

Contents

Preface *xii*

1 Maxwell's Equations 1

- 1.1 Maxwell's Equations, 1
- 1.2 Lorentz Force, 2
- 1.3 Constitutive Relations, 3
- 1.4 Negative Index Media, 7
- 1.5 Boundary Conditions, 7
- 1.6 Currents, Fluxes, and Conservation Laws, 9
- 1.7 Charge Conservation, 10
- 1.8 Energy Flux and Energy Conservation, 11
- 1.9 Harmonic Time Dependence, 13
- 1.10 Simple Models of Dielectrics, Conductors, and Plasmas, 16
- 1.11 Dielectrics, 17
- 1.12 Conductors, 20
- 1.13 Charge Relaxation in Conductors, 23
- 1.14 Power Losses, 23
- 1.15 Plasmas, 25
- 1.16 Energy Density in Lossless Dispersive Dielectrics, 26
- 1.17 Kramers-Kronig Dispersion Relations, 27
- 1.18 Group Velocity, Energy Velocity, 29
- 1.19 Problems, 31

2 Uniform Plane Waves 37

- 2.1 Uniform Plane Waves in Lossless Media, 37
- 2.2 Monochromatic Waves, 43
- 2.3 Energy Density and Flux, 46
- 2.4 Wave Impedance, 47
- 2.5 Polarization, 47
- 2.6 Uniform Plane Waves in Lossy Media, 54
- 2.7 Propagation in Weakly Lossy Dielectrics, 60
- 2.8 Propagation in Good Conductors, 61
- 2.9 Skin Effect in Cylindrical Wires, 62
- 2.10 Propagation in Oblique Directions, 62
- 2.11 Complex or Inhomogeneous Waves, 65
- 2.12 Doppler Effect, 67

- 2.13 Propagation in Negative-Index Media, 71
- 2.14 Problems, 74

3 Pulse Propagation in Dispersive Media 83

- 3.1 Propagation Filter, 83
- 3.2 Front Velocity and Causality, 85
- 3.3 Exact Impulse Response Examples, 88
- 3.4 Transient and Steady-State Behavior, 91
- 3.5 Pulse Propagation and Group Velocity, 95
- 3.6 Group Velocity Dispersion and Pulse Spreading, 99
- 3.7 Propagation and Chirping, 103
- 3.8 Dispersion Compensation, 105
- 3.9 Slow, Fast, and Negative Group Velocities, 106
- 3.10 Chirp Radar and Pulse Compression, 113
- 3.11 Further Reading, 123
- 3.12 Problems, 124

4 Propagation in Birefringent Media 132

- 4.1 Linear and Circular Birefringence, 132
- 4.2 Uniaxial and Biaxial Media, 133
- 4.3 Chiral Media, 135
- 4.4 Gyrotropic Media, 138
- 4.5 Linear and Circular Dichroism, 139
- 4.6 Oblique Propagation in Birefringent Media, 140
- 4.7 Problems, 147

5 Reflection and Transmission 153

- 5.1 Propagation Matrices, 153
- 5.2 Matching Matrices, 157
- 5.3 Reflected and Transmitted Power, 160
- 5.4 Single Dielectric Slab, 163
- 5.5 Reflectionless Slab, 166
- 5.6 Time-Domain Reflection Response, 174
- 5.7 Two Dielectric Slabs, 176
- 5.8 Reflection by a Moving Boundary, 178
- 5.9 Problems, 181

6 Multilayer Structures 186

- 6.1 Multiple Dielectric Slabs, 186
- 6.2 Antireflection Coatings, 188
- 6.3 Dielectric Mirrors, 193
- 6.4 Propagation Bandgaps, 204
- 6.5 Narrow-Band Transmission Filters, 204
- 6.6 Equal Travel-Time Multilayer Structures, 209
- 6.7 Applications of Layered Structures, 223
- 6.8 Chebyshev Design of Reflectionless Multilayers, 227
- 6.9 Problems, 234

7 Oblique Incidence 241

- 7.1 Oblique Incidence and Snell's Laws, 241
- 7.2 Transverse Impedance, 243
- 7.3 Propagation and Matching of Transverse Fields, 246
- 7.4 Fresnel Reflection Coefficients, 248
- 7.5 Maximum Angle and Critical Angle, 250
- 7.6 Brewster Angle, 259
- 7.7 Complex Waves, 261
- 7.8 Total Internal Reflection, 264
- 7.9 Oblique Incidence on a Lossy Medium, 266
- 7.10 Zenneck Surface Wave, 270
- 7.11 Surface Plasmons, 272
- 7.12 Oblique Reflection from a Moving Boundary, 275
- 7.13 Geometrical Optics, 279
- 7.14 Fermat's Principle, 282
- 7.15 Ray Tracing, 284
- 7.16 Snell's Law in Negative-Index Media, 295
- 7.17 Problems, 298

8 Multilayer Film Applications 303

- 8.1 Multilayer Dielectric Structures at Oblique Incidence, 303
- 8.2 Lossy Multilayer Structures, 305
- 8.3 Single Dielectric Slab, 307
- 8.4 Frustrated Total Internal Reflection, 309
- 8.5 Surface Plasmon Resonance, 313
- 8.6 Perfect Lens in Negative-Index Media, 322
- 8.7 Antireflection Coatings at Oblique Incidence, 330
- 8.8 Omnidirectional Dielectric Mirrors, 333
- 8.9 Polarizing Beam Splitters, 344
- 8.10 Reflection and Refraction in Birefringent Media, 346
- 8.11 Brewster and Critical Angles in Birefringent Media, 350
- 8.12 Multilayer Birefringent Structures, 353
- 8.13 Giant Birefringent Optics, 355
- 8.14 Problems, 361

9 Waveguides 362

- 9.1 Longitudinal-Transverse Decompositions, 363
- 9.2 Power Transfer and Attenuation, 368
- 9.3 TEM, TE, and TM modes, 371
- 9.4 Rectangular Waveguides, 374
- 9.5 Higher TE and TM modes, 376
- 9.6 Operating Bandwidth, 378
- 9.7 Power Transfer, Energy Density, and Group Velocity, 379
- 9.8 Power Attenuation, 381
- 9.9 Reflection Model of Waveguide Propagation, 384
- 9.10 Resonant Cavities, 386
- 9.11 Dielectric Slab Waveguides, 388
- 9.12 Asymmetric Dielectric Slab, 397

- 9.13 Problems, 408

10 Surface Waveguides 411

- 10.1 Plasmonic Waveguides, 411
- 10.2 Single Metal-Dielectric Interface, 419
- 10.3 Power Transfer, Energy & Group Velocities, 421
- 10.4 MDM Configuration - Lossless Case, 425
- 10.5 Oscillatory Modes, 437
- 10.6 MDM Configuration - Lossy Case, 443
- 10.7 Gap Surface Plasmons, 448
- 10.8 PEC Limit, 452
- 10.9 Anomalous Complex Modes, 454
- 10.10 DMD Configuration - Lossless Case, 457
- 10.11 DMD Configuration - Lossy Case, 467
- 10.12 Symmetric DMD Waveguides, 468
- 10.13 Asymmetric DMD Waveguides, 476
- 10.14 Note on Computations, 488
- 10.15 Sommerfeld Wire, 489
- 10.16 Power Transfer and Power Loss, 501
- 10.17 Connection to Zenneck Surface Wave, 504
- 10.18 Skin Effect for Round Wire, 506
- 10.19 Goubau Line, 509
- 10.20 Planar Limit of the Goubau Line, 526
- 10.21 Problems, 532

11 Transmission Lines 535

- 11.1 General Properties of TEM Transmission Lines, 535
- 11.2 Parallel Plate Lines, 541
- 11.3 Microstrip Lines, 542
- 11.4 Coaxial Lines, 546
- 11.5 Two-Wire Lines, 551
- 11.6 Distributed Circuit Model of a Transmission Line, 553
- 11.7 Wave Impedance and Reflection Response, 555
- 11.8 Two-Port Equivalent Circuit, 557
- 11.9 Terminated Transmission Lines, 558
- 11.10 Power Transfer from Generator to Load, 561
- 11.11 Open- and Short-Circuited Transmission Lines, 563
- 11.12 Standing Wave Ratio, 566
- 11.13 Determining an Unknown Load Impedance, 568
- 11.14 Smith Chart, 572
- 11.15 Time-Domain Response of Transmission Lines, 576
- 11.16 Problems, 583

12 Coupled Lines 594

- 12.1 Coupled Transmission Lines, 594
- 12.2 Crosstalk Between Lines, 600
- 12.3 Weakly Coupled Lines with Arbitrary Terminations, 603
- 12.4 Coupled-Mode Theory, 605

- 12.5 Fiber Bragg Gratings, 607
- 12.6 Diffuse Reflection and Transmission, 610
- 12.7 Problems, 612

13 Impedance Matching 614

- 13.1 Conjugate and Reflectionless Matching, 614
- 13.2 Multisection Transmission Lines, 616
- 13.3 Quarter-Wavelength Chebyshev Transformers, 617
- 13.4 Two-Section Dual-Band Chebyshev Transformers, 623
- 13.5 Quarter-Wavelength Transformer With Series Section, 629
- 13.6 Quarter-Wavelength Transformer With Shunt Stub, 632
- 13.7 Two-Section Series Impedance Transformer, 634
- 13.8 Single Stub Matching, 639
- 13.9 Balanced Stubs, 643
- 13.10 Double and Triple Stub Matching, 645
- 13.11 L-Section Lumped Reactive Matching Networks, 647
- 13.12 Pi-Section Lumped Reactive Matching Networks, 650
- 13.13 Reversed Matching Networks, 657
- 13.14 Problems, 659

14 S-Parameters 663

- 14.1 Scattering Parameters, 663
- 14.2 Power Flow, 667
- 14.3 Parameter Conversions, 668
- 14.4 Input and Output Reflection Coefficients, 669
- 14.5 Stability Circles, 671
- 14.6 Power Gains, 677
- 14.7 Generalized S-Parameters and Power Waves, 683
- 14.8 Simultaneous Conjugate Matching, 687
- 14.9 Power Gain Circles, 692
- 14.10 Unilateral Gain Circles, 693
- 14.11 Operating and Available Power Gain Circles, 695
- 14.12 Noise Figure Circles, 701
- 14.13 Problems, 706

15 Radiation Fields 709

- 15.1 Currents and Charges as Sources of Fields, 709
- 15.2 Retarded Potentials, 711
- 15.3 Harmonic Time Dependence, 714
- 15.4 Fields of a Linear Wire Antenna, 716
- 15.5 Fields of Electric and Magnetic Dipoles, 718
- 15.6 Ewald-Oseen Extinction Theorem, 723
- 15.7 Radiation Fields, 728
- 15.8 Radial Coordinates, 731
- 15.9 Radiation Field Approximation, 733
- 15.10 Computing the Radiation Fields, 734
- 15.11 Problems, 736

16 Transmitting and Receiving Antennas 739

- 16.1 Energy Flux and Radiation Intensity, 739
- 16.2 Directivity, Gain, and Beamwidth, 740
- 16.3 Effective Area, 745
- 16.4 Antenna Equivalent Circuits, 749
- 16.5 Effective Length, 751
- 16.6 Communicating Antennas, 753
- 16.7 Antenna Noise Temperature, 755
- 16.8 System Noise Temperature, 759
- 16.9 Data Rate Limits, 765
- 16.10 Satellite Links, 767
- 16.11 Radar Equation, 770
- 16.12 Problems, 772

17 Linear and Loop Antennas 775

- 17.1 Linear Antennas, 775
- 17.2 Hertzian Dipole, 777
- 17.3 Standing-Wave Antennas, 779
- 17.4 Half-Wave Dipole, 783
- 17.5 Monopole Antennas, 784
- 17.6 Traveling-Wave Antennas, 786
- 17.7 Vee and Rhombic Antennas, 788
- 17.8 Loop Antennas, 791
- 17.9 Circular Loops, 793
- 17.10 Square Loops, 795
- 17.11 Dipole and Quadrupole Radiation, 796
- 17.12 Problems, 798

18 Radiation from Apertures 799

- 18.1 Field Equivalence Principle, 799
- 18.2 Magnetic Currents and Duality, 801
- 18.3 Radiation Fields from Magnetic Currents, 803
- 18.4 Radiation Fields from Apertures, 804
- 18.5 Huygens Source, 807
- 18.6 Directivity and Effective Area of Apertures, 809
- 18.7 Uniform Apertures, 811
- 18.8 Rectangular Apertures, 812
- 18.9 Circular Apertures, 814
- 18.10 Vector Diffraction Theory, 816
- 18.11 Extinction Theorem, 821
- 18.12 Vector Diffraction for Apertures, 822
- 18.13 Fresnel Diffraction, 823
- 18.14 Knife-Edge Diffraction, 827
- 18.15 Geometrical Theory of Diffraction, 835
- 18.16 Problems, 841

19 Diffraction – Plane-Wave Spectrum 844

- 19.1 Rayleigh-Sommerfeld Diffraction Theory, 844
- 19.2 Plane-Wave Spectrum Representation, 849
- 19.3 Far-Field Diffraction Pattern, 852
- 19.4 One-Dimensional Apertures, 854
- 19.5 Plane-Wave Spectrum-Vector Case, 856
- 19.6 Far-Field Approximation, Radiation Pattern, 860
- 19.7 Radiated and Reactive Power, Directivity, 861
- 19.8 Smythe Diffraction Formulas, 865
- 19.9 Apertures in Conducting Screens, 872
- 19.10 Sommerfeld's Half-Plane Problem Revisited, 878
- 19.11 Diffraction by Small Holes – Bethe-Bouwkamp Model, 891
- 19.12 Plane-Wave Spectrum – Bethe-Bouwkamp Model, 905
- 19.13 Babinet Principle, 915
- 19.14 Problems, 921

20 Diffraction – Fourier Optics 923

- 20.1 Fresnel Approximation, 923
- 20.2 Self-Imaging of Periodic Structures – Talbot Effect, 930
- 20.3 Fraunhofer Approximation, 939
- 20.4 Cascading of Optical Elements, 944
- 20.5 Lenses – Transmittance Properties, 945
- 20.6 Magnification Properties of Lenses, 949
- 20.7 Point-Spread Function of a Lens, 950
- 20.8 Cylindrically-Symmetric and One-Dimensional Lenses, 953
- 20.9 Shift-Invariance and Coherent Transfer Function, 953
- 20.10 Fourier Transformation Properties of Lenses, 955
- 20.11 4F Optical Processor, 961
- 20.12 Apodization Design and Aperture Synthesis, 970
- 20.13 Prolate Window, 978
- 20.14 Taylor's One-Parameter Window, 981
- 20.15 Taylor's N-bar Window, 983
- 20.16 Circularly Symmetric Apodization Functions, 988
- 20.17 Hansen One-Parameter Window, 991
- 20.18 Fourier-Bessel and Dini Series Expansions, 993
- 20.19 Taylor's Two-Dimensional N-bar Window, 997
- 20.20 Star-Shaped Masks, Starshade Occulters, 1000
- 20.21 Superresolving Apertures, 1007
- 20.22 Superdirectivity, Superresolution, Superoscillations, 1018
- 20.23 Problems, 1038

21 Aperture Antennas 1042

- 21.1 Open-Ended Waveguides, 1042
- 21.2 Horn Antennas, 1046
- 21.3 Horn Radiation Fields, 1048
- 21.4 Horn Directivity, 1054
- 21.5 Horn Design, 1056
- 21.6 Microstrip Antennas, 1060

- 21.7 Parabolic Reflector Antennas, 1065
- 21.8 Gain and Beamwidth of Reflector Antennas, 1067
- 21.9 Aperture-Field and Current-Distribution Methods, 1071
- 21.10 Radiation Patterns of Reflector Antennas, 1074
- 21.11 Dual-Reflector Antennas, 1083
- 21.12 Lens Antennas, 1086

22 Antenna Arrays 1088

- 22.1 Antenna Arrays, 1088
- 22.2 Translational Phase Shift, 1088
- 22.3 Array Pattern Multiplication, 1090
- 22.4 One-Dimensional Arrays, 1100
- 22.5 Visible Region, 1102
- 22.6 Grating Lobes, 1104
- 22.7 Uniform Arrays, 1106
- 22.8 Array Directivity, 1110
- 22.9 Array Steering, 1111
- 22.10 Array Beamwidth, 1114
- 22.11 Problems, 1116

23 Array Design Methods 1119

- 23.1 Array Design Methods, 1119
- 23.2 Schelkunoff's Zero Placement Method, 1122
- 23.3 Fourier Series Method with Windowing, 1124
- 23.4 Sector Beam Array Design, 1125
- 23.5 Woodward-Lawson Frequency-Sampling Design, 1129
- 23.6 Discretization of Continuous Line Sources, 1134
- 23.7 Narrow-Beam Low-Sidelobe Designs, 1138
- 23.8 Binomial Arrays, 1142
- 23.9 Dolph-Chebyshev Arrays, 1144
- 23.10 Taylor One-Parameter Source, 1156
- 23.11 Prolate Array, 1160
- 23.12 Taylor Line Source, 1164
- 23.13 Villeneuve Arrays, 1167
- 23.14 Multibeam Arrays, 1168
- 23.15 Problems, 1170

24 Currents on Linear Antennas 1172

- 24.1 Hallén and Pocklington Integral Equations, 1172
- 24.2 Delta-Gap, Frill Generator, and Plane-Wave Sources, 1175
- 24.3 Solving Hallén's Equation, 1176
- 24.4 Sinusoidal Current Approximation, 1179
- 24.5 Reflecting and Center-Loaded Receiving Antennas, 1179
- 24.6 King's Three-Term Approximation, 1182
- 24.7 Evaluation of the Exact Kernel, 1189
- 24.8 Method of Moments, 1194
- 24.9 Delta-Function Basis, 1197
- 24.10 Pulse Basis, 1201

- 24.11 Triangular Basis, 1206
- 24.12 NEC Sinusoidal Basis, 1208
- 24.13 Hallén's Equation for Arbitrary Incident Field, 1211
- 24.14 Solving Pocklington's Equation, 1216
- 24.15 Problems, 1220

25 Coupled Antennas 1222

- 25.1 Near Fields of Linear Antennas, 1222
- 25.2 Improved Near-Field Calculation, 1225
- 25.3 Self and Mutual Impedance, 1233
- 25.4 Coupled Two-Element Arrays, 1239
- 25.5 Arrays of Parallel Dipoles, 1242
- 25.6 Yagi-Uda Antennas, 1251
- 25.7 Hallén Equations for Coupled Antennas, 1257
- 25.8 Problems, 1264

26 Appendices 1266

- A Physical Constants, 1266
- B Electromagnetic Frequency Bands, 1267
- C Vector Identities and Integral Theorems, 1269
- D Green's Functions, 1272
- E Coordinate Systems, 1278
- F Fresnel Integrals, 1281
- G Exponential, Sine, and Cosine Integrals, 1286
- H Stationary Phase Approximation, 1288
- I Gauss-Legendre and Double-Exponential Quadrature, 1291
- J Prolate Spheroidal Wave Functions, 1298
- K Lorentz Transformations, 1322
- L MATLAB Functions, 1330

References 1335

Index 1401