

Contents

Preface *xix*

1	Light Rays	1
1.1	Light Rays in Human Experience	1
1.2	Ray Optics	2
1.3	Reflection	2
1.3.1	Planar Mirrors	2
1.4	Refraction	3
1.4.1	Law of Refraction	3
1.4.2	Total Internal Reflection	4
1.5	Fermat's Principle: The Optical Path Length	5
1.5.1	Inhomogeneous Refractive Index	6
1.6	Prisms	8
1.6.1	Dispersion	9
1.7	Light Rays in Wave Guides	10
1.7.1	Ray Optics in Wave Guides	11
1.7.2	Step-Index Fibers	12
1.7.2.1	Numerical Aperture of an Optical Fiber	13
1.7.2.2	Propagation Velocity	13
1.7.3	Gradient-Index Fibers	13
1.8	Lenses and Curved Mirrors	15
1.8.1	Lenses	15
1.8.2	Concave Mirrors	16
1.9	Matrix Optics	17
1.9.1	Paraxial Approximation	17
1.9.2	ABCD Matrices	18
1.9.3	Lenses in Air	19
1.9.4	Lens Systems	21
1.9.5	Periodic Lens Systems	22
1.9.6	ABCD Matrices for Wave Guides	23
1.10	Ray Optics and Particle Optics	23
	Problems	25

2	Wave Optics	29
2.1	Electromagnetic Radiation Fields	29
2.1.1	Static Fields	30
2.1.2	Polarizable and Magnetizable Media	30
2.1.3	Dynamic Fields	31
2.1.4	Fourier Components	32
2.1.5	Maxwell's Equations for Optics	33
2.1.6	Continuity Equation and Superposition Principle	33
2.1.7	The Wave Equation	33
2.1.8	Energy Density, Intensity, and the Poynting Vector of Electromagnetic Waves	35
2.2	Wave Types	37
2.2.1	Planar Waves	37
2.2.2	Spherical Waves	38
2.2.3	Dipole Waves	39
2.3	Gaussian Beams	40
2.3.1	The Gaussian Principal Mode or TEM ₀₀ Mode	41
2.3.1.1	Rayleigh Zone, Confocal Parameter b	42
2.3.1.2	Radius of Wave Fronts $R(z)$	42
2.3.1.3	Beam Waist $2w_0$	42
2.3.1.4	Beam Radius $w(z)$	43
2.3.1.5	Divergence Θ_{div}	43
2.3.1.6	Gouy Phase $\eta(z)$	43
2.3.2	The ABCD Rule for Gaussian Modes	44
2.3.3	Paraxial Wave Equation	46
2.3.4	Higher Gaussian Modes	47
2.3.5	Creation of Gaussian Modes	49
2.3.6	More Gaussian Paraxial Beams	50
2.4	Vector Light: Polarization	50
2.4.1	Jones Vectors	52
2.4.2	Stokes Parameters	52
2.4.3	Polarization State and Poincaré Sphere	53
2.4.4	Jones Matrices, Polarization Control, and Measurement	54
2.4.5	Polarization and Projection	56
2.4.6	Polarization of Light Beams with Finite Extension	57
2.5	Optomechanics: Mechanical Action of Light Beams	58
2.5.1	Radiation Pressure	58
2.5.2	Angular Momentum of Light Beams	59
2.5.3	Beth's Experiment	60
2.5.4	Optical Angular Momentum (OAM)	60
2.5.4.1	Twisted Beams	61
2.5.4.2	Laguerre–Gaussian Modes	61
2.5.4.3	Transforming Hermite–Gaussian to Laguerre–Gaussian Beams	62
2.6	Diffraction	63
2.6.1	Scalar Diffraction Theory	64
2.7	Fraunhofer Diffraction	67
2.7.1	Optical Fourier Transformation, Fourier Optics	70

- 2.8 Fresnel Diffraction 71
- 2.8.1 Babinet's Principle 74
- 2.8.2 Fresnel Zones and Fresnel Lenses 75
- 2.9 Beyond Gaussian Beams: Diffraction Integral and ABCD Formalism 77
- Problems 77

3 Light Propagation in Matter: Interfaces, Dispersion, and Birefringence 83

- 3.1 Dielectric Interfaces 83
- 3.1.1 Refraction and Reflection at Glass Surfaces 84
- 3.1.1.1 s Polarization 84
- 3.1.1.2 p Polarization 86
- 3.1.2 Total Internal Reflection (TIR) 87
- 3.1.3 Complex Refractive Index 88
- 3.2 Interfaces of Conducting Materials 89
- 3.2.1 Wave Propagation in Conducting Materials 90
- 3.2.1.1 High Frequencies: $\omega_p \tau \gg \omega \tau \gg 1$ 90
- 3.2.1.2 Low Frequencies: $\omega \tau \ll 1 \ll \omega_p \tau$ 90
- 3.2.2 Metallic Reflection 91
- 3.2.3 Polaritons and Plasmons 92
- 3.2.3.1 Surface Plasmon Polaritons (SPPs) 92
- 3.2.3.2 Properties of Surface Plasmon Polaritons (SPPs) 93
- 3.3 Light Pulses in Dispersive Materials 94
- 3.3.1 Pulse Distortion by Dispersion 98
- 3.3.2 Solitons 101
- 3.4 Anisotropic Optical Materials 103
- 3.4.1 Birefringence 103
- 3.4.2 Ordinary and Extraordinary Light Rays 106
- 3.4.3 Construction of Retarder Plates 107
- 3.4.3.1 Lyot Filter 108
- 3.4.4 Birefringent Polarizers 109
- 3.5 Optical Modulators 110
- 3.5.1 Pockels Cell and Electro-optical Modulators 110
- 3.5.2 Liquid Crystal Modulators 112
- 3.5.3 Spatial Light Modulators 113
- 3.5.4 Acousto-Optical Modulators 114
- 3.5.5 Faraday Rotators 117
- 3.5.6 Optical Isolators and Diodes 118
- Problems 119

4 Light Propagation in Structured Matter 121

- 4.1 Optical Wave Guides and Fibers 122
- 4.1.1 Step-Index Fibers 123
- 4.1.1.1 Weakly Guiding Step Fibers 125
- 4.1.1.2 $\ell = 0$: TE and TM Modes 127
- 4.1.1.3 $\ell \geq 1$: HE and EH Modes 128

4.1.1.4	$\ell \geq 1$: LP Modes	128
4.1.2	Graded-Index Fiber	129
4.1.3	Fiber Absorption	130
4.1.4	Functional Types and Applications of Optical Fibers	130
4.1.4.1	Multimode Fibers	130
4.1.4.2	Single-Mode Fibers	131
4.1.4.3	Polarization-Maintaining (PM) Fibers	131
4.1.4.4	Photonic Crystal Fibers (PCF)	132
4.2	Dielectric Photonic Materials	132
4.2.1	Photonic Crystals	132
4.2.1.1	Light Propagation in 1D Periodically Structured Dielectrics	133
4.2.2	Bloch Waves	134
4.2.3	Photonic Bandgap in 1D	135
4.2.4	Bandgaps in 2D and 3D	137
4.2.4.1	2D Photonic Crystals	137
4.2.4.2	3D Photonic Crystals	139
4.2.5	Defects and Defect Modes	139
4.2.6	Photonic Crystal Fibers (PCFs)	141
4.3	Metamaterials	143
4.3.1	Dielectric (Plasmonic) Metamaterials	143
4.3.2	Magnetic Metamaterials and negative index of refraction	144
4.3.3	Constructing Magnetic Metamaterials	145
4.3.4	Applications of Metamaterials: The Perfect Lens	146
	Problems	147
5	Optical Images	149
5.1	Simple Lenses	149
5.2	The Human Eye	151
5.3	Magnifying Glass and Eyepiece	152
5.4	Microscopes	154
5.4.1	Resolving Power of Microscopes	155
5.4.1.1	Rayleigh Criterion and Numerical Aperture	155
5.4.1.2	Abbe's Theory of Resolution	156
5.4.1.3	Exploiting the Abbe–Rayleigh Resolution Limit	157
5.4.2	Analyzing and Improving Contrast	159
5.4.2.1	The Modulation Transfer Function (MTF)	159
5.4.2.2	Enhancing Contrast	160
5.5	Scanning Microscopy Methods	161
5.5.1	Depth of Focus and Confocal Microscopy	161
5.5.2	Scanning Near-Field Optical Microscopy (SNOM)	162
5.5.3	Overcoming the Rayleigh–Abbe Resolution Limits with Light	163
5.5.3.1	Single-Molecule Detection	164
5.5.3.2	PALM Microscopy	165
5.5.3.3	STED Microscopy	165
5.6	Telescopes	166
5.6.1	Theoretical Resolving Power of a Telescope	166
5.6.2	Magnification of a Telescope	167

5.6.3	Image Distortions of Telescopes	168
5.6.3.1	Lens Telescopes and Reflector Telescopes	168
5.6.3.2	Atmospheric Turbulence	169
5.7	Lenses: Designs and Aberrations	169
5.7.1	Types of Lenses	170
5.7.1.1	Planar Convex Lenses	170
5.7.1.2	Biconvex Lenses and Doublets	171
5.7.1.3	Meniscus Lenses	171
5.7.2	Aberrations: Seidel Aberrations	172
5.7.2.1	Ray Propagation in First Order	172
5.7.2.2	Ray Propagation in Third Order	172
5.7.2.3	Aperture Aberration or Spherical Aberration	173
5.7.2.4	Astigmatism	174
5.7.2.5	Coma and Distortion	175
5.7.3	Chromatic Aberration	176
	Problems	177
6	Coherence and Interferometry	181
6.1	Young's Double Slit	181
6.2	Coherence and Correlation	182
6.2.1	Correlation Functions	183
6.2.2	Beam Splitter	184
6.3	The Double-Slit Experiment	185
6.3.1	Transverse Coherence	186
6.3.2	Optical or Diffraction Gratings	188
6.3.3	Monochromators	190
6.4	Michelson interferometer: longitudinal coherence	191
6.4.1	Longitudinal or Temporal Coherence	192
6.4.2	Mach-Zehnder and Sagnac Interferometers	195
6.4.2.1	Mach-Zehnder Interferometer	195
6.4.2.2	Sagnac Interferometer	196
6.5	Fabry-Pérot Interferometer	197
6.5.1	Free Spectral Range, Finesse, and Resolution	200
6.6	Optical Cavities	202
6.6.1	Damping of Optical Cavities	202
6.6.2	Modes and Mode Matching	203
6.6.3	Resonance Frequencies of Optical Cavities	204
6.6.4	Symmetric Optical Cavities	205
6.6.5	Optical Cavities: Important Special Cases	205
6.6.5.1	Plane Parallel Cavity: $\ell/R = 0$	205
6.6.5.2	Confocal Cavity: $\ell/R = 1$	206
6.6.5.3	Concentric Cavity: $\ell/R = 2$	207
6.7	Thin Optical Films	208
6.7.1	Single-Layer Films	208
6.7.1.1	Minimal Reflection: AR Coating, AR Layer, and $\lambda/4$ Film	209
6.7.1.2	Reflection: Highly Reflective Films	209
6.7.2	Multilayer Films	209

6.8	Holography	210
6.8.1	Holographic Recording	211
6.8.2	Holographic Reconstruction	212
6.8.2.1	Zeroth Order	213
6.8.2.2	Halo	213
6.8.2.3	Reconstructed Signal Wave	213
6.8.2.4	Conjugated Wave	213
6.8.3	Properties	214
6.8.3.1	Three-Dimensional Reconstruction	214
6.8.3.2	Partial Reconstruction	214
6.8.3.3	Magnification	214
6.9	Laser Speckle (Laser Granulation)	214
6.9.1	Real and Virtual Speckle Patterns	215
6.9.2	Speckle Grain Sizes	215
	Problems	216
7	Light and Matter	219
7.1	Classical Radiation Interaction	220
7.1.1	Lorentz Oscillators	220
7.1.2	Macroscopic Polarization	224
7.1.2.1	Linear Polarization and Macroscopic Refractive Index	225
7.1.2.2	Absorption and Dispersion in Optically Thin Media	226
7.1.2.3	Dense Dielectric Media and Near Fields	227
7.2	Two-Level Atoms	229
7.2.1	Are There Any Atoms with Only Two Levels?	229
7.2.2	Dipole Interaction	230
7.2.3	Optical Bloch Equations	232
7.2.4	Pseudo-spin, Precession, and Rabi Nutation	234
7.2.5	Microscopic Dipoles and Ensembles	235
7.2.6	Optical Bloch Equations with Damping	235
7.2.7	Steady-State Inversion and Polarization	236
7.2.7.1	Steady-State Inversion and Saturation Intensity	236
7.2.7.2	Steady-State Polarization	238
7.3	Stimulated and Spontaneous Radiation Processes	239
7.3.1	Stimulated Emission and Absorption	241
7.3.2	Spontaneous Emission	242
7.4	Inversion and Amplification	242
7.4.1	Four-, Three-, and Two-Level Laser Systems	243
7.4.2	Generation of Inversion	243
7.4.3	Optical Gain	244
7.4.4	The Historical Path to the Laser	245
	Problems	246
8	The Laser	249
8.1	The Classic System: The He-Ne Laser	251
8.1.1	Construction	251
8.1.1.1	Amplifier	251

8.1.1.2	Operating Conditions	252
8.1.1.3	The Laser Resonator	253
8.1.2	Mode Selection in the He–Ne Laser	254
8.1.2.1	Laser Line Selection	254
8.1.3	Gain Profile, Laser Frequency, and Spectral Holes	255
8.1.4	The Single-Frequency Laser	256
8.1.5	Laser Power	257
8.1.6	Spectral Properties of the He–Ne Laser	258
8.1.6.1	Laser Linewidth	258
8.1.7	Optical Spectral Analysis	259
8.1.7.1	The Fabry–Pérot Spectrum Analyzer	259
8.1.7.2	The Heterodyne Method	259
8.1.8	Applications of the He–Ne Laser	261
8.2	Other Gas Lasers	261
8.2.1	The Argon Laser	261
8.2.1.1	The Amplifier	262
8.2.1.2	Operating Conditions	262
8.2.1.3	Features and Applications	263
8.2.2	Metal-Vapor Lasers	263
8.2.3	Molecular Gas Lasers	264
8.2.3.1	The CO ₂ Laser	265
8.2.3.2	Gain	265
8.2.3.3	Operating Conditions	267
8.2.3.4	The Excimer Laser	267
8.3	The Workhorses: Solid-State Lasers	268
8.3.1	Optical Properties of Laser Crystals	268
8.3.2	Rare-Earth Ions	269
8.4	Selected Solid-State Lasers	271
8.4.1	The Neodymium Laser	271
8.4.1.1	The Neodymium Amplifier	271
8.4.1.2	Configuration and Operation	272
8.4.2	Applications of Neodymium Lasers	273
8.4.2.1	Frequency-Doubled Neodymium Lasers	273
8.4.2.2	The Monolithically Integrated Laser (Miser)	274
8.4.3	Erbium Lasers, Erbium-Doped Fiber Amplifiers (EDFAs)	275
8.4.4	Fiber Lasers	276
8.4.4.1	Cladding Pumping	276
8.4.4.2	Fiber Bragg Gratings	277
8.4.5	Ytterbium Lasers: Higher Power with Thin-Disc and Fiber Lasers	278
8.5	Tunable Lasers with Vibronic States	279
8.5.1	Transition-Metal Ions	279
8.5.2	Color Centers	280
8.5.3	Dyes	281
8.6	Tunable Ring Lasers	281
	Problems	283

9	Laser Dynamics	285
9.1	Basic Laser Theory	285
9.1.1	The Resonator Field	285
9.1.2	Damping of the Resonator Field	286
9.1.3	Steady-State Laser Operation	288
9.1.3.1	Saturated Gain	289
9.1.3.2	Mode Pulling	289
9.1.3.3	Field Strength and Number of Photons in the Resonator	290
9.1.3.4	Laser Threshold	290
9.1.3.5	Laser Power and Outcoupling	291
9.2	Laser Rate Equations	291
9.2.1	Laser Spiking and Relaxation Oscillations	292
9.3	Threshold-Less Lasers and Micro-lasers	295
9.4	Laser Noise	298
9.4.1	Amplitude and Phase Noise	298
9.4.1.1	Amplitude Fluctuations	298
9.4.1.2	Phase Fluctuations	299
9.4.2	The Microscopic Origin of Laser Noise	301
9.4.3	Laser Intensity Noise	302
9.4.3.1	Quantum Limit of the Laser Amplitude	302
9.4.3.2	Relative Intensity Noise (RIN)	303
9.4.4	Schawlow–Townes Linewidth	304
9.5	Pulsed Lasers	305
9.5.1	“Q-Switch”	305
9.5.1.1	Technical Q-Switches	306
9.5.1.2	Cavity Dumping	306
9.5.2	Mode Locking	306
9.5.3	Methods of Mode Locking	309
9.5.4	Measurement of Short Pulses	312
9.5.5	Tera- and Petawatt Lasers	312
9.5.6	Coherent White Light	313
9.5.7	Frequency Combs	315
	Problems	316
10	Semiconductor Lasers	319
10.1	Semiconductors	319
10.1.1	Electrons and Holes	319
10.1.2	Doped Semiconductors	320
10.1.3	pn Junctions	321
10.2	Optical Properties of Semiconductors	322
10.2.1	Semiconductors for Optoelectronics	322
10.2.2	Absorption and Emission of Light	323
10.2.3	Inversion in the Laser Diode	325
10.2.4	Small Signal Gain	327
10.2.5	Homo- and Heterostructures	329
10.3	The Heterostructure Laser	330
10.3.1	Construction and Operation	330

- 10.3.1.1 Laser Crystal 330
- 10.3.1.2 Laser Operation 331
- 10.3.2 Spectral Properties 332
 - 10.3.2.1 Emission Wavelength and Mode Profile 332
 - 10.3.2.2 Electronic Wavelength Control 333
- 10.3.3 Quantum Films, Quantum Wires, and Quantum Dots 334
 - 10.3.3.1 Inversion in the Quantum Film 334
 - 10.3.3.2 Multiple Quantum Well (MQW) Lasers 336
 - 10.3.3.3 Quantum Wires and Quantum Dots 337
- 10.3.4 Quantum Cascade Lasers 338
- 10.4 Dynamic Properties of Semiconductor Lasers 339
 - 10.4.1 Modulation Properties 340
 - 10.4.1.1 Amplitude Modulation 340
 - 10.4.1.2 Phase Modulation 341
 - 10.4.2 Linewidth of the Semiconductor Laser 341
 - 10.4.3 Injection Locking 342
- 10.5 Laser Diodes, Diode Lasers, and Laser Systems 345
 - 10.5.1 Tunable Diode Lasers (Grating Tuned Lasers) 345
 - 10.5.2 DFB and DBR Lasers and VCSEL 346
- 10.6 High-Power Laser Diodes 348
 - Problems 350

- 11 Sensors for Light 353**
 - 11.1 Characteristics of Optical Detectors 354
 - 11.1.1 Sensitivity 354
 - 11.1.2 Quantum Efficiency 354
 - 11.1.3 Signal-to-Noise Ratio 355
 - 11.1.4 Noise Equivalent Power (NEP) 356
 - 11.1.5 Detectivity “*D*-Star” 356
 - 11.1.6 Rise Time 356
 - 11.1.7 Linearity and Dynamic Range 357
 - 11.2 Fluctuating Optoelectronic Quantities 357
 - 11.2.1 Dark Current Noise 357
 - 11.2.2 Intrinsic Amplifier Noise 358
 - 11.2.3 Measuring Amplifier Noise 358
 - 11.3 Photon Noise and Detectivity Limits 359
 - 11.3.1 Photon Statistics of Coherent Light Fields 360
 - 11.3.2 Photon Statistics in Thermal Light Fields 361
 - 11.3.3 Shot Noise Limit and “Square-Law” Detectors 363
 - 11.4 Thermal Detectors 364
 - 11.4.1 Thermopiles 365
 - 11.4.2 Bolometers 366
 - 11.4.3 Pyroelectric Detectors 366
 - 11.4.4 The Golay Cell 366
 - 11.5 Quantum Sensors I: Photomultiplier Tubes 366
 - 11.5.1 The Photoelectric Effect 366
 - 11.5.2 Photocathodes 367

- 11.5.2.1 Amplification 368
- 11.5.2.2 Counting Mode and Current Mode 368
- 11.5.2.3 Noise Properties of PMTs 369
- 11.5.2.4 Microchannel Plates and Channeltrons 370
- 11.6 Quantum Sensors II: Semiconductor Sensors 370
- 11.6.1 Photoconductors 370
- 11.6.1.1 Sensitivity 371
- 11.6.1.2 Noise Properties 372
- 11.6.2 Photodiodes or Photovoltaic Detectors 372
- 11.6.2.1 pn and Pin Diodes 373
- 11.6.2.2 Operating Modes 373
- 11.6.3 Avalanche Photodiodes 374
- 11.7 Position and Image Sensors 374
- 11.7.1 Photo-Capacitors 375
- 11.7.2 CCD Sensors 375
- 11.7.3 Image Intensifiers 377
- Problems 377

12 Laser Spectroscopy and Laser Cooling 379

- 12.1 Laser-Induced Fluorescence (LIF) 379
- 12.2 Absorption and Dispersion 380
- 12.2.1 Saturated Absorption 381
- 12.3 The Width of Spectral Lines 382
- 12.3.1 Natural Width and Homogeneous Linewidth 383
- 12.3.2 Doppler Broadening and Inhomogeneous Linewidth 383
- 12.3.3 Pressure Broadening 385
- 12.3.4 Time-of-Flight (TOF) Broadening 386
- 12.4 Doppler-Free Spectroscopy 388
- 12.4.1 Spectroscopy with Molecular Beams 388
- 12.4.2 Saturation Spectroscopy 388
- 12.4.3 Two-Photon Spectroscopy 391
- 12.5 Light Forces 394
- 12.5.1 Radiation Pressure in a Propagating Wave 395
- 12.5.2 Damping Forces 397
- 12.5.3 Heating Forces, Doppler Limit 399
- 12.5.4 Dipole Forces in a Standing Wave 401
- 12.5.5 Generalization 403
- 12.5.6 Optical Tweezers 403
- Problems 404

13 Coherent Light-Matter Interaction 407

- 13.1 Weak Coupling and Strong Coupling 407
- 13.1.1 AC Stark Effect and Dressed-Atom Model 408
- 13.2 Transient Phenomena 410
- 13.2.1 π Pulses 411
- 13.2.2 Free Induction Decay 411
- 13.2.3 Photon Echo 413

- 13.2.4 Quantum Beats 414
- 13.2.5 Wave Packets 415

14 Photons: An Introduction to Quantum Optics 417

- 14.1 Does Light Exhibit Quantum Character? 417
- 14.2 Quantization of the Electromagnetic Field 418
- 14.3 Spontaneous Emission 421
 - 14.3.1 Vacuum Fluctuations Perturb Excited Atoms 422
 - 14.3.2 Weisskopf and Wigner Theory of Spontaneous Emission 423
 - 14.3.3 Suppression of Spontaneous Emission 425
 - 14.3.4 Interpretation of Spontaneous Emission 426
 - 14.3.5 Open Quantum Systems and Reservoirs 426
- 14.4 Resonance Fluorescence 427
 - 14.4.1 The Spectrum of Resonance Fluorescence 427
 - 14.4.2 Spectra and Correlation Functions 428
 - 14.4.3 Spectra and Quantum Fluctuations 431
 - 14.4.4 Coherent and Incoherent Contributions of Resonance Fluorescence 432
 - 14.4.4.1 The Mollow Triplet 433
- 14.5 Light Fields in Quantum Optics 435
 - 14.5.1 Fluctuating Light Fields 435
 - 14.5.1.1 First-Order Coherence 435
 - 14.5.1.2 Second-Order Coherence 436
 - 14.5.1.3 Hanbury Brown and Twiss Experiment 437
 - 14.5.2 Quantum Properties of Important Light Fields 438
 - 14.5.2.1 Fock States or Number States 439
 - 14.5.2.2 Coherent Light Fields and Laser Light 439
 - 14.5.2.3 Thermal Light Fields 441
 - 14.5.3 Photon Number Distribution 441
 - 14.5.4 Bunching and Anti-bunching 443
 - 14.5.4.1 Bunching 443
 - 14.5.4.2 Anti-bunching 443
- 14.6 Two-Photon Optics 444
 - 14.6.1 Spontaneous Parametric Fluorescence, SPDC Sources 445
 - 14.6.2 Hong–Ou–Mandel Interferometer 446
- 14.7 Entangled Photons 448
 - 14.7.1 Entangled States According to Einstein–Podolsky–Rosen 448
 - 14.7.1.1 The Einstein–Podolsky–Rosen (EPR) Paradox 448
 - 14.7.2 Bell’s Inequality 450
 - 14.7.3 Bell’s Inequality and Quantum Optics 451
 - 14.7.4 Polarization-Entangled Photon Pairs 452
 - 14.7.5 A Simple Bell Experiment 453

Problems 455

15 Nonlinear Optics I: Optical Mixing Processes 457

- 15.1 Charged Anharmonic Oscillators 457
- 15.2 Second-Order Nonlinear Susceptibility 459

15.2.1	Mixing Optical Fields: Three-Wave Mixing	459
15.2.2	Symmetry Properties of Susceptibility	461
15.2.2.1	Intrinsic Permutation Symmetry	461
15.2.2.2	Real Electromagnetic Fields	461
15.2.2.3	Loss-Free Media	461
15.2.3	Two-Wave Polarization	462
15.2.3.1	Contracted Notation	462
15.2.3.2	Kleinman Symmetry	462
15.2.4	Crystal Symmetry	463
15.2.5	Effective Value of the Nonlinear d Coefficient	463
15.3	Wave Propagation in Nonlinear Media	464
15.3.1	Coupled Amplitude Equations	464
15.3.2	Coupled Amplitudes for Three-Wave Mixing	465
15.3.3	Energy Conservation	466
15.4	Frequency Doubling	466
15.4.1	Weak Conversion	467
15.4.2	Strong Conversion	468
15.4.3	Phase Matching in Nonlinear and Birefringent Crystals	469
15.4.3.1	Angle or Critical Phase Matching	471
15.4.3.2	Noncritical or 90° Phase Matching	471
15.4.4	Frequency Doubling with Gaussian Beams	472
15.4.5	Resonant Frequency Doubling	474
15.4.5.1	Passive Resonators	474
15.4.6	Quasi-phase Matching	476
15.5	Sum and Difference Frequency	477
15.5.1	Sum Frequency	477
15.5.2	Difference Frequency and Parametric Gain	478
15.6	Optical Parametric Oscillators	479
	Problems	482

16	Nonlinear Optics II: Four-Wave Mixing	485
16.1	Frequency Tripling in Gases	485
16.2	Nonlinear Refraction Coefficient (Optical Kerr Effect)	487
16.2.1	Self-Focusing	488
16.2.1.1	Kerr Lens Mode Locking	489
16.2.1.2	Spatial Solitons	490
16.2.1.3	Nonlinear Optical Devices	491
16.2.2	Phase Conjugation	491
16.3	Self-Phase Modulation	494
	Problems	495

A	Mathematics for Optics	497
A.1	Spectral Analysis of Fluctuating Measurable Quantities	497
A.1.1	Correlations	500
A.1.2	Schottky Formula	501
A.2	Time Averaging Formula	502

B	Supplements in Quantum Mechanics	<i>503</i>
B.1	Temporal Evolution of a Two-State System	<i>503</i>
B.1.1	Two-Level Atom	<i>503</i>
B.1.2	Temporal Development of Pure States	<i>503</i>
B.2	Density Matrix Formalism	<i>504</i>
B.3	Density of States	<i>505</i>

Bibliography *507*

Index *519*