# ELECTROMAGNETIC FIELDS AND WAVES

MAGDY F. ISKANDER

Professor of Electrical Engineering University of Utah



PRENTICE HALL, Englewood Cliffs, New Jersey 07632

# CONTENTS

#### PREFACE

## CHAPTER **1** VECTOR ANALYSIS AND MAXWELL'S EQUATIONS IN INTEGRAL FORM

- 1.1 Introduction 1
- 1.2 Vector Algebra 2
- 1.3 Coordinate Systems 8
- 1.4 Vector Representation in Various Coordinate Systems 16
- 1.5 Vector Coordinate Transformation 19
- 1.6 Electric and Magnetic Fields 26
- 1.7 Vector Integration 45
- 1.8 Maxwell's Equations in Integral Form 58
- 1.9 Displacement Current 70
- 1.10 General Characteristics of Maxwell's Equations 75 Summary 83 Problems 86

ix

# CHAPTER 2 MAXWELL'S EQUATIONS IN DIFFERENTIAL FORM

- 2.1 Introduction 99
- 2.2 Vector Differentiation 100
- 2.3 Gradient of Scalar Function 103
- 2.4 Divergence of Vector Field 110
- 2.5 Divergence Theorem 119
- 2.6 Differential Expressions of Maxwell's Divergence Relations 122
- 2.7 Curl of Vector Field 126
- 2.8 Stokes's Theorem 135
- 2.9 Ampere's and Faraday's Laws in Point (Differential) Form 139
- 2.10 Summary of Maxwell's Equations in Differential Forms 141
- 2.11 Continuity Equation and Maxwell's Displacement Current Term 147
- 2.12 Wave Equation in Source Free Region 150
- 2.13 Time Harmonic Fields and Their Phasor Representation 151
- 2.14 Uniform Plane Wave Propagation in Free Space 154
- 2.15 Polarization of Plane Waves 166

Summary 168 Problems 171

# CHAPTER 3

# MAXWELL'S EQUATIONS AND PLANE WAVE PROPAGATION IN MATERIALS

- 3.1 Introduction 179
- 3.2 Characterization of Materials 180
- 3.3 Conductors and Conduction Currents 181
- 3.4 Dielectric Materials and Their Polarization 183
- 3.5 Gauss's Law for Electric Field in Materials 193
- 3.6 Magnetic Materials and Their Magnetization 195
- 3.7 Ampere's Law and Magnetization Current 203
- 3.8 Maxwell's Equations in Material Regions 208

99

179

#### Contents

- 3.9 Boundary Conditions 211
- 3.10 Summary of Boundary Condition for Electric and Magnetic Fields 231
- 3.11 Uniform Plane Wave Propagation in Conductive Medium 238
- 3.12 Electromagnetic Power and Poynting Theorem 248 Summary 261 Problems 263

## CHAPTER 4 STATIC ELECTRIC AND MAGNETIC FIELDS

273

- 4.1 Introduction 273
- 4.2 Maxwell's Equations for Static Fields 274
- 4.3 Electrostatic Fields 275
- 4.4 Evaluation of Electric Field E from Electrostatic Potential Φ 279
- 4.5 Capacitance 284
- 4.6 Electrostatic Energy Density 291
- 4.7 Laplace's and Poisson's Equations 296
- 4.8 Numerical Solution of Poisson's and Laplace's Equations—Finite Difference Method 300
- 4.9 Numerical Solution of Electrostatic Problems—Method of Moments 313
- 4.10 Magnetostatic Fields and Magnetic Vector Potential 323
- 4.11 Magnetic Circuits 332
- 4.12 Self-Inductance and Mutual Inductance 344
- 4.13 Magnetic Energy 350 Summary 356 Problems 358

# CHAPTER 5

## NORMAL-INCIDENCE PLANE WAVE REFLECTION AND TRANSMISSION AT PLANE BOUNDARIES

371

- 5.1 Introduction 371
- 5.2 Normal-incidence Plane Wave Reflection and Transmission at Plane Boundary between Two Conductive Media 372

- 5.4 Reflection and Transmission at Multiple Interfaces 385
- 5.5 Reflection Coefficient and Total Field Impedance Solution Procedure 390
- 5.6 Graphical Solution Procedure Using the Smith Chart 400
- 5.7 Quarter- and Half-wavelength Transformers 416 Summary 425 Problems 427

# CHAPTER 6

## OBLIQUE INCIDENCE PLANE WAVE REFLECTION AND TRANSMISSION

- 6.1 Plane Wave Propagation at Arbitrary Angle 436
- 6.2 Reflection by Perfect Conductor—Arbitrary Angle of Incidence 440
- 6.3 Reflection and Refraction at Plane Interface between Two Media: Oblique Incidence 450
- 6.4 Comparison Between Reflection Coefficients  $\Gamma_{\parallel}$  and  $\Gamma_{\perp}$ for Parallel and Perpendicular Polarizations 458
- 6.5 Total Reflection at Critical Angle of Incidence 462
- 6.6 Electromagnetic Spectrum 466
- 6.7 Application to Optics 467 Summary 471 Problems 473

## CHAPTER 7

### TRANSMISSION LINES

- 7.1 Characteristics of Wave Propagation in Transmission Lines 480
- 7.2 Distributed Circuit Representation of Transmission Lines 482
- 7.3 Lossless Line 484
- 7.4 Voltage Reflection Coefficient 487
- 7.5 Transients on Transmission Line 492

436

479

#### Contents

- 7.6 Reflection Diagram 494
- 7.7 Tandem Connection of Transmission Lines 499
- 7.8 Pulse Propagation on Transmission Lines 507
- 7.9 Time-Domain Reflectometer 509
- 7.10 Sinusoidal Steady-State Analysis of Transmission Lines 516
- 7.11 Reflections on Transmission Lines with Sinusoidal Excitation 523
- 7.12 Use of Smith Chart 533
- 7.13 Analytical Expression of Transmission-Line Impedance 539
- 7.14 Impedance Matching of Lossless Lines 545
- 7.15 Voltage Standing-Wave Ratio (VSWR) along Transmission Lines 555
- 7.16 Use of VSWR Measurement to Determine Unknown Impedances 562 Summary 573

Problems 575

# CHAPTER 8

### WAVE GUIDES

- 8.1 Introduction 591
- 8.2 Guided Modes in Wave Guides 592
- 8.3 TM Modes in Rectangular Wave Guides 596
- 8.4 TE Modes in Rectangular Wave Guides 603
- 8.5 Field Configurations in Wave Guides 610
- 8.6 Excitation of Various Modes in Wave Guides 613
- 8.7 Energy Flow and Attenuation in Rectangular Wave Guides 616 Summary 630 Problems 632

## CHAPTER 9

### ANTENNAS

- 9.1 Introduction 637
- 9.2 Physical Aspects of Radiation 639

Contents

- 9.3 Radiation from Short Alternating Current Element 641
- 9.4 Basic Antenna Parameters 650
- 9.5 Linear Wire Antennas 658
- 9.6 Antenna Arrays 667 Summary 711 Problems 712

## APPENDIXES

A Vector Identities and Operations 716

B Units, Multiples, and Submultiples 720

C Trigonometric, Hyperbolic, and Logarithmic Relations 725

D Free-Space, Atomic, and Material Constants 727

E Cosine  $C_i(x)$  and Sine  $S_i(x)$  Integrals 732

F Answers to Selected Problems 736

INDEX

752

### viii