

Principles of Lasers

FOURTH EDITION

Orazio Svelto

Polytechnic Institute of Milan
and National Research Council
Milan, Italy

Translated from Italian and edited by

David C. Hanna

Southampton University
Southampton, England

Plenum Press • New York and London

Contents

<i>List of Examples</i>	xix
1. Introductory Concepts	1
1.1. Spontaneous and Stimulated Emission, Absorption	2
1.2. The Laser Idea	4
1.3. Pumping Schemes	7
1.4. Properties of Laser Beams	9
1.4.1. Monochromaticity	9
1.4.2. Coherence	9
1.4.3. Directionality	10
1.4.4. Brightness	11
1.4.5. Short Pulse Duration	13
1.5. Laser Types	14
Problems	14
2. Interaction of Radiation with Atoms and Ions	17
2.1. Introduction	17
2.2. Summary of Blackbody Radiation Theory	17
2.2.1. Modes of a Rectangular Cavity	19
2.2.2. Rayleigh-Jeans and Planck Radiation Formula	22
2.2.3. Planck's Hypothesis and Field Quantization	23
2.3. Spontaneous Emission	25
2.3.1. Semiclassical Approach	26
2.3.2. Quantum Electrodynamics Approach	29
2.3.3. Allowed and Forbidden Transitions	31
2.4. Absorption and Stimulated Emission	32
2.4.1. Absorption and Stimulated Emission Rates	32
2.4.2. Allowed and Forbidden Transitions	36
2.4.3. Transition Cross Section, Absorption, and Gain Coefficient	37
2.4.4. Einstein Thermodynamic Treatment	42
2.5. Line-Broadening Mechanisms	43

2.5.1. Homogeneous Broadening	44
2.5.2. Inhomogeneous Broadening	48
2.5.3. Concluding Remarks	49
2.6. Nonradiative Decay and Energy Transfer	50
2.6.1. Mechanisms of Nonradiative Decay	50
2.6.2. Combined Effects of Radiative and Nonradiative Processes	56
2.7. Degenerate or Strongly Coupled Levels	58
2.7.1. Degenerate Levels	58
2.7.2. Strongly Coupled Levels	60
2.8. Saturation	64
2.8.1. Saturation of Absorption: Homogeneous Line	64
2.8.2. Gain Saturation: Homogeneous Line	68
2.8.3. Inhomogeneously Broadened Line	69
2.9. Fluorescence Decay of an Optically Dense Medium	71
2.9.1. Radiation Trapping	71
2.9.2. Amplified Spontaneous Emission	71
2.10. Concluding Remarks	76
Problems	77
References	78
3. Energy Levels, Radiative, and Nonradiative Transitions in Molecules and Semiconductors	81
3.1. Molecules	81
3.1.1. Energy Levels	81
3.1.2. Level Occupation at Thermal Equilibrium	85
3.1.3. Stimulated Transitions	87
3.1.4. Radiative and Nonradiative Decay	91
3.2. Bulk Semiconductors	92
3.2.1. Electronic States	92
3.2.2. Density of States	96
3.2.3. Level Occupation at Thermal Equilibrium	97
3.2.4. Stimulated Transitions: Selection Rules	101
3.2.5. Absorption and Gain Coefficients	103
3.2.6. Spontaneous Emission and Nonradiative Decay	109
3.2.7. Concluding Remarks	111
3.3. Semiconductor Quantum Wells	112
3.3.1. Electronic States	112
3.3.2. Density of States	115
3.3.3. Level Occupation at Thermal Equilibrium	117
3.3.4. Stimulated Transitions: Selection Rules	118
3.3.5. Absorption and Gain Coefficients	120
3.3.6. Strained Quantum Wells	123
3.4. Quantum Wires and Quantum Dots	125
3.5. Concluding Remarks	126
Problems	127
References	128
4. Ray and Wave Propagation through Optical Media	129
4.1. Introduction	129

4.2. Matrix Formulation of Geometric Optics	129
4.3. Wave Reflection and Transmission at a Dielectric Interface	135
4.4. Multilayer Dielectric Coatings	137
4.5. Fabry–Perot Interferometer	140
4.5.1. Properties of a Fabry–Perot Interferometer	140
4.5.2. Fabry–Perot Interferometer as a Spectrometer	144
4.6. Diffraction Optics in the Paraxial Approximation	145
4.7. Gaussian Beams	148
4.7.1. Lowest Order Mode	148
4.7.2. Free-Space Propagation	151
4.7.3. Gaussian Beams and ABCD Law	154
4.7.4. Higher Order Modes	155
4.8. Conclusions	158
Problems	158
References	160
5. <i>Passive Optical Resonators</i>	161
5.1. Introduction	161
5.1.1. Plane Parallel (Fabry–Perot) Resonator	162
5.1.2. Concentric (Spherical) Resonator	163
5.1.3. Confocal Resonator	163
5.1.4. Generalized Spherical Resonator	163
5.1.5. Ring Resonator	164
5.2. Eigenmodes and Eigenvalues	165
5.3. Photon Lifetime and Cavity Q	167
5.4. Stability Condition	169
5.5. Stable Resonators	173
5.5.1. Resonators with Infinite Aperture	173
5.5.1.1. Eigenmodes	174
5.5.1.2. Eigenvalues	178
5.5.1.3. Standing and Traveling Waves in a Two-Mirror Resonator	180
5.5.2. Effects of a Finite Aperture	181
5.5.3. Dynamically and Mechanically Stable Resonators	184
5.6. Unstable Resonators	187
5.6.1. Geometric Optics Description	188
5.6.2. Wave Optics Description	190
5.6.3. Advantages and Disadvantages of Hard-Edge Unstable Resonators	193
5.6.4. Unstable Resonators with Variable-Reflectivity Mirrors	194
5.7. Concluding Remarks	198
Problems	198
References	200
6. <i>Pumping Processes</i>	201
6.1. Introduction	201
6.2. Optical Pumping by an Incoherent Light Source	204
6.2.1. Pumping Systems	204
6.2.2. Pump Light Absorption	206
6.2.3. Pump Efficiency and Pump Rate	208
6.3. Laser Pumping	210
6.3.1. Laser-Diode Pumps	212
6.3.2. Pump Transfer Systems	214

6.3.2.1. Longitudinal Pumping	214
6.3.2.2. Transverse Pumping	219
6.3.3. Pump Rate and Pump Efficiency	221
6.3.4. Threshold Pump Power for Four-Level and Quasi-Three-Level Lasers	223
6.3.5. Comparison between Diode Pumping and Lamp Pumping	226
6.4. Electrical Pumping	228
6.4.1. Electron Impact Excitation	231
6.4.1.1. Electron Impact Cross Section	232
6.4.2. Thermal and Drift Velocities	235
6.4.3. Electron Energy Distribution	237
6.4.4. Ionization Balance Equation	240
6.4.5. Scaling Laws for Electrical Discharge Lasers	241
6.4.6. Pump Rate and Pump Efficiency	242
6.5. Conclusions	244
Problems	244
References	247
7. <i>Continuous Wave Laser Behavior</i>	249
7.1. Introduction	249
7.2. Rate Equations	249
7.2.1. Four-Level Laser	250
7.2.2. Quasi-Three-Level Laser	255
7.3. Threshold Conditions and Output Power: Four-Level Laser	258
7.3.1. Space-Independent Model	258
7.3.2. Space-Dependent Model	265
7.4. Threshold Condition and Output Power: Quasi-Three-Level Laser	273
7.4.1. Space-Independent Model	273
7.4.2. Space-Dependent Model	274
7.5. Optimum Output Coupling	277
7.6. Laser Tuning	279
7.7. Reasons for Multimode Oscillation	281
7.8. Single-Mode Selection	284
7.8.1. Single-Transverse-Mode Selection	284
7.8.2. Single-Longitudinal-Mode Selection	285
7.8.2.1. Fabry-Perot Etalons as Mode-Selective Elements	285
7.8.2.2. Single-Mode Selection in Unidirectional Ring Resonators	288
7.9. Frequency Pulling and Limit to Monochromaticity	291
7.10. Laser Frequency Fluctuations and Frequency Stabilization	293
7.11. Intensity Noise and Intensity Noise Reduction	297
7.12. Conclusions	300
Problems	301
References	303
8. <i>Transient Laser Behavior</i>	305
8.1. Introduction	305
8.2. Relaxation Oscillations	305
8.3. Dynamic Instabilities and Pulsations in Lasers	310
8.4. <i>Q</i> -Switching	311
8.4.1. Dynamics of the <i>Q</i> -Switching Process	311
8.4.2. <i>Q</i> -Switching Methods	313
8.4.2.1. Electrooptical <i>Q</i> -Switching	313
8.4.2.2. Rotating Prisms	315

8.4.2.3. Acoustooptic <i>Q</i> -Switches	316
8.4.2.4. Saturable Absorber <i>Q</i> -Switch	317
8.4.3. Operating Regimes	319
8.4.4. Theory of Active <i>Q</i> -Switching	321
8.5. Gain Switching	329
8.6. Mode Locking	330
8.6.1. Frequency-Domain Description	331
8.6.2. Time-Domain Picture	336
8.6.3. Mode-Locking Methods	337
8.6.3.1. Active Mode Locking	337
8.6.3.2. Passive Mode Locking	342
8.6.4. Role of Cavity Dispersion in Femtosecond Mode-Locked Lasers	347
8.6.4.1. Phase Velocity, Group Velocity, and Group-Delay Dispersion	347
8.6.4.2. Limitation on Pulse Duration Due to Group-Delay Dispersion	350
8.6.4.3. Dispersion Compensation	351
8.6.4.4. Soliton-Type Mode Locking	353
8.6.5. Mode-Locking Regimes and Mode-Locking System	355
8.7. Cavity Dumping	359
8.8. Concluding Remarks	361
Problems	361
References	363
9. Solid-State, Dye, and Semiconductor Lasers	365
9.1. Introduction	365
9.2. Solid-State Lasers	365
9.2.1. Ruby Laser	367
9.2.2. Neodymium Lasers	370
9.2.2.1. Nd:YAG Laser	370
9.2.2.2. Nd:Glass Laser	373
9.2.2.3. Other Crystalline Hosts	373
9.2.3. Yb:YAG Laser	374
9.2.4. Er:YAG and Yb:Er:Glass Lasers	376
9.2.5. Tm:Ho:YAG Laser	377
9.2.6. Fiber Lasers	378
9.2.7. Alexandrite Laser	381
9.2.8. Titanium Sapphire Laser	383
9.2.9. Cr:LiSAF and Cr:LiCAF Lasers	385
9.3. Dye Lasers	386
9.3.1. Photophysical Properties of Organic Dyes	387
9.3.2. Characteristics of Dye Lasers	391
9.4. Semiconductor Lasers	394
9.4.1. Principle of Semiconductor Laser Operation	394
9.4.2. Homojunction Lasers	396
9.4.3. Double-Heterostructure Lasers	398
9.4.4. Quantum Well Lasers	402
9.4.5. Laser Devices and Performances	405
9.4.6. Distributed Feedback and Distributed Bragg Reflector Lasers	408
9.4.7. Vertical-Cavity Surface-Emitting Lasers	411
9.4.8. Semiconductor Laser Applications	413
9.5. Conclusions	415
Problems	415
References	417

<i>10. Gas, Chemical, Free-Electron, and X-Ray Lasers</i>	419
10.1. Introduction	419
10.2. Gas Lasers	419
10.2.1. Neutral Atom Lasers	420
10.2.1.1. Helium Neon Laser	420
10.2.1.2. Copper Vapor Laser	425
10.2.2. Ion Lasers	427
10.2.2.1. Argon Laser	427
10.2.2.2. He-Cd Laser	430
10.2.3. Molecular Gas Lasers	432
10.2.3.1. CO ₂ Laser	432
10.2.3.2. CO Laser	442
10.2.3.3. Nitrogen Laser	444
10.2.3.4. Excimer Lasers	445
10.3. Chemical Lasers	448
10.4. Free-Electron Lasers	452
10.5. X-Ray Lasers	456
10.6. Concluding Remarks	458
Problems	459
References	460
<i>11. Properties of Laser Beams</i>	463
11.1. Introduction	463
11.2. Monochromaticity	463
11.3. First-Order Coherence	464
11.3.1. Degree of Spatial and Temporal Coherence	464
11.3.2. Measurement of Spatial and Temporal Coherence	468
11.3.3. Relation between Temporal Coherence and Monochromaticity	471
11.3.4. Nonstationary Beams	473
11.3.5. Spatial and Temporal Coherence of Single-Mode and Multimode Lasers	473
11.3.6. Spatial and Temporal Coherence of a Thermal Light Source	475
11.4. Directionality	476
11.4.1. Beams with Perfect Spatial Coherence	477
11.4.2. Beams with Partial Spatial Coherence	479
11.4.3. The M ² Factor and the Spot Size Parameter of a Multimode Laser Beam	480
11.5. Laser Speckle	483
11.6. Brightness	486
11.7. Statistical Properties of Laser Light and Thermal Light	487
11.8. Comparison between Laser Light and Thermal Light	489
Problems	491
References	492
<i>12. Laser Beam Transformation: Propagation, Amplification, Frequency Conversion, Pulse Compression, and Pulse Expansion</i>	493
12.1. Introduction	493
12.2. Spatial Transformation: Propagation of a Multimode Laser Beam	494
12.3. Amplitude Transformation: Laser Amplification	495
12.3.1. Examples of Laser Amplifiers: Chirped-Pulse-Amplification	500
12.4. Frequency Conversion: Second-Harmonic Generation and Parametric Oscillation	504

12.4.1. Physical Picture	504
12.4.1.1. Second Harmonic Generation.	505
12.4.1.2. Parametric Oscillation.	512
12.4.2. Analytical Treatment.	514
12.4.2.1. Parametric Oscillation.	516
12.4.2.2. Second-Harmonic Generation.	520
12.5. Transformation in Time	523
12.5.1. Pulse Compression.	524
12.5.2. Pulse Expansion	529
Problems	530
References	532
<i>Appendices</i>	535
A. Semiclassical Treatment of the Interaction of Radiation and Matter.	535
B. Lineshape Calculation for Collision Broadening	541
C. Simplified Treatment of Amplified Spontaneous Emission.	545
References	548
D. Calculation of the Radiative Transition Rates of Molecular Transitions.	549
E. Space-Dependent Rate Equations	553
E.1. Four-Level Lasers	553
E.2. Quasi-Three-Level Lasers	559
F. Mode-Locking Theory: Homogeneous Line	563
F.1. Active Mode Locking	563
F.2. Passive Mode Locking.	568
References	569
G. Propagation of a Laser Pulse through a Dispersive Medium or a Gain Medium	571
Reference	575
H. Higher-Order Coherence	577
I. Physical Constants and Useful Conversion Factors.	581
<i>Answers to Selected Problems</i>	583
<i>Index</i>	595