \text{(Wb/m).} \qquad (6.75)$$

$$\widetilde{V}(\mathbf{R}) = \frac{1}{4\pi\varepsilon} \int_{\mathcal{V}'} \frac{\tilde{\rho}_v(\mathbf{R}_i)\, e^{-jkR'}}{R'}\, d\mathcal{V}' \quad \text{(V).} \qquad (6.82)$$

$$\widetilde{\mathbf{A}}(\mathbf{R}) = \frac{\mu}{4\pi} \int_{\mathcal{V}'} \frac{\widetilde{\mathbf{J}}(\mathbf{R}_i)\, e^{-jkR'}}{R'}\, d\mathcal{V}', \qquad (6.84)$$

$$\nabla \times \widetilde{\mathbf{H}} = j\omega\varepsilon \widetilde{\mathbf{E}} \quad \text{or} \quad \widetilde{\mathbf{E}} = \frac{1}{j\omega\varepsilon} \nabla \times \widetilde{\mathbf{H}}. \qquad (6.86)$$

$$\nabla \times \widetilde{\mathbf{E}} = -j\omega\mu \widetilde{\mathbf{H}}$$

$$\text{or} \qquad \widetilde{\mathbf{H}} = -\frac{1}{j\omega\mu} \nabla \times \widetilde{\mathbf{E}}. \qquad (6.87)$$

$$\nabla \cdot \widetilde{\mathbf{E}} = \tilde{\rho}_{\mathrm{v}}/\varepsilon, \tag{7.2a}$$
$$\nabla \times \widetilde{\mathbf{E}} = -j\omega\mu\widetilde{\mathbf{H}}, \tag{7.2b}$$
$$\nabla \cdot \widetilde{\mathbf{H}} = 0, \tag{7.2c}$$
$$\nabla \times \widetilde{\mathbf{H}} = \widetilde{\mathbf{J}} + j\omega\varepsilon\widetilde{\mathbf{E}}. \tag{7.2d}$$

$$\varepsilon_{\mathrm{c}} = \varepsilon - j\frac{\sigma}{\omega}\,, \tag{7.4}$$

$$\nabla \cdot \widetilde{\mathbf{E}} = 0, \tag{7.6a}$$
$$\nabla \times \widetilde{\mathbf{E}} = -j\omega\mu\widetilde{\mathbf{H}}, \tag{7.6b}$$
$$\nabla \cdot \widetilde{\mathbf{H}} = 0, \tag{7.6c}$$
$$\nabla \times \widetilde{\mathbf{H}} = j\omega\varepsilon_{\mathrm{c}}\widetilde{\mathbf{E}}. \tag{7.6d}$$

$$\nabla^2\widetilde{\mathbf{E}} - \gamma^2\widetilde{\mathbf{E}} = 0. \tag{7.15}$$

$$\nabla^2\widetilde{\mathbf{H}} - \gamma^2\widetilde{\mathbf{H}} = 0. \tag{7.16}$$

$$k = \omega\sqrt{\mu\varepsilon}\,. \tag{7.18}$$

$$\eta = \frac{\omega\mu}{k} = \frac{\omega\mu}{\omega\sqrt{\mu\varepsilon}} = \sqrt{\frac{\mu}{\varepsilon}} \qquad (\Omega), \tag{7.31}$$

$$u_{\mathrm{p}} = \frac{\omega}{k} = \frac{\omega}{\omega\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu\varepsilon}} \qquad \text{(m/s)}, \tag{7.35}$$

$$\lambda = \frac{2\pi}{k} = \frac{u_{\mathrm{p}}}{f} \qquad \text{(m)}. \tag{7.36}$$

$$\widetilde{\mathbf{H}} = \frac{1}{\eta}\,\hat{\mathbf{k}} \times \widetilde{\mathbf{E}}, \qquad (7.39a)$$

$$\widetilde{\mathbf{E}} = -\eta\,\hat{\mathbf{k}} \times \widetilde{\mathbf{H}}. \qquad (7.39b)$$

$$\alpha = \omega \left\{ \frac{\mu\varepsilon'}{2} \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1 \right] \right\}^{1/2} \quad (\text{Np/m}), \qquad (7.66a)$$

$$\beta = \omega \left\{ \frac{\mu\varepsilon'}{2} \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1 \right] \right\}^{1/2} \quad (\text{rad/m}). \qquad (7.66b)$$

$$\eta_{\mathrm{c}} = \sqrt{\frac{\mu}{\varepsilon_{\mathrm{c}}}} = \sqrt{\frac{\mu}{\varepsilon'}} \left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)^{-1/2} \quad (\Omega). \qquad (7.70)$$

$$\delta_{\mathrm{s}} = \frac{1}{\alpha} \quad (\text{m}), \qquad (7.72)$$

$$\alpha \cong \frac{\omega\varepsilon''}{2}\sqrt{\frac{\mu}{\varepsilon'}} = \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} \quad (\text{Np/m}), \qquad (7.75a)$$

$$\beta \cong \omega\sqrt{\mu\varepsilon'} = \omega\sqrt{\mu\varepsilon} \quad (\text{rad/m}). \qquad (7.75b)$$

$$\eta_{\mathrm{c}} \cong \sqrt{\frac{\mu}{\varepsilon'}} \left(1 + j\frac{\varepsilon''}{2\varepsilon'}\right) = \sqrt{\frac{\mu}{\varepsilon}} \left(1 + j\frac{\sigma}{2\omega\varepsilon}\right). \qquad (7.76a)$$

$$\eta_{\mathrm{c}} \cong \sqrt{\frac{\mu}{\varepsilon}}, \qquad (7.76b)$$

$$\alpha \cong \omega\sqrt{\frac{\mu\varepsilon''}{2}} = \omega\sqrt{\frac{\mu\sigma}{2\omega}} = \sqrt{\pi f \mu\sigma} \qquad \text{(Np/m)}, \tag{7.77a}$$

$$\beta = \alpha \cong \sqrt{\pi f \mu\sigma} \qquad \text{(rad/m)}, \tag{7.77b}$$

$$\eta_{\rm c} \cong \sqrt{j\frac{\mu}{\varepsilon''}} = (1+j)\sqrt{\frac{\pi f \mu}{\sigma}} = (1+j)\frac{\alpha}{\sigma} \qquad (\Omega). \tag{7.77c}$$

$$Z_{\rm s} = \frac{1+j}{\sigma\delta_{\rm s}} \qquad (\Omega). \tag{7.91}$$

$$R' = R'_1 + R'_2 = \frac{R_{\rm s}}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right) \qquad (\Omega/\text{m}). \tag{7.96}$$

$$\mathbf{S}_{\rm av} = \tfrac{1}{2}\,\mathfrak{Re}\left[\widetilde{\mathbf{E}}\times\widetilde{\mathbf{H}}^*\right] \qquad (\text{W/m}^2). \tag{7.100}$$

$$\begin{aligned}\mathbf{S}_{\rm av} &= \hat{\mathbf{z}}\,\frac{1}{2\eta}(|E_{x0}|^2+|E_{y0}|^2)\\ &= \hat{\mathbf{z}}\,\frac{|\widetilde{\mathbf{E}}|^2}{2\eta} \qquad (\text{W/m}^2),\end{aligned} \tag{7.105}$$

$$\mathbf{S}_{\rm av}(z) = \hat{\mathbf{z}}\,\frac{|\widetilde{E}(0)|^2}{2|\eta_{\rm c}|}\,e^{-2\alpha z}\cos\theta_\eta \quad (\text{W/m}^2), \tag{7.109}$$

$$\Gamma = \frac{E_0^{\mathrm{r}}}{E_0^{\mathrm{i}}} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad \text{(normal incidence)}, \qquad (8.12\text{a})$$

$$\tau = \frac{E_0^{\mathrm{t}}}{E_0^{\mathrm{i}}} = \frac{2\eta_2}{\eta_2 + \eta_1} \quad \text{(normal incidence)}. \qquad (8.12\text{b})$$

$$\tau = 1 + \Gamma \qquad \text{(normal incidence)}. \qquad (8.13)$$

$$\Gamma = \frac{\sqrt{\varepsilon_{\mathrm{r}_1}} - \sqrt{\varepsilon_{\mathrm{r}_2}}}{\sqrt{\varepsilon_{\mathrm{r}_1}} + \sqrt{\varepsilon_{\mathrm{r}_2}}} \quad \text{(nonmagnetic media)}. \qquad (8.14)$$

$$S = \frac{|\widetilde{E}_1|_{\max}}{|\widetilde{E}_1|_{\min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \,. \qquad (8.15)$$

$$-z = l_{\max} = \frac{\theta_{\mathrm{r}} + 2n\pi}{2k_1} = \frac{\theta_{\mathrm{r}}\lambda_1}{4\pi} + \frac{n\lambda_1}{2} \,, \quad \begin{cases} n = 1, 2, \ldots, & \text{if } \theta_{\mathrm{r}} < 0, \\ n = 0, 1, 2, \ldots, & \text{if } \theta_{\mathrm{r}} \geq 0, \end{cases} \qquad (8.16)$$

$$l_{\min} = \begin{cases} l_{\max} + \lambda_1/4, & \text{if } l_{\max} < \lambda_1/4, \\ l_{\max} - \lambda_1/4, & \text{if } l_{\max} \geq \lambda_1/4. \end{cases} \qquad (8.17)$$

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$$\frac{\tau^2}{\eta_2} = \frac{1 - \Gamma^2}{\eta_1} \qquad \text{(lossless media)}, \qquad (8.1)$$

$$\Gamma = \frac{\eta_{\mathrm{c}_2} - \eta_{\mathrm{c}_1}}{\eta_{\mathrm{c}_2} + \eta_{\mathrm{c}_1}} \,, \qquad (8.24\text{a})$$

$$\tau = 1 + \Gamma = \frac{2\eta_{\mathrm{c}_2}}{\eta_{\mathrm{c}_2} + \eta_{\mathrm{c}_1}} \,. \qquad (8.24\text{b})$$

$$\theta_{\mathrm{i}} = \theta_{\mathrm{r}} \quad \text{(Snell's law of reflection)}, \qquad (8.28a)$$

$$\frac{\sin\theta_{\mathrm{t}}}{\sin\theta_{\mathrm{i}}} = \frac{u_{\mathrm{p}_2}}{u_{\mathrm{p}_1}} = \sqrt{\frac{\mu_1\varepsilon_1}{\mu_2\varepsilon_2}} \quad \text{(Snell's law of refraction)}. \qquad (8.28b)$$

$$n = \frac{c}{u_{\mathrm{p}}} = \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}} = \sqrt{\mu_{\mathrm{r}}\varepsilon_{\mathrm{r}}}\,. \qquad (8.29)$$

$$\frac{\sin\theta_{\mathrm{t}}}{\sin\theta_{\mathrm{i}}} = \frac{n_1}{n_2} = \sqrt{\frac{\varepsilon_{\mathrm{r}_1}}{\varepsilon_{\mathrm{r}_2}}} = \frac{\eta_2}{\eta_1} \quad (\text{for } \mu_1 = \mu_2). \qquad (8.31)$$

$$\sin\theta_{\mathrm{c}} = \frac{n_2}{n_1}\sin\theta_{\mathrm{t}}\Big|_{\theta_{\mathrm{t}}=\pi/2} = \frac{n_2}{n_1} \qquad (8.32a)$$

$$= \sqrt{\frac{\varepsilon_{\mathrm{r}_2}}{\varepsilon_{\mathrm{r}_1}}} \quad (\text{for } \mu_1 = \mu_2). \qquad (8.32b)$$

$$\sin\theta_{\mathrm{a}} = \frac{1}{n_0}(n_{\mathrm{f}}^2 - n_{\mathrm{c}}^2)^{1/2}. \qquad (8.33)$$

$$\theta_{\mathrm{r}} = \theta_{\mathrm{i}} \quad \text{(Snell's law of reflection)}, \qquad (8.55)$$

$$\frac{\sin\theta_{\mathrm{t}}}{\sin\theta_{\mathrm{i}}} = \frac{k_1}{k_2} = \frac{\omega\sqrt{\mu_1\varepsilon_1}}{\omega\sqrt{\mu_2\varepsilon_2}} = \frac{n_1}{n_2} \quad \text{(Snell's law of refraction)}. \qquad (8.56)$$

$$\Gamma_{\perp} = \frac{E_{\perp 0}^{\mathrm{r}}}{E_{\perp 0}^{\mathrm{i}}} = \frac{\eta_2\cos\theta_{\mathrm{i}} - \eta_1\cos\theta_{\mathrm{t}}}{\eta_2\cos\theta_{\mathrm{i}} + \eta_1\cos\theta_{\mathrm{t}}}\,, \qquad (8.58a)$$

$$\tau_{\perp} = \frac{E_{\perp 0}^{\mathrm{t}}}{E_{\perp 0}^{\mathrm{i}}} = \frac{2\eta_2\cos\theta_{\mathrm{i}}}{\eta_2\cos\theta_{\mathrm{i}} + \eta_1\cos\theta_{\mathrm{t}}}\,. \qquad (8.58b)$$

$$\tau_\perp = 1 + \Gamma_\perp. \quad (8.59)$$

$$\Gamma_\perp = \frac{\cos\theta_\mathrm{i} - \sqrt{(\varepsilon_2/\varepsilon_1) - \sin^2\theta_\mathrm{i}}}{\cos\theta_\mathrm{i} + \sqrt{(\varepsilon_2/\varepsilon_1) - \sin^2\theta_\mathrm{i}}} \quad (\text{for } \mu_1 = \mu_2). \quad (8.60)$$

$$\Gamma_\parallel = \frac{E^\mathrm{r}_{\parallel 0}}{E^\mathrm{i}_{\parallel 0}} = \frac{\eta_2\cos\theta_\mathrm{t} - \eta_1\cos\theta_\mathrm{i}}{\eta_2\cos\theta_\mathrm{t} + \eta_1\cos\theta_\mathrm{i}}, \quad (8.66\mathrm{a})$$

$$\tau_\parallel = \frac{E^\mathrm{t}_{\parallel 0}}{E^\mathrm{i}_{\parallel 0}} = \frac{2\eta_2\cos\theta_\mathrm{i}}{\eta_2\cos\theta_\mathrm{t} + \eta_1\cos\theta_\mathrm{i}}. \quad (8.66\mathrm{b})$$

$$\tau_\parallel = (1 + \Gamma_\parallel)\,\frac{\cos\theta_\mathrm{i}}{\cos\theta_\mathrm{t}}. \quad (8.67)$$

$$\Gamma_\parallel = \frac{-(\varepsilon_2/\varepsilon_1)\cos\theta_\mathrm{i} + \sqrt{(\varepsilon_2/\varepsilon_1) - \sin^2\theta_\mathrm{i}}}{(\varepsilon_2/\varepsilon_1)\cos\theta_\mathrm{i} + \sqrt{(\varepsilon_2/\varepsilon_1) - \sin^2\theta_\mathrm{i}}} \quad (\text{for } \mu_1 = \mu_2). \quad (8.68)$$

$$\theta_{\mathrm{B}\parallel} = \sin^{-1}\sqrt{\frac{1}{1 + (\varepsilon_1/\varepsilon_2)}} = \tan^{-1}\sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \quad (\text{for } \mu_1 = \mu_2). \quad (8.72)$$

$$R_\perp = |\Gamma_\perp|^2, \quad (8.77)$$

$$R_\parallel = \frac{P^\mathrm{r}_\parallel}{P^\mathrm{i}_\parallel} = |\Gamma_\parallel|^2. \quad (8.78)$$

$$T_\perp = \frac{P^{\mathrm{t}}_\perp}{P^{\mathrm{i}}_\perp} = \frac{|E^{\mathrm{t}}_{\perp 0}|^2}{|E^{\mathrm{i}}_{\perp 0}|^2} \, \frac{\eta_1}{\eta_2} \, \frac{A\cos\theta_{\mathrm{t}}}{A\cos\theta_{\mathrm{i}}} = |\tau_\perp|^2 \left(\frac{\eta_1\cos\theta_{\mathrm{t}}}{\eta_2\cos\theta_{\mathrm{i}}}\right), \tag{8.79a}$$

$$T_\parallel = \frac{P^{\mathrm{t}}_\parallel}{P^{\mathrm{i}}_\parallel} = |\tau_\parallel|^2 \left(\frac{\eta_1\cos\theta_{\mathrm{t}}}{\eta_2\cos\theta_{\mathrm{i}}}\right). \tag{8.79b}$$

$$|\Gamma_\perp|^2 + |\tau_\perp|^2 \left(\frac{\eta_1\cos\theta_{\mathrm{t}}}{\eta_2\cos\theta_{\mathrm{i}}}\right) = 1, \tag{8.83a}$$

$$|\Gamma_\parallel|^2 + |\tau_\parallel|^2 \left(\frac{\eta_1\cos\theta_{\mathrm{t}}}{\eta_2\cos\theta_{\mathrm{i}}}\right) = 1. \tag{8.83b}$$

$$\widetilde{E}_x = \frac{-j}{k_{\mathrm{c}}^2}\left(\beta\,\frac{\partial\widetilde{E}_z}{\partial x} + \omega\mu\,\frac{\partial\widetilde{H}_z}{\partial y}\right), \tag{8.89a}$$

$$\widetilde{E}_y = \frac{j}{k_{\mathrm{c}}^2}\left(-\beta\,\frac{\partial\widetilde{E}_z}{\partial y} + \omega\mu\,\frac{\partial\widetilde{H}_z}{\partial x}\right), \tag{8.89b}$$

$$\widetilde{H}_x = \frac{j}{k_{\mathrm{c}}^2}\left(\omega\varepsilon\,\frac{\partial\widetilde{E}_z}{\partial y} - \beta\,\frac{\partial\widetilde{H}_z}{\partial x}\right), \tag{8.89c}$$

$$\widetilde{H}_y = \frac{-j}{k_{\mathrm{c}}^2}\left(\omega\varepsilon\,\frac{\partial\widetilde{E}_z}{\partial x} + \beta\,\frac{\partial\widetilde{H}_z}{\partial y}\right). \tag{8.89d}$$

$$f_{mn} = \frac{u_{\mathrm{p}_0}}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad \text{(TE and TM)}, \tag{8.106}$$

$$\beta = \frac{\omega}{u_{\mathrm{p}_0}}\sqrt{1 - \left(\frac{f_{mn}}{f}\right)^2}\,. \qquad \text{(TE and TM)} \tag{8.107}$$

$$u_{\mathrm{p}} = \frac{\omega}{\beta} = \frac{u_{\mathrm{p}_0}}{\sqrt{1-(f_{mn}/f)^2}} . \quad \text{(TE and TM)} \tag{8.108}$$

$$u_{\mathrm{g}} = \frac{1}{d\beta/d\omega} = u_{\mathrm{p}_0}\sqrt{1-(f_{mn}/f)^2} , \tag{8.114}$$

$$u_{\mathrm{p}} u_{\mathrm{g}} = u_{\mathrm{p}_0}^2 . \tag{8.115}$$

$$f_{mnp} = \frac{u_{\mathrm{p}_0}}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2} . \tag{8.122}$$

$$\widetilde{E}_\theta = \frac{jI_0 lk\eta_0}{4\pi}\left(\frac{e^{-jkR}}{R}\right)\sin\theta \quad (\text{V/m}), \tag{9.9a}$$

$$\widetilde{H}_\phi = \frac{\widetilde{E}_\theta}{\eta_0} \quad (\text{A/m}), \tag{9.9b}$$

$$\mathbf{S}_{\text{av}} = \tfrac{1}{2}\mathfrak{Re}\left(\widetilde{\mathbf{E}} \times \widetilde{\mathbf{H}}^*\right) \quad (\text{W/m}^2). \tag{9.10}$$

$$S(R,\theta) = \left(\frac{\eta_0 k^2 I_0^2 l^2}{32\pi^2 R^2}\right)\sin^2\theta = S_0 \sin^2\theta \quad (\text{W/m}^2). \tag{9.12}$$

$$d\Omega = \frac{dA}{R^2} = \sin\theta \, d\theta \, d\phi \quad (\text{sr}). \tag{9.18}$$

$$\Omega_{\text{p}} = \iint_{4\pi} F(\theta,\phi)\, d\Omega \quad (\text{sr}). \tag{9.21}$$

$$D = \frac{4\pi}{\Omega_{\text{p}}} \simeq \frac{4\pi}{\beta_{xz}\beta_{yz}} . \tag{9.26}$$

$$\xi = \frac{P_{\text{rad}}}{P_{\text{t}}} \quad (\text{dimensionless}). \tag{9.27}$$

$$G = \xi D \quad (\text{dimensionless}). \tag{9.29}$$

$$\xi = \frac{P_{\text{rad}}}{P_{\text{t}}} = \frac{P_{\text{rad}}}{P_{\text{rad}} + P_{\text{loss}}} = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}} . \tag{9.34}$$

$$R_{\text{rad}} = 80\pi^2 (l/\lambda)^2 \quad (\Omega). \tag{9.38}$$

$$\widetilde{E}_\theta = j\,60 I_0 \left\{ \frac{\cos[(\pi/2)\cos\theta]}{\sin\theta} \right\} \left(\frac{e^{-jkR}}{R} \right), \quad (9.44a)$$

$$\widetilde{H}_\phi = \frac{\widetilde{E}_\theta}{\eta_0}\,. \quad (9.44b)$$

$$F(\theta) = \frac{S(R,\theta)}{S_0} = \left\{ \frac{\cos[(\pi/2)\cos\theta]}{\sin\theta} \right\}^2 . \quad (9.46)$$

$$A_e = \frac{P_{int}}{S_i} \qquad (m^2). \quad (9.57)$$

$$A_e = \frac{3\lambda^2}{8\pi} \qquad (m^2) \quad \text{(short dipole)}. \quad (9.63)$$

$$A_e = \frac{\lambda^2 D}{4\pi} \qquad (m^2) \quad \text{(any antenna)}. \quad (9.64)$$

$$\frac{P_{rec}}{P_t} = \frac{\xi_t \xi_r A_t A_r}{\lambda^2 R^2} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 . \quad (9.69)$$

$$R \geq 2d^2/\lambda\,, \quad (9.73)$$

$$S(R,\theta) = S_0\, \text{sinc}^2(\pi l_x \sin\theta/\lambda) \quad (x\text{–}z \text{ plane}), \quad (9.83)$$

$$\beta_{xz} = 2\theta_2 \simeq 2\sin\theta_2 = 0.88 \frac{\lambda}{l_x} \qquad \text{(rad)}. \quad (9.88a)$$

$$\beta_{yz} = 0.88\, \frac{\lambda}{l_y} \qquad \text{(rad)}. \quad (9.88b)$$

$$\beta_{xz} = k_x \frac{\lambda}{l_x} \,, \tag{9.89}$$

$$S(R_0, \theta, \phi) = S_e(R_0, \theta, \phi)\, F_a(\theta). \tag{9.102}$$

$$F_a(\theta) = \left| \sum_{i=0}^{N-1} a_i e^{j\psi_i} e^{jikd\cos\theta} \right|^2 . \tag{9.104}$$

$$F_a(\gamma) = \left| \sum_{i=0}^{N-1} a_i e^{ji\gamma} \right|^2 \quad \text{(uniform phase)}. \tag{9.107}$$

$$F_a(\gamma) = \frac{\sin^2(N\gamma/2)}{\sin^2(\gamma/2)} \quad \text{(uniform amplitude and phase)}. \tag{9.114}$$

$$\gamma' = kd(\cos\theta - \cos\theta_0). \tag{9.120}$$

$$\delta = 2n_0\pi \left(\frac{\Delta f}{f_0} \right). \tag{9.127}$$

$$\cos\theta_0 = \frac{2n_0\pi}{kd} \left(\frac{\Delta f}{f_0} \right). \tag{9.128}$$

$$R_0 = \left(\frac{\mathrm{G} M_\mathrm{e} T^2}{4\pi^2} \right)^{1/3}, \tag{10.6}$$

$$S_\mathrm{n} = \frac{P_\mathrm{ri}}{P_\mathrm{ni}} = \frac{\Upsilon(\theta)\, P_\mathrm{t} G_\mathrm{t} G_\mathrm{r}}{K T_\mathrm{sys} B} \left(\frac{\lambda}{4\pi R} \right)^2. \tag{10.11}$$

$$R_\mathrm{u} = \frac{c T_\mathrm{p}}{2} = \frac{c}{2 f_\mathrm{p}}. \tag{10.14}$$

$$\Delta R = R_2 - R_1 = c\tau/2. \tag{10.16}$$

$$P_\mathrm{r} = \frac{P_\mathrm{t} G^2 \lambda^2 \sigma_\mathrm{t}}{(4\pi)^3 R^4} \qquad \text{(radar equation)}. \tag{10.23}$$

$$R_\mathrm{max} = \left[\frac{P_\mathrm{t} \tau G^2 \lambda^2 \sigma_\mathrm{t}}{(4\pi)^3 K T_\mathrm{sys} S_\mathrm{min}} \right]^{1/4}. \tag{10.27}$$