Contents

Preface xi

Chapter 1 Electromagnetic Fields and Waves 1

1.0 Introduction 1
1.1 Maxwell's Equations and Boundary Conditions 1
1.2 Energy Density and Poynting Vector 4
1.3 Monochromatic Fields and Complex-Function Formalism 6
1.4 Wave Equations and Monochromatic Plane Waves 8
1.5 Chromatic Dispersion and Group Velocity 13
1.6 Polarization States and Representations (Stokes Parameters and Poincaré Sphere) 19
1.7 Electromagnetic Propagation in Anisotropic Media (Crystals) 30
1.8 Plane Waves in Uniaxially Anisotropic Media—Phase Retardation 36
1.9 Jones Matrix Method 41
1.10 Elementary Theory of Coherence 56
Problems 59
References 65

Chapter 2 Rays and Optical Beams 66

2.0 Introduction 66
2.1 Ray Matrices 66
2.2 Skew Rays and Reentrant Rays 72
2.3 Rays in Lenslike Media 73
2.4 Wave Equation in Quadratic Index Media and Beams 77
2.5 Gaussian Beams in Homogeneous Media 79
2.6 Fundamental Gaussian Beam in a Lenslike Medium—The *ABCD* Law 83
2.7 Gaussian Beams in Lens Waveguide 87
2.8 High-Order Gaussian Beam Modes in a Homogeneous Medium 88
2.9 Gaussian Beam Modes in Quadratic Index Media 91
2.10 Propagation in Media with a Quadratic Gain Profile 95
2.11 Elliptic Gaussian Beams 97
2.12 Beam Propagation and Diffraction Integral 99
Problems 106
References 109

Chapter 3 Guided Waves in Dielectric Slabs and Fibers 110

3.0 Introduction 110
3.1 TE and TM Confined Modes in Symmetric Slab Waveguides 110

3.2 TE and TM Confined Modes in Asymmetric Slab Waveguides 118
3.3 Step-Index Circular Dielectric Waveguides (Linearly Polarized Modes in Optical Fibers) 126
3.4 Effective Index Theory 137
3.5 Waveguide Dispersion in Optical Fibers 140
3.6 Attenuation in Silica Fibers 145
Problems 149
References 153
Additional Reading 155

Chapter 4 Optical Resonators 156
4.0 Introduction 156
4.1 Fabry–Perot Etalon 160
4.2 Fabry–Perot Etalons as Optical Spectrum Analyzers 170
4.3 Optical Resonators with Spherical Mirrors 172
4.4 Mode Stability Criteria 176
4.5 Modes in a Generalized Resonator—Self-Consistent Method 178
4.6 Resonance Frequencies of Optical Resonators 180
4.7 Losses in Optical Resonators 183
4.8 Ring Resonators 184
4.9 Multicavity Etalons 194
4.10 Mode Matching and Coupling Loss 204
Problems 206
References 209
Additional Reading 210

Chapter 5 Interaction of Radiation and Atomic Systems 211
5.0 Introduction 211
5.1 Atomic Transitions and Electromagnetic Waves 211
5.2 Atomic Polarizability and Dielectric Constant 213
5.3 Classical Electron Model 214
5.4 Dispersion and Complex Refractive Index 216
5.5 Lineshape Function—Homogeneous and Inhomogeneous Broadening 221
5.6 Induced Transitions—Absorption and Amplification 225
5.7 Gain Saturation in Homogeneous Laser Media 230
5.8 Gain Saturation in Inhomogeneous Laser Media 232
Problems 235
References 236

Chapter 6 Theory of Laser Oscillation and Some Specific Laser Systems 237
6.0 Introduction 237
6.1 Fabry–Perot Laser 237
6.2 Oscillation Frequency 242

6.3 Three- and Four-Level Lasers 244
6.4 Power in Laser Oscillators 246
6.5 Optimum Output Coupling in Laser Oscillators 248
6.6 Multimode Laser Oscillation and Mode Locking 251
6.7 Mode Locking in Homogeneously Broadened Laser Systems 265
6.8 Pulse Length Measurement and Narrowing of Chirped Pulses 273
6.9 Giant Pulse (Q-Switched) Lasers 281
6.10 Hole Burning and the Lamb Dip in Doppler-Broadened Gas Lasers 287
6.11 Some Specific Laser Systems 290
6.12 Frequency Comb and Optical Frequency Metrology 303
Problems 308
References 309
Additional Reading 312

Chapter 7 Chromatic Dispersion and Polarization Mode Dispersion in Fibers 313
7.0 Introduction 313
7.1 Chromatic Dispersion in Optical Transmission Systems 313
7.2 Optical Pulse Spreading in Dispersive Media 317
7.3 Polarization Effects in Optical Fibers 322
7.4 Principal States of Polarization 325
7.5 Vector Analysis of Polarization Mode Dispersion 329
7.6 High-Order PMD and Compensators 346
Problems 350
References 353

Chapter 8 Nonlinear Optics 354
8.0 Introduction 354
8.1 On the Physical Origin of Nonlinear Polarization 354
8.2 Second-Order Nonlinear Phenomena—General Methodology 355
8.3 Electromagnetic Formulation and Optical Second-Harmonic Generation 358
8.4 Other Second-Order Nonlinear Processes 369
8.5 Quasi Phase Matching 377
8.6 Third-Order Nonlinear Optical Processes 380
8.7 Stimulated Brillouin Scattering 387
8.8 Four-Wave Mixing and Phase Conjugation 392
8.9 Frequency Tuning in Parametric Oscillation 399
Problems 402
References 404

Chapter 9 Electro-optic Modulation of Laser Beams 406
9.0 Introduction 406
9.1 Linear Electro-optic Effect 406
9.2 Electro-optic Modulation—Phase, Amplitude 418

9.3 High-Frequency Modulation Considerations 427
9.4 Electroabsorption and Electroabsorption Modulators 431
9.5 Electro-optical Effect in Liquid Crystals 434
9.6 Acousto-optic Effect (Photoelastic Effect) 440
9.7 Scattering of Light by Sound 446
9.8 Bragg Diffraction—Coupled-Wave Analysis 450
9.9 Bragg Cells and Beam Deflectors 458
Problems 461
References 463

Chapter 10 Noise in Optical Detection and Generation 465
10.0 Introduction 465
10.1 Limitations Due to Noise Power 466
10.2 Noise—Basic Definitions and Theorems 469
10.3 Spectral Density Function of a Train of Randomly Occurring Events 471
10.4 Shot Noise 473
10.5 Johnson Noise 475
10.6 Spontaneous Emission Noise in Laser Oscillators 479
10.7 Phasor Derivation of Laser Linewidth 484
10.8 Coherence and Interference 491
10.9 Error Probability in a Binary Pulse Code Modulation System 496
Problems 499
References 500

Chapter 11 Detection of Optical Radiation 501
11.0 Introduction 501
11.1 Optically Induced Transition Rates 501
11.2 Photomultiplier 503
11.3 Noise Mechanisms in Photomultipliers 505
11.4 Heterodyne Detection with Photomultipliers 507
11.5 Photoconductive Detectors 511
11.6 The *p-n* Junction 517
11.7 Semiconductor Photodiodes 521
11.8 Avalanche Photodiode 529
11.9 Power Fluctuation Noise in Lasers 532
Problems 536
References 537
Additional Reading 538

Chapter 12 Wave Propagation in Periodic Media 539
12.0 Introduction 539
12.1 Periodic Media 539

12.2 Periodic Layered Media—Bloch Waves 545
12.3 Bragg Reflectors 555
12.4 Coupled-Wave Analysis 560
12.5 Periodic Waveguides 573
12.6 Spectral Filters and Fiber Bragg Gratings 582
12.7 Chirped and Tapered Index Gratings 587
12.8 2-D and 3-D Periodic Media (Photonic Crystals) 594
Problems 600
References 601

Chapter 13 Waveguide Coupling 602
13.0 Introduction 602
13.1 General Properties of Modes 602
13.2 Dielectric Perturbation Theory and Mode Coupling 607
13.3 Coupling of Two Parallel Waveguides—Directional Coupler 611
13.4 Coupling of *N* Parallel Identical Waveguides—Supermodes 618
13.5 Phase Matching and Frequency Selective Coupling—Multiplexing 622
13.6 Mode Converters 626
Problems 630
References 632

Chapter 14 Nonlinear Optical Effects in Fibers 633
14.0 Introduction 633
14.1 Kerr Effect and Self-Phase Modulation 633
14.2 Cross-Phase Modulation—Polarization 637
14.3 Nondegenerate Four-Wave Mixing 641
14.4 Partially Degenerate Four-Wave Mixing 653
14.5 Optical Solitons 663
Problems 670
References 671

Chapter 15 Semiconductor Lasers—Theory and Applications 673
15.0 Introduction 673
15.1 Some Semiconductor Physics Background 674
15.2 Gain and Absorption in Semiconductor (Laser) Media 680
15.3 GaAs/$Ga_{1-x}Al_xAs$ Lasers 686
15.4 Some Real Laser Structures 691
15.5 Direct-Current Modulation of Semiconductor Lasers 696
15.6 Gain Suppression and Frequency Chirp in Current-Modulated Semiconductor Lasers 700
15.7 Integrated Optoelectronics 709
Problems 711
References 712

Chapter 16 Advanced Semiconductor Lasers 714
16.0 Introduction 714
16.1 Carriers in Quantum Wells (Advanced Topic) 715
16.2 Gain in Quantum Well Lasers 720
16.3 Distributed Feedback Lasers 724
16.4 Vertical Cavity Surface Emitting Semiconductor Lasers 738
Problems 746
References 746

Chapter 17 Optical Amplifiers 748
17.0 Introduction 748
17.1 Semiconductor Optical Amplifiers 749
17.2 Erbium-Doped Fiber Amplifiers 752
17.3 Amplified Spontaneous Emission 755
17.4 Optical Amplification in Fiber Links 761
17.5 Raman Optical Amplifiers 767
Problems 774
References 776

Chapter 18 Classical Treatment of Quantum Noise and Squeezed States 778
18.0 Introduction 778
18.1 The Uncertainty Principle and Quantum Noise 778
18.2 Squeezing of Optical Fields 787
Problems 795
References 796

Appendix A Wave Equation in Cylindrical Coordinates and Bessel Functions 797
Appendix B Exact Solutions of the Step-Index Circular Waveguide 802
Appendix C Kramers–Kronig Relations 812
Appendix D Transformation of a Coherent Electromagnetic Field by a Thin Lens 817
Appendix E Fermi Level and Its Temperature Dependence 820
Appendix F Electro-optic Effect in Cubic $\bar{4}3m$ Crystals 823
Appendix G Conversion for Power Units and Attenuation Units 827

Author Index 828
Subject Index 830