
FOUNDATIONS FOR MICROWAVE ENGINEERING

Second Edition

Robert E. Collin

*Professor of Electrical Engineering
Case Western Reserve University*

McGraw-Hill, Inc.

New York St. Louis San Francisco Auckland Bogotá
Caracas Lisbon London Madrid Mexico Milan Montreal
New Delhi Paris San Juan Singapore Sydney Tokyo Toronto

CONTENTS

Preface	xiii
1 Introduction	1
1.1 Microwave Frequencies	1
1.2 Microwave Applications	3
1.3 Microwave Circuit Elements and Analysis	6
References	16
2 Electromagnetic Theory	17
2.1 Maxwell's Equations	17
2.2 Constitutive Relations	23
2.3 Static Fields	28
2.4 Wave Equation	31
2.5 Energy and Power	33
2.6 Boundary Conditions	39
2.7 Plane Waves	44
Plane Waves in Free Space	44
2.8 Reflection from a Dielectric Interface	49
1. Parallel Polarization	49
2. Perpendicular Polarization	52
2.9 Reflection from a Conducting Plane	53
2.10 Potential Theory	56
*2.11 Derivation of Solution for Vector Potential	59
2.12 Lorentz Reciprocity Theorem	62
Problems	65
References	70
3 Transmission Lines and Waveguides	71
Part 1 Waves on Transmission Lines	72
3.1 Waves on An Ideal Transmission Line	72
3.2 Terminated Transmission Line: Resistive Load	78

3.3	Capacitive Termination	82
3.4	Steady-State Sinusoidal Waves	85
3.5	Waves on a Lossy Transmission Line	86
	Loss-Free Transmission Line	88
	Low-Loss Transmission Line	89
3.6	Terminated Transmission Line: Sinusoidal Waves	89
	Terminated Lossy Line	94
	Part 2 Field Analysis of Transmission Lines	96
3.7	Classification of Wave Solutions	96
	TEM Waves	99
	TE Waves	100
	TM Waves	102
3.8	Transmission Lines (Field Analysis)	104
	Lossless Transmission Line	104
	Transmission Line with Small Losses	108
3.9	Transmission-Line Parameters	112
3.10	Inhomogeneously Filled Parallel-Plate Transmission Line	117
	Low-Frequency Solution	121
	High-Frequency Solution	123
3.11	Planar Transmission Lines	125
3.12	Microstrip Transmission Line	130
	Low-Frequency Solutions	136
	Microstrip Attenuation	153
	High-Frequency Properties of Microstrip Lines	158
	Attenuation	163
3.13	Coupled Microstrip Lines	164
3.14	Strip Transmission Lines	170
	Attenuation	171
3.15	Coupled Strip Lines	173
3.16	Coplanar Transmission Lines	175
	Attenuation	178
	High-Frequency Dispersion	180
	Part 3 Rectangular and Circular Waveguides	180
3.17	Rectangular Waveguide	181
	TE Waves	182
	Power	186
	Attenuation	187
	Dominant TE_{10} Mode	190
	TM Modes	193
3.18	Circular Waveguides	194
	TM Modes	194
	TE Modes	196
3.19	Wave Velocities	198
	Phase Velocity	199
	Group Velocity	200
	Energy-Flow Velocity	204
3.20	Ridge Waveguide	205
3.21	Fin Line	208
	Problems	210
	References	219

4	Circuit Theory for Waveguiding Systems	220
4.1	Equivalent Voltages and Currents	221
4.2	Impedance Description of Waveguide Elements and Circuits	224
	One-Port Circuits	224
	Lossless One-Port Termination	228
*4.3	Foster's Reactance Theorem	230
*4.4	Even and Odd Properties of Z_{in}	232
4.5	N -Port Circuits	233
	Proof of Symmetry for the Impedance Matrix	235
	Proof of Imaginary Nature of $[Z]$ for a Lossless Junction	236
	Normalized Impedance and Admittance Matrices	237
4.6	Two-Port Junctions	238
	Some Equivalent Two-Port Circuits	245
4.7	Scattering-Matrix Formulation	248
	Symmetry of Scattering Matrix	250
	Scattering Matrix for a Lossless Junction	251
4.8	Scattering Matrix for a Two-Port Junction	254
4.9	Transmission-Matrix Representation	257
	Voltage-Current Transmission Matrix	257
	Wave-Amplitude Transmission Matrix	259
*4.10	Signal Flow Graphs	260
*4.11	Generalized Scattering Matrix for Power Waves	268
*4.12	Excitation of Waveguides	276
	Probe Coupling in a Rectangular Waveguide	276
	Radiation from Linear Current Elements	281
	Radiation from Current Loops	283
*4.13	Waveguide Coupling by Apertures	284
	Aperture in a Transverse Wall	286
	Aperture in Broad Wall of a Waveguide	290
	Problems	294
	References	302
5	Impedance Transformation and Matching	303
5.1	Smith Chart	304
5.2	Impedance Matching with Reactive Elements	308
	Single-Stub Matching	309
5.3	Double-Stub Matching Network	312
5.4	Triple-Stub Tuner	317
5.5	Impedance Matching with Lumped Elements	319
	Circuit Q and Bandwidth	325
5.6	Design of Complex Impedance Terminations	330
5.7	Invariant Property of Impedance Mismatch Factor	334
5.8	Waveguide Reactive Elements	339
	Shunt Inductive Elements	340
	Shunt Capacitive Elements	341
	Waveguide Stub Tuners	342

5.9	Quarter-Wave Transformers	343
5.10	Theory of Small Reflections	347
5.11	Approximate Theory for Multisection Quarter-Wave Transformers	348
5.12	Binomial Transformer	350
5.13	Chebyshev Transformer	352
*5.14	Chebyshev Transformer (Exact Results)	356
5.15	Filter Design Based on Quarter-Wave-Transformer Prototype Circuit	360
	Junction Capacitance and Length Compensation	365
5.16	Tapered Transmission Lines	370
	Exponential Taper	372
	Taper with Triangular Distribution	372
*5.17	Synthesis of Transmission-Line Tapers	373
*5.18	Chebyshev Taper	380
*5.19	Exact Equation for the Reflection Coefficient	383
	Problems	387
	References	393
6	Passive Microwave Devices	394
6.1	Terminations	394
	Variable Short Circuit	395
6.2	Attenuators	397
	Electronically Controlled Attenuators	400
6.3	Phase Shifters	404
	Rotary Phase Shifter	404
	Electronically Controlled Phase Shifters	409
6.4	Directional Couplers	413
	Directional-Coupler Designs	416
	Coupled-Line Directional Couplers	427
	Branch-Line Directional Coupler	432
	Lange Directional Coupler	434
6.5	Hybrid Junctions	435
	Magic T	435
	Hybrid Ring	437
6.6	Power Dividers	442
6.7	Microwave Propagation in Ferrites	450
6.8	Faraday Rotation	460
6.9	Microwave Devices Employing Faraday Rotation	464
	Gyrator	464
	Isolator	466
	Resonance Isolator	467
6.10	Circulators	468
	Three-Port Circulator	471
	Field Analysis of Three-Port Circulator	473
6.11	Other Ferrite Devices	476
	Problems	476
	References	479

7	Electromagnetic Resonators	481
7.1	Resonant Circuits	481
7.2	Transmission-Line Resonant Circuits	485
	Series Resonance; Short-Circuited Line	485
	Open-Circuited Line	487
	Antiresonance	488
7.3	Microstrip Resonators	490
	Circular Disk Resonator	496
7.4	Microwave Cavities	500
	Rectangular Cavity	500
	Cylindrical Cavity	504
7.5	Dielectric Resonators	508
7.6	Equivalent Circuits for Cavities	517
	Aperture-Coupled Cavity	517
	Loop-Coupled Cavity	523
★7.7	Field Expansion in a General Cavity	525
	Cavity Field Expansions in Terms of Short-Circuit Modes	527
	Electric Field Expansion	528
	Orthogonality Properties	529
	Magnetic Field Expansion	531
	Orthogonality Properties	531
	Relationship between $\mathbf{E}_n$ and $\mathbf{H}_n$ Modes	532
★7.8	Oscillations in a Source-Free Cavity	533
	Cavity with Lossy Walls	534
	Degenerate Modes	536
★7.9	Excitation of Cavities	538
★7.10	Cavity Perturbation Theory	541
	Problems	545
	References	548
8	Periodic Structures and Filters	550
8.1	Capacitively Loaded Transmission-Line-Circuit Analysis	551
8.2	Wave Analysis of Periodic Structures	557
8.3	Periodic Structures Composed of Unsymmetrical Two-Port Networks	559
8.4	Terminated Periodic Structures	560
8.5	Matching of Periodic Structures	563
8.6	k_0 - β Diagram	564
★8.7	Group Velocity and Energy Flow	566
8.8	Floquet's Theorem and Spatial Harmonics	569
8.9	Periodic Structures for Traveling-Wave Tubes	571
	Periodic Structures for Millimeter-Wave Traveling-Wave Tubes	577
8.10	Sheath Helix	580
★8.11	Some General Properties of a Helix	583
8.12	Introduction to Microwave Filters	585
8.13	Image-Parameter Method of Filter Design	587

8.14	Filter Design by Insertion-Loss Method	591
8.15	Specification of Power Loss Ratio	592
	Maximally Flat Filter Characteristic	593
	Chebyshev Filter	593
8.16	Some Low-Pass-Filter Designs	595
8.17	Frequency Transformations	598
	Frequency Expansion	599
	Low-Pass to High-Pass Transformation	599
	Low-Pass to Bandpass Transformation	600
	Period Bandpass Mapping	602
8.18	Impedance and Admittance Inverters	603
8.19	A Microstrip Half-Wave Filter	617
8.20	Microstrip Parallel Coupled Filter	626
8.21	Quarter-Wave-Coupled Cavity Filters	635
8.22	Direct-Coupled Cavity Filters	639
8.23	Other Types of Filters	642
	Problems	642
	References	647
9	Microwave Tubes	648
9.1	Introduction	648
9.2	Electron Beams with dc Conditions	650
	Ion-Neutralized Beam	650
	Beam with Axially Confined Flow	651
	Brillouin Flow	652
9.3	Space-Charge Waves on Beams with Confined Flow	654
9.4	Space-Charge Waves on Unfocused Beams	661
9.5	Ac Power Relations	667
9.6	Velocity Modulation	670
9.7	Two-Cavity Klystron	678
	Excitation of a Cylindrical Cavity	679
	Cavity Excitation by a Velocity-Modulated Beam	683
9.8	Reflex Klystron	686
9.9	Magnetron	690
9.10	O-Type Traveling-Wave Tube	692
9.11	M-Type Traveling-Wave Tube	699
9.12	Gyrotrons	701
	Field-Particle Interaction in a Gyrotron	703
9.13	Other Types of Microwave Tubes	708
	Problems	709
	References	712
10	Solid-State Amplifiers	713
10.1	Bipolar Transistors	716
	Transistor Biasing	720
10.2	Field-Effect Transistors	721
	FET Biasing	724

10.3	Circle-Mapping Properties of Bilinear Transformations	725
10.4	Microwave Amplifier Design Using S_{ij} Parameters	726
10.5	Amplifier Power Gain	728
	Derivation of Expressions for Gain	730
10.6	Amplifier Stability Criteria	735
	Conditionally Stable Devices	740
10.7	Constant Power-Gain Circles	744
	Properties of the Constant Gain Circles	746
	Stable Devices	746
	Unstable Devices	750
10.8	Basic Noise Theory	760
	Filtered Noise	762
	Noise in Active Devices	765
	Noisy Two-Port Networks	766
10.9	Low-Noise Amplifier Design	767
	Noise Figure	768
	Noise Figure for Cascaded Stages	770
	Constant Noise-Figure Circles	772
10.10	Constant Mismatch Circles	776
	Constant Input Mismatch Circle	778
	Output Impedance-Mismatch Circle	780
10.11	Microwave Amplifier Design	780
	Single-Stage Amplifier Design	781
	Design of Second Stage for a Two-Stage Amplifier	788
10.12	Other Aspects of Microwave Amplifier Design	793
	Problems	795
	References	798
11	Parametric Amplifiers	799
11.1	p - n Junction Diodes	800
11.2	Manley-Rowe Relations	804
11.3	Linearized Equations for Parametric Amplifiers	807
11.4	Parametric Up-Converter	809
11.5	Negative-Resistance Parametric Amplifier	814
11.6	Noise Properties of Parametric Amplifiers	821
	Problems	829
	References	830
12	Oscillators and Mixers	831
12.1	Gunn Oscillators	832
	Gunn Oscillator Circuits	835
12.2	IMPATT Diodes	837
12.3	Transistor Oscillators	840
12.4	Three-Port Description of a Transistor	843
12.5	Oscillator Circuits	849
12.6	Oscillator Design	851

12.7	Mixers	856
	Linear Mixer Operation	861
	Nonlinear Mixer Operation	862
12.8	Mixer Noise Figure	864
12.9	Balanced Mixers	865
12.10	Other Types of Mixers	868
12.11	Mixer Analysis Using Harmonic Balancing	869
	Problems	873
	References	875

Appendixes

I	Useful Relations from Vector Analysis	876
I.1	Vector Algebra	876
I.2	Vector Operations in Common Coordinate Systems	877
	Rectangular Coordinates	877
	Cylindrical Coordinates	877
	Spherical Coordinates	878
I.3	Vector Identities	879
I.4	Green's Identities	880
II	Bessel Functions	881
II.1	Ordinary Bessel Functions	881
II.2	Modified Bessel Functions	883
	References	885
III	Conformal Mapping Techniques	886
III.1	Conformal Mapping	886
III.2	Elliptic Sine Function	889
III.3	Capacitance between Two Parallel Strips	892
III.4	Strip Transmission Line	896
III.5	Conductor Loss	898
III.6	Conductor Losses for a Microstrip Transmission Line	903
III.7	Attenuation for a Coplanar Line	905
IV	Physical Constants and Other Data	911
IV.1	Physical Constants	911
IV.2	Conductivities of Materials	912
IV.3	Dielectric Constants of Materials	912
IV.4	Skin Depth in Copper	912
	Index	913