Contents

Preface **xvii**

1 Time-Varying and Time-Harmonic Electromagnetic Fields **1**

1.1 Introduction 1
1.2 Maxwell's Equations 1
1.2.1 *Differential Form of Maxwell's Equations* 2
1.2.2 *Integral Form of Maxwell's Equations* 3
1.3 Constitutive Parameters and Relations 5
1.4 Circuit-Field Relations 7
1.4.1 *Kirchhoff's Voltage Law* 7
1.4.2 *Kirchhoff's Current Law* 8
1.4.3 *Element Laws* 10
1.5 Boundary Conditions 12
1.5.1 *Finite Conductivity Media* 12
1.5.2 *Infinite Conductivity Media* 15
1.5.3 *Sources Along Boundaries* 17
1.6 Power and Energy 18
1.7 Time-Harmonic Electromagnetic Fields 21
1.7.1 *Maxwell's Equations in Differential and Integral Forms* 22
1.7.2 *Boundary Conditions* 22
1.7.3 *Power and Energy* 25
1.8 Multimedia 29
References 29
Problems 30

2 Electrical Properties of Matter **39**

2.1 Introduction 39
2.2 Dielectrics, Polarization, and Permittivity 41
2.3 Magnetics, Magnetization, and Permeability 48
2.4 Current, Conductors, and Conductivity 55
2.4.1 *Current* 55
2.4.2 *Conductors* 56
2.4.3 *Conductivity* 57
2.5 Semiconductors 59
2.6 Superconductors 64
2.7 Metamaterials 66

2.8 Linear, Homogeneous, Isotropic, and Nondispersive Media 67
2.9 A.C. Variations in Materials 68
2.9.1 *Complex Permittivity* 68
2.9.2 *Complex Permeability* 79
2.9.3 *Ferrites* 80
2.10 Multimedia 89
References 89
Problems 91

3 Wave Equation and its Solutions 99

3.1 Introduction 99
3.2 Time-Varying Electromagnetic Fields 99
3.3 Time-Harmonic Electromagnetic Fields 101
3.4 Solution to the Wave Equation 102
3.4.1 *Rectangular Coordinate System* 102
A. Source-Free and Lossless Media 102
B. Source-Free and Lossy Media 107
3.4.2 *Cylindrical Coordinate System* 110
3.4.3 *Spherical Coordinate System* 115
3.5 Multimedia 120
References 120
Problems 121

4 Wave Propagation and Polarization 123

4.1 Introduction 123
4.2 Transverse Electromagnetic Modes 123
4.2.1 *Uniform Plane Waves in an Unbounded Lossless Medium—Principal Axis* 124
A. Electric and Magnetic Fields 124
B. Wave Impedance 126
C. Phase and Energy (Group) Velocities, Power, and Energy Densities 128
D. Standing Waves 129
4.2.2 *Uniform Plane Waves in an Unbounded Lossless Medium—Oblique Angle* 131
A. Electric and Magnetic Fields 132
B. Wave Impedance 135
C. Phase and Energy (Group) Velocities 136
D. Power and Energy Densities 137
4.3 Transverse Electromagnetic Modes in Lossy Media 138
4.3.1 *Uniform Plane Waves in an Unbounded Lossy Medium—Principal Axis* 138
A. Good Dielectrics $[(\sigma/\omega\varepsilon)^2 \ll 1]$ 142
B. Good Conductors $[(\sigma/\omega\varepsilon)^2 \gg 1]$ 143
4.3.2 *Uniform Plane Waves in an Unbounded Lossy Medium—Oblique Angle* 143
4.4 Polarization 146
4.4.1 *Linear Polarization* 148
4.4.2 *Circular Polarization* 150

A. Right-Hand (Clockwise) Circular Polarization 150
B. Left-Hand (Counterclockwise) Circular Polarization 153
4.4.3 *Elliptical Polarization* 155
4.4.4 *Poincaré Sphere* 160
4.5 Multimedia 166
References 166
Problems 167

5 Reflection and Transmission 173

5.1 Introduction 173
5.2 Normal Incidence—Lossless Media 173
5.3 Oblique Incidence—Lossless Media 177
5.3.1 *Perpendicular (Horizontal or E) Polarization* 178
5.3.2 *Parallel (Vertical or H) Polarization* 182
5.3.3 *Total Transmission–Brewster Angle* 184
A. Perpendicular (Horizontal) Polarization 186
B. Parallel (Vertical) Polarization 187
5.3.4 *Total Reflection–Critical Angle* 188
A. Perpendicular (Horizontal) Polarization 188
B. Parallel (Vertical) Polarization 198
5.4 Lossy Media 198
5.4.1 *Normal Incidence: Conductor–Conductor Interface* 198
5.4.2 *Oblique Incidence: Dielectric–Conductor Interface* 201
5.4.3 *Oblique Incidence: Conductor–Conductor Interface* 205
5.5 Reflection and Transmission of Multiple Interfaces 205
5.5.1 *Reflection Coefficient of a Single Slab Layer* 206
5.5.2 *Reflection Coefficient of Multiple Layers* 213
A. Quarter-Wavelength Transformer 214
B. Binomial (Maximally Flat) Design 215
C. Tschebyscheff (Equal-Ripple) Design 217
D. Oblique-Wave Incidence 219
5.6 Polarization Characteristics on Reflection 220
5.7 Metamaterials 227
5.7.1 *Classification of Materials* 228
5.7.2 *Double Negative (DNG) Materials* 229
5.7.3 *Historical Perspective* 230
5.7.4 *Propagation Characteristics of DNG Materials* 231
5.7.5 *Refraction and Propagation Through DNG Interfaces and Materials* 233
5.7.6 *Negative-Refractive-Index (NRI) Transmission Lines* 241
5.8 Multimedia 245
References 246
Problems 247

6 Auxiliary Vector Potentials, Construction of Solutions, and Radiation and Scattering Equations 259

6.1 Introduction 259
6.2 The Vector Potential **A** 260
6.3 The Vector Potential **F** 262
6.4 The Vector Potentials **A** and **F** 263

6.5 Construction of Solutions 265
6.5.1 *Transverse Electromagnetic Modes: Source-Free Region* 265
A. Rectangular Coordinate System 265
B. Cylindrical Coordinate System 269
6.5.2 *Transverse Magnetic Modes: Source-Free Region* 272
A. Rectangular Coordinate System 273
B. Cylindrical Coordinate System 275
6.5.3 *Transverse Electric Modes: Source-Free Region* 276
A. Rectangular Coordinate System 276
B. Cylindrical Coordinate System 278
6.6 Solution of the Inhomogeneous Vector Potential Wave Equation 279
6.7 Far-Field Radiation 283
6.8 Radiation and Scattering Equations 284
6.8.1 *Near Field* 284
6.8.2 *Far Field* 286
A. Rectangular Coordinate System 290
B. Cylindrical Coordinate System 299
6.9 Multimedia 305
References 305
Problems 306

7 Electromagnetic Theorems and Principles 311

7.1 Introduction 311
7.2 Duality Theorem 311
7.3 Uniqueness Theorem 313
7.4 Image Theory 315
7.4.1 *Vertical Electric Dipole* 317
7.4.2 *Horizontal Electric Dipole* 321
7.5 Reciprocity Theorem 323
7.6 Reaction Theorem 325
7.7 Volume Equivalence Theorem 326
7.8 Surface Equivalence Theorem: Huygens's Principle 328
7.9 Induction Theorem (Induction Equivalent) 333
7.10 Physical Equivalent and Physical Optics Equivalent 337
7.11 Induction and Physical Equivalent Approximations 339
7.12 Multimedia 344
References 344
Problems 345

8 Rectangular Cross-Section Waveguides and Cavities 351

8.1 Introduction 351
8.2 Rectangular Waveguide 352
8.2.1 *Transverse Electric* (TE^z) 353
8.2.2 *Transverse Magnetic* (TM^z) 361
8.2.3 *Dominant* TE_{10} *Mode* 365
8.2.4 *Power Density and Power* 372
8.2.5 *Attenuation* 374
A. Conduction (Ohmic) Losses 374
B. Dielectric Losses 378
C. Coupling 381

8.3 Rectangular Resonant Cavities 382
8.3.1 *Transverse Electric* (TE^z) *Modes* 385
8.3.2 *Transverse Magnetic* (TM^z) *Modes* 389
8.4 Hybrid (LSE and LSM) Modes 390
8.4.1 *Longitudinal Section Electric* (LSE^y) *or Transverse Electric* (TE^y) *or* $\boldsymbol{H}^y$ *Modes* 390
8.4.2 *Longitudinal Section Magnetic* (LSM^y) *or Transverse Magnetic* (TM^y) *or* $\boldsymbol{E}^y$ *Modes* 393
8.5 Partially Filled Waveguide 393
8.5.1 *Longitudinal Section Electric* (LSE^y) *or Transverse Electric* (TE^y) 393
8.5.2 *Longitudinal Section Magnetic* (LSM^y) *or Transverse Magnetic* (TM^y) 400
8.6 Transverse Resonance Method 405
8.6.1 *Transverse Electric* (TE^y) *or Longitudinal Section Electric* (LSE^y) *or* $\boldsymbol{H}^y$ 407
8.6.2 *Transverse Magnetic* (TM^y) *or Longitudinal Section Magnetic* (LSM^y) *or* $\boldsymbol{E}^y$ 408
8.7 Dielectric Waveguide 408
8.7.1 *Dielectric Slab Waveguide* 408
8.7.2 *Transverse Magnetic* (TM^z) *Modes* 410
A. TM^z (Even) 411
B. TM^z (Odd) 414
C. Summary of TM^z (Even) and TM^z (Odd) Modes 414
D. Graphical Solution for TM^z_m (Even) and TM^z_m (Odd) Modes 416
8.7.3 *Transverse Electric* (TE^z) *Modes* 419
8.7.4 *Ray-Tracing Method* 423
A. Transverse Magnetic (TM^z) Modes (Parallel Polarization) 428
B. Transverse Electric (TE^z) Modes (Perpendicular Polarization) 431
8.7.5 *Dielectric-Covered Ground Plane* 433
8.8 Artificial Impedance Surfaces 436
8.8.1 *Corrugations* 439
8.8.2 *Artificial Magnetic Conductors (AMC), Electromagnetic Band-Gap (EBG), and Photonic Band-Gap (PBG) Surfaces* 441
8.8.3 *Antenna Applications* 444
A. Monopole 444
B. Aperture 444
C. Microstrip 446
8.8.4 *Design of Mushroom AMC* 448
8.8.5 *Surface Wave Dispersion Characteristics* 451
8.8.6 *Limitations of the Design* 454
8.9 Stripline and Microstrip Lines 455
8.9.1 *Stripline* 457
8.9.2 *Microstrip* 459
8.9.3 *Microstrip: Boundary-Value Problem* 465
8.10 Ridged Waveguide 466
8.11 Multimedia 470
References 471
Problems 474

9 Circular Cross-Section Waveguides and Cavities **483**

9.1 Introduction 483
9.2 Circular Waveguide 483
9.2.1 *Transverse Electric (TE^z) Modes* 483
9.2.2 *Transverse Magnetic (TM^z) Modes* 488
9.2.3 *Attenuation* 495
9.3 Circular Cavity 500
9.3.1 *Transverse Electric (TE^z) Modes* 503
9.3.2 *Transverse Magnetic (TM^z) Modes* 504
9.3.3 *Quality Factor Q* 505
9.4 Radial Waveguides 509
9.4.1 *Parallel Plates* 509
A. Transverse Electric (TE^z) Modes 509
B. Transverse Magnetic (TM^z) Modes 512
9.4.2 *Wedged Plates* 513
A. Transverse Electric (TE^z) Modes 514
B. Transverse Magnetic (TM^z) Modes 515
9.5 Dielectric Waveguides and Resonators 516
9.5.1 *Circular Dielectric Waveguide* 516
9.5.2 *Circular Dielectric Resonator* 526
A. TE^z Modes 528
B. TM^z Modes 529
C. $TE_{01\delta}$ Mode 530
9.5.3 *Optical Fiber Cable* 532
9.5.4 *Dielectric-Covered Conducting Rod* 534
A. TM^z Modes 534
B. TE^z Modes 540
9.6 Multimedia 541
References 541
Problems 543

10 Spherical Transmission Lines and Cavities **549**

10.1 Introduction 549
10.2 Construction of Solutions 549
10.2.1 *The Vector Potential* $\mathbf{F}(\mathbf{J} = 0, \mathbf{M} \neq 0)$ 550
10.2.2 *The Vector Potential* $\mathbf{A}(\mathbf{J} \neq 0, \mathbf{M} = 0)$ 552
10.2.3 *The Vector Potentials* **F** *and* **A** 552
10.2.4 *Transverse Electric (TE) Modes: Source-Free Region* 553
10.2.5 *Transverse Magnetic (TM) Modes: Source-Free Region* 555
10.2.6 *Solution of the Scalar Helmholtz Wave Equation* 556
10.3 Biconical Transmission Line 557
10.3.1 *Transverse Electric (TE^r) Modes* 557
10.3.2 *Transverse Magnetic (TM^r) Modes* 559
10.3.3 *Transverse Electromagnetic (TEM^r) Modes* 559
10.4 The Spherical Cavity 561
10.4.1 *Transverse Electric (TE^r) Modes* 562
10.4.2 *Transverse Magnetic (TM^r) Modes* 564
10.4.3 *Quality Factor Q* 566
10.5 Multimedia 569

References 569
Problems 569

11 Scattering **575**

11.1 Introduction 575
11.2 Infinite Line-Source Cylindrical Wave Radiation 575
11.2.1 *Electric Line Source* 576
11.2.2 *Magnetic Line Source* 580
11.2.3 *Electric Line Source Above Infinite Plane Electric Conductor* 580
11.3 Plane Wave Scattering by Planar Surfaces 583
11.3.1 TM^z *Plane Wave Scattering from a Strip* 584
11.3.2 TE^x *Plane Wave Scattering from a Flat Rectangular Plate* 591
11.4 Cylindrical Wave Transformations and Theorems 599
11.4.1 *Plane Waves in Terms of Cylindrical Wave Functions* 599
11.4.2 *Addition Theorem of Hankel Functions* 601
11.4.3 *Addition Theorem for Bessel Functions* 604
11.4.4 *Summary of Cylindrical Wave Transformations and Theorems* 606
11.5 Scattering by Circular Cylinders 607
11.5.1 *Normal Incidence Plane Wave Scattering by Conducting Circular Cylinder:* TM^z *Polarization* 607
A. Small Radius Approximation 610
B. Far-Zone Scattered Field 610
11.5.2 *Normal Incidence Plane Wave Scattering by Conducting Circular Cylinder:* TE^z *Polarization* 612
A. Small Radius Approximation 614
B. Far-Zone Scattered Field 615
11.5.3 *Oblique Incidence Plane Wave Scattering by Conducting Circular Cylinder:* TM^z *Polarization* 617
A. Far-Zone Scattered Field 621
11.5.4 *Oblique Incidence Plane Wave Scattering by Conducting Circular Cylinder:* TE^z *Polarization* 623
A. Far-Zone Scattered Field 627
11.5.5 *Line-Source Scattering by a Conducting Circular Cylinder* 628
A. Electric Line Source (TM^z Polarization) 628
B. Magnetic Line Source (TE^z Polarization) 632
11.6 Scattering By a Conducting Wedge 639
11.6.1 *Electric Line-Source Scattering by a Conducting Wedge:* TM^z *Polarization* 639
A. Far-Zone Field 643
B. Plane Wave Scattering 644
11.6.2 *Magnetic Line-Source Scattering by a Conducting Wedge:* TE^z *Polarization* 644
11.6.3 *Electric and Magnetic Line-Source Scattering by a Conducting Wedge* 648
11.7 Spherical Wave Orthogonalities, Transformations, and Theorems 650
11.7.1 *Vertical Dipole Spherical Wave Radiation* 650
11.7.2 *Orthogonality Relationships* 652
11.7.3 *Wave Transformations and Theorems* 653
11.8 Scattering by a Sphere 655
11.8.1 *Perfect Electric Conducting (PEC) Sphere* 655
11.8.2 *Lossy Dielectric Sphere* 663

11.9 Multimedia 665
References 666
Problems 668

12 Integral Equations and the Moment Method 679

12.1 Introduction 679
12.2 Integral Equation Method 679
12.2.1 *Electrostatic Charge Distribution* 680
A. Finite Straight Wire 680
B. Bent Wire 684
12.2.2 *Integral Equation* 686
12.2.3 *Radiation Pattern* 688
12.2.4 *Point-Matching (Collocation) Method* 689
12.2.5 *Basis Functions* 691
A. Subdomain Functions 691
B. Entire-Domain Functions 693
12.2.6 *Application of Point Matching* 695
12.2.7 *Weighting (Testing) Functions* 697
12.2.8 *Moment Method* 697
12.3 Electric and Magnetic Field Integral Equations 703
12.3.1 *Electric Field Integral Equation* 704
A. Two-Dimensional EFIE: TM^z Polarization 705
B. Two-Dimensional EFIE: TE^z Polarization 709
12.3.2 *Magnetic Field Integral Equation* 713
A. Two-Dimensional MFIE: TM^z Polarization 715
B. Two-Dimensional MFIE: TE^z Polarization 717
C. Solution of the Two-Dimensional MFIE TE^z Polarization 719
12.4 Finite Diameter Wires 723
12.4.1 *Pocklington's Integral Equation* 724
12.4.2 *Hallén's Integral Equation* 727
12.4.3 *Source Modeling* 729
A. Delta Gap 729
B. Magnetic Frill Generator 729
12.5 Computer Codes 732
12.5.1 *Two-Dimensional Radiation and Scattering* 732
A. Strip 733
B. Circular, Elliptical, or Rectangular Cylinder 733
12.5.2 *Pocklington's Wire Radiation and Scattering* 734
A. Radiation 734
B. Scattering 734
12.5.3 *Numerical Electromagnetics Code* 734
12.6 Multimedia 735
References 735
Problems 737

13 Geometrical Theory of Diffraction 741

13.1 Introduction 741
13.2 Geometrical Optics 742
13.2.1 *Amplitude Relation* 745

13.2.2 *Phase and Polarization Relations* 749
13.2.3 *Reflection from Surfaces* 751
13.3 Geometrical Theory of Diffraction: Edge Diffraction 761
13.3.1 *Amplitude, Phase, and Polarization Relations* 761
13.3.2 *Straight Edge Diffraction: Normal Incidence* 765
A. Modal Solution 767
B. High-Frequency Asymptotic Solution 768
C. Method of Steepest Descent 772
D. Geometrical Optics and Diffracted Fields 777
E. Diffraction Coefficients 780
13.3.3 *Straight Edge Diffraction: Oblique Incidence* 800
13.3.4 *Curved Edge Diffraction: Oblique Incidence* 808
13.3.5 *Equivalent Currents in Diffraction* 815
13.3.6 *Slope Diffraction* 819
13.3.7 *Multiple Diffractions* 821
A. Higher-Order Diffractions 822
B. Self-Consistent Method 824
C. Overlap Transition Diffraction Region 827
13.4 Computer Codes 829
13.4.1 *Wedge Diffraction Coefficients* 830
13.4.2 *Fresnel Transition Function* 831
13.4.3 *Slope Wedge Diffraction Coefficients* 831
13.5 Multimedia 831
References 832
Problems 835

14 Diffraction by Wedge with Impedance Surfaces **849**

14.1 Introduction 849
14.2 Impedance Surface Boundary Conditions 850
14.3 Impedance Surface Reflection Coefficients 851
14.4 The Maliuzhinets Impedance Wedge Solution 854
14.5 Geometrical Optics 857
14.6 Surface Wave Terms 865
14.7 Diffracted Fields 868
14.7.1 *Diffraction Terms* 868
14.7.2 *Asymptotic Expansions* 869
14.7.3 *Diffracted Field* 870
14.8 Surface Wave Transition Field 875
14.9 Computations 877
14.10 Multimedia 879
References 880
Problems 883

15 Green's Functions **885**

15.1 Introduction 885
15.2 Green's Functions in Engineering 886
15.2.1 *Circuit Theory* 886
15.2.2 *Mechanics* 889
15.3 Sturm–Liouville Problems 891

15.3.1 *Green's Function in Closed Form* 893
15.3.2 *Green's Function in Series* 898
A. Vibrating String 898
B. Sturm-Liouville Operator 899
15.3.3 *Green's Function in Integral Form* 904
15.4 Two-Dimensional Green's Function in Rectangular Coordinates 908
15.4.1 *Static Fields* 908
A. Closed Form 908
B. Series Form 914
15.4.2 *Time-Harmonic Fields* 917
15.5 Green's Identities and Methods 919
15.5.1 *Green's First and Second Identities* 920
15.5.2 *Generalized Green's Function Method* 922
A. Nonhomogeneous Partial Differential Equation with Homogeneous Dirichlet Boundary Conditions 923
B. Nonhomogeneous Partial Differential Equation with Nonhomogeneous Dirichlet Boundary Conditions 923
C. Nonhomogeneous Partial Differential Equation with Homogeneous Neumann Boundary Conditions 924
D. Nonhomogeneous Partial Differential Equation with Mixed Boundary Conditions 925
15.6 Green's Functions of the Scalar Helmholtz Equation 925
15.6.1 *Rectangular Coordinates* 925
15.6.2 *Cylindrical Coordinates* 928
15.6.3 *Spherical Coordinates* 933
15.7 Dyadic Green's Functions 938
15.7.1 *Dyadics* 938
15.7.2 *Green's Functions* 939
15.8 Multimedia 941
References 941
Problems 942

Appendix I Identities 947

Appendix II Vector Analysis 951

Appendix III Fresnel Integrals 961

Appendix IV Bessel Functions 967

Appendix V Legendre Polynomials and Functions 981

Appendix VI The Method of Steepest Descent (Saddle-Point Method) 997

Index 1003