OPTICAL CONSTANTS
Complex index of refraction
\[ N = \eta + ik \] (2.94)
Absorption coefficient
\[ \alpha = 2\alpha_k = \frac{2\omega k}{c} \] (2.98)
Frequency-dependent relationships for optical constants
\[ \eta^2 - k^2 = 1 + \frac{Ne^2}{m\varepsilon_0} \left( \frac{\omega^2 - \omega_0^2}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2} \right) \] (2.102)
\[ 2\eta K = \frac{Ne^2}{m\varepsilon_0} \left( \frac{\gamma\omega}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2} \right) \] (2.103)
Sellmeier’s formula
\[ N^2 - \eta^2 = 1 + \frac{Ne^2}{m\varepsilon_0} \sum_j \left( \frac{f_j}{\omega_j^2 - \omega^2} \right) \] (2.105)

COHERENCE
Temporal coherence (longitudinal coherence)
\[ l_c = \lambda \left( \frac{\lambda}{\Delta \lambda} \right) = \frac{\lambda^2}{\Delta \lambda} \] (2.116)
Spatial coherence (transverse coherence)
\[ l_t = \frac{r_s}{\sqrt{S}} = \frac{\lambda}{\theta_t} \] (2.117)

RELATION BETWEEN OSCILLATOR STRENGTH AND TRANSITION PROBABILITY
\[ A_{\omega l} = \frac{e^2\omega_0^2}{2\pi \varepsilon_0 m c^3} \left( \frac{g_l}{g_n} \right) f_{lu} = 2\pi e^2 v_0^2 \left( \frac{g_l}{g_n} \right) f_{lu} \]
\[ = \frac{2\pi e^2}{\varepsilon_0 m c \lambda^2} \left( \frac{g_l}{g_n} \right) f_{lu} \] (4.78)
Relation between absorption and emission oscillator strengths
\[ f_{ul} = -\frac{g_l}{g_n} f_{lu} \] (4.79)
Empirical expression for relationship between \( A_{ul} \) and \( f_{ul} \)
\[ A_{ul} = \frac{10^{-4} (f_{ul})^2}{1.5 (g_n/g_l)^{1/2} \lambda_{ul}} \] s^{-1} [\lambda in m] (4.7)

HOMOGENEOUS BROADENING
Homogeneous linewidth
\[ \Delta \nu_{ul}^H = \frac{\gamma_{ul}^T}{2\pi} = \frac{1}{2\pi} \left[ \sum_i A_{ui} + \sum_j A_{lj} \right] + \frac{1}{T_i} + \frac{1}{T_j} + \frac{2}{T_2} \] (4.44)
Homogeneous lineshape
\[ I(\nu) = I_0 \frac{\nu_{ul}^T/4\pi^2}{(\nu - \nu_0)^2 + (\nu_{ul}^T/4\pi)^2} \] (4.37)

DOPPLER (INHOMOGENEOUS) BROADENING
Average velocity
\[ \bar{v} = \sqrt{8kT \over M\pi} \] (4.49)
Doppler width
\[ \Delta \nu_D = 2\nu_0 \sqrt{2(2\ln 2)kT \over Mc^2} \]
\[ = (7.16 \times 10^{-7}) \nu_0 \sqrt{T \over M_N} \] (4.59)
[Doppler lineshape
\[ I(\nu) = 2(2\ln 2)^{1/2} \pi^{1/2} \Delta \nu_D \nu_0 \exp \left\{ -\left[ (4(2\ln 2)(\nu - \nu_0)^2) \over (\Delta \nu_D)^2 \right] \right\} \] (4.60)

SELECTION RULES FOR ALLOWED ELECTRIC DIPOLE TRANSITIONS
For atoms
\[ \Delta l = \pm 1 \quad \text{for the changing electron} \]
\[ \Delta S = 0, \quad \Delta L = 0, \pm 1 \] (4.104)
\[ \Delta J = 0, \pm 1 \quad \text{but } J = 0 \Rightarrow J = 0 \]
\[ \Delta M_J = 0, \pm 1 \quad \text{but } M_J = 0 \Rightarrow M_J = 0 \text{ if } \Delta J = 0 \]
Also parity must change
For molecules
Rotational transitions
\[ \Delta J = 0, \pm 1, \quad \Delta K = \pm 1 \] (5.15)
Rotational–vibrational transitions
\[ \Delta v = \pm 1 \] (5.17)
\[ \Delta J = 0, \pm 1, \quad \Delta J = J_u - J_l \] (5.18)
Branch definitions
\[ \Delta J = -1 \quad \text{P branch} \]
\[ \Delta J = 0 \quad \text{Q branch} \] (5.19)
\[ \Delta J = +1 \quad \text{R branch} \]
Electronic transitions
\[ \Delta \Lambda = 0, \pm 1 \] (5.21)
\[ \Delta S = 0 \] (5.22)
\begin{align*}
\text{BLACKBODY RADIATION (intensity per unit } \lambda) \\
I_{BB}(v) &= \frac{2\pi \hbar v^3}{c^2} \frac{1}{e^{h/vkT} - 1} \quad (6.39) \\
I_{BB}(\lambda, T) &= \frac{2\pi^2 \hbar}{\lambda^3 (e^{h/\lambda kT} - 1)} \\
I_{BB}(\lambda, T) &= \frac{3.75 \times 10^{-22}}{\lambda^3 (e^{0.044/\lambda kT} - 1)} \text{ W/m}^2\cdot\mu\text{m} \\
I_{BB}(\lambda, T) &= \frac{3.75 \times 10^{-25}}{\lambda^3 (e^{0.0044/\lambda kT} - 1)} \text{ W/m}^2\cdot\text{nm} \\
\text{[}\lambda \text{ in m, } T \text{ in K]} \\
\text{[}\lambda \text{ in m, } T \text{ in K}] \\
\text{EINSTEIN A AND B COEFFICIENTS} \\
g_a/B_a = 1 \text{ or } g_s/B_s = g_a B_{ad} \\
B_{ad} = \frac{c^3}{8\pi\hbar^2 v^3} A_{ad} \\
\text{Ratio between stimulated emission rate and spontaneous emission rate} \\
B_{ad}(v) &= \frac{1}{A_{ad}} e^{h/vkT} - 1 \\
\text{GAIN COEFFICIENTS AND STIMULATED EMISSION CROSS SECTION} \\
g^H(v) &= \frac{N_a - g_s}{g_l} N_l c^2 \left[ \frac{\lambda^2}{8\pi^2 v^2} \left( \frac{\nu_{ad}}{4\pi^2} \right) \right] A_{ad} \\
\Delta N_{ad} &= \frac{N_a - g_s}{g_l} N_l \\
\sigma^H(v) &= \frac{c^2}{8\pi^2 v^2} A_{ad}(v) \\
\sigma^H(v) &= \frac{c^2}{8\pi^2 v^2} \left[ \frac{\nu_{ad}}{4\pi^2} \right] A_{ad} \\
g^H(v = v_0) &= g^H(v_0) \\
\sigma^H(v_0) &= \frac{c^2}{2\pi\nu_{ad}^2} A_{ad} \left[ \frac{N_a - g_s}{g_l} N_l \right] \\
\sigma^H_{ad}(v) &= \frac{c^2 A_{ad}}{2\pi\nu_{ad}^2} \gamma_{ad} = \frac{\lambda^2_{ad} A_{ad}}{4\pi\nu_{ad}^2} \\
\text{Exponential growth} \\
I = I_0 e^{g^H(v_0) z} = I_0 e^{\sigma^H_{ad}(v_0)(N_a - (g_s/g_l) N_l) z} \\
I_0 = I_0 e^{g^H(v_0) \Delta N_{ad} z} \\
\text{Doppler broadening} \\
g^D(v) &= \sqrt{\ln 2} \frac{c^2 A_{ad}}{16\pi^3 \eta^2 v_{vd}^2 \Delta v_D} \left[ N_a - g_s N_l \right] \\
&\times \exp \left\{ - \frac{4 \ln 2 (v - v_0)^2}{\Delta v_D^2} \right\} \\
\Delta v_D^2 &\equiv \frac{g^D(v)}{g^D(v_0)} \\
\sigma^D_{ad}(v_0) &= \sqrt{\ln 2} \frac{2}{16\pi^3} \Delta v_D \left[ N_a - g_s N_l \right] \\
\sigma^D(v) &= \sigma^D_{ad}(v) \left[ N_a - g_s N_l \right] = \sigma^D_{ad}(v) \Delta N_{ad} \\
\sigma^D_{ad}(v_0) &= \sqrt{\ln 2} \frac{2}{16\pi^3} \Delta v_D \\
\sigma^D_{ad}(v_0) &= (1.74 \times 10^{-1})A_{ad} \Delta v_D \sqrt{M_N / T} \\
\text{[}\lambda \text{ in m, } A_{ad} \text{ in s}^{-1}, T \text{ in K, } M_N \text{ is mass number}]
\text{Exponential growth} \\
I = I_0 e^{g^D(v_0) z} = I_0 e^{\sigma^D_{ad}(v_0)(N_a - (g_s/g_l) N_l) z} \\
I_0 = I_0 e^{\sigma^D_{ad}(v_0) \Delta N_{ad} z} \\
\text{SATURATION INTENSITY} \\
I_{sat} &= \frac{\hbar v_{vd}}{\sigma^H_{ad}(v_0) \tau_a} \\
F_{sat} &= \frac{\hbar v_{vd}}{\sigma_{ad}} \\
\text{GAIN SATURATION} \\
g &= \frac{g_s}{1 + I/I_{sat}} = \frac{\sigma_{ad} \Delta N_{ad}^0}{1 + I/I_{sat}} \\
\text{THRESHOLD CONDITIONS FOR LASERS} \\
\sigma_{ad} \Delta N_{ad} L_{sat} \geq 12 \pm 5 \\
\text{One mirror} \\
\sigma_{ad} \Delta N_{ad}(2L) \geq 12 \pm 5 \quad [L_{sat} = 2L] \\
\text{Two mirrors} \\
\sigma_{ad} \Delta N_{ad} L_{sat} \geq 12 \pm 5 \\
g_{th} = \frac{1}{2L} \ln \frac{1}{R^2} \\
g_{th} = \frac{1}{2L} \ln \frac{1}{R_1 R_2 (1 - a_1)(1 - a_2) + \alpha} \\
t_s = m[^{\eta_c} (d - L) + \eta L] / c \\
\text{© in this web service Cambridge University Press} 
www.cambridge.org
LASER FUNDAMENTALS
SECOND EDITION

A well-known introduction to the physical and engineering principles of laser operation and design, this second edition includes much new material, especially in the areas of solid-state lasers, semiconductor lasers, and laser cavities. It now also contains a new chapter on laser operation above threshold, including extensive discussion of laser amplifiers; details of new types of lasers; and a new section on diode-pumping of solid-state lasers.

The book develops the fundamental wave and quantum properties of light, and then uses those properties to develop the concepts of population inversion, gain, saturation intensity, laser operation above threshold, excitation or pumping, and cavity properties. It examines the development of population inversions in low-density materials as well as in three- or four-level systems of high-density materials. Included are extensive accounts of both solid-state and semiconductor lasers, and detailed descriptions and data tables of the most common lasers.

Throughout the text, this book uses simple explanations on key concepts to lead the reader from the basics of laser action to advanced topics in laser physics and engineering. Thorough explanations, worked examples, and many homework problems make this book essential reading for undergraduates and first-year graduates in science and engineering taking courses on lasers. Researchers will find the summaries of key types of lasers, the use of many unique theoretical descriptions, and the extensive bibliography a valuable source of reference for their careers.

WILLIAM SILFVAST received a B.Sc. degree in both physics and mathematics and a Ph.D. in physics from the University of Utah. In 1990, he joined the faculty of the University of Central Florida in Orlando, where he was Professor of Physics and Electrical Engineering as well as a member of the College of Optics and Photonics (CREOL). In 1999 he also became a Professor of Optics at the School of Optics. He is presently Emeritus Professor of Optics. He is a Fellow of the American Physical Society, the Optical Society of America, and the IEEE. He has carried out pioneering work in the fields of metal vapor lasers, recombination lasers, photoionization-pumped lasers, laser plasmas, and EUV lithography. He is the author of over 100 technical papers and holds more than 30 patents.
LASER FUNDAMENTALS
SECOND EDITION

WILLIAM T. SILFVAST
School of Optics / CREOL
University of Central Florida
To my wife, Susan, and my three children, Scott, Robert and Stacey,
all of whom are such an important part of my life.
Contents

Preface to the Second Edition  xix
Preface to the First Edition  xxi
Acknowledgments  xxiii

1 INTRODUCTION  1
OVERVIEW  1
Introduction  1
Definition of the Laser  1
Simplicity of a Laser  2
Unique Properties of a Laser  2
The Laser Spectrum and Wavelengths  3
A Brief History of the Laser  4
Overview of the Book  5

SECTION 1. FUNDAMENTAL WAVE PROPERTIES OF LIGHT  9

2 WAVE NATURE OF LIGHT – THE INTERACTION OF LIGHT WITH MATERIALS  9
OVERVIEW  9
2.1 Maxwell’s Equations  9
2.2 Maxwell’s Wave Equations  12
Maxwell’s Wave Equations for a Vacuum  12
Solution of the General Wave Equation – Equivalence of Light and Electromagnetic Radiation  13
Wave Velocity – Phase and Group Velocities  17
Generalized Solution of the Wave Equation  20
Transverse Electromagnetic Waves and Polarized Light  21
Flow of Electromagnetic Energy  21
Radiation from a Point Source (Electric Dipole Radiation)  22
2.3 Interaction of Electromagnetic Radiation (Light) with Matter  23
Speed of Light in a Medium  23
Maxwell’s Equations in a Medium  24
Application of Maxwell’s Equations to Dielectric Materials – Laser Gain Media  25
Complex Index of Refraction – Optical Constants  28
Absorption and Dispersion  29
## CONTENTS

- Estimating Particle Densities of Materials for Use in the Dispersion Equations 34
- 2.4 Coherence
  - Temporal Coherence 37
  - Spatial Coherence 38
- REFERENCES 39
- PROBLEMS 39

### SECTION 2. FUNDAMENTAL QUANTUM PROPERTIES OF LIGHT

3 PARTICLE NATURE OF LIGHT – DISCRETE ENERGY LEVELS 45

**OVERVIEW** 45

3.1 Bohr Theory of the Hydrogen Atom
- Historical Development of the Concept of Discrete Energy Levels 45
- Energy Levels of the Hydrogen Atom 46
- Frequency and Wavelength of Emission Lines 49
- Ionization Energies and Energy Levels of Ions 51
- Photons 54

3.2 Quantum Theory of Atomic Energy Levels
- Wave Nature of Particles 54
- Heisenberg Uncertainty Principle 56
- Wave Theory 56
- Wave Functions 57
- Quantum States 57
- The Schrödinger Wave Equation 59
- Energy and Wave Function for the Ground State of the Hydrogen Atom 61
- Excited States of Hydrogen 63
- Allowed Quantum Numbers for Hydrogen Atom Wave Functions 66

3.3 Angular Momentum of Atoms
- Orbital Angular Momentum 67
- Spin Angular Momentum 68
- Total Angular Momentum 69

3.4 Energy Levels Associated with One-Electron Atoms
- Fine Structure of Spectral Lines 70
- Pauli Exclusion Principle 72

3.5 Periodic Table of the Elements
- Quantum Conditions Associated with Multiple Electrons Attached to Nuclei 72
- Shorthand Notation for Electronic Configurations of Atoms Having More Than One Electron 76

3.6 Energy Levels of Multi-Electron Atoms
- Energy-Level Designation for Multi-Electron States 77
- Russell–Saunders or LS Coupling – Notation for Energy Levels 78
- Energy Levels Associated with Two Electrons in Unfilled Shells 79
- Rules for Obtaining S, L, and J for LS Coupling 82
- Degeneracy and Statistical Weights 84
- j–j Coupling 85
- Isoelectronic Scaling 85
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFERENCES</td>
<td>86</td>
</tr>
<tr>
<td>PROBLEMS</td>
<td>86</td>
</tr>
<tr>
<td>4 RADIATIVE TRANSITIONS AND EMISSION LINEWIDTH</td>
<td>89</td>
</tr>
<tr>
<td>OVERVIEW</td>
<td>89</td>
</tr>
<tr>
<td>4.1 Decay of Excited States</td>
<td>90</td>
</tr>
<tr>
<td>Radiative Decay of Excited States of Isolated Atoms – Spontaneous Emission</td>
<td>90</td>
</tr>
<tr>
<td>Spontaneous Emission Decay Rate – Radiative Transition Probability</td>
<td>94</td>
</tr>
<tr>
<td>Lifetime of a Radiating Electron – The Electron as a Classical Radiating Harmonic Oscillator</td>
<td>95</td>
</tr>
<tr>
<td>Nonradiative Decay of the Excited States – Collisional Decay</td>
<td>98</td>
</tr>
<tr>
<td>4.2 Emission Broadening and Linewidth Due to Radiative Decay</td>
<td>101</td>
</tr>
<tr>
<td>Classical Emission Linewidth of a Radiating Electron</td>
<td>101</td>
</tr>
<tr>
<td>Natural Emission Linewidth as Deduced by Quantum Mechanics (Minimum Linewidth)</td>
<td>103</td>
</tr>
<tr>
<td>4.3 Additional Emission-Broadening Processes</td>
<td>105</td>
</tr>
<tr>
<td>Broadening Due to Nonradiative (Collisional) Decay</td>
<td>106</td>
</tr>
<tr>
<td>Broadening Due to Dephasing Collisions</td>
<td>107</td>
</tr>
<tr>
<td>Amorphous Crystal Broadening</td>
<td>109</td>
</tr>
<tr>
<td>Doppler Broadening in Gases</td>
<td>109</td>
</tr>
<tr>
<td>Voigt Lineshape Profile</td>
<td>114</td>
</tr>
<tr>
<td>Broadening in Gases Due to Isotope Shifts</td>
<td>115</td>
</tr>
<tr>
<td>Comparison of Various Types of Emission Broadening</td>
<td>118</td>
</tr>
<tr>
<td>4.4 Quantum Mechanical Description of Radiating Atoms</td>
<td>121</td>
</tr>
<tr>
<td>Electric Dipole Radiation</td>
<td>122</td>
</tr>
<tr>
<td>Electric Dipole Matrix Element</td>
<td>123</td>
</tr>
<tr>
<td>Electric Dipole Transition Probability</td>
<td>124</td>
</tr>
<tr>
<td>Oscillator Strength</td>
<td>124</td>
</tr>
<tr>
<td>Selection Rules for Electric Dipole Transitions Involving Atoms with a Single Electron in an Unfilled Subshell</td>
<td>125</td>
</tr>
<tr>
<td>Selection Rules for Radiative Transitions Involving Atoms with More Than One Electron in an Unfilled Subshell</td>
<td>129</td>
</tr>
<tr>
<td>Parity Selection Rule</td>
<td>130</td>
</tr>
<tr>
<td>Inefficient Radiative Transitions – Electric Quadrupole and Other Higher-Order Transitions</td>
<td>131</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>131</td>
</tr>
<tr>
<td>PROBLEMS</td>
<td>131</td>
</tr>
<tr>
<td>5 ENERGY LEVELS AND RADIATIVE PROPERTIES OF MOLECULES, LIQUIDS, AND SOLIDS</td>
<td>135</td>
</tr>
<tr>
<td>OVERVIEW</td>
<td>135</td>
</tr>
<tr>
<td>5.1 Molecular Energy Levels and Spectra</td>
<td>135</td>
</tr>
<tr>
<td>Energy Levels of Molecules</td>
<td>135</td>
</tr>
<tr>
<td>Classification of Simple Molecules</td>
<td>138</td>
</tr>
<tr>
<td>Rotational Energy Levels of Linear Molecules</td>
<td>139</td>
</tr>
<tr>
<td>Rotational Energy Levels of Symmetric-Top Molecules</td>
<td>141</td>
</tr>
<tr>
<td>Selection Rules for Rotational Transitions</td>
<td>141</td>
</tr>
</tbody>
</table>
CONTENTS

Vibrational Energy Levels 143
Selection Rule for Vibrational Transitions 143
Rotational–Vibrational Transitions 144
Probabilities of Rotational and Vibrational Transitions 148
Electronic Energy Levels of Molecules 149
Electronic Transitions and Associated Selection Rules of Molecules 150
Emission Linewidth of Molecular Transitions 150
The Franck–Condon Principle 151
Excimer Energy Levels 152

5.2 Liquid Energy Levels and Their Radiation Properties 153
Structure of Dye Molecules 153
Energy Levels of Dye Molecules 155
Excitation and Emission of Dye Molecules 156
Detrimental Triplet States of Dye Molecules 157

5.3 Energy Levels in Solids – Dielectric Laser Materials 158
Host Materials 158
Laser Species – Dopant Ions 159
Narrow-Linewidth Laser Materials 161
Broadband Tunable Laser Materials 166
Broadening Mechanism for Solid-State Lasers 168

5.4 Energy Levels in Solids – Semiconductor Laser Materials 168
Energy Bands in Crystalline Solids 168
Energy Levels in Periodic Structures 170
Energy Levels of Conductors, Insulators, and Semiconductors 172
Excitation and Decay of Excited Energy Levels – Recombination Radiation 173
Direct and Indirect Bandgap Semiconductors 174
Electron Distribution Function and Density of States in Semiconductors 175
Intrinsic Semiconductor Materials 179
Extrinsic Semiconductor Materials – Doping 179
p–n Junctions – Recombination Radiation Due to Electrical Excitation 182
Heterojunction Semiconductor Materials 184
Quantum Wells 186
Variation of Bandgap Energy and Radiation Wavelength with Alloy Composition 191
Recombination Radiation Transition Probability and Linewidth 195
REFERENCES 195
PROBLEMS 195

6 RADIATION AND THERMAL EQUILIBRIUM – ABSORPTION AND STIMULATED EMISSION 199
OVERVIEW 199
6.1 Equilibrium 199
Thermal Equilibrium 199
Thermal Equilibrium via Conduction and Convection 200
Thermal Equilibrium via Radiation 200
6.2 Radiating Bodies
- Stefan-Boltzmann Law
- Wien's Law
- Irradiance and Radiance

6.3 Cavity Radiation
- Counting the Number of Cavity Modes
- Rayleigh-Jeans Formula
- Planck's Law for Cavity Radiation
- Relationship between Cavity Radiation and Blackbody Radiation
- Wavelength Dependence of Blackbody Emission

6.4 Absorption and Stimulated Emission
- The Principle of Detailed Balance
- Absorption and Stimulated Emission Coefficients

REFERENCES

SECTION 3. LASER AMPLIFIERS
7 CONDITIONS FOR PRODUCING A LASER – POPULATION INVERSIONS, GAIN, AND GAIN SATURATION
7.1 Absorption and Gain
- Absorption and Gain on a Homogeneously Broadened Radiative Transition (Lorentzian Frequency Distribution)
- Gain Coefficient and Stimulated Emission Cross Section for Homogeneous Broadening
- Absorption and Gain on an Inhomogeneously Broadened Radiative Transition (Doppler Broadening with a Gaussian Distribution)
- Gain Coefficient and Stimulated Emission Cross Section for Doppler Broadening
- Statistical Weights and the Gain Equation
- Relationship of Gain Coefficient and Stimulated Emission Cross Section to Absorption Coefficient and Absorption Cross Section

7.2 Population Inversion (Necessary Condition for a Laser)
7.3 Saturation Intensity (Sufficient Condition for a Laser)
7.4 Development and Growth of a Laser Beam
- Growth of Beam for a Gain Medium with Homogeneous Broadening
- Shape or Geometry of Amplifying Medium
- Growth of Beam for Doppler Broadening

7.5 Exponential Growth Factor (Gain)
7.6 Threshold Requirements for a Laser
- Laser with No Mirrors
- Laser with One Mirror
- Laser with Two Mirrors

REFERENCES

PROBLEMS
## CONTENTS

### 8 LASER OSCILLATION ABOVE THRESHOLD

**OVERVIEW**

- **8.1 Laser Gain Saturation**
  - Rate Equations of the Laser Levels That Include Stimulated Emission
  - Population Densities of Upper and Lower Laser Levels with Beam Present
  - Small-Signal Gain Coefficient
  - Saturation of the Laser Gain above Threshold

- **8.2 Laser Beam Growth beyond the Saturation Intensity**
  - Change from Exponential Growth to Linear Growth
  - Steady-State Laser Intensity

- **8.3 Optimization of Laser Output Power**
  - Optimum Output Mirror Transmission
  - Optimum Laser Output Intensity
  - Estimating Optimum Laser Output Power

- **8.4 Energy Exchange between Upper Laser Level Population and Laser Photons**
  - Decay Time of a Laser Beam within an Optical Cavity
  - Basic Laser Cavity Rate Equations
  - Steady-State Solutions below Laser Threshold
  - Steady-State Operation above Laser Threshold

- **8.5 Laser Output Fluctuations**
  - Laser Spiking
  - Relaxation Oscillations

- **8.6 Laser Amplifiers**
  - Basic Amplifier Uses
  - Propagation of a High-Power, Short-Duration Optical Pulse through an Amplifier
  - Saturation Energy Fluence
  - Amplifying Long Laser Pulses
  - Amplifying Short Laser Pulses
  - Comparison of Efficient Laser Amplifiers Based upon Fundamental Saturation Limits
  - Mirror Array and Resonator (Regenerative) Amplifiers

### 9 REQUIREMENTS FOR OBTAINING POPULATION INVERSIONS

**OVERVIEW**

- **9.1 Inversions and Two-Level Systems**
- **9.2 Relative Decay Rates – Radiative versus Collisional**
- **9.3 Steady-State Inversions in Three- and Four-Level Systems**
  - Three-Level Laser with the Intermediate Level as the Upper Laser Level
  - Three-Level Laser with the Upper Laser Level as the Highest Level
  - Four-Level Laser
- **9.4 Transient Population Inversions**

### REFERENCES

PROBLEMS
### CONTENTS

**9.5 Processes That Inhibit or Destroy Inversions**
- Radiation Trapping in Atoms and Ions
- Electron Collisional Thermalization of the Laser Levels in Atoms and Ions
- Comparison of Radiation Trapping and Electron Collisional Mixing in a Gas Laser
- Absorption within the Gain Medium

**REFERENCES**
- 319

**PROBLEMS**
- 319

**10 LASER PUMPING REQUIREMENTS AND TECHNIQUES**

**OVERVIEW**
- 322

**10.1 Excitation or Pumping Threshold Requirements**

**10.2 Pumping Pathways**
- Excitation by Direct Pumping
- Excitation by Indirect Pumping (Pump and Transfer)
- Specific Pump-and-Transfer Processes

**10.3 Specific Excitation Parameters Associated with Optical Pumping**
- Pumping Geometries
- Pumping Requirements
- A Simplified Optical Pumping Approximation
- Transverse Pumping
- End Pumping
- Diode Pumping of Solid-State Lasers
- Characterization of a Laser Gain Medium with Optical Pumping (Slope Efficiency)

**10.4 Specific Excitation Parameters Associated with Particle Pumping**
- Electron Collisional Pumping
- Heavy Particle Pumping
- A More Accurate Description of Electron Excitation Rate to a Specific Energy Level in a Gas Discharge
- Electrical Pumping of Semiconductors

**REFERENCES**
- 363

**PROBLEMS**
- 364

### SECTION 4. LASER RESONATORS

**11 LASER CAVITY MODES**

**OVERVIEW**
- 371

**11.1 Introduction**

**11.2 Longitudinal Laser Cavity Modes**
- Fabry–Perot Resonator
- Fabry–Perot Cavity Modes
- Longitudinal Laser Cavity Modes
- Longitudinal Mode Number
- Requirements for the Development of Longitudinal Laser Modes
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>11.3 Transverse Laser Cavity Modes</td>
<td>384</td>
</tr>
<tr>
<td>Fresnel–Kirchhoff Diffraction Integral Formula</td>
<td>385</td>
</tr>
<tr>
<td>Development of Transverse Modes in a Cavity with Plane-Parallel Mirrors</td>
<td>386</td>
</tr>
<tr>
<td>Transverse Modes Using Curved Mirrors</td>
<td>390</td>
</tr>
<tr>
<td>Transverse Mode Spatial Distributions</td>
<td>391</td>
</tr>
<tr>
<td>Transverse Mode Frequencies</td>
<td>392</td>
</tr>
<tr>
<td>Gaussian-Shaped Transverse Modes within and beyond the Laser Cavity</td>
<td>393</td>
</tr>
<tr>
<td>11.4 Properties of Laser Modes</td>
<td>396</td>
</tr>
<tr>
<td>Mode Characteristics</td>
<td>396</td>
</tr>
<tr>
<td>Effect of Modes on the Gain Medium Profile</td>
<td>397</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>399</td>
</tr>
<tr>
<td>PROBLEMS</td>
<td>399</td>
</tr>
<tr>
<td>12 STABLE LASER RESONATORS AND GAUSSIAN BEAMS</td>
<td>402</td>
</tr>
<tr>
<td>OVERVIEW</td>
<td></td>
</tr>
<tr>
<td>12.1 Stable Curved Mirror Cavities</td>
<td>402</td>
</tr>
<tr>
<td>Curved Mirror Cavities</td>
<td>402</td>
</tr>
<tr>
<td>ABCD Matrices</td>
<td>404</td>
</tr>
<tr>
<td>Cavity Stability Criteria</td>
<td>406</td>
</tr>
<tr>
<td>12.2 Properties of Gaussian Beams</td>
<td>410</td>
</tr>
<tr>
<td>Propagation of a Gaussian Beam</td>
<td>411</td>
</tr>
<tr>
<td>Gaussian Beam Properties of Two-Mirror Laser Cavities</td>
<td>412</td>
</tr>
<tr>
<td>Properties of Specific Two-Mirror Laser Cavities</td>
<td>417</td>
</tr>
<tr>
<td>Mode Volume of a Hermite–Gaussian Mode</td>
<td>421</td>
</tr>
<tr>
<td>12.3 Properties of Real Laser Beams</td>
<td>423</td>
</tr>
<tr>
<td>12.4 Propagation of Gaussian Beams Using ABCD Matrices – Complex Beam Parameter</td>
<td>425</td>
</tr>
<tr>
<td>Complex Beam Parameter Applied to a Two-Mirror Laser Cavity</td>
<td>428</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>432</td>
</tr>
<tr>
<td>PROBLEMS</td>
<td>432</td>
</tr>
<tr>
<td>13 SPECIAL LASER CAVITIES AND CAVITY EFFECTS</td>
<td>434</td>
</tr>
<tr>
<td>OVERVIEW</td>
<td></td>
</tr>
<tr>
<td>13.1 Unstable Resonators</td>
<td>434</td>
</tr>
<tr>
<td>13.2 Q-Switching</td>
<td>439</td>
</tr>
<tr>
<td>General Description</td>
<td>439</td>
</tr>
<tr>
<td>Theory</td>
<td>441</td>
</tr>
<tr>
<td>Methods of Producing Q-Switching within a Laser Cavity</td>
<td>446</td>
</tr>
<tr>
<td>13.3 Gain-Switching</td>
<td>450</td>
</tr>
<tr>
<td>13.4 Mode-Locking</td>
<td>451</td>
</tr>
<tr>
<td>General Description</td>
<td>451</td>
</tr>
<tr>
<td>Theory</td>
<td>451</td>
</tr>
<tr>
<td>Techniques for Producing Mode-Locking</td>
<td>456</td>
</tr>
<tr>
<td>13.5 Pulse Shortening Techniques</td>
<td>462</td>
</tr>
<tr>
<td>Self-Phase Modulation</td>
<td>463</td>
</tr>
<tr>
<td>Pulse Shortening or Lengthening Using Group Velocity Dispersion</td>
<td>464</td>
</tr>
<tr>
<td>Pulse Compression (Shortening) with Gratings or Prisms</td>
<td>465</td>
</tr>
<tr>
<td>Ultrashort-Pulse Laser and Amplifier System</td>
<td>467</td>
</tr>
</tbody>
</table>
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6 Ring Lasers</td>
<td>468</td>
</tr>
<tr>
<td>Monolithic Unidirectional Single-Mode Nd:YAG Ring Laser</td>
<td>469</td>
</tr>
<tr>
<td>Two-Mirror Ring Laser</td>
<td>470</td>
</tr>
<tr>
<td>13.7 Complex Beam Parameter Analysis Applied to Multi-Mirror Laser Cavities</td>
<td>470</td>
</tr>
<tr>
<td>Three-Mirror Ring Laser Cavity</td>
<td>470</td>
</tr>
<tr>
<td>Three- or Four-Mirror Focused Cavity</td>
<td>473</td>
</tr>
<tr>
<td>13.8 Cavities for Producing Spectral Narrowing of Laser Output</td>
<td>478</td>
</tr>
<tr>
<td>Cavity with Additional Fabry–Perot Etalon for Narrow-Frequency Selection</td>
<td>478</td>
</tr>
<tr>
<td>Tunable Cavity</td>
<td>478</td>
</tr>
<tr>
<td>Broadband Tunable cw Ring Lasers</td>
<td>480</td>
</tr>
<tr>
<td>Tunable Cavity for Ultranarrow-Frequency Output</td>
<td>480</td>
</tr>
<tr>
<td>Distributed Feedback (DFB) Lasers</td>
<td>481</td>
</tr>
<tr>
<td>Distributed Bragg Reflection Lasers</td>
<td>484</td>
</tr>
<tr>
<td>13.9 Laser Cavities Requiring Small-Diameter Gain Regions – Astigmatically Compensated Cavities</td>
<td>484</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>486</td>
</tr>
<tr>
<td>PROBLEMS</td>
<td>488</td>
</tr>
</tbody>
</table>

## SECTION 5. SPECIFIC LASER SYSTEMS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Laser Systems Involving Low-Density Gain Media</td>
<td>491</td>
</tr>
<tr>
<td>Overview</td>
<td>491</td>
</tr>
<tr>
<td>14.1 Atomic Gas Lasers</td>
<td>491</td>
</tr>
<tr>
<td>Introduction</td>
<td>491</td>
</tr>
<tr>
<td>Helium–Neon Laser</td>
<td>492</td>
</tr>
<tr>
<td>General Description</td>
<td>492</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>493</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>494</td>
</tr>
<tr>
<td>Applications</td>
<td>497</td>
</tr>
<tr>
<td>Argon Ion Laser</td>
<td>497</td>
</tr>
<tr>
<td>General Description</td>
<td>497</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>498</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>499</td>
</tr>
<tr>
<td>Krypton Ion Laser</td>
<td>500</td>
</tr>
<tr>
<td>Applications</td>
<td>501</td>
</tr>
<tr>
<td>Helium–Cadmium Laser</td>
<td>501</td>
</tr>
<tr>
<td>General Description</td>
<td>501</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>502</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>504</td>
</tr>
<tr>
<td>Applications</td>
<td>505</td>
</tr>
<tr>
<td>Copper Vapor Laser</td>
<td>505</td>
</tr>
<tr>
<td>General Description</td>
<td>505</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>507</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>507</td>
</tr>
<tr>
<td>Applications</td>
<td>509</td>
</tr>
</tbody>
</table>
### CONTENTS

#### 14.2 Molecular Gas Lasers
- Introduction 510
- **Carbon Dioxide Laser** 511
  - General Description 511
  - Laser Structure 511
  - Excitation Mechanism 515
  - Applications 515
- **Excimer Lasers** 516
  - General Description 516
  - Laser Structure 517
  - Excitation Mechanism 518
  - Applications 520
- **Nitrogen Laser** 520
  - General Description 520
  - Laser Structure and Excitation Mechanism 521
  - Applications 522
- **Far-Infrared Gas Lasers** 522
  - General Description 522
  - Laser Structure 523
  - Excitation Mechanism 523
  - Applications 524
- **Chemical Lasers** 524
  - General Description 524
  - Laser Structure 524
  - Excitation Mechanism 524
  - Applications 525

#### 14.3 X-Ray Plasma Lasers
- Introduction 525
- Pumping Energy Requirements 525
- Excitation Mechanism 528
- Optical Cavities 532
- X-Ray Laser Transitions 532
- Applications 532

#### 14.4 Free-Electron Lasers
- Introduction 535
- Laser Structure 536
- Applications 537

#### REFERENCES 537

#### 15 LASER SYSTEMS INVOLVING HIGH-DENSITY GAIN MEDIA

**OVERVIEW** 539

#### 15.1 Organic Dye Lasers
- Introduction 539
- Laser Structure 540
- Excitation Mechanism 543
- Applications 544

#### 15.2 Solid-State Lasers
- Introduction 545
## CONTENTS

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruby Laser</td>
<td>547</td>
</tr>
<tr>
<td>General Description</td>
<td>547</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>548</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>548</td>
</tr>
<tr>
<td>Applications</td>
<td>549</td>
</tr>
<tr>
<td>Neodymium:YLF Lasers</td>
<td>550</td>
</tr>
<tr>
<td>General Description</td>
<td>550</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>551</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>553</td>
</tr>
<tr>
<td>Applications</td>
<td>554</td>
</tr>
<tr>
<td>Neodymium:Yttrium Vanadate (Nd:YVO₄) Lasers</td>
<td>557</td>
</tr>
<tr>
<td>General Description</td>
<td>557</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>557</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>558</td>
</tr>
<tr>
<td>Applications</td>
<td>558</td>
</tr>
<tr>
<td>Ytterbium:YAG Lasers</td>
<td>559</td>
</tr>
<tr>
<td>General Description</td>
<td>559</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>560</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>560</td>
</tr>
<tr>
<td>Applications</td>
<td>561</td>
</tr>
<tr>
<td>Alexandrite Laser</td>
<td>562</td>
</tr>
<tr>
<td>General Description</td>
<td>562</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>563</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>563</td>
</tr>
<tr>
<td>Applications</td>
<td>564</td>
</tr>
<tr>
<td>Titanium Sapphire Laser</td>
<td>565</td>
</tr>
<tr>
<td>General Description</td>
<td>565</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>566</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>567</td>
</tr>
<tr>
<td>Applications</td>
<td>568</td>
</tr>
<tr>
<td>Chromium LiSAF and LiCAF Lasers</td>
<td>568</td>
</tr>
<tr>
<td>General Description</td>
<td>568</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>568</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>569</td>
</tr>
<tr>
<td>Applications</td>
<td>570</td>
</tr>
<tr>
<td>Fiber Lasers</td>
<td>570</td>
</tr>
<tr>
<td>General Description</td>
<td>570</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>571</td>
</tr>
<tr>
<td>Excitation Mechanism</td>
<td>571</td>
</tr>
<tr>
<td>Applications</td>
<td>572</td>
</tr>
<tr>
<td>Color Center Lasers</td>
<td>573</td>
</tr>
<tr>
<td>General Description</td>
<td>573</td>
</tr>
<tr>
<td>Laser Structure</td>
<td>574</td>
</tr>
</tbody>
</table>
CONTENTS

Excitation Mechanism 574
Applications 576
15.3 Semiconductor Diode Lasers 576
Introduction 576
Four Basic Types of Laser Materials 579
Laser Structure 581
Frequency Control of Laser Output 591
Quantum Cascade Lasers 592
p-Doped Germanium Lasers 594
Excitation Mechanism 594
Applications 596
REFERENCES 597

SECTION 6. FREQUENCY MULTIPLICATION OF LASER BEAMS
16 FREQUENCY MULTIPLICATION OF LASERS AND OTHER NONLINEAR OPTICAL EFFECTS
OVERVIEW 601
16.1 Wave Propagation in an Anisotropic Crystal 601
16.2 Polarization Response of Materials to Light 603
16.3 Second-Order Nonlinear Optical Processes 604
Second Harmonic Generation 604
Sum and Difference Frequency Generation 605
Optical Parametric Oscillation 607
16.4 Third-Order Nonlinear Optical Processes 607
Third Harmonic Generation 608
Intensity-Dependent Refractive Index – Self-Focusing 609
16.5 Nonlinear Optical Materials 610
16.6 Phase Matching 610
Description of Phase Matching 610
Achieving Phase Matching 613
Types of Phase Matching 615
16.7 Saturable Absorption 615
16.8 Two-Photon Absorption 617
16.9 Stimulated Raman Scattering 618
16.10 Harmonic Generation in Gases 619
REFERENCES 619

Appendix 621
Index 625
Preface to the Second Edition

I am very pleased to have completed this Second Edition of *Laser Fundamentals*. The encouragement I have received over the past few years from readers as well as from my editors was sufficient to provide me with the enthusiasm to take on this new task. Writing the first edition was essentially a ten-year endeavor from first thoughts to the completed book. I thought I had a better way to explain to senior-level and first-year graduate students how lasers work. Apparently there were others who agreed with me, judging from comments I have received. Writing the second edition was an attempt to fill in some of the gaps, so to speak; not surprisingly, it took much more time than I had anticipated. Some of the areas of the First Edition were not as complete as I would have liked. There were also errors that had to be corrected. In addition, there have been advances – primarily in the areas of solid-state and semiconductor lasers – that needed to be included. I think the new edition addresses those issues pretty well. I suppose it’s up to the readers to make that judgment.

Naturally one can’t take on a task like this without gleaning information from experts in the various fields of lasers. I offer special thanks to my colleagues at the School of Optics/CREOL at the University of Central Florida: Michael Bass, Glenn Boreman, Peter Delfyett, Dave Hagan, Hans Jenssen, Patrick Li Kam Wa, Alexandra Rapaport, Kathleen Richardson, Martin Richardson, Craig Siders, Eric Van Stryland, Nikolai Vorobiev, and Boris Zeldovich. Others who were very helpful include Norm Hodgson, Jason Eichenholz, Jack Jewell, Shuji Nakamura, Jorge Rocca, Rita Petersen, and Colin Webb (and I’m sure I’ve inadvertently left out a few).

I am grateful to have Simon Capelin as my editor at Cambridge University Press. He has been most encouraging without pressing me with a specific deadline. It is also a pleasure to work again with Matt Darnell as my production editor. Most importantly, I thank my wonderful wife, Susan, who was always very supportive while putting up with the many long hours that I spent in completing this Second Edition.
Preface to the First Edition

I wrote *Laser Fundamentals* with the idea of simplifying the explanation of how lasers operate. It is designed to be used as a senior-level or first-year graduate student textbook and/or as a reference book. The first draft was written the first time I taught the course “Laser Principles” at the University of Central Florida. Before that, I authored several general laser articles and taught short courses on the subject, giving careful consideration to the sequence in which various topics should be presented. During that period I adjusted the sequence, and I am now convinced that it is the optimal one.

Understanding lasers involves concepts associated with light, viewed either as waves or as photons, and its interaction with matter. I have used the first part of the book to introduce these concepts. Chapters 2 through 6 include fundamental wave properties, such as the solution of the wave equation, polarization, and the interaction of light with dielectric materials, as well as the fundamental quantum properties, including discrete energy levels, emission of radiation, emission broadening (in gases, liquids, and solids), and stimulated emission. The concept of amplification is introduced in Chapter 7, and further properties of laser amplifiers dealing with inversions and pumping are covered in Chapters 8 and 9 [Chapters 8–10 in the Second Edition – Ed.]. Chapter 10 [11] discusses cavity properties associated with both longitudinal and transverse modes, and Chapters 11 and 12 [12 and 13] follow up with Gaussian beams and special laser cavities. Chapters 13 and 14 [14 and 15] provide descriptions of the most common lasers. The book concludes in Chapter 15 [16] with a brief overview of some of the nonlinear optical techniques for laser frequency conversion.

Some of the unique aspects of the book are the treatment of emission linewidth and broadening in Chapter 4, the development of a simple model of a laser amplifier in Chapter 7, the discussion of special laser cavities in Chapter 12 [13], and the laser summaries in Chapters 13 and 14 [14 and 15]. Throughout the book, whenever a particular concept is introduced, I have tried to relate that concept to all the various types of laser amplifiers including gas lasers, liquid (dye) lasers, and solid-state lasers. My intention is to give the reader a good understanding, not just of one specific type of laser but rather of all types of lasers, as each concept is introduced.
The book can be used in either a one- or two-semester course. In one semester the topics of Chapters 2 through 12 would be emphasized. In two semesters, extended coverage of the specific lasers of Chapters 13 and 14, as well as the frequency multiplication in Chapter 15, could be included. In a one-semester course I have been able to cover a portion of the material in Chapters 13 and 14 by having each student write a report about one specific laser and then give a ten- or fifteen-minute classroom presentation about that laser. The simple quantum mechanical descriptions in Chapters 3 and 4 were introduced to describe how radiative transitions occur in matter. If the instructor chooses to avoid quantum mechanics in the course, it would be sufficient to stress the important results that are highlighted at the ends of each of those sections.

Writing this book has been a rewarding experience for me. I have been associated with lasers since shortly after their discovery in 1960 when, as an undergraduate student at the University of Utah, I helped build a ruby laser for a research project under Professor Frank Harris. He was the first person to instill in me an enthusiasm for optics and light. I was then very fortunate to be able to do my thesis work with Professor Grant Fowles, who encouraged me to reduce ideas to simple concepts. We discovered many new metal vapor lasers during that period. I also thank Dr. John Sanders for giving me the opportunity to do postdoctoral work at the Clarendon Laboratory at Oxford University in England, and Dr. Kumar Patel for bringing me to Bell Laboratories in Holmdel, New Jersey. Being a part of a stimulating group of researchers at Bell Laboratories during the growth of the field of lasers was an unparalleled opportunity. During that period I was also able to spend an extremely rewarding sabbatical year at Stanford University with Professor Steve Harris. Finally, to round out my career I put on my academic hat at the University of Central Florida as a member of the Center for Research and Education in Optics and Lasers (CREOL) and the Department of Physics and of Electrical and Computer Engineering. Working in the field of lasers at several different institutions has provided me with a broad perspective that I hope has successfully contributed to the manner in which many of the concepts are presented in this book.
Acknowledgments

I first acknowledge the support of my wife, Susan. Without her encouragement and patience, I would never have completed this book.

Second, I am deeply indebted to Mike Langlais, an undergraduate student at the University of Central Florida and a former graphics illustrator, who did most of the figures for the book. I provided Mike with rough sketches, and a few days later he appeared with professional quality figures. These figures add immensely to the completeness of the book.

Colleagues who have helped me resolve particular issues associated with this book include Michael Bass, Peter Delfyett, Luis Elias, David Hagan, James Harvey, Martin Richardson, and Eric Van Stryland of CREOL; Tao Chang, Larry Colldren, Dick Fork, Eric Ippen, Jack Jewell, Wayne Knox, Herwig Kogelnik, Tingye Li, David Miller, Peter Smith, Ben Tell, and Obert Wood of Bell Laboratories; Bob Byer, Steve Harris, and Tony Siegman of Stanford University; Boris Stoicheff of the University of Toronto; Gary Eden of the University of Illinois; Ron Waynant of the FDA; Arto Nurmiko of Brown University; Dennis Matthews of Lawrence Livermore National Laboratories; Syzmon Suckewer of Princeton University; Colin Webb of Oxford University; John Macklin of Stanford University and Bell Labs; Jorgé Rocca of Colorado State University; Frank Tittle of Rice University; Frank Duarte of Kodak; Alan Petersen of Spectra Physics; Norman Goldblatt of Coherent, Inc.; and my editor friend, Irwin Cohen. I also thank the many laser companies who contributed figures, primarily in Chapters 13 and 14 [14 and 15 in 2e]. I’m sure that I have left a few people out; for that, I apologize to them. In spite of all the assistance, I accept full responsibility for the final text.

I thank my editor, Philip Meyler, at Cambridge University Press for convincing me that CUP was the best publishing company and for assisting me in determining the general layout of my book. I also thank editor Matt Darnell for doing such a skillful job in taking my manuscript and making it into a “real” book.

I am indebted to several graduate students at CREOL. Howard Bender, Jason Eichenholz, and Art Hanzo helped with several of the figures. In addition, Jason Eichenholz assisted me in taking the cover photo, Howard Bender and Art Hanzo helped with the laser photo on the back cover, and Marc Klosner did a careful
ACKNOWLEDGMENTS

proofreading of one of the later versions of the text. I am also indebted to Al Ducharme for suggesting the title for the book.

Finally, I thank the students who took the “Laser Principles” course the first year I taught it (Fall 1991). At that point I was writing and passing out drafts of my chapters to the students at a frantic pace. Because those students had to suffer through that first draft, I promised all of them a free copy of the book. I stand by that promise and hope those students will get in touch with me to collect.