# Contents

· ELEC	CTROMAGNETIC THEORY 1
1.1	Introduction to Microwave Engineering 1 Applications of Microwave Engineering 2 A Short History of Microwave Engineering 4
1.2	Maxwell's Equations 6
1.3	Fields in Media and Boundary Conditions 10
	Fields at a General Material Interface 12 Fields at a Dielectric Interface 14 Fields at the Interface with a Perfect Conductor (Electric Wall) 14 The Magnetic Wall Boundary Condition 15 The Radiation Condition 15
1.4	The Wave Equation and Basic Plane Wave Solutions 15
	The Helmholtz Equation 15 Plane Waves in a Lossless Medium 16 Plane Waves in a General Lossy Medium 17 Plane Waves in a Good Conductor 19
1.5	General Plane Wave Solutions 20
	Circularly Polarized Plane Waves 24
1.6	Energy and Power 25
	Power Absorbed by a Good Conductor 27
1.7	Plane Wave Reflection from a Media Interface 28
	General Medium 28 Lossless Medium 30
	Good Conductor 31 Perfect Conductor 32 The Surface Impedance Concept 33
1.8	Oblique Incidence at a Dielectric Interface 35
	Parallel Polarization 36 Perpendicular Polarization 37 Total Reflection and Surface Waves 38
1.0	Some Useful Theorems 40

The Reciprocity Theorem 40

Image Theory 42

2	TRANSMISSION LINE THEORY 48		
	2.1 The Lumped-Element Circuit Model for a Transmission Line 48		
	Wave Propagation on a Transmission Line 50 The Lossless Line		
	Field Analysis of Transmission Lines 51		
	Transmission Line Parameters 51 The Telegrapher Equations Derived from Field Analysis of a Coaxial Line 54 Propagation Constant, Impedance, and Power Flow for the Lossless Coaxial Line 56		
	2.3 The Terminated Lossless Transmission Line 56		
	Special Cases of Lossless Terminated Lines 59		
	<ul><li>2.4 The Smith Chart 63</li><li>The Combined Impedance–Admittance Smith Chart 67</li><li>The Slotted Line 68</li></ul>		
	2.5 The Quarter-Wave Transformer 72		
	The Impedance Viewpoint 72 The Multiple-Reflection Viewpoint 74		
	2.6 Generator and Load Mismatches 76		
	Load Matched to Line 77 Generator Matched to Loaded Line 77 Conjugate Matching 77		
	2.7 Lossy Transmission Lines 78		
	The Low-Loss Line 79 The Distortionless Line 80 The Terminated Lossy Line 81 The Perturbation Method for Calculating Attenuation 82 The Wheeler Incremental Inductance Rule 83		
	2.8 Transients on Transmission Lines 85		
	Reflection of Pulses from a Terminated Transmission Line 86 Bounce Diagrams for Transient Propagation 87		
3	TRANSMISSION LINES AND WAVEGUIDES 95		
	3.1 General Solutions for TEM, TE, and TM Waves 96		
	TEM Waves 98 TE Waves 100 TM Waves 100 Attenuation Due to Dielectric Loss 101		
	3.2 Parallel Plate Waveguide 102		
	TEM Modes 103 TM Modes 104 TE Modes 107		
	3.3 Rectangular Waveguide 110		
	TE Modes 110 TM Modes 115 $TE_{m0}$ Modes of a Partially Loaded Waveguide 119		
	3.4 Circular Waveguide 121		
	TE Modes 122 TM Modes 125		
	3.5 Coaxial Line 130		
	TEM Modes 130 Higher Order Modes 131		

3.6	Surface Waves on a Grounded Dielectric Sheet 135
	TM Modes 135 TE Modes 137
3.7	Stripline 141
	Formulas for Propagation Constant, Characteristic Impedance, and Attenuation 141 An Approximate Electrostatic Solution 144
3.8	Microstrip Line 147
	Formulas for Effective Dielectric Constant, Characteristic Impedance, and Attenuation 148 Frequency-Dependent Effects and Higher Order Modes 150
3.9	The Transverse Resonance Technique 153
	TE <sub>0n</sub> Modes of a Partially Loaded Rectangular Waveguide 153
3.10	Wave Velocities and Dispersion 154
	Group Velocity 155
3.11	Summary of Transmission Lines and Waveguides 157 Other Types of Lines and Guides 158
MICF	ROWAVE NETWORK ANALYSIS 165
4.1	Impedance and Equivalent Voltages and Currents 166
	Equivalent Voltages and Currents 166 The Concept of Impedance 170 Even and Odd Properties of $Z(\omega)$ and $\Gamma(\omega)$ 173
4.2	Impedance and Admittance Matrices 174
	Reciprocal Networks 175 Lossless Networks 177
4.3	The Scattering Matrix 178
	Reciprocal Networks and Lossless Networks 181  A Shift in Reference Planes 184  Power Waves and Generalized Scattering Parameters 185
4.4	The Transmission (ABCD) Matrix 188
	Relation to Impedance Matrix 191 Equivalent Circuits for Two-Port Networks 191
4.5	Signal Flow Graphs 194
	Decomposition of Signal Flow Graphs 195 Application to Thru-Reflect-Line Network Analyzer Calibration 197
4.6	Discontinuities and Modal Analysis 203
	Modal Analysis of an <i>H</i> -Plane Step in Rectangular Waveguide 203
4.7	Excitation of Waveguides—Electric and Magnetic Currents 210
	Current Sheets That Excite Only One Waveguide Mode 210  Mode Excitation from an Arbitrary Electric or Magnetic Current Source 212
4.8	B Excitation of Waveguides—Aperture Coupling 215
	Coupling Through an Aperture in a Transverse Waveguide Wall 218 Coupling Through an Aperture in the Broad Wall of a Waveguide 220

5	_ IMPEDANCE MATCHING AND TUNING 228		
	5.1 Matching with Lumped Elements (L Networks) 229		
	Analytic Solutions 230 Smith Chart Solutions 231		
	5.2 Single-Stub Tuning 234		
	Shunt Stubs 235 Series Stubs 238		
	5.3 Double-Stub Tuning 241		
	Smith Chart Solution 242 Analytic Solution 245		
	5.4 The Quarter-Wave Transformer 246		
	5.5 The Theory of Small Reflections 250 Single Section Transformer 250 Multiportion Transformer 251		
	Single-Section Transformer 250 Multisection Transformer 251		
	5.6 Binomial Multisection Matching Transformers 252		
	5.7 Chebyshev Multisection Matching Transformers 256		
	Chebyshev Polynomials 257 Design of Chebyshev Transformers 258		
	5.8 Tapered Lines 261  Exponential Taper 262 Triangular Taper 263		
	Exponential Taper 262 Triangular Taper 263 Klopfenstein Taper 264		
	5.9 The Bode–Fano Criterion 266		
6	_ MICROWAVE RESONATORS 272		
	6.1 Series and Parallel Resonant Circuits 272		
	Series Resonant Circuit 272 Parallel Resonant Circuit 275 Loaded and Unloaded $Q$ 277		
	6.2 Transmission Line Resonators 278		
	Short-Circuited $\lambda/2$ Line 278 Short-Circuited $\lambda/4$ Line 281 Open-Circuited $\lambda/2$ Line 282		
	6.3 Rectangular Waveguide Cavity Resonators 284		
	Resonant Frequencies 284 Unloaded $Q$ of the $TE_{10\ell}$ Mode 286		
	6.4 Circular Waveguide Cavity Resonators 288		
	Resonant Frequencies 289 Unloaded $Q$ of the $TE_{nm\ell}$ Mode 291		
	6.5 Dielectric Resonators 293		
	Resonant Frequencies of $TE_{01\delta}$ Mode 294		
	6.6 Excitation of Resonators 297		
	The Coupling Coefficient and Critical Coupling 298 A Gap-Coupled Microstrip Resonator 299 An Aperture-Coupled Cavity 302 Determining Unloaded <i>Q</i> from Two-Port Measurements 305		
	6.7 Cavity Perturbations 306		

Material Perturbations 306

Shape Perturbations 309

<u></u>	POWER DIVIDERS AND DIRECTIONAL COUPLERS 317
	7.1 Basic Properties of Dividers and Couplers 317
	Three-Port Networks (T-Junctions) 318
	Four-Port Networks (Directional Couplers) 320
	<b>7.2 The T-Junction Power Divider 324</b> Lossless Divider 324 Resistive Divider 326
	<b>7.3 The Wilkinson Power Divider 328</b> Even-Odd Mode Analysis 328
	Even-Odd Mode Analysis 328 Unequal Power Division and <i>N</i> -Way Wilkinson Dividers 332
	7.4 Waveguide Directional Couplers 333
	Bethe Hole Coupler 334 Design of Multihole Couplers 338
	7.5 The Quadrature (90°) Hybrid 343
	Even-Odd Mode Analysis 344
	7.6 Coupled Line Directional Couplers 347
	Coupled Line Theory 347 Design of Coupled Line Couplers 351 Design of Multisection Coupled Line Couplers 356
	7.7 The Lange Coupler 359
	7.8 The 180° Hybrid 362
	Even-Odd Mode Analysis of the Ring Hybrid 364 Even-Odd Mode Analysis of the Tapered Coupled Line Hybrid 367 Waveguide Magic-T 371
	7.9 Other Couplers 372
8	MICROWAVE FILTERS 380
	8.1 Periodic Structures 381
	Analysis of Infinite Periodic Structures 382 Terminated Periodic Structures 384
	$k$ - $\beta$ Diagrams and Wave Velocities 385
	8.2 Filter Design by the Image Parameter Method 388
	Image Impedances and Transfer Functions for Two-Port Networks 388 Constant- <i>k</i> Filter Sections 390 <i>m</i> -Derived Filter Sections 393 Composite Filters 396
	8.3 Filter Design by the Insertion Loss Method 399
	Characterization by Power Loss Ratio 399  Maximally Flat Low-Pass Filter Prototype 402  Equal-Ripple Low-Pass Filter Prototype 404  Linear Phase Low-Pass Filter Prototypes 406
	8.4 Filter Transformations 408

Impedance and Frequency Scaling 408
Bandpass and Bandstop Transformations 411

8.5 Filter Implementation 415

10.2 Noise Figure 502

	Richards' Transformation 416 Kuroda's Identities 416 Impedance and Admittance Inverters 421
8.6	Stepped-Impedance Low-Pass Filters 422
	Approximate Equivalent Circuits for Short Transmission Line Sections 422
8.7	Coupled Line Filters 426
	Filter Properties of a Coupled Line Section 426 Design of Coupled Line Bandpass Filters 430
8.8	Filters Using Coupled Resonators 437
	Bandstop and Bandpass Filters Using Quarter-Wave Resonators 437 Bandpass Filters Using Capacitively Coupled Series Resonators 441 Bandpass Filters Using Capacitively Coupled Shunt Resonators 443
9 THEC	DRY AND DESIGN OF FERRIMAGNETIC COMPONENTS 451
9.1	Basic Properties of Ferrimagnetic Materials 452
	The Permeability Tensor 452 Circularly Polarized Fields 458 Effect of Loss 460 Demagnetization Factors 462
9.2	Plane Wave Propagation in a Ferrite Medium 465
	Propagation in Direction of Bias (Faraday Rotation) 465 Propagation Transverse to Bias (Birefringence) 469
9.3	Propagation in a Ferrite-Loaded Rectangular Waveguide 471
	$TE_{m0}$ Modes of Waveguide with a Single Ferrite Slab 471 $TE_{m0}$ Modes of Waveguide with Two Symmetrical Ferrite Slabs 474
9.4	Ferrite Isolators 475
	Resonance Isolators 476 The Field Displacement Isolator 479
9.5	Ferrite Phase Shifters 482
	Nonreciprocal Latching Phase Shifter 482 Other Types of Ferrite Phase Shifters 485 The Gyrator 486
9.6	Ferrite Circulators 487
	Properties of a Mismatched Circulator 488 Junction Circulator 488
10 Nois	E AND NONLINEAR DISTORTION 496
10.1	Noise in Microwave Circuits 496
	Dynamic Range and Sources of Noise 497  Noise Power and Equivalent Noise Temperature 498  Measurement of Noise Temperature 501

Definition of Noise Figure 502 Noise Figure of a Cascaded System 504 Noise Figure of a Passive Two-Port Network 506 Noise Figure of a Mismatched Lossy Line 508 Noise Figure of a Mismatched Amplifier 510

10.3	Nonlinear	Distortion	511
10.0	TACHILINGAL	DISTULTION	~11

Gain Compression 512 Harmonic and Intermodulation Distortion 513
Third-Order Intercept Point 515 Intercept Point of a Cascaded System 516
Passive Intermodulation 519

# 10.4 Dynamic Range 519

Linear and Spurious Free Dynamic Range 519

# 11 \_\_ ACTIVE RF AND MICROWAVE DEVICES 524

#### 11.1 Diodes and Diode Circuits 525

Schottky Diodes and Detectors 525
PIN Diodes and Control Circuits 530
Vernoter Diodes 527 Other Diodes

Varactor Diodes 537 Other Diodes 538 Power Combining 539

# 11.2 Bipolar Junction Transistors 540

Bipolar Junction Transistor 540 Heterojunction Bipolar Transistor 542

# 11.3 Field Effect Transistors 543

Metal Semiconductor Field Effect Transistor 544
Metal Oxide Semiconductor Field Effect Transistor 546
High Electron Mobility Transistor 546

# 11.4 Microwave Integrated Circuits 547

Hybrid Microwave Integrated Circuits 548
Monolithic Microwave Integrated Circuits 548

#### 11.5 Microwave Tubes 552

# 12 MICROWAVE AMPLIFIER DESIGN 558

#### 12.1 Two-Port Power Gains 558

Definitions of Two-Port Power Gains 559
Further Discussion of Two-Port Power Gains 562

### **12.2 Stability 564**

Stability Circles 564 Tests for Unconditional Stability 567

# 12.3 Single-Stage Transistor Amplifier Design 571

Design for Maximum Gain (Conjugate Matching) 571

Constant-Gain Circles and Design for Specified Gain 575

Low-Noise Amplifier Design 580 Low-Noise MOSFET Amplifier 582

# 12.4 Broadband Transistor Amplifier Design 585

Balanced Amplifiers 586 Distributed Amplifiers 588 Differential Amplifiers 593

### 12.5 Power Amplifiers 596

Characteristics of Power Amplifiers and Amplifier Classes 597 Large-Signal Characterization of Transistors 598 Design of Class A Power Amplifiers 599

4	^	
1	٦.	

# OSCILLATORS AND MIXERS 604

#### 13.1 RF Oscillators 605

General Analysis 606 Oscillators Using a Common Emitter BJT 607 Oscillators Using a Common Gate FET 609 Practical Considerations 610 Crystal Oscillators 612

#### 13.2 Microwave Oscillators 613

Transistor Oscillators 615 Dielectric Resonator Oscillators 617

#### 13.3 Oscillator Phase Noise 622

Representation of Phase Noise 623 Leeson's Model for Oscillator Phase Noise 624

# 13.4 Frequency Multipliers 627

Reactive Diode Multipliers (Manley–Rowe Relations) 628
Resistive Diode Multipliers 631 Transistor Multipliers 633

#### 13.5 Mixers 637

Mixer Characteristics 637 Single-Ended Diode Mixer 642
Single-Ended FET Mixer 643 Balanced Mixer 646
Image Reject Mixer 649
Differential FET Mixer and Gilbert Cell Mixer 650 Other Mixers 652

# 14 INTRODUCTION TO MICROWAVE SYSTEMS 658

### 14.1 System Aspects of Antennas 658

Fields and Power Radiated by an Antenna 660
Antenna Pattern Characteristics 662
Antenna Gain and Efficiency 664
Aperture Efficiency and Effective Area 665
Background and Brightness Temperature 666
Antenna Noise Temperature and *G/T* 669

# 14.2 Wireless Communications 671

The Friis Formula 673
Link Budget and Link Margin 674
Radio Receiver Architectures 676
Noise Characterization of a Receiver 679
Digital Modulation and Bit Error Rate 681
Wireless Communication Systems 684

# 14.3 Radar Systems 690

The Radar Equation 691 Pulse Radar 693 Doppler Radar 694 Radar Cross Section 695

#### 14.4 Radiometer Systems 696

Theory and Applications of Radiometry 697 Total Power Radiometer 699
The Dicke Radiometer 700

#### 14.5 Microwave Propagation 701

Atmospheric Effects 701 Ground Effects 703 Plasma Effects 704

# Biological Effects and Safety 706 **APPENDICES 712** Prefixes 713 Vector Analysis 713 В **Bessel Functions** 715 $\mathbf{C}$ Other Mathematical Results 718 D $\mathbf{E}$ Physical Constants 718 F **Conductivities for Some Materials 719** G Dielectric Constants and Loss Tangents for Some Materials 719 H **Properties of Some Microwave Ferrite Materials** 720 I Standard Rectangular Waveguide Data 720 Standard Coaxial Cable Data 721 J ANSWERS TO SELECTED PROBLEMS 722

Power Transfer 705

14.6 Other Applications and Topics 705

Microwave Heating 705

INDEX 725