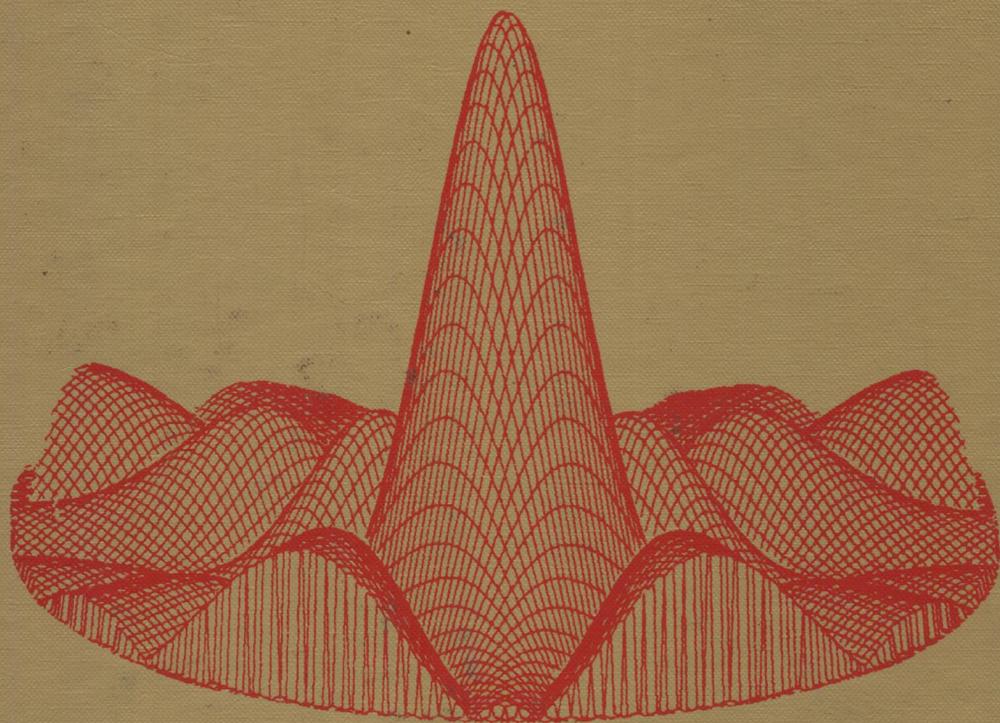


ANTENNA
THEORY
ANALYSIS AND DESIGN



CONSTANTINE A. BALANIS

Contents

Preface xv

Chapter 1 Antennas 1

- 1.1 Introduction 1
- 1.2 Types of Antennas 1
Wire Antennas; Aperture Antennas; Array Antennas; Reflector Antennas; Lens Antennas
- 1.3 Radiation Mechanism 7
- 1.4 Current Distribution on a Thin Wire Antenna 11
- 1.5 Historical Advancement 15
References 15

Chapter 2 Fundamental Parameters of Antennas 17

- 2.1 Introduction 17
- 2.2 Radiation Pattern 17
Isotropic, Directional, and Omnidirectional Patterns; Principal Patterns; Radiation Pattern Lobes; Field Regions; Radian and Steradian

2.3	Radiation Power Density	25
2.4	Radiation Intensity	27
2.5	Directivity	29
2.6	Numerical Techniques	37
2.7	Gain	42
2.8	Antenna Efficiency	44
2.9	Half-Power Beamwidth	46
2.10	Beam Efficiency	46
2.11	Bandwidth	47
2.12	Polarization	48
	<i>Linear, Circular, and Elliptical Polarizations; Polarization Loss Factor</i>	
2.13	Input Impedance	53
2.14	Antenna Radiation Efficiency	57
2.15	Antenna as an Aperture: Effective Aperture	59
2.16	Directivity and Maximum Effective Aperture	61
2.17	Friis Transmission Equation and Radar Range Equation	63
	<i>Friis Transmission Equation; Radar Range Equation</i>	
2.18	Antenna Temperature	67
	References	70
	Problems	71
	Computer Program—Polar Plot	75
	Computer Program—Linear Plot	78
	Computer Program—Directivity	80
Chapter 3 Radiation Integrals and Auxiliary Potential Functions 82		
3.1	Introduction	82
3.2	The Vector Potential \mathbf{A} for an Electric Current Source \mathbf{J}	83
3.3	The Vector Potential \mathbf{F} for a Magnetic Current Source \mathbf{M}	85
3.4	Electric and Magnetic Fields for Electric (\mathbf{J}) and Magnetic (\mathbf{M}) Current Sources	86
3.5	Solution of the Inhomogeneous Vector Potential Wave Equation	88
3.6	Far-Field Radiation	92
3.7	Duality Theorem	93
3.8	Reciprocity and Reaction Theorems	94
	<i>Reciprocity for Radiation Patterns</i>	
	References	99
	Problems	99
Chapter 4 Linear Wire Antennas 100		
4.1	Introduction	100
4.2	Infinitesimal Dipole	100
	<i>Radiated Fields; Power Density and Radiation Resistance; Near-Field ($kr \ll 1$) Region; Intermediate-Field ($kr > 1$) Region; Far-Field ($kr \gg 1$) Region; Directivity</i>	

- 4.3 Small Dipole 109
- 4.4 Region Separation 112
Far-Field (Fraunhofer) Region; Radiating Near-Field (Fresnel) Region; Reactive Near-Field Region
- 4.5 Finite Length Dipole 118
Current Distribution; Radiated Fields: Element Factor, Space Factor, and Pattern Multiplication; Power Density, Radiation Intensity, and Radiation Resistance; Directivity; Input Resistance; Finite Feed Gap
- 4.6 Half-Wavelength Dipole 130
- 4.7 Linear Elements Near or on Infinite Plane Conductors 132
Image Theory; Vertical Electric Dipole; Horizontal Electric Dipole
- 4.8 Ground Effects 148
Vertical Electric Dipole; Horizontal Electric Dipole; Earth Curvature
 References 159
 Problems 159
 Computer Program—Linear Dipole: Directivity, Radiation Resistance, and Input Resistance 162

Chapter 5 Loop Antennas 164

- 5.1 Introduction 164
- 5.2 Small Circular Loop 164
Radiated Fields; Small Loop and Infinitesimal Magnetic Dipole; Power Density and Radiation Resistance; Near-Field ($kr \ll 1$) Region; Far-Field ($kr \gg 1$) Region; Radiation Intensity and Directivity
- 5.3 Circular Loop of Constant Current 176
Radiated Fields; Power Density, Radiation Intensity, Radiation Resistance, and Directivity
- 5.4 Circular Loop with Nonuniform Current 184
- 5.5 Ground and Earth Curvature Effects for Circular Loops 188
- 5.6 Polygonal Loop Antennas 191
Square Loop; Triangular, Rectangular, and Rhombic Loops
- 5.7 Ferrite Loop 196
 References 198
 Problems 199
 Computer Program—Circular Loop: Directivity and Radiation Resistance 201

Chapter 6 Arrays: Linear, Planar, and Circular 204

- 6.1 Introduction 204
- 6.2 Two-Element Array 205
- 6.3 N -Element Linear Array: Uniform Amplitude and Spacing 212

	<i>Broadside Array; Ordinary End-Fire Array; Phased (Scanning) Array; Hansen-Woodyard End-Fire Array</i>	
6.4	<i>N-Element Linear Array: Directivity</i>	229
	<i>Broadside Array; Ordinary End-Fire Array; Hansen-Woodyard End-Fire Array</i>	
6.5	<i>N-Element Linear Array: Three-Dimensional Characteristics</i>	235
	<i>N-Elements Along Z-Axis; N-Elements Along X- or Y-Axis</i>	
6.6	<i>Rectangular-to-Polar Graphical Solution</i>	238
6.7	<i>N-Element Linear Array: Uniform Spacing, Nonuniform Amplitude</i>	240
	<i>Array Factor; Binomial Array; Dolph-Tschebyscheff Array</i>	
6.8	<i>Superdirectivity</i>	257
6.9	<i>Planar Array</i>	260
	<i>Array Factor; Beamwidth; Directivity</i>	
6.10	<i>Circular Array</i>	274
	<i>Array Factor</i>	
	<i>References</i>	279
	<i>Problems</i>	280

Chapter 7 Self- and Mutual Impedances of Linear Elements and Arrays, and Finite Diameter Effects (Moment Method) 283

7.1	<i>Introduction</i>	283
7.2	<i>Near-Fields of Dipole</i>	285
7.3	<i>Input Impedance of Dipole</i>	290
	<i>Induced emf Method; Finite Dipole Input Impedance</i>	
7.4	<i>Mutual Impedance Between Linear Elements</i>	296
7.5	<i>Finite Diameter Wires: The Moment Method</i>	304
	<i>Integral Equation; Moment Method Solution; Basis Functions; Weighting (Testing) Functions; Current Distribution; Input Impedance; Radiation Pattern; Source Modeling</i>	
	<i>References</i>	317
	<i>Problems</i>	318
	<i>Computer Program—Finite Diameter Dipole: Current Distribution, Input Impedance, and Radiation Pattern</i>	319

Chapter 8 Broadband Dipoles and Matching Techniques 322

8.1	<i>Introduction</i>	322
8.2	<i>Biconical Antenna</i>	323
	<i>Radiated Fields; Input Impedance</i>	
8.3	<i>Triangular Sheet, Bow-Tie, and Wire Simulation</i>	330
8.4	<i>Cylindrical Dipole</i>	332
	<i>Bandwidth; Input Impedance; Resonance and Ground Plane Simulation; Radiation Patterns; Equivalent Radii; Dielectric Coating</i>	

- 8.5 Folded Dipole 340
- 8.6 Discone and Conical Skirt Monopole 346
- 8.7 Sleeve Dipole 347
- 8.8 Matching Techniques 349
*Stub-Matching; Quarter-Wavelength Transformer; T-Match;
 Gamma Match; Omega Match; Baluns and Transformers*
- References 368
- Problems 369

Chapter 9 Traveling Wave and Broadband Antennas 372

- 9.1 Introduction 372
- 9.2 Traveling Wave Antennas 372
Long Wire; V Antenna; Rhombic Antenna
- 9.3 Broadband Antennas 385
*Helical Antenna; Electric-Magnetic Dipole; Yagi-Uda Array of
 Linear Elements; Yagi-Uda Array of Loops*
- References 409
- Problems 411

Chapter 10 Frequency Independent Antennas and Antenna Miniaturization 413

- 10.1 Introduction 413
- 10.2 Theory 414
- 10.3 Equiangular Spiral Antennas 416
Planar Spiral; Conical Spiral
- 10.4 Log-Periodic Antennas 423
Planar and Wire Surfaces; Dipole Array; Design of Dipole Array
- 10.5 Fundamental Limits of Electrically Small Antennas 439
- References 444
- Problems 445

Chapter 11 Aperture Antennas, and Ground Plane Edge Effects (Geometrical Theory of Diffraction) 446

- 11.1 Introduction 446
- 11.2 Field Equivalence Principle: Huygens' Principle 447
- 11.3 Radiation Equations 454
- 11.4 Directivity 456
- 11.5 Rectangular Apertures 457
*Uniform Distribution on an Infinite Ground Plane; Uniform
 Distribution in Space; TE_{10} -Mode Distribution on an Infinite
 Ground Plane; Beam Efficiency*
- 11.6 Circular Apertures 478
*Uniform Distribution on an Infinite Ground Plane; TE_{11} -Mode
 Distribution on an Infinite Ground Plane; Beam Efficiency*
- 11.7 Microstrip Antennas 487
*Radiated Fields; Radiation Conductance; Directivity; Bandwidth;
 Arrays; Circular Polarization*

- 11.8 Babinet's Principle 496
- 11.9 Ground Plane Edge Effects: The Geometrical Theory of Diffraction 502
Edge Diffraction Coefficient; Aperture on a Finite-Size Ground Plane; Curved-Edge Diffraction; Equivalent Currents in Diffraction; Oblique Incidence Edge Diffraction
 References 522
 Problems 524
 Computer Program—Diffraction Coefficient 529

Chapter 12 Horns 532

- 12.1 Introduction 532
- 12.2 *E*-Plane Sectoral Horn 532
Aperture Fields; Radiated Fields; Directivity
- 12.3 *H*-Plane Sectoral Horn 550
Aperture Fields; Radiated Fields; Directivity
- 12.4 Pyramidal Horn 565
Aperture Fields, Equivalent, and Radiated Fields; Directivity; Design Procedure
- 12.5 Conical Horn 577
- 12.6 Corrugated Horn 579
- 12.7 Phase Center 587
 References 589
 Problems 590

Chapter 13 Reflectors and Lens Antennas 593

- 13.1 Introduction 593
- 13.2 Plane Reflector 594
- 13.3 Corner Reflector 594
90° Corner Reflector; Other Corner Reflectors
- 13.4 Parabolic Reflector 604
Front-Fed Parabolic Reflector; Cassegrain Reflectors
- 13.5 Spherical Reflector 642
- 13.6 Lens Antennas 646
Lenses with $n > 1$; Lenses with $n < 1$; Lenses with Variable Index of Refraction
 References 654
 Problems 656

Chapter 14 Antenna Synthesis and Continuous Sources 658

- 14.1 Introduction 658
- 14.2 Continuous Sources 659
Line-Source; Discretization of Continuous Sources
- 14.3 Schelkunoff Polynomial Method 661
- 14.4 Fourier Transform Method 666
Line-Source; Linear Array

- 14.5 Woodward Method 673
Line-Source; Linear Array
- 14.6 Taylor Line-Source (Tschebyscheff Error) 679
Design Procedure
- 14.7 Taylor Line-Source (One-Parameter) 684
- 14.8 Triangular, Cosine, and Cosine-Squared Amplitude
 Distributions 690
- 14.9 Line-Source Phase Distributions 694
- 14.10 Continuous Aperture Sources 696
Rectangular Aperture; Circular Aperture
 References 698
 Problems 699

Chapter 15 Antenna Measurements 703

- 15.1 Introduction 703
- 15.2 Antenna Ranges 704
Reflection Ranges; Free-Space Ranges
- 15.3 Radiation Patterns 710
Instrumentation; Amplitude Pattern; Phase Measurements
- 15.4 Gain Measurements 716
*Absolute-Gain Measurements; Gain-Transfer (Gain-Comparison)
 Measurements*
- 15.5 Directivity Measurements 723
- 15.6 Radiation Efficiency 725
- 15.7 Impedance Measurements 725
- 15.8 Current Measurements 727
- 15.9 Polarization Measurements 728
- 15.10 Scale Model Measurements 733
 References 734

Appendix I $f(x) = \frac{\sin(x)}{x}$ 737

Appendix II $f_N(x) = \left| \frac{\sin(Nx)}{N\sin(x)} \right|$, $N = 1, 3, 5, 10, 20$ 740

Appendix III Cosine and Sine Integrals 743

Appendix IV Fresnel Integrals 748

Appendix V Bessel Functions 755

Appendix VI Identities 768

Appendix VII Vector Analysis 771

Appendix VIII Television and Radio Frequency Spectrum 781

Index 783