

SPONSORED BY THE
OPTICAL SOCIETY OF AMERICA

HANDBOOK OF OPTICS

FIBER OPTICS & NONLINEAR OPTICS

• SECOND EDITION •

VOLUME

IV

MICHAEL S. DODD, EDITOR IN CHIEF

JAY M. ENOCH • ERIC W. VAN DYCK • WILLIAM J. WYLLIE

CONTENTS

Contributors xi

Preface xiii

Part 1. Fiber Optics

Chapter 1. Optical Fibers and Fiber-Optic Communications *Tom G. Brown* **1.3**

- 1.1 Glossary / 1.3
- 1.2 Introduction / 1.5
- 1.3 Principles of Operation / 1.6
- 1.4 Fiber Dispersion and Attenuation / 1.10
- 1.5 Polarization Characteristics of Fibers / 1.13
- 1.6 Optical and Mechanical Properties of Fibers / 1.14
- 1.7 Optical Fiber Communications / 1.21
- 1.8 Nonlinear Optical Properties of Fibers / 1.39
- 1.9 Optical Fiber Materials: Chemistry and Fabrication / 1.44
- 1.10 References / 1.48
- 1.11 Further Reading / 1.51

Chapter 2. Optical Fiber Communication Technology and System Overview *Ira Jacobs* **2.1**

- 2.1 Introduction / 2.1
- 2.2 Basic Technology / 2.2
- 2.3 Receiver Sensitivity / 2.7
- 2.4 Bit Rate and Distance Limits / 2.10
- 2.5 Optical Amplifiers / 2.12
- 2.6 Fiber-Optic Networks / 2.13
- 2.7 Analog Transmission on Fiber / 2.14
- 2.8 Technology and Applications Directions / 2.16
- 2.9 References / 2.16

Chapter 3. Nonlinear Effects in Optical Fibers *John A. Buck* **3.1**

- 3.1 Key Issues in Nonlinear Optics in Fibers / 3.1
- 3.2 Self- and Cross-Phase Modulation / 3.3
- 3.3 Stimulated Raman Scattering / 3.4
- 3.4 Stimulated Brillouin Scattering / 3.7
- 3.5 Four-Wave Mixing / 3.9
- 3.6 Conclusion / 3.12
- 3.7 References / 3.12

- 4.1 Introduction / 4.1
- 4.2 Double Heterostructure Laser Diodes / 4.3
- 4.3 Operating Characteristics of Laser Diodes / 4.9
- 4.4 Transient Response of Laser Diodes / 4.15
- 4.5 Noise Characteristics of Laser Diodes / 4.22
- 4.6 Quantum Well and Strained Lasers / 4.28
- 4.7 Distributed Feedback (DFB) and Distributed Bragg Reflector (DBR) Lasers / 4.34
- 4.8 Light-Emitting Diodes (LEDs) / 4.39
- 4.9 Vertical Cavity Surface-Emitting Lasers (VCSELS) / 4.45
- 4.10 Lithium Niobate Modulators / 4.50
- 4.11 Electroabsorption Modulators for Fiber-Optic Systems / 4.57
- 4.12 Electro-Optic and Electrorefractive Semiconductor Modulators / 4.64
- 4.13 PIN Diodes / 4.66
- 4.14 Avalanche Photodiodes, MSM Detectors, and Schottky Diodes / 4.76
- 4.15 References / 4.78

- 5.1 Introduction / 5.1
- 5.2 Rare-Earth-Doped Amplifier Configuration and Operation / 5.2
- 5.3 EDFA Physical Structure and Light Interactions / 5.3
- 5.4 Gain Formation in Other Rare-Earth Systems / 5.6
- 5.5 References / 5.7

- 6.1 Introduction / 6.1
- 6.2 Figures of Merit: SNR, BER, MER, and SFDR / 6.2
- 6.3 Link Budget Analysis: Installation Loss / 6.7
- 6.4 Link Budget Analysis: Optical Power Penalties / 6.9
- 6.5 References / 6.18

- 7.1 Introduction / 7.1
- 7.2 Nature of the Classical Soliton / 7.2
- 7.3 Properties of Solitons / 7.4
- 7.4 Classical Soliton Transmission Systems / 7.5
- 7.5 Frequency-Guiding Filters / 7.7
- 7.6 Sliding Frequency-Guiding Filters / 7.8
- 7.7 Wavelength Division Multiplexing / 7.9
- 7.8 Dispersion-Managed Solitons / 7.12
- 7.9 Wavelength-Division Multiplexed Dispersion-Managed Soliton Transmission / 7.15
- 7.10 Conclusion / 7.17
- 7.11 References / 7.18

- 8.1 Introduction / 8.1
- 8.2 Achromaticity / 8.3

8.3	Wavelength Division Multiplexing / 8.4
8.4	1 × N Power Splitters / 8.4
8.5	Switches and Attenuators / 8.5
8.6	Mach-Zehnder Devices / 8.6
8.7	Polarization Devices / 8.6
8.8	Summary / 8.8
8.9	References / 8.8

Chapter 9. Fiber Bragg Gratings *Kenneth O. Hill*

9.1

9.1	Glossary / 9.1
9.2	Introduction / 9.1
9.3	Photosensitivity / 9.2
9.4	Properties of Bragg Gratings / 9.3
9.5	Fabrication of Fiber Gratings / 9.5
9.6	The Application of Fiber Gratings / 9.8
9.7	References / 9.9

Chapter 10. Micro-Optics-Based Components for Networking *Joseph C. Palais* **10.1**

10.1	Introduction / 10.1
10.2	Generalized Components / 10.1
10.3	Network Functions / 10.2
10.4	Subcomponents / 10.5
10.5	Components / 10.8
10.6	References / 10.11

Chapter 11. Semiconductor Optical Amplifiers and Wavelength Conversion *Ulf Österberg*

11.1

11.1	Glossary / 11.1
11.2	Why Optical Amplification? / 11.2
11.3	Why Optical Wavelength Conversion? / 11.7
11.4	References / 11.9

Chapter 12. Optical Time-Division Multiplexed Communication Networks *Peter J. Delfyett*

12.1

12.1	Glossary / 12.1
12.2	Introduction / 12.3
12.3	Time-Division Multiplexing and Time-Division Multiple Access / 12.16
12.4	Introduction to Device Technology / 12.24
12.5	Summary and Future Outlook / 12.42
12.6	Further Reading / 12.42

Chapter 13. Wavelength Domain Multiplexed (WDM) Fiber-Optic Communication Networks *Alan E. Willner and Yong Xia*

13.1

13.1	Introduction / 13.1
13.2	Fiber Impairments / 13.3
13.3	Basic Architecture of WDM Networks / 13.12
13.4	Erbium-Doped Fiber Amplifiers in WDM Networks / 13.17

- 13.5 Dynamic Channel Power Equalization / 13.21
- 13.6 Crosstalk in WDM Networks / 13.24
- 13.7 Summary / 13.26
- 13.8 Acknowledgments / 13.27
- 13.9 References / 13.27

Chapter 14. Infrared Fibers *James A. Harrington*

14.1

- 14.1 Introduction / 14.1
- 14.2 Nonoxide and Heavy-Metal Oxide Glass IR Fibers / 14.4
- 14.3 Crystalline Fibers / 14.8
- 14.4 Hollow Waveguides / 14.11
- 14.5 Summary and Conclusions / 14.13
- 14.6 References / 14.14

Chapter 15. Optical Fiber Sensors *Richard O. Claus, Ignacio Matias, and Francisco Arregui*

15.1

- 15.1 Introduction / 15.1
- 15.2 Extrinsic Fabry-Perot Interferometric Sensors / 15.2
- 15.3 Intrinsic Fabry-Perot Interferometric Sensors / 15.4
- 15.4 Fiber Bragg Grating Sensors / 15.5
- 15.5 Long-Period Grating Sensors / 15.9
- 15.6 Comparison of Sensing Schemes / 15.14
- 15.7 Conclusion / 15.14
- 15.8 References / 15.14
- 15.9 Further Reading / 15.15

Chapter 16. Fiber-Optic Communication Standards *Casimer DeCusatis*

16.1

- 16.1 Introduction / 16.1
- 16.2 ESCON / 16.1
- 16.3 FDDI / 16.2
- 16.4 Fibre Channel Standard / 16.4
- 16.5 ATM/SONET / 16.6
- 16.6 Gigabit Ethernet / 16.7
- 16.7 References / 16.7

Part 2. Nonlinear and Quantum Optics

Chapter 17. Third-Order Optical Nonlinearities *Mansoor Sheik-Bahae and Michael P. Hasselbeck*

17.3

- 17.1 Introduction / 17.3
- 17.2 Quantum Mechanical Picture / 17.6
- 17.3 Nonlinear Absorption (NLA) and Nonlinear Refraction (NLR) / 17.9
- 17.4 Kramers-Kronig Dispersion Relations / 17.11
- 17.5 Optical Kerr Effect / 17.13
- 17.6 Third-Harmonic Generation / 17.16
- 17.7 Stimulated Scattering / 17.16
- 17.8 Two-Photon Absorption / 17.21
- 17.9 Effective Third-Order Nonlinearities; Cascaded $\chi^{(1)}\chi^{(1)}$ Processes / 17.22

- 17.10 Effective Third-Order Nonlinearities; Cascaded $\chi^{(2)}\text{-}\chi^{(2)}$ Processes / 17.24
- 17.11 Propagation Effects / 17.26
- 17.12 Common Experimental Techniques and Applications / 17.28
- 17.13 References / 17.34

Chapter 18. Stimulated Raman and Brillouin Scattering *J. Reintjes and M. Bashkansky*

18.1

- 18.1 Introduction / 18.1
- 18.2 Raman Scattering / 18.1
- 18.3 Stimulated Brillouin Scattering / 18.44
- 18.4 References / 18.55
- 18.5 Further Reading / 18.61

Chapter 19. Optical Limiting *David J. Hagan*

19.1

- 19.1 Introduction / 19.1
- 19.2 Basic Principles of Passive Optical Limiting / 19.4
- 19.3 Examples of Passive Optical Limiting in Specific Materials / 19.9
- 19.4 References / 19.13

Chapter 20. Photonic Bandgap Materials *Pierre R. Villeneuve*

20.1

- 20.1 Glossary / 20.1
- 20.2 Introduction / 20.2
- 20.3 Maxwell's Equations / 20.3
- 20.4 Three-Dimensional Photonic Crystals / 20.4
- 20.5 Microcavities in Three-Dimensional Photonic Crystals / 20.6
- 20.6 Microcavities in Photonic Crystals with Two-Dimensional Periodicity / 20.9
- 20.7 Waveguides / 20.13
- 20.8 Conclusion / 20.18
- 20.9 References / 20.18

Chapter 21. All-Optical Switching *George I. Stegeman*

21.1

- 21.1 Introduction / 21.1
- 21.2 How Do You Switch? / 21.2
- 21.3 Real Materials / 21.2
- 21.4 How Material Properties Affect Switching in Communications / 21.3
- 21.5 Other Device Geometries / 21.5
- 21.6 Examples of Operation of All-Optical Devices / 21.6
- 21.7 Summary / 21.7
- 21.8 References / 21.7

Chapter 22. Optical Parametric Oscillators *M. Ebrahimzadeh and M. H. Dunn*

22.1

- 22.1 Introduction / 22.1
- 22.2 Basic Principles / 22.2
- 22.3 Optical Parametric Generation and Amplification / 22.8
- 22.4 Optical Parametric Devices / 22.12
- 22.5 Optical Parametric Oscillators / 22.13
- 22.6 Continuous-Wave Optical Parametric Oscillators / 22.15

22.7	Pulsed Parametric Oscillators /	22.50
22.8	Synchronously-Pumped Parametric Oscillators /	22.54
22.9	Parametric Oscillator Design Issues /	22.61
22.10	Conclusions /	22.65
22.11	References /	22.65

Chapter 23. Electromagnetically Induced Transparency *J. P. Marangos*

23.1

23.1	Glossary /	23.1
23.2	Introduction /	23.2
23.3	Coherence in Two- and Three-Level Atomic Systems /	23.4
23.4	The Physical Basis of Electromagnetically Induced Transparency /	23.5
23.5	Electromagnetically Induced Transparency Phenomena /	23.9
23.6	Electromagnetically Induced Transparency with Laser Pulses /	23.14
23.7	Steady-State Electromagnetically Induced Transparency with CW Lasers /	23.15
23.8	Gain and Lasing without Inversion /	23.17
23.9	Refractive Index Modifications for Dressed Atoms /	23.18
23.10	Pulse Propagation Effects /	23.19
23.11	Ultralow Light Pulses /	23.21
23.12	Electromagnetically Induced Transparency in Nonlinear Frequency Mixing /	23.22
23.13	Nonlinear Optics at Maximal Atomic Coherence /	23.26
23.14	Nonlinear Optics at the Few Photon Level /	23.27
23.15	Further Reading /	23.28
23.16	References /	23.28

Chapter 24. Coherent Optical Transients *P. R. Berman and D. G. Steel*

24.1

24.1	Glossary /	24.1
24.2	Introduction /	24.2
24.3	Optical Bloch Equations /	24.3
24.4	Maxwell-Bloch Equations /	24.5
24.5	Free Polarization Decay /	24.7
24.6	Photon Echo /	24.11
24.7	Stimulated Photon Echo /	24.15
24.8	Phase Conjugate Geometry and Optical Ramsey Fringes /	24.18
24.9	Two-Photon Transitions and Atom Interferometry /	24.21
24.10	Chirped Pulse Excitation /	24.24
24.11	Experimental Considerations /	24.25
24.12	Conclusion /	24.27
24.13	Acknowledgments /	24.27
24.14	References /	24.27

Chapter 25. Nonlinear Optical Processes for Ultrashort Pulse Generation *U. Siegner and U. Keller*

25.1

25.1	Glossary /	25.1
25.2	Abbreviations /	25.3
25.3	Introduction /	25.3
25.4	Saturable Absorbers: Macroscopic Description /	25.6
25.5	Kerr Effect /	25.11
25.6	Semiconductor Ultrafast Nonlinearities: Microscopic Processes /	25.15
25.7	References /	25.24

Chapter 26. Quantum Theory of the Laser *János A. Bergou, Berthold-Georg Englert, Melvin Lax, Marian O. Scully, Herbert Walther, and M. Suhail Zubairy*

26.1

- 26.1 Glossary / 26.2
- 26.2 Introduction / 26.6
- 26.3 Some History of the Photon Concept / 26.7
- 26.4 Quantum Theory of the Laser / 26.15
- 26.5 The Laser Phase-Transition Analogy / 26.37
- 26.6 Exotic Masers and Lasers / 26.42
- 26.7 Acknowledgments / 26.46
- 26.8 References / 26.47

Chapter 27. Laser Stabilization *John L. Hall, Matthew S. Taubman, and Jun Ye*

27.1

- 27.1 Introduction and Overview / 27.1
- 27.2 Servo Principles and Issues / 27.5
- 27.3 Practical Issues / 27.12
- 27.4 Summary and Outlook / 27.22
- 27.5 Conclusions and Recommendations / 27.22
- 27.6 Acknowledgments / 27.23
- 27.7 References / 27.23

Chapter 28. Laser Cooling and Trapping of Atoms *H. J. Metcalf and P. van der Straten*

28.1

- 28.1 Introduction / 28.1
- 28.2 General Properties Concerning Laser Cooling / 28.2
- 28.3 Theoretical Description / 28.4
- 28.4 Slowing Atomic Beams / 28.9
- 28.5 Optical Molasses / 28.11
- 28.6 Cooling Below the Doppler Limit / 28.15
- 28.7 Trapping of Neutral Atoms / 28.19
- 28.8 Applications / 28.24
- 28.9 References / 28.38