Contents

1 ***Maxwell's Equations and Electromagnetic Waves*** 1

1.1 Review of Maxwell's Equations 5

1.2 Time-Harmonic Maxwell's Equations 8

1.3 Electromagnetic Boundary Conditions 10

1.4 Electromagnetic Waves 12

1.5 Summary 14

2 ***Waves in an Unbounded Medium*** 15

2.1 Plane Waves in a Simple, Source-Free, and Lossless Medium ... 19
2.1.1 Relation between $\overline{\mathscr{E}}$ and $\overline{\mathscr{H}}$ 24

2.2 Time-Harmonic Uniform Plane Wave in a Lossless Medium 27
2.2.1 The Electromagnetic Spectrum 35

2.3 Plane Waves in Lossy Media 38
2.3.1 Uniform Plane Wave Propagation in Lossy Dielectrics 45
2.3.2 Uniform Plane Wave Propagation in a Good Conductor 53

2.4 Electromagnetic Energy Flow and the Poynting Vector 59
2.4.1 Flow of Electromagnetic Energy and Poynting's Theorem 59
2.4.2 Electromagnetic Power Carried by a Uniform Pane Wave in a Lossless Medium 67
2.4.3 Instantaneous and Time-Average Power and the Complex Poynting Theorem 71
2.4.4 Radiation Pressure and Electromagnetic Momentum 75

2.5 Polarization of Electromagnetic Waves 78
2.5.1 Linear Polarization 79
2.5.2 Circular Polarization 80
2.5.3 Elliptical Polarization 85

2.5.4 Poynting Vector for Elliptically Polarized Waves 94
2.5.5 Polarization in Practice 94

2.6 Arbitrarily Directed Uniform Plane Waves 96
2.6.1 Uniform Plane Waves in an Arbitrary Direction 96
2.6.2 Nonuniform Plane Waves 101

2.7 Nonplanar Electromagnetic Waves 101
2.7.1 Uniform Cylindrical Waves 102
2.7.2 Uniform Spherical Waves 104

2.8 Summary 105

2.9 Problems 107

3 *Reflection, Transmission, and Refraction of Waves at Planar Interfaces* 120

3.1 Normal Incidence on a Perfect Conductor 122
3.1.1 More on the Reflection Process and Radiation Pressure 130

3.2 Normal Incidence on a Lossless Dielectric 132
3.2.1 Reflection and Transmission Coefficients 133
3.2.2 Propagating and Standing Waves 136
3.2.3 Electromagnetic Power Flow 139

3.3 Multiple Dielectric Interfaces 140
3.3.1 Application of Boundary Conditions 142
3.3.2 Impedance Transformation and Transmission Line Analogy 146

3.4 Oblique Incidence upon a Perfect Conductor 155
3.4.1 Perpendicular Polarization 157
3.4.2 Parallel Polarization 162

3.5 Oblique Incidence at a Dielectric Boundary 167
3.5.1 Perpendicular Polarization 171
3.5.2 Parallel Polarization 177
3.5.3 Brewster's Angle 179
3.5.4 Fresnel's Formulas 185

3.6 Total Internal Reflection 189
3.6.1 Reflection Coefficients 190
3.6.2 The Electromagnetic Field in Medium 2: The Refracted "Wave" 194

3.7 Normal Incidence on a Lossy Medium 201
3.7.1 Reflection from an Imperfect Conducting Plane 201
3.7.2 Reflection from Multiple Lossy Interfaces 209

3.8 Oblique Incidence on a Lossy Medium 215
3.8.1 The Refracted Electromagnetic Field in Medium 2 217
3.8.2 Oblique Incidence Reflection from a Lossy Medium 223

3.9 Summary 229

3.10 Problems 232

4 *Parallel-Plate and Dielectric Slab Waveguides* 249

4.1 Waves Between Parallel Metal Plates 255
4.1.1 Field Solutions for TE and TM Waves 259
4.1.2 Cutoff Frequency, Phase Velocity, and Wavelength 263
4.1.3 TE and TM Modes as Superpositions of TEM Waves 269
4.1.4 Attenuation in Parallel-Plate Waveguides 273
4.1.5 Voltage, Current, and Impedance in a Parallel-Plate Waveguide 281
4.1.6 Electric and Magnetic Field Distributions 284

4.2 Dielectric Waveguides 286
4.2.1 Dielectric Slab Waveguide: Mode Theory 287
4.2.2 Dielectric Covered Ground Plane 298
4.2.3 Dielectric Slab Waveguide: Ray Theory 302

4.3 Wave Velocities and Waveguide Dispersion 307
4.3.1 Group Velocity 309
4.3.2 Dispersion (β–ω) Diagrams 313
4.3.3 Group Velocity as Energy Velocity 316

4.4 Summary 319

4.5 Problems 321

5 *Cylindrical Waveguides and Cavity Resonators* 327

5.1 Rectangular Waveguides 331
5.1.1 Field Solutions for TM and TE Modes 333
5.1.2 Some Practical Considerations 342
5.1.3 Attenuation in Rectangular Waveguides 348

5.2 Cylindrical Waveguides with Circular Cross Section 353
5.2.1 Circular Waveguide 354
5.2.2 Coaxial Lines 365
5.2.3 Dielectric Waveguide with Circular Cross Section 371

5.3 Cavity Resonators 378
5.3.1 Rectangular Resonator 380
5.3.2 Circular Cavity Resonators 391
5.3.3 Coaxial Resonators 396

5.4 Summary 400

5.5 Problems 402

6 *Field–Matter Interactions and Elementary Antennas* 414

6.1 Charged-Particle Motion Driven by Electric and Magnetic Fields 416
6.1.1 Motion of a Charged Particle in an Electric Field 420
6.1.2 Motion of a Charged Particle in a Magnetic Field 423
6.1.3 Motion of a Charged Particle in Crossed $\overline{\mathscr{E}}$ and $\overline{\mathscr{B}}$ Fields 429
6.1.4 The Hall Effect 434
6.1.5 Electromagnetic Forces on Material Bodies and Radiation Pressure 437

6.2 Wave Propagation in Ionized Gases (Plasmas) 440
6.2.1 Plasma Oscillations and the Electron Plasma Frequency 444
6.2.2 Electromagnetic Wave Propagation in a Plasma 447
6.2.3 Wave Propagation in a Plasma with a Static Magnetic Field 453

6.3 Frequency Response of Dielectrics and conductors 460
6.3.1 Frequency Response of Dielectric Materials 461
6.3.2 Frequency Response of Metals 466

6.4 Electromagnetic Wave Propagation in Ferrites 467
6.4.1 Magnetic Dipole Moment and Magnetization in Ferrites 469
6.4.2 Magnetic Permeability Tensor for Time-Harmonic Fields 471
6.4.3 Electromagnetic Waves in Ferrites 472

6.5 Electromagnetic Radiation and Elementary Antennas 476
6.5.1 Retarded Potentials 479
6.5.2 Elementary Electric Dipole (Hertzian Dipole) 483
6.5.3 Short Linear Antenna and the Half-Wave Dipole 494

6.6 Summary 500

6.7 Problems 503

A *Vector Analysis* App-1

A.1 Vector Components, Unit Vectors, and Vector Addition App-2

A.2 Vector Multiplication App-4
A.2.1 The Dot Product App-4
A.2.2 The Cross Product App-5
A.2.3 Triple Products App-6

A.3 Cylindrical and Spherical Coordinate Systems **App-6**
A.3.1 Cylindrical Coordinates App-7
A.3.2 Spherical Coordinates App-10

A.4 Vector Identities **App-14**
A.4.1 Identities Involving ∇ App-15

A.5 Gradient, Divergence, and Curl **App-17**
A.5.1 Gradient of a Scalar App-17
A.5.2 Divergence of a Vector Field App-18
A.5.3 Curl of a Vector Field App-21

B *Useful Tables* **App-25**

Symbols and Units for Basic Quantities **App-29**

General Bibliography **App-32**

Answers to Odd Numbered Problems **App-33**

Index **App-41**