

Second Edition

# Optoelectronics and Photonics: Principles and Practices

S.O. Kasap

*University of Saskatchewan*

*Canada*

*International Edition Contributions by*

Ravindra Kumar Sinha

*Delhi Technological University*

*India*

**PEARSON**

Boston Columbus Indianapolis New York San Francisco Upper Saddle River  
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montréal Toronto  
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

# CONTENTS

## Chapter 1 Wave Nature of Light 19

- 1.1 Light Waves in a Homogeneous Medium 19
  - A. Plane Electromagnetic Wave 19
  - B. Maxwell's Wave Equation and Diverging Waves 22
    - Example 1.1.1 A diverging laser beam 26
- 1.2 Refractive Index and Dispersion 26
  - Example 1.2.1 Sellmeier equation and diamond 29
  - Example 1.2.2 Cauchy equation and diamond 30
- 1.3 Group Velocity and Group Index 30
  - Example 1.3.1 Group velocity 33
  - Example 1.3.2 Group velocity and index 33
  - Example 1.3.3 Group and phase velocities 34
- 1.4 Magnetic Field, Irradiance, and Poynting Vector 34
  - Example 1.4.1 Electric and magnetic fields in light 37
  - Example 1.4.2 Power and irradiance of a Gaussian beam 37
- 1.5 Snell's Law and Total Internal Reflection (TIR) 38
  - Example 1.5.1 Beam displacement 41
- 1.6 Fresnel's Equations 42
  - A. Amplitude Reflection and Transmission Coefficients ( $r$  and  $t$ ) 42
  - B. Intensity, Reflectance, and Transmittance 48
  - C. Goos-Hänchen Shift and Optical Tunneling 49
    - Example 1.6.1 Reflection of light from a less dense medium (internal reflection) 51
    - Example 1.6.2 Reflection at normal incidence, and internal and external reflection 52
    - Example 1.6.3 Reflection and transmission at the Brewster angle 53
- 1.7 Antireflection Coatings and Dielectric Mirrors 54
  - A. Antireflection Coatings on Photodetectors and Solar Cells 54
    - Example 1.7.1 Antireflection coating on a photodetector 55
  - B. Dielectric Mirrors and Bragg Reflectors 56
    - Example 1.7.2 Dielectric mirror 58
- 1.8 Absorption of Light and Complex Refractive Index 59
  - Example 1.8.1 Complex refractive index of InP 62
  - Example 1.8.2 Reflectance of CdTe around resonance absorption 63
- 1.9 Temporal and Spatial Coherence 63
  - Example 1.9.1 Coherence length of LED light 66
- 1.10 Superposition and Interference of Waves 67

|  |           |
|--|-----------|
| <b>1.11 Multiple Interference and Optical Resonators</b>                                       | <b>69</b> |
| <b>Example 1.11.1</b> Resonator modes and spectral width of a semiconductor Fabry–Perot cavity | 73        |
| <b>1.12 Diffraction Principles</b>   | <b>74</b> |
| <b>A. Fraunhofer Diffraction</b>   | <b>74</b> |
| <b>Example 1.12.1</b> Resolving power of imaging systems                                       | 79        |
| <b>B. Diffraction Grating</b>  | <b>80</b> |
| <b>Example 1.12.2</b> A reflection grating   | 83        |
| <b>Additional Topics</b>   | <b>84</b> |
| <b>1.13 Interferometers</b>  | <b>84</b> |
| <b>1.14 Thin Film Optics: Multiple Reflections in Thin Films</b>                               | <b>86</b> |
| <b>Example 1.14.1</b> Thin film optics   | 88        |
| <b>1.15 Multiple Reflections in Plates and Incoherent Waves</b>                                | <b>89</b> |
| <b>1.16 Scattering of Light</b>  | <b>90</b> |
| <b>1.17 Photonic Crystals</b>  | <b>92</b> |
| <i>Questions and Problems</i>  | 98        |

## Chapter 2 **Dielectric Waveguides and Optical Fibers** 111

|  |            |
|--|------------|
| <b>2.1 Symmetric Planar Dielectric Slab Waveguide</b>          | <b>111</b> |
| <b>A. Waveguide Condition</b>                                  | <b>111</b> |
| <b>B. Single and Multimode Waveguides</b>                      | <b>116</b> |
| <b>C. TE and TM Modes</b>                                      | <b>116</b> |
| <b>Example 2.1.1</b> Waveguide modes                           | 117        |
| <b>Example 2.1.2</b> $V$ -number and the number of modes       | 118        |
| <b>Example 2.1.3</b> Mode field width, $2w_g$                  | 119        |
| <b>2.2 Modal and Waveguide Dispersion in Planar Waveguides</b> | <b>120</b> |
| <b>A. Waveguide Dispersion Diagram and Group Velocity</b>      | <b>120</b> |
| <b>B. Intermodal Dispersion</b>                                | <b>121</b> |
| <b>C. Intramodal Dispersion</b>                                | <b>122</b> |
| <b>2.3 Step-Index Optical Fiber</b>                            | <b>123</b> |
| <b>A. Principles and Allowed Modes</b>                         | <b>123</b> |
| <b>Example 2.3.1</b> A multimode fiber                         | 128        |
| <b>Example 2.3.2</b> A single-mode fiber                       | 128        |
| <b>B. Mode Field Diameter</b>                                  | <b>128</b> |
| <b>Example 2.3.3</b> Mode field diameter                       | 129        |
| <b>C. Propagation Constant and Group Velocity</b>              | <b>130</b> |
| <b>Example 2.3.4</b> Group velocity and delay                  | 131        |
| <b>D. Modal Dispersion in Multimode Step-Index Fibers</b>      | <b>132</b> |
| <b>Example 2.3.5</b> A multimode fiber and dispersion          | 132        |

|   |            |
|---|------------|
| <b>2.4 Numerical Aperture</b>   | <b>133</b> |
| <b>Example 2.4.1</b> A multimode fiber and total acceptance angle     | 134        |
| <b>Example 2.4.2</b> A single-mode fiber                              | 134        |
| <b>2.5 Dispersion In Single-Mode Fibers</b>                           | <b>135</b> |
| <b>A. Material Dispersion</b>   | <b>135</b> |
| <b>B. Waveguide Dispersion</b>  | <b>136</b> |
| <b>C. Chromatic Dispersion</b>  | <b>138</b> |
| <b>D. Profile and Polarization Dispersion Effects</b>                 | <b>138</b> |
| <b>Example 2.5.1</b> Material dispersion                              | 140        |
| <b>Example 2.5.2</b> Material, waveguide, and chromatic dispersion    | 141        |
| <b>Example 2.5.3</b> Chromatic dispersion at different wavelengths    | 141        |
| <b>Example 2.5.4</b> Waveguide dispersion                             | 142        |
| <b>2.6 Dispersion Modified Fibers and Compensation</b>                | <b>142</b> |
| <b>A. Dispersion Modified Fibers</b>                                  | <b>142</b> |
| <b>B. Dispersion Compensation</b>                                     | <b>144</b> |
| <b>Example 2.6.1</b> Dispersion compensation                          | 146        |
| <b>2.7 Bit Rate, Dispersion, and Electrical and Optical Bandwidth</b> | <b>146</b> |
| <b>A. Bit Rate and Dispersion</b>                                     | <b>146</b> |
| <b>B. Optical and Electrical Bandwidth</b>                            | <b>149</b> |
| <b>Example 2.7.1</b> Bit rate and dispersion for a single-mode fiber  | 151        |
| <b>2.8 The Graded Index (GRIN) Optical Fiber</b>                      | <b>151</b> |
| <b>A. Basic Properties of GRIN Fibers</b>                             | <b>151</b> |
| <b>B. Telecommunications</b>  | <b>155</b> |
| <b>Example 2.8.1</b> Dispersion in a graded index fiber and bit rate  | 156        |
| <b>Example 2.8.2</b> Dispersion in a graded index fiber and bit rate  | 157        |
| <b>2.9 Attenuation in Optical Fibers</b>                              | <b>158</b> |
| <b>A. Attenuation Coefficient and Optical Power Levels</b>            | <b>158</b> |
| <b>Example 2.9.1</b> Attenuation along an optical fiber               | 160        |
| <b>B. Intrinsic Attenuation in Optical Fibers</b>                     | <b>160</b> |
| <b>C. Intrinsic Attenuation Equations</b>                             | <b>162</b> |
| <b>Example 2.9.2</b> Rayleigh scattering equations                    | 163        |
| <b>D. Bending losses</b>  | <b>164</b> |
| <b>Example 2.9.3</b> Bending loss for SMF                             | 167        |
| <b>2.10 Fiber Manufacture</b>   | <b>168</b> |
| <b>A. Fiber Drawing</b>   | <b>168</b> |
| <b>B. Outside Vapor Deposition</b>                                    | <b>169</b> |
| <b>Example 2.10.1</b> Fiber drawing                                   | 171        |
| <b>Additional Topics</b>  | <b>171</b> |
| <b>2.11 Wavelength Division Multiplexing: WDM</b>                     | <b>171</b> |
| <b>2.12 Nonlinear Effects in Optical Fibers and DWDM</b>              | <b>173</b> |

- 2.13 Bragg Fibers 175
- 2.14 Photonic Crystal Fibers—Holey Fibers 176
- 2.15 Fiber Bragg Gratings and Sensors 179
  - Example 2.15.1** Fiber Bragg grating at 1550 nm 183
  - Questions and Problems* 183

### Chapter 3 Semiconductor Science and Light-Emitting Diodes 195

- 3.1 Review of Semiconductor Concepts and Energy Bands 195
  - A. Energy Band Diagrams, Density of States, Fermi–Dirac Function and Metals 195
  - B. Energy Band Diagrams of Semiconductors 198
- 3.2 Semiconductor Statistics 200
- 3.3 Extrinsic Semiconductors 203
  - A. *n*-Type and *p*-Type Semiconductors 203
  - B. Compensation Doping 206
  - C. Nondegenerate and Degenerate Semiconductors 207
  - D. Energy Band Diagrams in an Applied Field 208
    - Example 3.3.1** Fermi levels in semiconductors 209
    - Example 3.3.2** Conductivity of *n*-Si 209
- 3.4 Direct and Indirect Bandgap Semiconductors: *E*-*k* Diagrams 210
- 3.5 *pn* Junction Principles 214
  - A. Open Circuit 214
  - B. Forward Bias and the Shockley Diode Equation 217
  - C. Minority Carrier Charge Stored in Forward Bias 222
  - D. Recombination Current and the Total Current 222
- 3.6 *pn* Junction Reverse Current 225
- 3.7 *pn* Junction Dynamic Resistance and Capacitances 227
  - A. Depletion Layer Capacitance 227
  - B. Dynamic Resistance and Diffusion Capacitance for Small Signals 229
- 3.8 Recombination Lifetime 230
  - A. Direct Recombination 230
  - B. Indirect Recombination 232
    - Example 3.8.1** A direct bandgap *pn* junction 232
- 3.9 *pn* Junction Band Diagram 234
  - A. Open Circuit 234
  - B. Forward and Reverse Bias 236
    - Example 3.9.1** The built-in voltage from the band diagram 237
- 3.10 Heterojunctions 238

- 3.11 Light-Emitting Diodes: Principles 240
  - A. Homojunction LEDs 240
  - B. Heterostructure High Intensity LEDs 242
  - C. Output Spectrum 244
    - Example 3.11.1 LED spectral linewidth 247
    - Example 3.11.2 LED spectral width 248
    - Example 3.11.3 Dependence of the emission peak and linewidth on temperature 249
- 3.12 Quantum Well High Intensity LEDs 249
  - Example 3.12.1 Energy levels in the quantum well 252
- 3.13 LED Materials and Structures 253
  - A. LED Materials 253
  - B. LED Structures 254
    - Example 3.13.1 Light extraction from a bare LED chip 257
- 3.14 LED Efficiencies and Luminous Flux 258
  - Example 3.14.1 LED efficiencies 260
  - Example 3.14.2 LED brightness 261
- 3.15 Basic LED Characteristics 261
- 3.16 LEDs for Optical Fiber Communications 262
- 3.17 Phosphors and White LEDs 265
- Additional Topics 267**
- 3.18 LED Electronics 267
  - Questions and Problems 270*

## Chapter 4 Stimulated Emission Devices: Optical Amplifiers and Lasers 281

- 4.1 Stimulated Emission, Photon Amplification, and Lasers 281
  - A. Stimulated Emission and Population Inversion 281
  - B. Photon Amplification and Laser Principles 282
  - C. Four-Level Laser System 285
- 4.2 Stimulated Emission Rate and Emission Cross-Section 286
  - A. Stimulated Emission and Einstein Coefficients 286
    - Example 4.2.1 Minimum pumping power for three-level laser systems 288
  - B. Emission and Absorption Cross-Sections 289
    - Example 4.2.2 Gain coefficient in a  $\text{Nd}^{3+}$ -doped glass fiber 291
- 4.3 Erbium-Doped Fiber Amplifiers 292
  - A. Principle of Operation and Amplifier Configurations 292
  - B. EDFA Characteristics, Efficiency, and Gain Saturation 296
    - Example 4.3.1 An erbium-doped fiber amplifier 299
  - C. Gain-Flattened EDFAs and Noise Figure 300

- 4.4 Gas Lasers: The He-Ne Laser 303
  - Example 4.4.1 Efficiency of the He-Ne laser 306
- 4.5 The Output Spectrum of a Gas Laser 306
  - Example 4.5.1 Doppler broadened linewidth 309
- 4.6 Laser Oscillations: Threshold Gain Coefficient and Gain Bandwidth 311
  - A. Optical Gain Coefficient  $g$  311
  - B. Threshold Gain Coefficient  $g_{th}$  and Output Power 312
    - Example 4.6.1 Threshold population inversion for the He-Ne laser 315
  - C. Output Power and Photon Lifetime in the Cavity 315
    - Example 4.6.2 Output power and photon cavity lifetime  $\tau_{ph}$  317
  - D. Optical Cavity, Phase Condition, Laser Modes 317
- 4.7 Broadening of the Optical Gain Curve and Linewidth 319
- 4.8 Pulsed Lasers: Q-Switching and Mode Locking 323
  - A. Q-Switching 323
  - B. Mode Locking 326
- 4.9 Principle of the Laser Diode 327
- 4.10 Heterostructure Laser Diodes 331
  - Example 4.10.1 Modes in a semiconductor laser and the optical cavity length 336
- 4.11 Quantum Well Devices 337
  - Example 4.11.1 A GaAs quantum well 339
- 4.12 Elementary Laser Diode Characteristics 340
  - Example 4.12.1 Laser output wavelength variation with temperature 346
  - Example 4.12.2 Laser diode efficiencies for a sky-blue LD 346
  - Example 4.12.3 Laser diode efficiencies 347
- 4.13 Steady State Semiconductor Rate Equations: The Laser Diode Equation 348
  - A. Laser Diode Equation 348
  - B. Optical Gain Curve, Threshold, and Transparency Conditions 351
    - Example 4.13.1 Threshold current and optical output power from a Fabry-Perot heterostructure laser diode 352
- 4.14 Single Frequency Semiconductor Lasers 354
  - A. Distributed Bragg Reflector LDs 354
  - B. Distributed Feedback LDs 355
  - C. External Cavity LDs 358
    - Example 4.14.1 DFB LD wavelength 360
- 4.15 Vertical Cavity Surface Emitting Lasers 360
- 4.16 Semiconductor Optical Amplifiers 364

**Additional Topics 366**

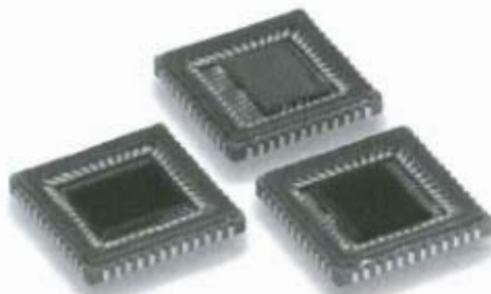
- 4.17 Superluminescent and Resonant Cavity LEDs:  
SLD and RCLED 366
- 4.18 Direct Modulation of Laser Diodes 367
- 4.19 Holography 370
  - Questions and Problems 373*

**Chapter 5 Photodetectors and Image Sensors 381**

- 5.1 Principle of the *pn* Junction Photodiode 381
  - A. Basic Principles 381
  - B. Energy Band Diagrams and Photodetection Modes 383
  - C. Current-Voltage Convention and Modes of Operation 385
- 5.2 Shockley–Ramo Theorem and External Photocurrent 386
- 5.3 Absorption Coefficient and Photodetector Materials 388
- 5.4 Quantum Efficiency and Responsivity 391
  - Example 5.4.1** Quantum efficiency and responsivity 394
  - Example 5.4.2** Maximum quantum efficiency 395
- 5.5 The *pin* Photodiode 395
  - Example 5.5.1** Operation and speed of a *pin* photodiode 399
  - Example 5.5.2** Photocarrier diffusion in a *pin* photodiode 399
  - Example 5.5.3** Responsivity of a *pin* photodiode 400
  - Example 5.5.4** Steady state photocurrent in the *pin* photodiode 401
- 5.6 Avalanche Photodiode 402
  - A. Principles and Device Structures 402
    - Example 5.6.1** InGaAs APD responsivity 406
    - Example 5.6.2** Silicon APD 406
  - B. Impact Ionization and Avalanche Multiplication 406
    - Example 5.6.3** Avalanche multiplication in Si APDs 408
- 5.7 Heterojunction Photodiodes 409
  - A. Separate Absorption and Multiplication APD 409
  - B. Superlattice APDs 411
- 5.8 Schottky Junction Photodetector 413
- 5.9 Phototransistors 417
- 5.10 Photoconductive Detectors and Photoconductive Gain 418
- 5.11 Basic Photodiode Circuits 421
- 5.12 Noise in Photodetectors 424
  - A. The *pn* Junction and *pin* Photodiodes 424
    - Example 5.12.1** NEP of a Si *pin* photodiode 428

|                  |   |     |
|------------------|---|-----|
|                  | <b>Example 5.122</b> Noise of an ideal photodetector                | 428 |
|                  | <b>Example 5.123</b> SNR of a receiver                              | 429 |
|                  | <b>B. Avalanche Noise in the APD</b>                                | 430 |
|                  | <b>Example 5.124</b> Noise in an APD                                | 430 |
| <b>5.13</b>      | <b>Image Sensors</b>  | 431 |
|                  | <b>A. Basic Principles</b>  | 431 |
|                  | <b>B. Active Matrix Array and CMOS Image Sensors</b>                | 433 |
|                  | <b>C. Charge-Coupled Devices</b>                                    | 435 |
|                  | <b>Additional Topics</b>  | 437 |
| <b>5.14</b>      | <b>Photovoltaic Devices: Solar Cells</b>                            | 437 |
|                  | <b>A. Basic Principles</b>  | 437 |
|                  | <b>B. Operating Current and Voltage and Fill Factor</b>             | 439 |
|                  | <b>C. Equivalent Circuit of a Solar Cell</b>                        | 440 |
|                  | <b>D. Solar Cell Structures and Efficiencies</b>                    | 442 |
|                  | <b>Example 5.141</b> Solar cell driving a load                      | 444 |
|                  | <b>Example 5.142</b> Open circuit voltage and short circuit current | 445 |
|                  | <i>Questions and Problems</i>                                       | 445 |
| <b>Chapter 6</b> | <b>Polarization and Modulation of Light</b>                         | 457 |
| <b>6.1</b>       | <b>Polarization</b>   | 457 |
|                  | <b>A. State of Polarization</b>                                     | 457 |
|                  | <b>Example 6.1.1</b> Elliptical and circular polarization           | 460 |
|                  | <b>B. Malus's Law</b>   | 460 |
| <b>6.2</b>       | <b>Light Propagation in an Anisotropic Medium: Birefringence</b>    | 461 |
|                  | <b>A. Optical Anisotropy</b>  | 461 |
|                  | <b>B. Uniaxial Crystals and Fresnel's Optical Indicatrix</b>        | 463 |
|                  | <b>C. Birefringence of Calcite</b>                                  | 466 |
|                  | <b>D. Dichroism</b>   | 467 |
| <b>6.3</b>       | <b>Birefringent Optical Devices</b>                                 | 468 |
|                  | <b>A. Retarding Plates</b>  | 468 |
|                  | <b>Example 6.3.1</b> Quartz-half wave plate                         | 469 |
|                  | <b>Example 6.3.2</b> Circular polarization from linear polarization | 470 |
|                  | <b>B. Soleil-Babinet Compensator</b>                                | 470 |
|                  | <b>C. Birefringent Prisms</b>                                       | 471 |
| <b>6.4</b>       | <b>Optical Activity and Circular Birefringence</b>                  | 472 |
| <b>6.5</b>       | <b>Liquid Crystal Displays</b>                                      | 474 |
| <b>6.6</b>       | <b>Electro-Optic Effects</b>  | 478 |
|                  | <b>A. Definitions</b>   | 478 |

|  |     |
|--|-----|
| B. Pockels Effect                                    | 479 |
| <b>Example 6.6.1</b> Pockels Cell Modulator          | 484 |
| C. Kerr Effect                                       | 484 |
| <b>Example 6.6.2</b> Kerr Effect Modulator           | 486 |
| 6.7 Integrated Optical Modulators                    | 486 |
| A. Phase and Polarization Modulation                 | 486 |
| B. Mach-Zehnder Modulator                            | 487 |
| C. Coupled Waveguide Modulators                      | 489 |
| <b>Example 6.7.1</b> Modulated Directional Coupler   | 492 |
| 6.8 Acousto-Optic Modulator                          | 492 |
| A. Photoelastic Effect and Principles                | 492 |
| B. Acousto-Optic Modulators                          | 494 |
| <b>Example 6.8.1</b> AO Modulator                    | 499 |
| 6.9 Faraday Rotation and Optical Isolators           | 499 |
| <b>Example 6.9.1</b> Faraday rotation                | 500 |
| 6.10 Nonlinear Optics and Second Harmonic Generation | 501 |
| <b>Additional Topics</b>                             | 505 |
| 6.11 Jones Vectors                                   | 505 |
| <i>Questions and Problems</i>                        | 506 |
| <b>Appendices</b>                                    |     |
| <i>Appendix A Gaussian Distribution</i>              | 514 |
| <i>Appendix B Solid Angles</i>                       | 516 |
| <i>Appendix C Basic Radiometry and Photometry</i>    | 518 |
| <i>Appendix D Useful Mathematical Formulae</i>       | 521 |
| <i>Appendix E Notation and Abbreviations</i>         | 523 |
| <b>Index</b>   | 535 |



CMOS image sensors with wide dynamic range. (Courtesy of New Imaging Technologies (NIT), France)