CONTENTS

CHAPTER 1 STATIONARY ELECTRIC FIELDS 1

1.1 Introduction 1

BASIC LAWS AND CONCEPTS OF ELECTROSTATICS 2

1.2 Force Between Electric Charges; The Concept of Electric Field 2
1.3 The Concept of Electric Flux and Flux Density; Gauss's Law 6
1.4 Examples of the Use of Gauss's Law 9
1.5 Surface and Volume Integrals; Gauss's Law in Vector Form 13
1.6 Tubes of Flux; Plotting of Field Lines 15
1.7 Energy Considerations; Conservative Property of Electrostatic Fields 17
1.8 Electrostatic Potential : Equipotentials 20
1.9 Capacitance 27

DIFFERENTIAL FORMS OF ELECTROSTATIC LAWS 28

1.10 Gradient 28
1.11 The Divergence of an Electrostatic Field 30
1.12 Laplace's and Poisson's Equations 35
1.13 Static Fields Arising from Steady Currents 37
1.14 Boundary Conditions in Electrostatics 38
1.15 Direct Integration of Laplace's Equation: Field Between Coaxial Cylinders with Two Dielectrics 42
1.16 Direct Integration of Poisson's Equation : The *pn* Semiconductor Junction 44
1.17 Uniqueness of Solutions 47

SPECIAL TECHNIQUES FOR ELECTROSTATIC PROBLEMS 48
1.18 The Use of Images 48
1.19 Graphical Field Mapping 53
1.20 Examples of Information Obtained from Field Maps 56
ENERGY IN FIELDS 58
1.21 Energy of an Electrostatic System 58
Problems 61

CHAPTER 2 STATIONARY MAGNETIC FIELDS 68

2.1 Introduction 68
STATIC MAGNETIC FIELD LAWS AND CONCEPTS 70
2.2 Concept of a Magnetic Field 70
2.3 Ampere's Law 71
2.4 The Line Integral of Magnetic Field 75
2.5 Inductance from Flux Linkages; External Inductance 79
DIFFERENTIAL FORMS FOR MAGNETOSTATICS AND THE USE OF POTENTIAL 82
2.6 The Curl of a Vector Field 82
2.7 Curl of Magnetic Field 86
2.8 Relation Between Differential and Integral Forms of the Field Equations 88
2.9 Vector Magnetic Potential 91
2.10 Distant Field of Current Loop: Magnetic Dipole 94
2.11 Divergence of Magnetic Flux Density 96
2.12 Differential Equation for Vector Magnetic Potential 96
2.13 Scalar Magnetic Potential for Current-Free Regions 98
2.14 Boundary Conditions for Static Magnetic Fields 99
2.15 Materials with Permanent Magnetization 100
MAGNETIC FIELD ENERGY 104
2.16 Energy of a Static Magnetic Field 104
2.17 Inductance from Energy Storage; Internal Inductance 106
Problems 107

CHAPTER 3 MAXWELL'S EQUATIONS 111

3.1 Introduction 111
LARGE-SCALE AND DIFFERENTIAL FORMS OF MAXWELL'S EQUATIONS 113

3.2 Voltages Induced by Changing Magnetic Fields 113
3.3 Faraday's Law for a Moving System 116
3.4 Continuity of Charge and the Concept of Displacement Current 119
3.5 Physical Pictures of Displacement Current 120
3.6 Maxwell's Equations in Differential Equation Form 123
3.7 Maxwell's Equations in Large-Scale Form 126
3.8 Maxwell's Equations for the Time-Periodic Case 127

EXAMPLES OF USE OF MAXWELL'S EQUATIONS 130

3.9 Maxwell's Equations and Plane Waves 130
3.10 Uniform Plane Waves with Steady-State Sinusoids 133
3.11 The Wave Equation in Three Dimensions 135
3.12 Power Flow in Electromagnetic Fields—Poynting's Theorem 137
3.13 Poynting's Theorem for Phasors 141
3.14 Continuity Conditions for ac Fields at a Boundary; Uniqueness of Solutions 143
3.15 Boundary Conditions at a Perfect Conductor for ac Fields 146
3.16 Penetration of Electromagnetic Fields into a Good Conductor 147
3.17 Internal Impedance of a Plane Conductor 151
3.18 Power Loss in a Plane Conductor 154

POTENTIALS FOR TIME-VARYING FIELDS 156

3.19 A Possible Set of Potentials for Time-Varying Fields 156
3.20 The Retarded Potentials as Integrals over Charges and Currents 158
3.21 The Retarded Potentials for the Time-Periodic Case 160

Problems 161

CHAPTER 4 THE ELECTROMAGNETICS OF CIRCUITS 168

4.1 Introduction

THE IDEALIZATIONS OF CLASSICAL CIRCUIT THEORY 169

4.2 Kirchhoff's Voltage Law 169
4.3 Kirchhoff's Current Law and Multimesh Circuits 174

SKIN EFFECT IN PRACTICAL CONDUCTORS 178

4.4 Distribution of Time-Varying Currents in Conductors of Circular Cross Section 178
4.5 Impedance of Round Wires 180

CALCULATION OF CIRCUIT ELEMENTS 184

4.6 Self-Inductance Calculations 184
4.7 Mutual Inductance 187
4.8 Inductance of Practical Coils 191
4.9 Self- and Mutual Capacitance 193

CIRCUITS THAT ARE NOT SMALL COMPARED WITH WAVELENGTH 196
4.10 Distributed Effects and Retardation 196
4.11 Circuit Formulation Through the Retarded Potentials 198
4.12 Circuits with Radiation 203
Problems 206

CHAPTER 5 TRANSMISSION LINES 210

5.1 Introduction 210
TIME AND SPACE DEPENDENCE OF SIGNALS ON IDEAL TRANSMISSION LINES 211
5.2 Voltage and Current Variations Along an Ideal Transmission Line 211
5.3 Relation of Field and Circuit Analysis of Transmission Lines 215
5.4 Reflection and Transmission at a Resistive Discontinuity 216
SINUSOIDAL WAVES ON IDEAL TRANSMISSION LINES WITH DISCONTINUITIES 223
5.5 Reflection and Transmission Coefficients and Impedance and Admittance Transformations for Sinusoidal Voltages 223
5.6 Standing-Wave Ratio 226
5.7 The Smith Transmission-Line Chart 229
5.8 Purely Standing Wave on an Ideal Line 238
NONIDEAL TRANSMISSION LINES 241
5.9 Power Loss and Attenuation in Low-Loss Lines 241
5.10 Input Impedance and Quality Factor for Resonant Transmission Lines 243
5.11 Transmission Lines with General Forms of Distributed Impedances; ω–β Diagram 247
5.12 Group and Energy Velocities 254
5.13 Backward Waves 257
5.14 Transmission Lines Used with Pulses 258
5.15 Nonuniform Transmission Lines 261
Problems 263

CHAPTER 6 PLANE WAVE PROPAGATION AND REFLECTION 270

6.1 Introduction 270
PLANE WAVE PROPAGATION 271

6.2	Uniform Plane Waves in a Perfect Dielectric	271
6.3	Polarization of Plane Waves	276
6.4	Waves in Imperfect Dielectrics and Conductors	279
	PLANE WAVES NORMALLY INCIDENT ON DISCONTINUITIES	283
6.5	Reflection of Normally Incident Plane Waves from Perfect Conductors	283
6.6	Transmission-Line Analogy of Wave Propagation : The Impedance Concept	285
6.7	Normal Incidence on a Dielectric	288
6.8	Reflection Problems with Several Dielectrics	291
	PLANE WAVES OBLIQUELY INCIDENT ON DISCONTINUITIES	296
6.9	Incidence at Any Angle on Perfect Conductors	296
6.10	Phase Velocity and Impedance for Waves at Oblique Incidence	299
6.11	Incidence at Any Angle on Dielectrics	302
6.12	Total Reflection	306
6.13	Polarizing or Brewster Angle	308
6.14	Multiple Dielectric Boundaries with Oblique Incidence	309
Problems		312

CHAPTER 7	TWO- AND THREE-DIMENSIONAL BOUNDARY VALUE PROBLEMS	317
7.1	Introduction	317
	THE BASIC DIFFERENTIAL EQUATIONS AND NUMERICAL METHODS	318
7.2	Roles of Helmholtz, Laplace, and Poisson Equations	319
7.3	Numerical Solution of the Laplace, Poisson, and Helmholtz Equations	320
	METHOD OF CONFORMAL TRANSFORMATION	326
7.4	Method of Conformal Transformation and Introduction to Complex-Function Theory	326
7.5	Properties of Analytic Functions of Complex Variables	328
7.6	Conformal Mapping for Laplace's Equation	331
7.7	The Schwarz Transformation for General Polygons	340
7.8	Conformal Mapping for Wave Problems	343
	PRODUCT-SOLUTION METHOD	346
7.9	Laplace's Equation in Rectangular Coordinates	346

7.10 Static Field Described by a Single Rectangular Harmonic 349
7.11 Fourier Series and Integral 351
7.12 Series of Rectangular Harmonics for Two- and Three-Dimensional Static Fields 355
7.13 Cylindrical Harmonics for Static Fields 360
7.14 Bessel Functions 364
7.15 Bessel Function Zeros and Formulas 369
7.16 Expansion of a Function as a Series of Bessel Functions 371
7.17 Fields Described by Cylindrical Harmonics 373
7.18 Spherical Harmonics 375
7.19 Product Solutions for the Helmholtz Equation in Rectangular Coordinates 382
7.20 Product Solutions for the Helmholtz Equation in Cylindrical Coordinates 383
Problems 384

CHAPTER 8 WAVEGUIDES WITH CYLINDRICAL CONDUCTING BOUNDARIES 392

8.1 Introduction 392
GENERAL FORMULATION FOR GUIDED WAVES 393
8.2 Basic Equations and Wave Types for Uniform Systems 393
CYLINDRICAL WAVEGUIDES OF VARIOUS CROSS SECTIONS 396
8.3 Waves Guided by Perfectly Conducting Parallel Plates 396
8.4 Guided Waves Between Parallel Planes as Superposition of Plane Waves 402
8.5 Parallel-Plane Guiding System with Losses 405
8.6 Stripline and Microstrip Transmission Systems 407
8.7 Rectangular Waveguides 411
8.8 The TE_{10} Wave in a Rectangular Guide 418
8.9 Circular Waveguides 422
8.10 Higher Order Modes on Coaxial Lines 428
8.11 Excitation and Reception of Waves in Guides 430
GENERAL PROPERTIES OF GUIDED WAVES 434
8.12 General Properties of ***TEM*** Waves on Multiconductor Lines 434
8.13 General Properties of ***TM*** Waves in Cylindrical Conducting Guides of Arbitrary Cross Section 438
8.14 General Properties of ***TE*** Waves in Cylindrical Conducting Guides of Arbitrary Cross Section 442

8.15 Waves Below and Near Cutoff 444
8.16 Dispersion of Signals Along Transmission Lines and Waveguides 446
Problems 449

CHAPTER 9 SPECIAL WAVEGUIDE TYPES 456

9.1 Introduction 456
9.2 Dielectric Slab Guides 457
9.3 Parallel-Plane Radial Transmission Lines 460
9.4 Circumferential Modes in Radial Lines; Sectoral Horns 464
9.5 Duality; Propagation Between Inclined Planes 466
9.6 Waves Guided by Conical Systems 467
9.7 Ridge Waveguide 469
9.8 The Idealized Helix and Other Slow-Wave Structures 471
9.9 Surface Guiding 474
9.10 Periodic Structures and Spatial Harmonics 477
Problems 482

CHAPTER 10 RESONANT CAVITIES 486

10.1 Introduction 486
10.2 Elemental Concepts of Cavity Resonators 487
RESONATORS OF SIMPLE SHAPE 489
10.3 Fields of Simple Rectangular Resonator 489
10.4 Energy Storage, Losses, and Q of Simple Resonator 491
10.5 Other Modes in the Rectangular Resonator 492
10.6 Circular Cylindrical Resonator 495
10.7 Wave Solutions in Spherical Coordinates 498
10.8 Spherical Resonators 502
SMALL-GAP CAVITIES AND COUPLING 504
10.9 Small-Gap Cavities 504
10.10 Coupling to Cavities 507
10.11 Cavity Q and Other Figures of Merit 509
10.12 Cavity Perturbations 512
10.13 Dielectric Resonators 515
Problems 520

CHAPTER 11 MICROWAVE NETWORKS 523

11.1 Introduction 523
11.2 The Network Formulation 525
11.3 Conditions for Reciprocity 528
TWO-PORT WAVEGUIDE JUNCTIONS 530
11.4 Equivalent Circuits for a Two Port 530
11.5 Determination of Circuit Parameters by Measurement 532
11.6 Scattering and Transmission Coefficients 535
11.7 Scattering Coefficients by Measurement 538
11.8 Cascaded Two Ports 538
11.9 Examples of Microwave and Optical Filters 542
N-PORT WAVEGUIDE JUNCTIONS 547
11.10 Circuit and S-Parameter Representation of N Ports 547
11.11 Directional Couplers and Hybrid Networks 551
FREQUENCY CHARACTERISTICS OF WAVEGUIDE NETWORKS 555
11.12 Properties of a One-Port Impedance 555
11.13 Equivalent Circuits Showing Frequency Characteristics of One Ports 558
11.14 Examples of Cavity Equivalent Circuits 562
11.15 Circuits Giving Frequency Characteristics of N Ports 566
JUNCTION PARAMETERS BY ANALYSIS 567
11.16 Quasistatic and Other Methods of Junction Analysis 567
Problems 572

CHAPTER 12 RADIATION 577

12.1 Introduction 577
12.2 Some Types of Practical Radiating Systems 579
FIELD AND POWER CALCULATIONS WITH CURRENTS ASSUMED ON THE ANTENNA 582
12.3 Electric and Magnetic Dipole Radiators 582
12.4 Systemization of Calculation of Radiating Fields and Power from Currents on an Antenna 586
12.5 Long Straight Wire Antenna; Half-Wave Dipole 589
12.6 Radiation Patterns and Antenna Gain 592
12.7 Radiation Resistance 595
12.8 Antennas Above Earth or Conducting Plane 596
12.9 Traveling Wave on a Straight Wire 598

12.10 V and Rhombic Antennas 600
12.11 Methods of Feeding Wire Antennas 604
RADIATION FROM FIELDS OVER AN APERTURE 607
12.12 Fields as Sources of Radiation 607
12.13 Plane Wave Sources 610
12.14 Examples of Radiating Apertures Excited by Plane Waves 612
12.15 Electromagnetic Horns 617
12.16 Resonant Slot Antenna 619
12.17 Lenses for Directing Radiation 621
ARRAYS OF ELEMENTS 623
12.18 Radiation Intensity with Superposition of Effects 623
12.19 Linear Arrays 627
12.20 Radiation from Diffraction Gratings 631
12.21 Polynomial Formulation of Arrays and Limitations on Directivity 633
12.22 Yagi–Uda Arrays 635
12.23 Frequency-Independent Antennas: Logarithmically Periodic Arrays 637
FIELD ANALYSIS OF ANTENNAS 640
12.24 The Antenna as a Boundary-Value Problem 640
12.25 Direct Calculation of Input Impedance for Wire Antennas 647
12.26 Mutual Impedance Between Thin Dipoles 650
RECEIVING ANTENNAS AND RECIPROCITY 652
12.27 A Transmitting–Receiving System 652
12.28 Reciprocity Relations 655
12.29 Equivalent Circuit of the Receiving Antenna 658
Problems 659

CHAPTER 13 ELECTROMAGNETIC PROPERTIES OF MATERIALS 666

13.1 Introduction 666
LINEAR ISOTROPIC MEDIA 667
13.2 Characteristics of Dielectrics 667
13.3 Imperfect Conductors and Semiconductors 672
13.4 Perfect Conductors and Superconductors 676
13.5 Diamagnetic and Paramagnetic Responses 679
NONLINEAR ISOTROPIC MEDIA 680
13.6 Materials with Residual Magnetization 680
13.7 Nonlinear Optics 685

	ANISOTROPIC MEDIA	689
13.8	Representation of Anisotropic Dielectric Crystals	689
13.9	Plane Wave Propagation in Anisotropic Crystals	691
13.10	Plane Wave Propagation in Uniaxial Crystals	695
13.11	Electro-Optic Effects	698
13.12	Permittivity of a Stationary Plasma in a Magnetic Field	703
13.13	*TEM* Waves on a Plasma with Infinite Magnetic Field	706
13.14	Space-Charge Waves on a Moving Plasma with Infinite Magnetic Field	707
13.15	*TEM* Waves on a Stationary Plasma in a Finite Magnetic Field	709
13.16	Faraday Rotation	713
13.17	Permeability Matrix for Ferrites	715
13.18	*TEM* Wave Propagation in Ferrites	719
13.19	Ferrite Devices	721
Problems		726

CHAPTER 14 OPTICS **732**

14.1	Introduction	732
	RAY OR GEOMETRICAL OPTICS	733
14.2	Geometrical Optics Through Applications of Laws of Reflection and Refraction	733
14.3	Geometrical Optics as Limiting Case of Wave Optics	739
14.4	Rays in Inhomogeneous Media	741
14.5	Paraxial Ray Optics—Ray Matrices	746
14.6	Guiding of Rays by a Periodic Lens Systems or in Spherical Mirror Resonators	749
	DIELECTRIC OPTICAL WAVEGUIDES	752
14.7	Dielectric Guides of Planar Form	752
14.8	Dielectric Guides of Rectangular Form	756
14.9	Dielectric Guides of Circular Cross Section	759
14.10	Weakly Guiding Fibers: Dispersion	762
14.11	Propagation of Gaussian Beams in Graded-Index Fibers	765
	GAUSSIAN BEAMS IN SPACE AND IN OPTICAL RESONATORS	768
14.12	Propagation of Gaussian Beams in a Homogeneous Medium	768
14.13	Transformation of Gaussian Beams by Ray Matrix	771
14.14	Gaussian Modes in Optical Resonators	774
14.15	Stability and Resonant Frequencies of Optical-Resonator Modes	779