An Introduction to Photonics and Laser Physics with Applications

Online at: https://doi.org/10.1088/978-0-7503-5226-0

IOP Series in Advances in Optics, Photonics and Optoelectronics

SERIES EDITOR

Professor Rajpal S Sirohi Consultant Scientist

About the Editor

Rajpal S Sirohi is currently working as a faculty member in the Department of Physics, Alabama A&M University, Huntsville, Alabama (USA). Prior to this, he was a consultant scientist at the Indian Institute of Science, Bangalore, and before that he held a chair and was professor in the Department of Physics, Tezpur University, Assam. During 2000–11, he was an academic administrator, being vice-chancellor to a couple of universities and the director of the Indian Institute of Technology, Delhi. He is the recipient of many international and national awards and the author of more than 400 papers. Dr Sirohi is involved with research concerning optical metrology, optical instrumentation, holography, and speckle phenomena.

About the series

Optics, photonics, and optoelectronics are enabling technologies in many branches of science, engineering, medicine, and agriculture. These technologies have reshaped our outlook and our ways of interacting with each other and have brought people closer. They help us to understand many phenomena better and provide a deeper insight into the functioning of nature. Furthermore, these technologies themselves are evolving at a rapid rate. Their applications encompass very large spatial scales from nanometers to astronomical and a very large temporal range from picoseconds to billions of years. This series on advances on optics, photonics, and optoelectronics aims to cover topics that are of interest to both academia and industry. Some of the topics to be covered by the books in this series include biophotonics and medical imaging, devices, electromagnetics, fiber optics, information storage, instrumentation, light sources, CCD and CMOS imagers, metamaterials, optical metrology, optical networks, photovoltaics, free-form optics and its evaluation, singular optics, cryptography, and sensors.

About IOP ebooks

The authors are encouraged to take advantage of the features made possible by electronic publication to enhance the reader experience through the use of color, animation, and video and by incorporating supplementary files in their work.

Do you have an idea for a book you'd like to explore?

For further information and details of submitting book proposals, see iopscience.org/books or contact Ashley Gasque on Ashley.gasque@iop.org.

A full list of titles published in this series can be found here: https://iopscience.iop.org/bookListInfo/series-on-advances-in-optics-photonics-and-optoelectronics.

An Introduction to Photonics and Laser Physics with Applications

Prem B Bisht
IIT Madras

IOP Publishing, Bristol, UK

ISBN 978-0-7503-5226-0 (ebook)
ISBN 978-0-7503-5225-3 (print)
ISBN 978-0-7503-5227-7 (myPrint)
ISBN 978-0-7503-5235-2 (mobi)

DOI 10.1088/978-0-7503-5226-0

Version: 20220801

IOP ebooks

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, Temple Circus, Temple Way, Bristol, BS1 6HG, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

...वसुधैव कुटुम्बकम्...*the whole earth is a family—(Mahopnishad)*

Dedicated to people all over the world.

Contents

Preface xix

Author biography xxii

Foreword xxiii

Part I Basics of photonics and lasers

1 The photon and photonics 1-1

1.1 The photon 1-2
1.2 Branches of photonics 1-2
  1.2.1 Conventional optics 1-3
  1.2.2 Electromagnetism and wave optics 1-3
  1.2.3 Quantum optics 1-3
  1.2.4 Light–matter interaction or quantum electronics 1-3
  1.2.5 Optoelectronics 1-4
  1.2.6 Electro-optics 1-4
  1.2.7 Light-wave technology 1-4
1.3 Maxwell's equations and their connection to optics 1-4
1.4 A few topics related to lasers and optics 1-7
  1.4.1 Phase velocity and group velocity 1-7
  1.4.2 Power flow and Poynting vector 1-8
  1.4.3 Radiation pressure and angular momentum 1-8
  1.4.4 Radiation emitted by the accelerated charge 1-10
  1.4.5 Refractive index 1-10
  1.4.6 Dispersion curve 1-11
  1.4.7 Normal dispersion and anomalous dispersion 1-12
1.5 Comparison of an electronic circuit and a photonic circuit 1-13
1.6 Nobel prizes related to lasers 1-14
Questions and problems 1-15
Bibliography 1-16

2 Light–matter interaction and the essentials of spectroscopy 2-1

2.1 Light sources and types of spectra 2-2
2.2 Laser: a tool covering the EM spectrum 2-3
2.3 Photoelectric effect 2-3
2.4 Rutherford's experiment 2-5

2.5 Bohr's atomic model: atomic energy levels 2-6
2.6 Franck–Hertz experiment 2-8
2.7 Stern–Gerlach experiment: spin quantization 2-9
2.8 Compton effect 2-11
2.9 Quantum mechanical picture of matter 2-11
  2.9.1 Wave functions 2-12
  2.9.2 The Schrödinger equation 2-12
  2.9.3 Infinite quantum well 2-13
  2.9.4 Stationary states and the coherent state 2-14
  2.9.5 Heisenberg's uncertainty principle 2-15
  2.9.6 Atomic quantum states 2-15
  2.9.7 Molecular quantum states 2-19
  2.9.8 Energy–momentum diagrams in semiconductors 2-27
  2.9.9 Energy levels in solids: doped insulators 2-28
2.10 Raman spectroscopy 2-29
Questions and problems 2-29
Bibliography 2-30

3 Polarization of light 3-1

3.1 EM waves and linearly polarized light 3-2
3.2 Types of polarization 3-4
  3.2.1 Ordinary and extraordinary light beams 3-4
  3.2.2 Classification of polarized light 3-5
3.3 Jones vector representation of polarization 3-8
  3.3.1 Jones vector 3-8
  3.3.2 Jones vectors for some common types of light 3-9
  3.3.3 Jones matrix for a medium 3-10
3.4 Methods of generating polarized light 3-12
  3.4.1 Wire-grid polarizer in the microwave region 3-12
  3.4.2 Long polymer chain 3-13
  3.4.3 Polarization based on reflection 3-13
  3.4.4 Polarization based on dichroism 3-17
  3.4.5 Polarization based on double refraction 3-17
3.5 Change of state of polarization 3-20
  3.5.1 Electro-optic effects 3-20
  3.5.2 Magneto-optic effect 3-21
3.6 Quarter-wave and half-wave plates 3-22

3.7 Polarized light in nature 3-22

Questions and problems 3-23

Bibliography 3-24

4 Spontaneous and stimulated emission 4-1

4.1 Thermal radiation and Planck's law 4-2

4.1.1 Radiation density in a cavity 4-2

4.1.2 Density of modes in a closed container 4-2

4.1.3 Wein's displacement law 4-3

4.2 Boltzmann statistics 4-5

4.3 Planck's law of radiation 4-7

4.4 Einstein's A and B coefficients 4-8

4.4.1 Stimulated absorption coefficient 4-8

4.4.2 Spontaneous emission 4-9

4.4.3 Coefficient of stimulated emission 4-10

4.4.4 Rate equation analysis 4-11

Questions and problems 4-16

Bibliography 4-16

5 The Beer–Lambert law and the gain coefficient 5-1

5.1 The Beer–Lambert law 5-2

5.2 Absorption coefficient 5-3

5.3 Gain media 5-5

5.4 Gain coefficient 5-6

5.5 Round-trip gain 5-7

5.6 Gain saturation 5-8

5.7 Applications of the Beer–Lambert law 5-9

Questions and problems 5-10

Bibliography 5-11

6 Population inversion with moderate pumping 6-1

6.1 Population inversion schemes 6-2

6.1.1 Two-level system 6-2

6.1.2 A low-efficiency scheme: the three-level system 6-4

6.1.3 Population inversion in a four-level system 6-4

6.2 Rate equation analysis for a four-level system and a multilevel system 6-5

6.2.1 Population inversion between E_2 and E_1 6-7

6.2.2 Metastable state 6-8
6.2.3 Plot of output power after population inversion 6-8
6.3 Typical laser systems 6-9
6.3.1 Nd:YAG laser 6-9
6.3.2 Helium–neon laser 6-10
6.3.3 Argon-ion laser 6-12
6.3.4 Nitrogen laser and superradiance 6-13
Questions and problems 6-14
Bibliography 6-15

7 Pumping mechanisms and types of optical cavity 7-1

7.1 Pumping via electrical excitation 7-2
7.1.1 Collisions of the first kind 7-2
7.1.2 Collisions of the second kind 7-2
7.1.3 Electrical pumping 7-3
7.2 Optical pumping 7-3
7.2.1 Lamps 7-4
7.2.2 Light-emitting diodes and lasers 7-5
7.3 Thermal and gas-dynamic pumping 7-6
7.4 Chemical pumping 7-7
7.5 Nuclear pumping 7-8
7.6 Pump-cavity geometries 7-8
7.6.1 Optical side pumping 7-9
7.6.2 Optical transverse pumping 7-9
7.6.3 Optical face pumping 7-10
7.6.4 Other optical pumping geometries 7-11
Questions and problems 7-11
Bibliography 7-12

8 Line-broadening mechanisms 8-1

8.1 The small-gain coefficient in practice 8-2
8.2 Spectral resolving power 8-2
8.3 Line broadening in He–Ne lasers 8-4
8.4 Harmonic oscillator 8-4
8.5 Broadening mechanisms 8-5
8.5.1 Fourier transform 8-5
8.5.2 Homogeneous broadening and the Lorentzian expression 8-6
8.5.3 Inhomogeneous broadening and the Gaussian expression 8-9

8.6 Correction of the small-gain coefficient 8-11
8.7 Voigt profile 8-12
8.8 The effect of amorphous or crystalline hosts 8-13
8.9 Hole burning and the Lamb dip 8-14
Questions and problems 8-16
Bibliography 8-17

9 The Fabry–Pérot resonator 9-1

9.1 Modes in a two-dimensional cavity 9-2
  9.1.1 Active medium and gain bandwidth 9-2
  9.1.2 Modes of a cavity 9-3
  9.1.3 Free spectral range 9-3
9.2 Resonant cavity: the Fabry–Pérot resonator 9-5
  9.2.1 A beam splitter in the path of the light 9-5
  9.2.2 Phase difference between reflected and refracted light 9-6
  9.2.3 Field transmitted by a passive cavity: the Airy function 9-6
  9.2.4 Effect of the reflectivity of beam splitters 9-9
  9.2.5 Longitudinal modes 9-9
  9.2.6 Properties of FP resonators 9-10
9.3 FP etalon 9-13
9.4 Fresnel number 9-13
9.5 Mode pulling 9-14
Questions and problems 9-15
Bibliography 9-17

10 Basic properties of lasers: directionality, brightness, and coherence 10-1

10.1 Directionality of a laser beam 10-2
10.2 Brightness of a light source 10-3
  10.2.1 Sun 10-3
  10.2.2 Sodium lamp 10-4
  10.2.3 A laser—the He–Ne laser 10-4
10.3 Monochromaticity 10-6
10.4 Coherence 10-7
  10.4.1 Visibility or contrast in interference fringes 10-8
  10.4.2 Temporal coherence: the idea of ‘coherence length’ 10-9
  10.4.3 Spatial or transverse coherence 10-10

10.4.4 Coherence surface and coherence volume 10-12
Questions and problems 10-12
Bibliography 10-14

11 ABCD matrices and stability diagrams 11-1

11.1 Geometrical optics and ABCD matrices 11-2
11.1.1 Translation matrix 11-2
11.1.2 Reflection matrix 11-3
11.1.3 Refraction matrix 11-5
11.2 Round trip in a cavity 11-8
11.2.1 Light ray from the middle of the cavity 11-8
11.2.2 Light initiated at a mirror 11-9
11.3 Cavity with several round trips 11-10
11.3.1 Stability condition for m round trips 11-11
11.3.2 Stability diagram 11-12
11.4 Nearly stable or marginally stable resonators 11-13
11.5 Stable resonators 11-15
11.6 Unstable resonators 11-15
11.6.1 Negative-branch confocal unstable cavity 11-16
11.6.2 Positive-branch confocal unstable cavity 11-16
Questions and problems 11-17
Bibliography 11-18

12 Stability conditions according to Gaussian beam analysis 12-1

12.1 Cavity mirrors as diffracting elements 12-2
12.2 Laser light: a plane or spherical wave? 12-2
12.3 Kirchhoff's diffraction 12-3
12.3.1 Single diffraction 12-3
12.3.2 Multiple diffractions 12-4
12.4 Directional properties of laser light 12-6
12.4.1 Obtaining the Helmholtz equation from the wave equation 12-6
12.4.2 Slowly varying envelope approximation (SVEA) 12-7
12.4.3 Transverse Helmholtz equation 12-7
12.4.4 Radius of curvature of the beam 12-8
12.4.5 Beam waist 12-10
12.4.6 Rayleigh range in terms of the minimum beam waist 12-11

12.4.7 Laser beam spot and Gaussian expression 12-12
12.4.8 Angular spread 12-13
12.4.9 Special cases of $R(z)$ 12-13
12.4.10 Appearance of the Gouy phase in a Gaussian beam 12-14
12.5 Stability condition and Gaussian wave analysis 12-15
12.6 TEM modes 12-15
Questions and problems 12-17
Bibliography 12-19

Part II Pulsed lasers and nonlinear optical applications

13 Laser spiking and *Q*-switching 13-1
13.1 Pulsed light sources 13-2
13.1.1 External modulation 13-2
13.1.2 Intra-cavity modulation 13-3
13.2 The spiking phenomenon 13-4
13.2.1 Pump flash duration and population inversion 13-4
13.2.2 Laser spiking 13-5
13.3 The *Q*-switching phenomenon 13-6
13.3.1 Conditions for *Q*-switching 13-6
13.3.2 Methods of *Q*-switching 13-8
Questions and problems 13-12
Bibliography 13-13

14 Introduction to nonlinear optical phenomena 14-1
14.1 Review of linear dielectrics 14-2
14.2 Wave equation in nonlinear optics 14-3
14.2.1 Interatomic field strength 14-3
14.2.2 Higher terms of polarization 14-4
14.3 Units and estimates of susceptibilities 14-5
14.4 Characteristics of second-order susceptibility 14-6
14.4.1 Optical rectification (OR) 14-6
14.4.2 Second-harmonic generation 14-7
14.5 Virtual levels 14-8
14.6 Linear and nonlinear optics 14-8
Questions and problems 14-8
Bibliography 14-9

15 Second-order susceptibility, phase matching, and applications 15-1

15.1 Sum- and difference-frequency generation 15-2
  15.1.1 Three-wave mixing processes 15-3
15.2 Signal and idler photons 15-3
15.3 Properties of, and contracted notation for, $\chi^{(2)}$ 15-4
15.4 Conditions for refractive-index matching 15-7
  15.4.1 Angle dependence of the extraordinary refractive index 15-8
  15.4.2 Phase matching for SHG in a crystal 15-8
  15.4.3 Effects of the length and area of nonlinear crystals 15-10
  15.4.4 Types of phase-matching interaction 15-13
15.5 Parametric oscillation and amplification 15-18
  15.5.1 Optical parametric oscillation 15-18
  15.5.2 Noncollinear geometries of parametric amplification 15-19
15.6 Superfluorescence 15-21
15.7 Generation of polarization-entangled photons 15-23
Questions and problems 15-25
Bibliography 15-26

16 Third-order nonlinear optical processes 16-1

16.1 Parametric and nonparametric processes 16-2
16.2 Third-order nonlinear optical susceptibility 16-2
16.3 Symmetry properties of the susceptibility tensor 16-3
16.4 Four-wave mixing due to $\chi^{(3)}$ 16-4
16.5 Third-harmonic generation 16-5
16.6 Optical Kerr effect 16-6
  16.6.1 Transverse OKE 16-7
  16.6.2 Longitudinal OKE: the effect of self-phase modulation 16-8
16.7 Optical phase conjugation 16-11
16.8 Stimulated Raman and Brillouin scattering 16-11
16.9 Four-photon parametric generation 16-13
16.10 Cross-phase modulation 16-13
16.11 Self-steepening 16-14
16.12 Saturable absorption 16-14
16.13 Photonic circuit based on the SA effect 16-16
Questions and problems 16-19
Bibliography 16-20

17 Mode locking 17-1

17.1 The requirement for short-duration optical pulses 17-2
17.2 Mode locking of lasers 17-3
  17.2.1 Longitudinal modes with random phases 17-3
  17.2.2 Longitudinal modes with identical phases 17-3
17.3 Methods of mode locking 17-7
  17.3.1 Active mode locking: the acousto-optic method 17-7
  17.3.2 Synchronous pumping 17-9
  17.3.3 Passive mode locking 17-10
17.4 Shortening of pulse length 17-14
17.5 Spectra of mode-locked laser pulses 17-14
Questions and problems 17-16
Bibliography 17-17

18 Characterization of ultrafast laser pulses 18-1

18.1 Introduction 18-2
18.2 Autocorrelators 18-3
  18.2.1 Intensity autocorrelation 18-3
  18.2.2 Background-free intensity autocorrelation 18-6
  18.2.3 Interferometric autocorrelation 18-10
18.3 Frequency-resolved optical gating 18-12
18.4 Spectral phase interferometry 18-13
18.5 Frequency up- and downconversion 18-16
18.6 Dispersion of ultrafast laser pulses 18-17
  18.6.1 Linear chirp 18-17
  18.6.2 Nonlinear chirp 18-18
18.7 Dispersion compensation 18-18
  18.7.1 Grating compressor 18-19
  18.7.2 Prism compressor 18-21
18.8 Dispersion-free autocorrelator 18-22
18.9 Chirped pulse amplification 18-24
Questions and problems 18-24
Bibliography 18-25

19 Optical phase conjugation 19-1

19.1 Two-beam interference and Bragg diffraction 19-2
19.2 Four-wave mixing: phase conjugation 19-3

19.2.1 Diffraction efficiency and $\chi^{(3)}$ 19-5
19.2.2 Six-wave mixing and $\chi^{(5)}$ 19-6
19.3 Time-reversal in phase conjugation 19-6
19.4 Applications of phase conjugation 19-7
19.4.1 Reversal of the wavefront 19-7
19.4.2 Correction of aberrations and imaging 19-9
Questions and problems 19-10
Bibliography 19-12

20 Multiphoton absorption 20-1

20.1 Higher photon absorption processes 20-2
20.2 Units of absorption cross-sections 20-3
20.3 Selection rules 20-4
20.3.1 Advantage of multiphoton processes 20-4
20.4 Reverse saturable absorption 20-5
20.4.1 Excited-state absorption 20-6
20.4.2 Free-carrier absorption 20-6
20.4.3 2PA and MPA processes 20-7
20.5 Estimating the number of photons 20-7
20.6 Second-harmonic or multiphoton emission? 20-8
Questions and problems 20-11
Bibliography 20-11

21 White-light continuum generation 21-1

21.1 Spatial self-phase modulation 21-2
21.2 White-light continuum generation 21-3
21.3 Phenomena responsible for WLC generation 21-4
21.4 Spectrum of the WLC in a water–D_2O mixture 21-5
21.5 Supercontinuum with photonic crystal fiber 21-8
21.5.1 Structure of photonic crystal fiber 21-8
21.5.2 The mechanism responsible for the supercontinuum in PCF 21-9
21.6 Filamentation and conical emission 21-11
21.7 Dark-core beam generation 21-11
Questions and problems 21-13
Bibliography 21-14

22 Semiconductor lasers **22-1**

22.1 Semiconductors 22-2
22.2 Bandgaps in semiconductors 22-3
22.3 Excitons 22-4
22.4 Fermi level 22-5
22.5 Direct and indirect bandgaps 22-6
22.6 Density of states 22-6
22.7 p-type and n-type semiconductors 22-7
22.8 The $p-n$ junction and electrical excitation 22-7
    22.8.1 The light-emitting diode: a forward-biased p–n junction 22-8
    22.8.2 Diode lasers 22-9
22.9 Semiconductor heterostructures 22-10
22.10 Vertical-cavity surface-emitting lasers 22-12
22.11 Quantum cascade laser: a unipolar device 22-12
    22.11.1 Quantum size effect 22-12
    22.11.2 Mechanism of lasing in the QCL 22-12
    22.11.3 Advantages of the QCL over laser diodes 22-14
    Questions and problems 22-15
    Bibliography 22-16

23 Fiber lasers **23-1**

23.1 Fiber laser technology 23-2
    23.1.1 Structure of an optical fiber 23-2
    23.1.2 Acceptance angle and numerical aperture 23-3
23.2 Gain media for fiber lasers 23-5
23.3 Chromatic dispersion and nonlinear effects 23-6
    23.3.1 Material dispersion 23-7
    23.3.2 Mode dispersion 23-7
    23.3.3 Polarization dispersion 23-8
23.4 Optical nonlinearity 23-8
23.5 Fiber amplifiers and lasers 23-10
23.6 Figure-of-eight laser 23-11
    23.6.1 Optical isolator 23-12
    23.6.2 Nonlinear amplifying loop mirror 23-12
    23.6.3 Mode-locked operation in the F8L 23-13
23.7 High-power fiber lasers 23-13
23.8 Raman fiber laser 23-14

23.9 Optical fiber communication 23-15
  23.9.1 Losses due to fiber absorption 23-15
  23.9.2 Fiber scattering losses 23-16
  23.9.3 Gain medium 23-16
  23.9.4 Soliton formation 23-17
  23.9.5 Higher-order dispersion and other effects 23-18
  Questions and problems 23-18
  Bibliography 23-19

24 Coherent radiation obtained using special geometries 24-1

24.1 Mirrorless laser cavities 24-2
  24.1.1 Principle of DFB lasers 24-3
  24.1.2 Ultrashort pulses and the tunability of DFB lasers 24-5
24.2 Coherent radiation based on acceleration of charge 24-5
  24.2.1 Free-electron lasers 24-5
  24.2.2 Extreme UV and soft x-ray lasers 24-6
24.3 Present and future outlook 24-11
  Questions and problems 24-12
  Bibliography 24-14

Appendix A: Suggested further reading A-1

Appendix B: Luminescence B-1

Appendix C: Physical constants C-1

Preface

Lasers are ubiquitous, from deep space communication to lab-on-the-chip to supermarket product scanning. Although they form an integral part of optics and photonics, the modern laser industry has contributed to interdisciplinary areas in scientific research and technology. Therefore, it is an appropriate time to make a self-sufficient, comprehensive text describing laser-related concepts available to beginners. This book aims to do just that. A list of books is provided at the end in an appendix for the reader who wishes to undertake comprehensive study in a particular area. A bibliography at the end of each chapter also connects the reader to original literature. The book is written with the intention of preparing a textbook for undergraduate and graduate students as well as reference material for any student working with lasers in the fields of optics, biosciences, and engineering. Sufficient mathematics, instead of details, have been given for the reader to be able to understand the topic.

The structure of the book is shown schematically in the following chart.

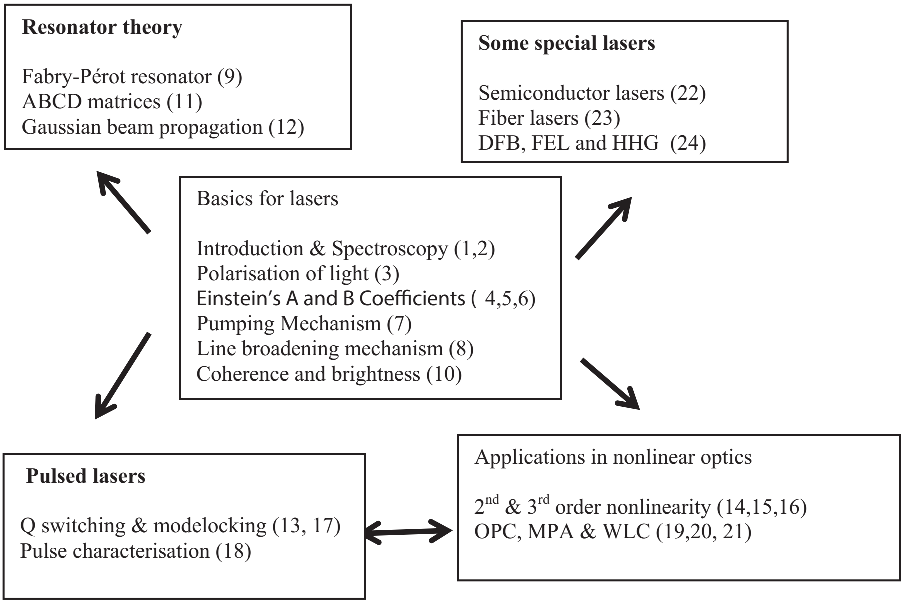


Chart: Schematic of the theme of the book. The chapter numbers are given in parentheses. Arrows indicate the interconnections between the chapters and the subsections.

As can be seen from the chart above, this book has been divided into two sections: **section I:** *Basics of photonics and lasers* and **section II:** *Pulsed lasers and nonlinear optics*. This book has five subsections, which can be grouped as follows:

- Basics of lasers (chapters 1–8 and 10);
- Resonator theory (chapters 9, 11, and 12);

- Pulsed lasers (chapters 13, 17, and 18);
- Nonlinear optical phenomena (chapters 14–16 and 18–21);
- Some special lasers (chapters 22–24).

The book starts with the basics of photons and their connection to light according to EM theory. The subject matter proceeds with the old and traditional subject of spectroscopy and subsequently develops toward the state of the art as the chapters progress. In part I we begin with a look at the basics of photons and the connection between optics and electrodynamics (chapter 1). This part helps the reader to review the study material required to understand the working principle of lasers and some of their applications. Chapter 2 in this part provides the required knowledge of spectroscopy and quantum mechanics. Chapters 4 to 12 are closely related and need to be studied in the given sequence. Chapters 13–21 of part II provide the background and applications of nonlinear optics, which was mainly developed following the invention of ultrafast pulsed lasers. A chapter on semiconductor lasers and one on fiber lasers are separately provided in this section. For the curious reader, a clear distinction between semiconductor lasers (diode lasers, vertical-cavity surface-emitting lasers (VCSELs)) and quantum cascade lasers (QCLs) is elucidated. Some other lasers with unique designs (mirrorless lasers) and lasers in the extreme ultraviolet and soft x-ray regions with pulse durations on the scale of attoseconds are described in chapter 24.

In each chapter, a few questions and end-of-chapter problems are included to aid in the understanding of the material. Most of the problems are not based on numerical answers. For a better understanding of the applications, extra information related to the topic is denoted by a ♣ symbol. Similarly, related information elsewhere in the book has been marked with a ♠ symbol.

Each chapter starts with a summary along with a diagram for those curious about the subject matter. Learning objectives are clearly outlined at the start of each chapter so that students can study on their own. I am conscious of the availability of additional reading material for the different topics spread over a large number of books/ journals. Therefore, full details of the references are given at the end of each chapter. Where appropriate, footnotes are given to help explain the concept further.

For the instructor, the material covered in this book can be used to make a course of about 45–50 classes. The book can also be split into two courses, as follows: (A) fundamentals of lasers and (B) ultrafast lasers and applications in photonics. For course (A), part I can be used with some selected material from part II. On the other hand, for course (B), chapters 13 to 24 must be preceded with introductory material from the previous section, depending on the level of the class. Additionally, some rescheduling may be necessary to interchange the sequence of chapter 17 (mode locking) with chapter 13 (Q-switching).

This book specifically targets the problems faced by research students and professionals in various fields, including biology. For example, the identification of materials based on *second-harmonic generation* or *two-photon absorption* is outlined towards the end of chapter 20. A word for researchers in biology: chapter 20 (multiphoton absorption) may be extremely useful, in addition to chapters 16–19.

Useful data from research papers have been provided as reference materials in a few tables for ready use.

I thank IIT Madras for permitting me to spend four months of sabbatical, during which I stayed in my home town of Champawat to initiate this humongous task. The climate of the Himalayan region and the company of the villagers was just excellent for this task. Besides the experiments with lasers at IIT Madras, my earlier stays at other institutes have created great interest in writing this book. Starting with DSB College (Kumuan University, Nainital), these include the Tata Institute of Fundamental Research, Mumbai, research visits to the Raja Ramanna Center of Advanced Technology (RRCAT) Indore, the Institute for Molecular Science (IMS, Okazaki), Kyoto Institute of Technology (Kyoto), Ludwig Maximilian University (Munich), the Optoelectronic Research Centre, University of Southampton (Southampton), and Dublin City University (Dublin). The academic training received from Professor H B Tripathi and Professor D D Pant as a graduate student followed by the interactions with Professors Keitaro Yoshihara, Satoshi Hirayama, Hrvoje Petek, Eberhard Riedle, and John Costello are gratefully acknowledged. At IIT Madras, the foundation laid down by Professor B M Sivaram and Professor J P Raina in developing ultrafast lasers also motivated the writing of this book. My colleagues Doctors G C Joshi, H C Joshi, K K Pandey, Sanjay Pant, Debi Pant, H Kandori, S Kumazaki, A Yartsev, S Kasiviswanathan, the staff at the instrument center of IMS and the scientists, Doctors S M Oak and K S Bindra of RRCAT, Indore also encouraged the idea of writing this book on several occasions. I thank all my former and present PhD students for the discussions on the topics of the book. A special mention is given to the students of various departments of IIT Madras over last two decades who took the courses I taught on lasers. I acknowledge the help in reading the first version of a few chapters given by Professor S N Thakur, Dr Srini Krishnamurthy (SRI international), Dr R Aravind and Dr Prabha Mandayam (IITM), and Dr Rama Chari (RRCAT). Thanks are due to Professor Anurag Sharma for readily agreeing to write the foreword of this book. Finally, I thank my wife Mamta and my sons Anupam and Sameer for their patience and for helping me in every way they could, during the course of this task.

8th March 2022

Prem B Bisht
IIT Madras, Chennai

Author biography

Prem B Bisht

Prem B Bisht is Professor of Physics at one of the Indian Institutes of Technology, IIT Madras at Chennai. His research interests include ultrafast laser spectroscopy and its application to nanomaterials with a special interest in noncollinear optical parametric amplifiers and fluorescence microscopy. Following his PhD in physics from Kumaun University, Nainital in 1991, Prem has been with IIT Madras since 1997 as a teacher and researcher. Prem has been a JSPS fellow and a member of the Indian Laser Association, the Optical Society of India, the Indian Association of Physics Teachers, the Indian Science Congress, and SPIE and is currently a senior member of Optica. Bisht's scientific career includes collaborations with several national and international laboratories on experimental physics using lasers. He has been associated with the organization of several national and international conferences in ultrafast optics at IIT Madras. He has four patents with two others filed. He has published 250 scientific papers, one edited book, and several book chapters. He has delivered about 100 talks at various institutes and conferences and has supervised 15 PhD students and over 35 UG/PG (Res) students to completion.

Foreword

Photonics and optics have contributed greatly to the development of societies around the world and have provided solutions to many societal problems in recent times. Since the invention of the laser in 1960, progress is this field has been very rapid, leading to developments in nonlinear optics, laser spectroscopy, fiber optics and optical communications, ultrafast optics, optical sensing, and many other areas. These contributions to the welfare and development of mankind were recognized by the UN in their declaration of 2015 as the Year of Light and Light-based Technologies and their subsequent nomination of May 16 as the International Day of Light. Research and education in this field have also seen unprecedented growth over the last few decades. In particular, lasers are central to most developments that have taken place. Many developments and applications involving lasers are still confined to monographs and advanced texts and are therefore largely inaccessible to undergraduate and postgraduate students. There are many textbooks on laser and laser theory, but they do not include recent developments and applications. This new book fills this gap admirably. It describes the fundamentals of lasers, including the necessary basis of optics and photonics, and includes recent applications such as laser spectroscopy, nonlinear optics, ultrafast pulses, supercontinuum generation, and fiber lasers.

This book has many notable features. First and foremost, the author, Professor Prem B Bisht, is a well-known experimentalist in the field with over 35 years of experience in laser spectroscopy and nonlinear optics. His hands-on expertise is amply reflected in the book by examples and descriptions of experiments drawn from his own laboratory. The mathematical details have been kept at the essential level and there is a greater focus on discussing physical understanding and practical details. Second, the material in the book has grown out of his experience of teaching courses at IIT Madras for several years, and the text is an outcome of the organic growth of the author's teaching and research experience. Thus, while the subject dealt with is very advanced, it is brought to an appropriate level for senior undergraduate and postgraduate students. Third, as mentioned above, there is an emphasis on applications and practical details. Some of the notable applications, in addition to the ones already mentioned, are the sensing technique of cavity ring-down spectroscopy and applications of optical parametric processes. Some of the applications are in interdisciplinary areas, such as imaging with nonlinear optics for biotechnology as well as fiber lasers and semiconductor lasers in the area of engineering. The applications of various spectroscopic methods will be useful to chemistry and materials science students. Finally, I personally like the format of this book, which has short sections and a large number of figures. These help the reader to directly focus on the desired topic while using this book as a reference book.

This book is a welcome and valuable addition to the educational literature on the subject and would benefit students in science and engineering who wish to learn about lasers and photonics and their applications.

March 15, 2022

Anurag Sharma
IIT Delhi

Part I

Basics of photonics and lasers

IOP Publishing

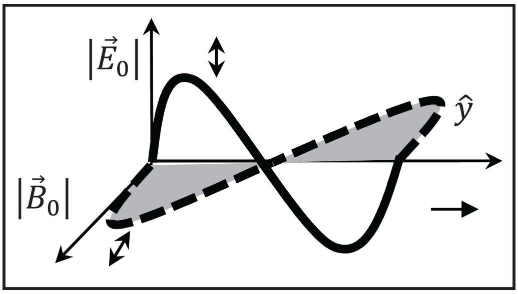
An Introduction to Photonics and Laser Physics
with Applications

Prem B Bisht

Chapter 1

The photon and photonics

The full form of the acronym **‘laser’** *is light amplification by stimulated emission of radiation.* The laser was invented in 1960 as a so-called ‘tool looking for an application’. Within six decades, lasers have found applications in all walks of life, including industries based on them. Micromachining, waveguide fabrication, welding, cutting, nondestructive testing, and pulsed-laser deposition of thin films are some of their applications in materials science. In the field of electrical engineering, fiber optics has revolutionized the field of optical communication. In aerospace engineering applications involving jet and scramjet engines, studies of the mixing of fuel sprays require laser-induced fluorescence techniques. The defense, medical, and cosmetic fields, as well as scientific research, are interdisciplinary areas that make extensive use of lasers. Like the flow of electrons that completes *electronic circuits* in *electronics*, photons are related to *photonic circuits* in the field of *photonics.* Maxwell’s equations suggest that light is an electromagnetic (EM) wave. Therefore, this chapter connects optics with EM theory. The figure shows an electric field (E, in the y direction) and a magnetic field (B, in the x direction), which are mutually perpendicular to each other. The EM wave is propagating in the y direction; the details are given in this chapter.



doi:10.1088/978-0-7503-5226-0ch1

Learning objectives
After reading this chapter, the learner will be able to:
Identify the various branches of photonics;
Relate Maxwell's equation to optics;
Define radiation pressure and the angular momentum of light;
Explain radiation using accelerating charge;
Describe the refractive index and dispersion of a material;
Differentiate between electronic and photonic circuits.

1.1 The photon

Max Planck suggested the idea of energy packets known as 'quanta' in 1900. While Einstein called these packets 'energy particles' in 1905, it took until 1923 for this idea to be reinforced by the discovery of the Compton effect. These particles were named *photons* by Gilbert Lewis in 1926; this term denoted 'carriers of radiant energy'. Just as the electron is associated with electricity, light of wavelength λ or frequency ν consists of photons of energy $h\nu$. Here, h is Planck's constant.

The photon:

(i) has no charge,
(ii) is considered to have zero rest mass but
(iii) carries momentum ($p = h/\lambda$),
(iv) has a constant velocity $(c) \sim 10^8$ m s^{-1} in vacuum,
(v) carries a spin of 1 and thus follows Bose–Einstein statistics,
(vi) is immune to EM noise (as it has no charge), and
(vii) does not undergo photon–photon interactions in linear optics.

The property of photons being *immune to EM noise* makes a light beam a special tool as compared to electrical circuits that are prone to picking up stray EM signals. Similarly, photon–photon interactions cannot take place under normal light levels. In the same way that *electronics* deals with the flow of electrons in electrical circuits, photon-related studies address *photonic circuits* that fall within the domain of *photonics*. This means that the two light rays can cross without interacting with each other. The photon–electron interaction, which falls within the domain of *light–matter interactions*, is an important area of interdisciplinary research. Chapter 2 introduces this aspect, along with spectroscopy.

1.2 Branches of photonics

This term photonics is used to describe the control of photons and the photon nature of light. This is one of the modern area of optics that deals with the technologies used to generate and harness light. 'Laser applications' is an interdisciplinary field that uses the principles of conventional optics, electromagnetism, spectroscopy, and quantum optics. Therefore, several subcategories (shown in figure 1.1) are encompassed by the term *photonics*. In addition, electrodynamics, which is a self-sufficient theory, is used in various areas of optical technologies.

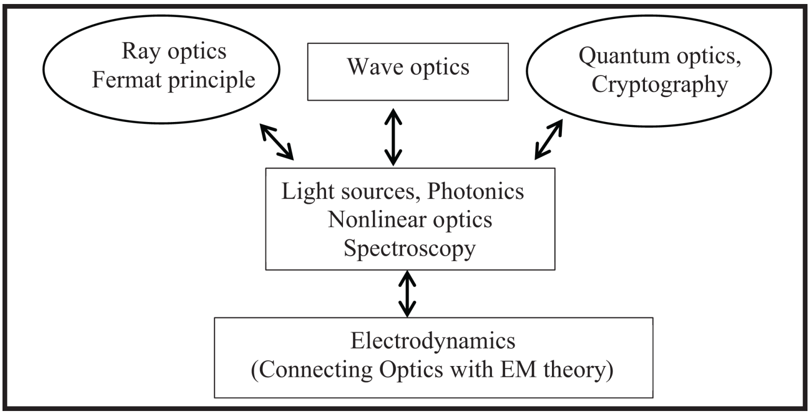


Figure 1.1. Interdisciplinary nature of photonics, illustrating some application areas.

1.2.1 Conventional optics

According to Fermat's principle, light rays travel along the path that can be traversed in the least time. When light propagates through large objects in which the wavelength of light is smaller than the dimensions of the object, its behavior can be explained by drawing light rays. We experience this in the form of reflection or refraction of light rays from a surface. Under such circumstances, the light rays follow the rules of geometrical optics. This method of understanding light falls under *ray optics*.

1.2.2 Electromagnetism and wave optics

Light is an electromagnetic wave and, as such, its electric and magnetic fields are represented in their vector forms (see section 1.3). However, in *wave optics*, the scalar representation of EM fields is sufficient. In Young's double-slit interference experiment, for example, Huygens' principle of secondary wavelets is used to explain wave interference. This can be achieved without taking the components of the EM field into account.

1.2.3 Quantum optics

Certain phenomena cannot be explained using EM theory. Optical phenomena that can only be explained by treating light as a stream of photons, such as coherent states and photon entanglement (♠ see chapter 15) fall within this category. The Mach–Zehnder interferometer (♠ see chapter 9) is used to experimentally test the basic theoretical proposals in quantum optics, such as the entanglement of photons and Bell's inequalities. Quantum cryptography also is the subject of *quantum optics*.

1.2.4 Light–matter interaction or quantum electronics

This topic addresses the interactions of light with matter. The phenomena of absorption and spontaneous and stimulated emission (i.e. the spectroscopy of atoms and molecules) are studied here. Nonlinear optics, bulk spectroscopy, and the spectroscopy of low-dimensional materials in the form of monolayers, quantum wires, or quantum dots fall into this category.

1.2.5 Optoelectronics

This is an area in which both electrical current and light are required for the operation of a device. The presence of electronics in the device controls the optical character of the device. Devices that fall into this category are electronic in nature but evolve light. Examples include the light-emitting diodes, solar cells, and display devices in modern equipment, including smartphones. Edison's bulb may fall into this category as well. Specialized centers are dedicated to this topic worldwide. This research area has immense applications in the photonics industry.

1.2.6 Electro-optics

An optical switch that operates the automated door of an elevator or an office falls into this category. In this field, the electronics in an item of equipment is used to control the device in combination with an optical effect. Electro-optic shutters fall into this category. In addition, the change in the optical response (absorption/transmission) of a material due to AC or DC electric/magnetic fields falls within this area. Examples of devices based on electro-optics include those based on the Kerr effect or Faraday rotation (♠ see chapter 3).

1.2.7 Light-wave technology

The whole of modern-day communication is based on data exchange with a large frequency bandwidth. This includes the communication used by television, the internet, and the telephone. Devices and systems that are used in optical communication and optical signal processing fall into this category. Fiber-optic communication is the key example in this field.

1.3 Maxwell's equations and their connection to optics

Optics is connected to EM theory through Maxwell's equations (MEs). The basic laws of reflection and refraction can be derived from the electric ($\vec{E}$) and magnetic ($\vec{B}$) field vectors via solution of the plane-wave equation. The set of Maxwell's four equations for EM fields in vacuum from classical electrodynamics are written as follows:

$$\begin{array}{ll} \text{(i). } \vec{\nabla}.\,\vec{E} = \dfrac{\rho}{\varepsilon_0} & \text{(ii). } \vec{\nabla}.\,\vec{B} = 0 \\ \text{(Gauss's law)} & \text{(No name)} \\ \text{(iii). } \vec{\nabla} \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} & \text{(iv). } \vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \dfrac{\partial \vec{E}}{\partial t} \\ \text{(Faraday's Law)} & \text{(Ampère's law fixed by Maxwell)} \end{array} \tag{1.1}$$

Here, ϵ_0 and μ_0, are known as the permittivity (in farad m^{-1}) and permeability (in Henry m^{-1}) of free space, respectively; ρ is the charge density in Cm^{-3}, and $\vec{J}$ is the current density in A m^{-2} in the region. It should be noted that these equations are of the *first order* in time and space. The equations do not have symmetry in either the $\vec{E}$ or $\vec{B}$ fields. By working on these equations a little, we can obtain symmetric equations for either of the fields, as follows. For instance, on taking the curl of the Faraday's law (equation (iii)),

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = \vec{\nabla} \times (-)\frac{\partial \vec{B}}{\partial t} \equiv -\frac{\partial}{\partial t}(\vec{\nabla} \times \vec{B}).$$

Using the vector identity $\vec{\nabla} \times \vec{\nabla} \times \vec{E} = \vec{\nabla}(\vec{\nabla}.\ \vec{E}) - \vec{\nabla}^2 E$, the above equation can be rewritten as

$$\vec{\nabla}(\vec{\nabla}.\ \vec{E}) - \vec{\nabla}^2 E = -\frac{\partial}{\partial t}(\vec{\nabla} \times \vec{B}).$$

For charge-free (ρ =0) and current-free ($\vec{J} = 0$)regions, we can use equations (i) and (ii) to write the following wave equation:

$$\frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} - \nabla^2 \vec{E} = 0. \tag{1.2}$$

Here, c is the speed of light $\left(c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}\right)$ in m s^{-1}. We have obtained equation (1.2) for one variable ($\vec{E}$) at the cost of using a *second-order* differential equation. Similarly, one can write the wave equation for the $\vec{B}$ field as well.

We can assume a general solution of equation (1.2) for $\vec{E}(\vec{r},t)$ in units of V m^{-1} as

$$\vec{E}(\vec{r}, t) = |\ E_0\ |\ \hat{n} \cos(\vec{k}.\ \vec{r} - \omega t + \phi). \tag{1.3}$$

Here, E_0 is the amplitude of the wave. For a simple case, we take a wave propagating in the z direction (i.e. $\vec{k}.\ \vec{r} = kz$), as shown in the diagram below (figure 1.2). This is known as the plane-wave solution. The unit vector $\hat{n}$ indicates the direction of

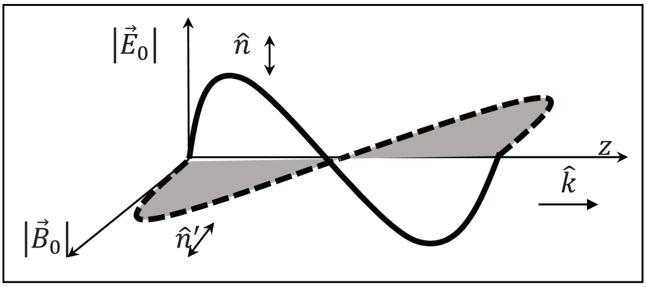


Figure 1.2. The electric field ($\vec{E}_0$), magnetic field ($\vec{B}_0$), and the direction of propagation of an EM wave ($\hat{k}$) make a triad. The polarizations of the field vectors are indicated by $\hat{n}$ and $\hat{n}'$, respectively.

oscillation of $\vec{E}$ and is known as the *polarization* of the field vector; k is the propagation constant or the wavevector, i.e. the number of waves per unit length; ω is the frequency; and ϕ is the phase factor.

In Euler's form, equation (1.3) is the real part of equation (1.4) as follows:

$$\vec{E}(\vec{r},\, t) = E_0\hat{n}e^{i(\vec{k}.\vec{r}-\omega t+\phi)}. \tag{1.4}$$

By using this solution for equation (1.2), we obtain

$$\frac{\partial}{\partial t}(e^{-i\omega t}) = -i\omega e^{-i\omega t};\ \text{and}\nabla(e^{i\vec{k}.\vec{r}}) = i\vec{k}(e^{i\vec{k}.\vec{r}}).$$

From these relations, we can effectively replace $\nabla$with $i\vec{k}$ and $\frac{\partial}{\partial t}$ with $-i\omega$ for plane-wave equations. Now, using ME (iii), we can write the relation between the electric and magnetic field vectors with $\hat{k}$ as follows:

$$\frac{E(\hat{k}\times\hat{n})}{c} = B\hat{n}'.$$

This explains the *transverse nature of the EM wave* indicated in the diagram. The oscillation of the field vectors is perpendicular to the propagation direction of the wave. We recall that this is in contrast to sound waves, in which the rarefaction and densification of the medium's particles takes place in the propagation direction of the wave—for this reason, sound waves are generally called *longitudinal waves.*

The unit vector ($\hat{k}$) indicates the direction of propagation of the wave. From ME (ii), we can see that that the $\vec{B}$ field of an EM wave that has $\hat{n}'$ as its direction of oscillation is perpendicular to $\hat{k}$ (i.e., $\hat{n}'\bullet\hat{k} = 0$). Similarly, $\hat{n}$ and $\hat{k}$ are mutually perpendicular to each other, as can be seen in the figure.

The corresponding Maxwell's equations in matter are written by introducing the displacement vector ($\vec{\mathrm{D}}$ in Cm^{-2}), the available charge and current densities, and the $\vec{H}$ field (in $\mathrm{A\,m}-1$). The $\vec{\mathrm{D}}$ field is defined as $\vec{D} = \epsilon\vec{E}$ and $\vec{H}$ is related to $\vec{B}$ according to $\vec{H} = \frac{\vec{B}}{\mu}$. Here, ϵ and μ are the permittivity and permeability of the *medium*. In metals, the current density ($\vec{J}$) is related to the conductivity (σ) by $\vec{J} = \sigma\vec{E}$. In metals, the square root of the product of the quantities ω, μ, and σ is defined as the inverse of the *skin depth* (s) according to $s = \sqrt{\frac{2}{\omega\mu\sigma}}$ (♠ see question 7). Measured in units of nm, s is the distance over which the amplitude of the EM waves decays to $1/e$ of its original value while propagating in the material with given parameters.

♣ The relation $\vec{J} = \sigma\vec{E}$ is known as 'Ohm's law'. The elementary form of this law is studied in high school. It states that the current (I) across a resistor is proportional to the potential difference (V) between the two ends of the resistor (R), according to $V = IR$. As an exercise, one can obtain this relation by expressing E in terms of V across a metal bar of length L with resistance R and conductivity σ. It is necessary to replace $|\,\vec{J}\,|$ with the current (I) per unit area (A) according to this definition.

Exercise 1.1. A linearly polarized plane EM wave is propagating in the z direction, and its plane of polarization is the x direction. The electric field of the wave has an amplitude given by $\mid E_0 \mid$. The frequency of the wave is ω, and its wave number is k. What are the electric and magnetic fields of the wave?

Solution: The electric field vector of the wave ($\vec{E}$) is $\vec{E} = \mid E_0 \mid \hat{e}_x \cos(kz - \omega t)(Vm^{-1})$. The magnetic field vector is written as $\vec{B} = \frac{(\vec{k}\times\vec{E})}{\omega} = \frac{1}{\omega}k \mid E_0 \mid (\hat{e}_z \times \hat{e}_x)\cos(kz - \omega t)$.

Therefore $\vec{B} = \frac{k}{\omega} \mid E_0 \mid (\hat{e}_y)\cos(kz - \omega t)$ tesla (T). Note that we have ignored the phase part.

Exercise 1.2. (a). Show that the dimension of skin depth (s) is that of length.

(b). What is the typical value of s for copper for the frequencies in the visible region ($\omega\tilde{\ }10^{15}$Hz)?

Solution:

(a). This is easy to verify if we take the dimension of charge to be [Q]. To get the dimension of skin depth (s) as $[L]$, use the dimensions $[T^{-1}]$, $[M\,LQ^{-2}]$, and $[M^{-1}L^{-3}T\,Q^{2}]$ for ω, μ, and σ, respectively.

(b). For copper, the value of $\sigma = 10^{7}(\Omega\mathrm{cm}^{-1})$. Using the value of $\mu = 10^{-6}N/A^{2}$ and an angular frequency for the visible region of $\omega = 10^{15}$Hz, we get the value of $s\tilde{\ }$ 10 nm. This indicates that visible radiation can access the surface of the copper for distances up to the order of 10 nm!

Exercise 1.3. While ME (iii) is responsible for the generation of electricity, which equation is used in the mechanism of cooking by induction stove?

Solution: We know that Faraday's law suggests that changing magnetic fields give rise to current; ME (iv) suggests that a changing electric field gives rise to a magnetic field. In an induction stove, when an AC current passes through the coil of a conducting wire, it induces a magnetic field within the skin depth of the ferromagnetic base of the cooking pan. The eddy currents induced by the magnetic field in the thick base of the cooking pan result in Joule heating due to its resistivity. This heat is responsible for cooking the food contents of the pan by heat conduction.

1.4 A few topics related to lasers and optics

1.4.1 Phase velocity and group velocity

The electric field of the wave (i.e. $\vec{E}(\vec{r}, t)$) is given in three dimensions by equation (1.3). For the one-dimensional case (i.e. along z), it can be rewritten as $\vec{E}(z, t) = \mid E_0 \mid \hat{n}\cos(\vec{k}\,.\,\vec{z} - \omega t + \phi)$. At a certain numerical value of the phase, the movement of the wave can be tracked so that the derivative $\frac{d\phi}{dt} = 0$. The plot of ω vs k can be used to define two important concepts regarding the velocity of the wave: (i) the phase velocity ($\vec{v}$) of the waveform is defined as the ratio of ω and k according to $\mid \vec{v} \mid = \frac{\omega}{k}$; (ii) the instantaneous derivative $\left(\frac{d\omega}{dk}\right)$, on the other hand, comes into the picture when the waveform consists of slightly varying frequencies and wave vectors.

In this case, the waveform propagates as a superposition of two or more modulated waves known as a *wave packet.* The speed of the modulated signal is defined as the *group velocity*, $\left(v_g = \frac{d\omega}{dk}\right)$. For a nondispersive medium, v_g remains equal to the magnitude of $\vec{v}$.

1.4.2 Power flow and Poynting vector

We know, for instance, that heat is also transported by sunlight to the Earth. An important aspect of electromagnetic (EM) wave transport is the propagation of energy. The energy densities in electric (u_{E}) and magnetic (u_{B}) fields are given by $\mathrm{u_E} = \frac{\epsilon 0}{2}E^2$, and $\mathrm{u_B} = \frac{1}{2\mu_0}B^2$, respectively. The energy density of the EM field is given by

$$\mathrm{u_{em}} = \frac{1}{2}\left(\frac{1}{\mu_0}B^2 + \epsilon_0 E^2\right).$$

Maxwell's equations help in the derivation of an energy conservation equation. The energy flow per unit area per unit time is given by the Poynting vector ($\vec{\mathrm{S}}$),

$$\vec{\mathrm{S}} = \frac{1}{\mu_0}(\vec{E} \times \vec{B}). \tag{1.5}$$

1.4.3 Radiation pressure and angular momentum

The tail of a comet in orbit around the Sun always points away from the Sun. This happens due to the radiation pressure exerted by the momentum of the light. From a dimensional analysis, we can see that the magnitude of the linear momentum ($\vec{p} = \hbar\vec{k}$) imparted by a single photon of linearly polarized light is given by the ratio of the energy $\Delta U(=h\nu)$ absorbed to the speed of light, as follows:

$$\vec{\mathrm{p}} = (h\nu/c)\hat{k}. \tag{1.6}$$

Alternatively, the momentum of a photon can be written in terms of its wavelength λ as $p = h/\lambda$. Using equation (1.5), with $|\vec{E}| = c|\vec{B}|$, the density of the linear momentum in the EM field is given by

$$<\boldsymbol{P}_{em}> = \frac{\vec{\mathrm{S}}}{c^2} = \quad \epsilon_0(\vec{E} \times \vec{B}). \tag{1.7}$$

When a stream of N photons per unit area per second falls perpendicularly on a perfectly black surface, it is assumed that all the photons are absorbed, thereby completely transferring their momenta to the surface. The irradiance (I') in units of W m^{-2} and the energy (ΔU) absorbed by the area (A) in time (Δt) are related by $\Delta U = I' A \Delta t$. As the energy is completely absorbed, the gain in momentum based on equation (1.7) is

$$\Delta p = \Delta U/c \equiv I' A \Delta t/c.$$

The force (F) is defined as the rate of change of momentum, i.e., $F = \Delta p/\Delta t \equiv I'A/c$. Therefore, the radiation pressure (P_r) which is equivalent to the force per unit area is given by the following:

$$P_r = I'/c. \tag{1.8}$$

♣ The radiation pressure also has applications in the micromanipulation of particles using laser beams.

For a 100% reflecting surface, the photon undergoes a change of momentum equal to $2p$. Therefore, the pressure exerted on the surface is equal to $2I'/c$.

If a beam of circularly polarized light (♠ see chapter 3) is incident on an absorbing medium, the surface experiences a torque as predicted by classical EM theory. The magnitude of the torque $|\ \zeta\ |$ per unit area is given by

$$\zeta \quad = \frac{I'}{\omega} \equiv \frac{Mh}{2\pi}.$$

Here, M is the total number of photons. This indicates that the angular momentum ($\vec{l}_{em}$) of the photon is $h/2\pi$. This value of intrinsic momentum of photon is known as the *spin angular momentum* (SAM) and its value is taken as 1 unit. While for right circularly polarized light, the spin of the photon is parallel to the direction of propagation, it is antiparallel for left circularly polarized light.

In addition, the angular momentum carried by the *phase part of the wavefront* (also known as the *phase front*) of the light is called the orbital angular momentum (OAM). This is included in the expression for the cross-product of the radius vector $\vec{r}(r,\ 0,\ z)$ of the beam and $\vec{p}_{\mathrm{em}}$ as follows:

$$\vec{l}_{\mathrm{em}} = \vec{r} \times \vec{p}_{\mathrm{em}} \equiv \epsilon_0[\vec{r} \times (\vec{E} \times \vec{B})]. \tag{1.9}$$

Equation (1.9) includes both the SAM and OAM contributions of light. Although the details are beyond the scope of this book, it is sufficient to mention that a light beam with an azimuthal phase dependence of $e^{i|l|\phi'}$ in its cross section has an OAM value that is higher by several factors than the SAM. Here, ϕ' is the azimuthal coordinate and l is an integer known as the *azimuthal mode index* or, the *order* of OAM.

♣ The transfer of SAM was first experimentally observed using a torque experienced by a suspended quarter-wave plate by Beth in 1936.

♣ For linearly polarized light, $<\vec{l}_{em}> =0$. The same is true for unpolarized light, as this is considered to be a mixture of right circularly and left circularly polarized lights. The only difference is that for linearly polarized light, the mixture is coherent (♠ see chapter 3).

♣ It is also of contemporary interest that light beams with different orders of OAM can be produced; these are known as *vortex beams* and find applications in super-resolution light microscopy and photonics.

♣ The magnitude of the OAM of the vortex beam is said to be related to the *topological charge* of the beam by $\pm|l|\hbar$.

1.4.4 Radiation emitted by the accelerated charge

For a single point charge q, the dipole moment can be given as $\vec{p}_{dip}(t) = q\vec{d}(t)$, where $\vec{d}$ is the position of the charge with respect to the origin. An oscillating dipole produces EM radiation in the perpendicular direction. The power (P) radiated by an accelerating charge with acceleration a is given by the generalized Larmor formula as follows:

$$P \propto \frac{\mu_0 q^2 \gamma^6 a^2}{6\pi c}, \tag{1.10}$$

with $\gamma = 1/\sqrt{1 - v^2/c^2}$, where v is the velocity of the relativistic particles. It can be seen that the power radiated by the charged particle is proportional to the square of the acceleration. The factor γ^6 indicates that the radiated power increases drastically for particles with speeds near to the speed of light.

Exercise 1.4. Write down the Poynting vector for the waves mentioned in exercise 1.1 by including the phase part, ϕ_1.

Solution: The electric field in V/m can be written as $\vec{E} = \mid E_0 \mid \hat{e}_x \cos(kz - \omega t + \phi_1)$. By obtaining the corresponding $\vec{B} = \frac{(\vec{k} \times \vec{E})}{\omega}$ (T), the Poynting vector is given by

$$\vec{S} = \frac{1}{\mu_0}(\vec{E} \times \vec{B}) = \frac{k \mid E_0 \mid^2}{\mu_0 \omega}(\hat{e}_z) \cos^2\!\big(kz - \omega t + \phi_1\big)(\mathrm{Wm}^{-2}).$$

1.4.5 Refractive index

The refractive index (n) of a medium is defined as the ratio of the speed of the light in vacuum (c) to that in the medium (v). It should be noted that a change in the speed of the light wave results in a change in its wavelength. However, the oscillation frequency of a wave remains unchanged in any medium. We can also write the expression for the refractive index as follows:

$$n^2 = \frac{\epsilon \mu}{\epsilon_0 \mu_0} \text{ or } \epsilon_r \mu_r. \tag{1.11}$$

For a vacuum, the values of the relative quantities μ_r and ϵ_r are taken to be unity. For most optical media (viz. transparent glass) other than ferromagnetic materials, the value of μ is taken to be the same as that of vacuum. Therefore, the relative permittivity ϵ_r is given by n^2. The quantity ϵ_r often denotes the dielectric constant of the material, which is related to the electrical susceptibility as follows:

$$\epsilon_r \quad \equiv \quad n^2 = (1 + \chi_e).$$

In this formula, n is known as the high-frequency dielectric constant and is a function of the frequency. From here, an estimate of χ_e can be obtained, provided that the dielectric constant of a material is known.

1.4.6 Dispersion curve

In a non-conducting (or dielectric) isotropic medium, the electrons are bound to atoms. If a dielectric is placed in in external electric field ($\vec{E}$), the electronic charge (q) is displaced from its equilibrium position. From classical electrodynamics, we know that the induced polarization $\vec{P}_{\text{ind}}$ for a number of oscillators per unit volume, N, is given by

$$\vec{P}_{\text{ind}} = N\vec{p}_{\text{ind}}.$$

We can write the expression for a damped oscillation forced by an external time-varying field (in the y direction) as

$$m\ddot{\vec{y}} + m\gamma\dot{\vec{y}} + K\vec{y} = q\vec{E}$$

or

$$\ddot{\vec{y}} + \gamma\dot{\vec{y}} + \omega_0^2\vec{y} = \frac{q\vec{E}}{m}, \tag{1.12}$$

where K is the force constant, m is the mass of the electron, ω_0 is the effective resonance frequency ($=\sqrt{K/m}$) of the bound electrons, and γ is the damping constant. Similar to the mass–spring system in mechanics, we assume a solution of equation (1.12) such as $\vec{y} = \vec{y}_0 \quad e^{i\omega t}$ to obtain the complex amplitude of oscillation as follows:

$$\vec{y}_0 = \frac{q\vec{E}}{m(\omega_0^2 - \omega^2 - i\gamma\omega)}.$$

As a result, an induced electric dipole moment $\vec{p}_{\text{ind}}$ is created in the y direction, as given by

$$\vec{p}_{\text{ind}} = \frac{q^2\vec{E}}{m(\omega_0^2 - \omega^2 - i\gamma\omega)}.$$

As a result of the incident $\vec{E}$, the $\vec{P}_{\text{ind}}$ in the dielectric is also given by $\vec{P}_{\text{ind}} = \epsilon_0\chi_{\text{e}}\vec{E}$, and we can obtain the value of χ_{e} as follows:

$$\chi_{\text{e}} = \frac{Nq^2}{\epsilon_0 m(\omega_0^2 - \omega^2 - i\gamma\omega)}.$$

The frequency dependence of the refractive index $n(\omega)$ leads to dispersion, which is represented as a complex quantity due to $n^2 = (1 + \chi_e)$ as follows:

$$n^2 = 1 + \frac{Nq^2}{\epsilon_0 m(\omega_0^2 - \omega^2 - i\gamma\omega)}. \tag{1.13}$$

For a large number of frequencies, this equation can be rewritten as

$$n^2 = 1 + \frac{Nq^2}{\epsilon_0 m}\Sigma_j\left(\frac{f_j}{\omega_0^2 - \omega_j^2 - i\gamma\omega}\right). \tag{1.14}$$

Here, f_j describes the relative potential strengths of the oscillation frequencies. For small values of γ (which are neglected), equation (1.14) can be written as follows:

$$n^2 = 1 + \frac{Nq^2}{\epsilon_0 m}\sum_j\left(\frac{f_j}{\omega_0^2 - \omega_j^2}\right). \tag{1.15}$$

This equation, when written in terms of the wavelength (λ), is known as Sellmeier's formula, an empirical relation proposed by Sellmeier in 1872 as follows:

$$n^2 = 1 + A_0\left(\frac{\lambda^2}{\lambda^2 - \lambda_0^2}\right), \tag{1.16}$$

where $A_0 = \frac{Nq^2\lambda_0}{4\pi^2\epsilon_0 mc^2}$ is known as Sellmeier's coefficient. Equations (1.15) and (1.16) are extremely useful formulae used to estimate the refractive index data for various wavelength regions for applications in linear and nonlinear optics. The original dispersion relation, which did not take account of anomalous dispersion, was proposed by Cauchy as early as 1836 (♠ see question 11).

1.4.7 Normal dispersion and anomalous dispersion

For simple systems such as gaseous media, $n(\omega) \cong 1$, we can write $(n^2 - 1)$ in equation (1.13) as $(n + 1)(n - 1) \approx 2n$. Near the resonant frequency, we can take $|\omega + \omega_0| \approx 2\omega_0$ and $|\omega - \omega_0| \ll \omega_0$. To separate $n(\omega)$ into refractive or real (n') and absorptive or imaginary (n'') parts, we take $n = n' + in''$. So, from equation (1.13),

$$(n' + in'')^2 = 1 + \frac{Nq^2}{\epsilon_0 m(\omega_0^2 - \omega^2 - i\gamma\omega)}.$$

By rationalizing the second term and separating it into real and imaginary parts, we get

$$n'^2 - n''^2 = 1 + \frac{Nq^2}{\epsilon_0 m}\left(\frac{(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}\right) \tag{1.17}$$

$$2n'n'' = \frac{Nq^2}{\epsilon_0 m}\left(\frac{\gamma\omega}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}\right). \tag{1.18}$$

Here, γ is related to the decay rate of the population. We can use these two relations to check the relation at the resonant frequency (i.e. $\omega = \omega_0$) as follows:

$$n'^2 - n''^2 = 1 \tag{1.19}$$

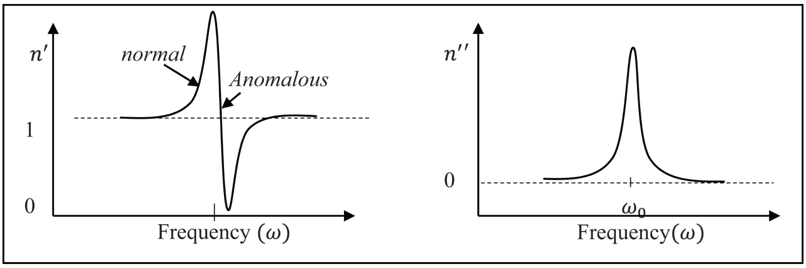


Figure 1.3. The real (n') and imaginary (n'') parts of the refractive index as a function of the frequency (ω). The *normal* and *anomalous* dispersion regimes are also indicated.

and

$$2n'n'' = \frac{Nq^2}{\epsilon_0 m\gamma\omega_0}. \tag{1.20}$$

Using equation (1.20), equation (1.19) can be rewritten as a quadratic equation, as follows:

$n'^4 - n'^2 - \left(\frac{Nq^2}{2m\epsilon_0\gamma\omega_0}\right)^2 = 0$ to give the roots of n'^2 as $n'^2 = \frac{1}{2} \pm \frac{1}{2}\sqrt{1 + \left(\frac{Nq^2}{m\epsilon_0\gamma\omega_0}\right)^2}$.

Only a positive root can represent real values. At very high frequencies, n' will approach unity. The variables n' and n'' are known as optical constants and are plotted in figure 1.3 based on equations (1.17) and (1.18). The plot of n' vs ω is known as the dispersion curve. The value of n' generally increases with frequency (known as normal dispersion), except for a narrow range where it falls sharply followed by a dip. This small region represents anomalous dispersion. The normal and anomalous dispersion regimes are indicated in the figure.

A plot of n'' against frequency shows a maximum at ω_0, indicating the resonant frequency dependence of the absorption coefficient. The anomalous or, negative dispersion regions find applications in the dispersion compensation of ultrafast laser pulses and optical communication, respectively (♠ see chapters 22 and 23 for more details).

1.5 Comparison of an electronic circuit and a photonic circuit

A basic electronics circuit used to charge and discharge a capacitor is shown in figure 1.4. Here, a capacitor (C) is charged by the battery through the resistor (R) when the switch (S_1) is closed (and switch S_2 is open). It is discharged through the resistor when S_1 is open (and S_2 is closed).

A simple photonic circuit can be produced with the help of two polarizers (P1 and P2) placed in the path of a polarized light beam. Depending on the orientation of P2 (i.e. whether it is parallel or perpendicular to the optical axis of P1), a photodetector will record changes in the signal. This photonic circuit can represent the output (i.e. the light sensed by the detector) in terms of binary numbers using one when P1 is parallel to P2 and zero when P1 is perpendicular to P2. (♠ see chapter 3 for detailed description of the phenomenon of polarization).

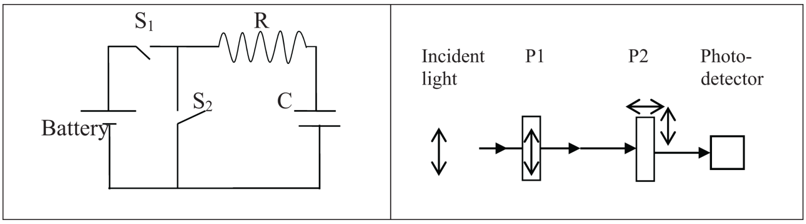


Figure 1.4. Typical electronic circuit used to *charge* and *discharge* a capacitor (C) through a resistor (R) and a battery (left panel). Representation of a photonic circuit (right panel) realized using polarized light (indicated by double arrows) with two polarizers (P1 and P2) and a photodetector.

Table 1.1. Notable Nobel prizes for laser-related work following the invention of the ruby laser in 1960 by Maiman.

Year	Laser-related Nobel prizes
1964	Townes, Basov, and Prokhorov for the **maser–laser** principle.
1971	Gabor for the basic ideas of the **holographic** method.
1981	Nicolaas Bloembergen and Arthur Schawlow for **laser spectroscopy**.
1997	Claude Cohen-Tannoudji, Americans Steven Chu and William Phillips for the development of **methods to cool and trap atoms using laser light**.
1999	Ahmed Zewail for **ultrafast laser techniques**
2000	Zhores Alferov and Herbert Kroemer for **developing semiconductor heterostructures for continuous wave semiconductor diode lasers**.
2001	Eric Cornell, Wolfgang Ketterle, and Carl E. Wieman for **Bose–Einstein condensation**.
2005	Theodor Hansch and John Hall for the **development of laser-based precision spectroscopy**, known as the optical frequency comb technique.
2009	Charles K. Kao, Willard S. Boyle, and G. E. Smith for **fiber-optic communication and the CCD sensor**
2012	Serge Haroche and David J. Wineland for **experimental methods that enable the measurement and manipulation of individual quantum systems**.
2014	Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura for the **invention of efficient blue light-emitting diodes** (Physics)
2014	Eric Betzig, Stefan W. Hell, and William E. Moerner for **stimulated-emission-depletion (STED)** microscopy using laser beams (Chemistry)
2017	Rainer Weiss, Kip S Thorne, and Barry C Barish for **the LIGO detector and the observation of gravitational waves**
2018	Arthur Ashkin, Gerald Mourou, and Donna Strickland for **optical trapping of particles and chirped pulse amplification of laser pulses**

1.6 Nobel prizes related to lasers

When the laser was invented by Maiman in 1960, it was '*an invention searching for an application*'. Since then, lasers have contributed to the fundamental discoveries and applications of modern technologies that could not have been achieved otherwise. Table 1.1 gives some of the notable Nobel prizes for laser-related work in last six decades.

Questions and problems

1. What is the difference between electro-optics and optoelectronics? Give one example of each.
2.
    - (i) With reference to the properties of the photon, why is light immune to EM noise?
    - (ii) How do we eliminate external EM noise in experiments that use electronic devices?
3.
    - (i) Which of MEs is responsible for the generation of electricity, and which one describes the absence of magnetic monopoles?
    - (ii) Estimate the speed of light using MEs in vacuum [Use $\epsilon_0 = 8.85 \times 10^{-12}\,\mathrm{C^2N^{-1}m^{-2}}$ and $\mu_0 = 4\pi \times 10^{-7}\mathrm{NA^{-2}}$].
4. Write down the *plane-wave solution* of a wave equation derived from MEs for charge-free, current-free regions. With reference to plane waves, what is the difference between the terms *wavefront* and *phase front*?
5. Using the solution of the wave equation in Euler's form, use ME (iii) to show that light is an EM wave and that $\vec{E}$ and $\vec{B}$ are perpendicular to each other.
6. If ρ_f and J_f are corresponding 'free' charge and current densities, respectively, $\vec{\mathrm{D}}$ and $\vec{H}$ are the displacement vectors and $\vec{H}$ the field (often referred to as the magnetic field), write down the ME for a medium for which the permittivity and permeability are ϵ and μ, respectively.
7. Assume that the displacement current term is too small to be neglected in ME (iv). For a charge-free and current-free region, let the wave equation be given by equation (1.2) and the speed of light in a medium be $=\sqrt{1/(\epsilon\mu)}$. Using the solution of the wave equation $\vec{E}(\vec{r}, t) = E_0\hat{n}e^{i(\vec{k}.\vec{r}-\omega t)}$, obtain the value of the skin depth for a metal of conductivity σ.
8. Differentiate between the phase velocity and the group velocity for a wave. Show that in the absence of dispersion, both velocities are equal.
9. Describe how an accelerated charge radiates.
10. Half of the Nobel prize was awarded for work on the optical trapping of microparticles in 2018. What is the principle of optical trapping? ♣You may like to read the original paper by *Arthur Ashkin (PNAS*, 94 (10), (1997), pp 4853–4860). You will know that the particle size matters with respect to the wavelength of the light used for optical levitation. The scattering and gradient forces balance to trap the particle on the focussed laser beam.
11. The general form of Sellmeier's empirical relation equation (1.16) is given by $n^2 = 1 + \sum_j \left(\frac{A_j\lambda^2}{\lambda^2 - \lambda_j^2}\right)$. For $\lambda \gg \lambda_j$ and $A_j = A$, prove that it approaches Cauchy's formula $n = C_1 + \frac{C_2}{\lambda^2} + ..$ for $C_1 = \sqrt{(1 + A)}$ and $C_2 = \frac{A\lambda_0^2}{2\sqrt{(1 + A)}}$.
12. How do you define the normal and anomalous dispersion regimes?
13. In the dispersion curve, at what frequency is the absorption coefficient maximized?

14. For a photonic circuit for a logic gate that uses polarisers, write down the truth table, which is similar to that for electronic gates.

Bibliography

[1] Beth R A 1936 Mechanical detection and measurement of the angular momentum of light *Phys. Rev.* **50** 115–25

[2] Fowles G R (ed) 1975 *Introduction to Modern Optics* 2nd edn (New York: Dover)

[3] Griffiths D J (ed) 1989 *Electrodynamics* 2nd edn (Englewood Cliffs, NJ: Prentice-Hall)

[4] Allen L, Beijersbergen M W, Spreeuw R J C and Woerdman J P 1992 Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes *Phys. Rev.* A **45** 8185–9

[5] Sang X, Tienb E-K and Boyraz O 2009 Applications of two-photon absorption in silicon *J. Optoelectron. Adv. Mater.* **11** 15–25

Full list of references

Chapter 1

[1] Beth R A 1936 Mechanical detection and measurement of the angular momentum of light *Phys. Rev.* **50** 115–25

[2] Fowles G R (ed) 1975 *Introduction to Modern Optics* 2nd edn (New York: Dover)

[3] Griffiths D J (ed) 1989 *Electrodynamics* 2nd edn (Englewood Cliffs, NJ: Prentice-Hall)

[4] Allen L, Beijersbergen M W, Spreeuw R J C and Woerdman J P 1992 Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes *Phys. Rev.* A **45** 8185–9

[5] Sang X, Tienb E-K and Boyraz O 2009 Applications of two-photon absorption in silicon *J. Optoelectron. Adv. Mater.* **11** 15–25

Chapter 2

[1] Herzberg G and Spinks J W T 1944 *Atomic Spectra and Atomic Structure.* (New York: Dover)

[2] Herzberg G 1950 *Molecular Spectra and Molecular Structure: Spectra of Diatomic Molecules* (Princeton, NJ: Van Nostrand)

[3] Wilson J and Hawkes J F B 1989 *Optoelectronics: An Introduction* 2nd edn (Upper Saddle River, NJ: Prentice-Hall)

[4] Benwell 1994 *Fundamentals of Molecular and Spectroscopy* (New Delhi: McGraw-Hill Education (India) Pvt Limited)

[5] Lakowicz J R 2013 *Principles of Fluorescence Spectroscopy* (New York: Springer US)

[6] Raman C V and Krishnan K S 1928 A new type of secondary radiation *Nature* **121** 501

[7] Serway R A 1986 *Physics for Scientists and Engineers* 3rd edn (Philadelphia, PA: Saunders College Publishing)

[8] Bisht P B, Petek H, Yoshihara K and Nagashima U 1995 Excited state enol-keto tautomerization in salicylic acid: a supersonic free jet study *J. Chem. Phys.* **103** 5290–307

[9] Sailaja R and Bisht P B 2007 Tunable multiline distributed feedback dye laser based on the phenomenon of excitation energy transfer *Org. Electron.* **8** 175–83

Chapter 3

[1] Anderson J A 1908 The rotation of a crystal of tourmaline by plane polarised light *Nature* **78** 413

[2] Cronin T W and Marshall J 2011 Patterns and properties of polarized light in air and water *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **366** 619–26

[3] Greif S, Borissov I, Yovel Y and Holland R A 2014 A functional role of the sky's polarization pattern for orientation in the greater mouse-eared bat *Nat. Commun.* **5** 4488

[4] Saleh B E A and Teich M C 1991 *Fundamentals of Photonics* (New York: Wiley)

[5] Menzel R P 2001 *Linear and Nonlinear Interactions of Laser Light and Matter* (Berlin: Springer)

[6] Fowles G R 1975 *Introduction to Modern Optics* (New York: Dover)

Chapter 4

[1] Einstein A 1917 Zur Quantentheorie der Strahlung *Phys Z.* **18** 121–8

[2] Gordon JP, Zeiger HJ and Townes CH 1955 The maser—new type of microwave amplifier, frequency standard, and spectrometer *Phys. Rev.* **99** 1264–74

[3] Maiman TH 1960 Stimulated optical radiation in ruby *Nature* **187** 493

[4] Basov N G and Prokhorov A M 1954 Application of molecular beams for the radio-spectroscopic study of rotational molecular spectra *Zh. Eksp. Teor. Fiz.* **27** 431–8

[5] Karlov NV, Krokhin ON and Lukishova SG 2010 History of quantum electronics at the Moscow Lebedev and General Physics Institutes: Nikolaj Basov and Alexander Prokhorov. *Appl. Opt.* **49** F32–46

Chapter 5

[1] Rabek J F 1991 *Photochemistry and Photophysics* vol III (Boca Raton, FL: CRC Press)

[2] Tolman R C 1924 Duration of molecules in upper quantum states *Phys. Rev.* **23** 693–709

[3] Berden G, Peeters R and Meijer G 2000 Cavity ring-down spectroscopy: experimental schemes and applications *Int. Rev. Phys. Chem.* **19** 565–607

[4] O'Keefe A and Deacon D A G 1988 Cavity ring-down optical spectrometer for absorption measurements using pulsed laser sources *Rev. Sci. Instrum.* **59** 2544–51

[5] Stelmaszczyk K, Fechner M and Rohwetter P *et al* 2009 Towards supercontinuum cavity ring-down spectroscopy *Appl. Phys.* B **94** 369–73

Chapter 6

[1] Javan A, Bennett W R and Herriott D R 1961 Population inversion and continuous optical maser oscillation in a gas discharge containing a He–Ne mixture *Phys. Rev. Lett.* **6** 106–10

[2] Huestis D L 1982 Introduction and overview *Gas Lasers* ed ; E W McDaniel and W L Nighan (New York: Academic), **1** 1–34

[3] Phillips D T and West J 1970 The poor man's nitrogen laser *Am. J. Phys.* **38** 655–57

[4] Lofthus A and Krupenie P H 1977 The spectrum of molecular nitrogen *J. Phys. Chem. Ref. Data* **6** 113–307

[5] Diels J-C and Rudolph W 2006 Diagnostic techniques *Ultrashort Laser Pulse Phenomena* 2nd edn (Burlington: Academic),**9** 457–89

[6] Laurain A, Scheller M and Polynkin P 2014 Low-threshold bidirectional air lasing *Phys. Rev. Lett.* **113** 253901

Chapter 7

[1] Huestis D L 1982 Introduction and overview *Gas Lasers* ed E W McDaniel and W L Nighan (New York: Academic), pp 1–34

[2] Javan A, Bennett W R and Herriott D R 1961 Population inversion and continuous optical maser oscillation in a gas discharge containing a He–Ne mixture *Phys. Rev. Lett.* **6** 106–10

[3] Patel C K N 1965 Cw high power N_2–CO_2 laser *Appl. Phys. Lett.* **7** 15–7

[4] Phillips D T and West J 1970 The poor man's nitrogen laser *Am. J. Phys.* **38** 655–57

[5] Heard H G 1963 Ultra-violet gas laser at room temperature *Nature* **200** 667

[6] Lofthus A and Krupenie P H 1977 The spectrum of molecular nitrogen *J. Phys. Chem. Ref. Data* **6** 113–307

[7] Anderson J D 1976 *Thermodynamics and Vibrational Kinetics of the CO_2–N_2–H_2O or He Gas Dynamic Laser* (New York: Academic), pp 15–33

[8] Kasper J V V and Pimentel G C 1965 HCl chemical laser *Phys. Rev. Lett.* **14** 352–54

[9] Yuryshev N P V *et al* 1984 Chemical oxygen-iodine laser utilizing low-strength hydrogen peroxide *Sov. J. Quantum Electron.* **14** 1138

[10] Benard D J, McDermott W C, Pchelkin N R and Bousek R R 1979 Efficient operation of a 100-W transverse-flow oxygen-iodine chemical laser *Appl. Phys. Lett.* **34** 40–1

[11] Manke G, Cooper C, Dass S, Madden T and Hager G 2003 A multi-watt all gas-phase iodine laser (AGIL) *34th AIAA Plasma Dynamics and Lasers Conf. Fluid Dynamics and Co-located Conferences* (Reston, VA: American Institute of Aeronautics and Astronautics)

[12] Svelto O and Hanna D C 1988 *Principles of Lasers* (Berlin: Springer)

[13] Lu J *et al* 2000 Optical properties and highly efficient laser oscillation of Nd:YAG ceramics *Appl. Phys.* B **71** 469–73

Chapter 8

[1] Demtröder W L 2014 *Spectroscopy* (Berlin: Springer)

[2] Preston D W 1996 Doppler-free saturated absorption: laser spectroscopy *Am. J. Phys.* **64** 1432–6

[3] Lamb W E 1964 Theory of an optical maser *Phys. Rev.* **134** A1429–450

[4] Bennett W R 1962 Hole burning effects in a He–Ne optical maser *Phys. Rev.* **126** 580–93

[5] Mitchell A and Zemansky M 1971 *Resonance Radiations and Excited Atoms* (Cambridge: Cambridge University Press)

Chapter 9

[1] Bach R, Pope D, Liou S-H and Batelaan H 2013 Controlled double-slit electron diffraction *New J. Phys.* **15** 33018

[2] Mulligan J F 1998 Who were Fabry and Pérot? *Am. J. Phys.* **66** 797–802

[3] Rayleigh L 1910 CXII. The problem of the whispering gallery *The London, Edinburgh, Dublin Philos. Mag. J. Sci.* **20** 1001–4

[4] Bongu S R *et al* 2014 Influence of localized surface plasmons on Pauli blocking and optical limiting in graphene under femtosecond pumping *J. Appl. Phys.* **116** 073101

[5] Fabry C H and Pérot A 1899 Theorie et applications d'une nouvelle methode de spectroscopic interferentielle *Ann. Chim. Phys.* **16** 115–44

[6] Pérot A and Fabry C 1899 Methodes interferentielles pour la mesure des grandes epaisseurs et la comparaison des longueurs d'onde *Ann. Chim. Phys.* **16** 289–338

Chapter 10

[1] Crease R P 2002 The most beautiful experiment *Phys. World* **15** 17

[2] Sinha U, Couteau C, Jennewein T, Laflamme R and Weihs G 2010 Ruling out multi-order interference in quantum mechanics *Science* **329** 418–21

Chapter 11

[1] Eakin D M and Davis S P 1966 An application of matrix optics *Am. J. Phys.* **34** 758–61

[2] Halbach K 1964 Matrix representation of gaussian optics *Am. J. Phys.* **32** 90–108

[3] Tovar A A and Casperson L W 1995 Generalized Sylvester theorems for periodic applications in matrix optics *J. Opt. Soc. Am.* A **12** 578–90

[4] Dantham V R, Bisht P B and Namboodiri C K R 2011 Enhancement of Raman scattering by two orders of magnitude using photonic nanojet of a microsphere *J. Appl. Phys.* **109** 103103

Chapter 12

[1] Turyshev S (ed) 2009 *From Quantum to Cosmos* (Singapore: World Scientific)

[2] Siegman A E 1986 *Lasers* (Mill Valley, CA: University Science)

[3] Fowles G R 1975 *Introduction to Modern Optics* 2nd edn (New York: Dover Publications)

[4] Feng S and Winful H G 2001 Physical origin of the Gouy phase shift *Opt. Lett.* **26** 485–7

[5] Gouy L G 1890 Sur une propriete nouvelle des ondes lumineuses *C. R. Acad. Sci., Paris* **110** 1251

[6] Rubinowicz A 1938 On the anomalous propagation of phase in the focus *Phys. Rev.* **54** 931

[7] Gouy L G 1890 Sur la propagation anomale des ondes *Compt. Rendue Acad. Sci. Paris* **111** 33

Chapter 13

[1] Muybridge E photographer. (ca. 1878) The Horse in motion. 'Sallie Gardner,' owned by Leland Stanford; running at a 1:40 gait over the Palo Alto track, 19th June/ Muybridge. California Palo Alto, ca. 1878. [Photograph] Retrieved from the Library of Congress, https://loc.gov/item/97502309/

[2] Edgerton H E Bullet through Apple, 1964, printed 1984, dye transfer print, Smithsonian American

[3] Collins R J and Kisliuk P 1962 Control of population inversion in pulsed optical masers by feedback modulation *J. Appl. Phys.* **33** 2009–11

[4] Maydan D and Chesler R B 1971 *Q*-switching and cavity dumping of Nd:YAG lasers *J. Appl. Phys.* **42** 1031–4

[5] McClung F J and Hellwarth R W 1962 Giant optical pulsations from ruby *J. Appl. Phys.* **33** 828

[6] Wagner W G and Lengyel B A 1963 Evolution of the giant pulse in a laser *J. Appl. Phys.* **34** 2040

Chapter 14

[1] Shen Y R 2003 *The Principles of Nonlinear Optics* (New York: Wiley Interscience)

[2] Boyd R W 2003 *Nonlinear Optics* 2nd edn (New York: Academic)

[3] Bass M, Franken P A, Ward J F and Weinreich G 1962 Optical rectification *Phys. Rev. Lett.* **9** 446–8

[4] Bloembergen N, Chang R K, Jha S S and Lee C H 1968 Optical second-harmonic generation in reflection from media with inversion symmetry *Phys. Rev.* **174** 813–22

[5] Burresi M, van Oosten D, Kampfrath T, Schoenmaker H, Heideman R, Leinse A and Kuipers L 2009 Probing the magnetic field of light at optical frequencies *Science* **326** 550–3

[6] Franken P A, Hill A E, Peters C W and Weinreich G 1961 Generation of optical harmonics *Phys. Rev. Lett.* **7** 118–9

[7] Tomasino A, Parisi A, Stivala S, Livreri P, Cino A C, Busacca A C and Morandotti R 2013 Wideband THz time domain spectroscopy based on optical rectification and electro-optic sampling *Sci. Rep.* **3** 3116

Chapter 15

[1] Boyd R W 2003 *Nonlinear Optics* 2nd edn (New York: Academic)

[2] Sutherland R and Thompson B 2003 *Handbook of Nonlinear Optics* (Boca Raton, FL: CRC Press)

[3] Giordmaine J A and Miller R C 1965 Tunable coherent parametric oscillation in $LiNbO_3$ at optical frequencies *Phys. Rev. Lett.* **14** 973–6

[4] Hong C K, Ou Z Y and Mandel L 1987 Measurement of subpicosecond time intervals between two photons by interference *Phys. Rev. Lett.* **59** 2044–6

[5] Halbout J, Blit S, Donaldson W and Chung T Oct. 1979 Efficient phase-matched second-harmonic generation and sum-frequency mixing in urea *IEEE J. Quantum Electron* **15** 1176–80

[6] Yamada M, Nada N, Saitoh M and Watanabe K 1993 First-order quasi-phase matched $LiNbO_3$ waveguide periodically poled by applying an external field for efficient blue second-harmonic generation *Appl. Phys. Lett.* **62** 435–6

[7] Ukachi T, Lane R J, Bosenberg W R and Tang C I 1992 Phase-matched second-harmonic generation and growth of a *J. Opt. Soc. Am.* B **9** 1128–33

[8] Franken P A, Hill A E, Peters C W and Weinreich G 1961 Generation of optical harmonics *Phys. Rev. Lett.* **7** 118–9

[9] Dehlinger D and Mitchell M W 2002 Entangled photon apparatus for the undergraduate laboratory *Am. J. Phys.* **70** 898–902

[10] Armstrong J A, Bloembergen N, Ducuing J and Pershan PS 1962 Interactions between light waves in a nonlinear dielectric *Phys. Rev.* **127** 1918–37

[11] Kim B-J, Choi H–J and Cha M 2012 Angle-tuned second-harmonic generation in periodically-poled lithium niobate *Appl. Phys.* B **107** 349–53

[12] Wilhelm T, Piel J and Riedle E 1997 Sub-20-fs pulses tunable across the visible from a blue-pumped single-pass noncollinear parametric converter *Opt. Lett.* **22** 1494–6

[13] Nautiyal A 2009 *PhD Thesis* (IIT Madras)

[14] Abramczyk H 2005 *Introduction to Laser Spectroscopy* (Amsterdam: Elsevier)

Chapter 16

[1] Bokor J, Bucksbaum P H and Freeman R R 1983 Generation of 35.5-nm coherent radiation *Opt. Lett.* **8** 217–9

[2] Deeg F W and Fayer M D 1989 Analysis of complex molecular dynamics in an organic liquid by polarization selective subpicosecond transient grating experiments *J. Chem. Phys.* **91** 2269–79

[3] Sheik-Bahae M *et al* 1990 Sensitive measurement of optical nonlinearities using a single beam *IEEE J. Quantum Electron.* **26** 760–9

[4] Klewitz S *et al* 1996 Tunable stimulated Raman scattering by pumping with Bessel beams *Opt. Lett.* **21** 248–50

[5] Sailaja R, Sreeja V and Bisht PB 2005 Studies of self-phase modulation under cw and picosecond laser pumping: White light continuum generation in water *Indian J. Phys.* **79** 1299–304

[6] Xing Q, Yoo K M and Alfano R R Apr. 1993 Conical emission by four-photon parametric generation by using femtosecond laser pulses *Appl. Opt.* **32** 2087–9

[7] DeMartini F *et al* 1967 Self-steepening of light pulses *Phys. Rev.* **164** 312–23

[8] Kranitzky W *et al* 1981 A new infrared laser dye of superior photostability tunable to 1.24 μm with picosecond excitation *Opt. Commun.* **36** 149–52

Chapter 17

[1] Smith P W *et al* 1974 Mode-locking of lasers *Prog. Quantum Electron.* **3** 107–229

[2] Haus H A 2000 Mode-locking of lasers *IEEE J. Sel. Top. Quantum Electron.* **6** 1173–85

[3] Benfey D P *et al* 1992 Diode-pumped dye laser analysis and design *Appl. Opt.* **31** 7034–41

[4] Kranitzky W *et al* 1981 A new infrared laser dye of superior photostability tunable to 1.24 μm with picosecond excitation *Opt. Commun.* **36** 149–52

[5] Keller U *et al* 1996 Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers *IEEE J. Sel. Top. Quantum Electron.* **2** 435–53

[6] Saraceno C J *et al* 2012 SESAMs for high-power oscillators: design guidelines and damage thresholds *IEEE J. Sel. Top. Quantum Electron.* **18** 29–41

[7] Ali S A 2013 *Ph D Thesis* IIT Madras

[8] Ell R *et al* 2001 Generation of 5-fs pulses and octave-spanning spectra directly from a Ti: sapphire laser *Opt. Lett.* **26** 373–5

[9] Bausa L E, Vergara I, Jaque F and Garcia Sole J 1990 Ultraviolet laser excited luminescence of Ti-sapphire *J. Phys. Condens. Matter* **2** 9919

[10] Eckstein J N, Ferguson A I and Hänsch T W 1978 High-resolution two-photon spectroscopy with picosecond light pulses *Phys. Rev. Lett.* **40** 847

Chapter 18

[1] Andersson T and Eng S T 1983 Determination of the pulse response from intensity autocorrelation measurements of ultrashort laser pulses *Opt. Commun.* **47** 288–90

[2] Kane D J and Trebino R Feb. 1993 Characterization of arbitrary femtosecond pulses using frequency-resolved optical gating *IEEE J. Quantum Electron.* **29** 571–9

[3] DeLong K W, Trebino R, Hunter J and White W E 1994 Frequency-resolved optical gating with the use of second-harmonic generation *J. Opt. Soc. Am.* B **11** 2206–15

[4] Baltuska A, Pshenichnikov M S and Wiersma D A 1999 Second-harmonic generation frequency-resolved optical gating in the single-cycle regime *IEEE J. Quantum Electron.* **35** 459–78

[5] Trebino R 2000 *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* (Cambridge, MA: Academic Press)

[6] Homann C, Krebs N and Riedle E Aug. 2011 Convenient pulse length measurement of sub-20-fs pulses down to the deep UV via two-photon absorption in bulk material *Appl. Phys.* B **104** 783

[7] Mashiko H, Suda A and Midorikawa K May 2003 All-reflective interferometric autocorrelator for the measurement of ultra-short optical pulses *Appl. Phys.* B **76** 525–30

[8] Gordon J P and Fork R L May 1984 Optical resonator with negative dispersion *Opt. Lett.* **9** 153–5

[9] Martinez O E, Gordon J P and Fork R L Oct. 1984 Negative group-velocity dispersion using refraction *J. Opt. Soc. Am.* A **1** 1003–6

[10] Osvay K, Kovacs A P, Heiner Z, Kurdi G, Klebniczki J and Csatari M 2004 Angular dispersion and temporal change of femtosecond pulses from misaligned pulse compressors *IEEE J. Sel. Top. Quantum Electron.* **10** 213–20

[11] Diels J-C and Rudolph W 2006 *Ultrashort Laser Pulse Phenomena* 2nd edn (Cambridge, MA: Academic Press)

[12] Strickland D and Mourou G 1985 Compression of amplified chirped optical pulses *Opt. Commun.* **56** 219–21

[13] Ali A 2013 *PhD Thesis* IIT Madras

[14] Kalanoor B S 2012 *PhD Thesis* IIT Madras

Chapter 19

[1] Eichler H J, Günter P and Pohl D W 1986 *Laser-Induced Dynamic Gratings* (Berlin: Springer)

[2] Rajesh R J and Bisht P B 2002 Theoretical and experimental studies on photo-physical parameters of N,N′-bis(2,5,-di-tert-butylphenyl)-3,4:9-10-perylenebis(dicarboximide) DBPI by using transient grating technique *Chem. Phys. Lett.* **357** 420–5

[3] Rajesh R J 2003 *PhD Thesis* IIT Madras

[4] Kogelnik H 1969 Coupled wave theory for thick hologram gratings *Bell Syst. Tech. J.* **48** 2909–47

[5] Jena K C 2008 *PhD Thesis* IIT Madras

[6] Pepper D M 1986 Applications of optical phase conjugation *Sci. Am.* **254** 74–83

[7] He G S 2002 Optical phase conjugation: principles, techniques, and applications *Prog. Quantum Electron.* **26** 131–91

[8] Giuliano C R 1981 Applications of optical phase conjugation *Phys. Today* **34** 27

[9] Yariv A 1976 Three-dimensional pictorial transmission in optical fibers *Appl. Phys. Lett.* **28** 88–9

[10] Fisher R A, Suydam B R and Yevick D 1983 Optical phase conjugation for time-domain undoing of dispersive self-phase-modulation effects *Opt. Lett.* **8** 611

[11] Duignan M T, Feldman B J and Whitney W T 1987 Stimulated Brillouin scattering and phase conjugation of hydrogen fluoride laser radiation *Opt. Lett.* **12** 111–3

[12] Whitney W T, Duignan M T and Feldman B J 1992 Stimulated Brillouin scattering phase conjugation of an amplified hydrogen fluoride laser beam *Appl. Opt.* **31** 699–702

[13] Uchida N and Niizeki N 1973 Acoustooptic deflection materials and techniques *Proc. IEEE* **61** 1073–92

[14] Chatterjee M R and Chen S-T 1994 Multiple plane-wave scattering analysis of light diffraction by parallel Raman–Nath and Bragg ultrasonic cells with arbitrary frequency ratios *J. Opt. Soc. Am.* A **11** 637–48

Chapter 20

[1] Göppert M 1929 Über die Wahrscheinlichkeit des Zusammenwirkens zweier Lichtquanten in einem Elementarakt *Naturwissenschaften* **17** 932

[2] Kim D Y *et al* 2005 Large two-photon absorption (2PA) cross-section of directly linked fused diporphyrins *J. Phys. Chem.* A **109** 2996–9

[3] Volkmer A, Hatrick D A and Birch D J S 1997 Time-resolved nonlinear fluorescence spectroscopy using femtosecond multiphoton excitation and single-photon timing detection *Meas. Sci. Technol.* **8** 1339

[4] Parker C A 1968 *Photoluminescence of Solutions* (New York: Elsevier Publishing Co)

[5] Sailaja R, Bisht P B, Singh C P, Bindra K S and Oak S M 2007 Influence of multiphoton events in measurement of two-photon absorption cross-sections and optical nonlinear parameters under femtosecond pumping *Opt. Commun.* **277** 433–9

[6] Ali A, Bisht P B, Senthilmurugan A and Aidhen I S 2011 A new fluorescent probe with stimulated emission and multiphoton absorption properties *Chem. Phys.* **382** 68–73

[7] Perry S W, Burke R M and Brown E B 2012 Two-photon and second harmonic microscopy in clinical and translational cancer research *Ann. Biomed. Eng.* **40** 277–91

Chapter 21

[1] Alfano R R 2016 *The Supercontinuum Laser Source* (New York: Springer)

[2] Brodeur A and Chin S L 1999 Ultrafast white-light continuum generation and self-focusing in transparent condensed media *J. Opt. Soc. Am.* B **16** 637

[3] Dey S, Bongu S R and Bisht P B 2017 Broad band nonlinear optical absorption measurements of the laser dye IR26 using white light continuum Z-scan *J. Appl. Phys.* **121** 113107

[4] Sailaja R, Sreeja V and Bisht P B 2005 Studies of self-phase modulation under CW and picosecond laser pumping: White light continuum generation in water *Indian J. Phys.* **79** 1299–304

[5] Sailaja R 2007 *PhD Thesis* (IIT Madras)

[6] Klewitz S, Leiderer P, Herminghaus S and Sogomonian S 1996 Tunable stimulated Raman scattering by pumping with Bessel beams *Opt. Lett.* **21** 248–50

[7] Russell P 2003 Photonic crystal fibers *Science* **299** 358–62

[8] Ranka J K, Windeler R S and Stentz A J 2000 Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm *Opt. Lett.* **25** 25

[9] Gratson G M *et al* 2006 Direct-write assembly of three-dimensional photonic crystals: conversion of polymer scaffolds to silicon hollow-woodpile structures *Adv. Mater.* **18** 461–5

[10] Ali S A *et al* 2010 Conical emission in β-barium borate under femtosecond pumping with phase matching angles away from second harmonic generation *J. Opt. Soc. Am.* B **27** 1751–6

[11] Couairon A and Mysyrowicz A 2007 Femtosecond filamentation in transparent media *Phys. Rep.* **441** 47–189

[12] Dey S, Rallabandi S, Singh S and Bisht P 2021 Study of a dark core beam generated by nonlinear thermo-optical effect *Opt. Laser Tech* **134** 106652

[13] Kudlinski A *et al* 2009 Dispersion-engineered photonic crystal fibers for CW-pumped supercontinuum sources *J. Light. Technol.* **27** 1556–64

[14] Durbin S D, Arakelian S M and Shen Y R 1981 Laser-induced diffraction rings from a nematic-liquid-crystal *Opt. Lett.* **6** 411–13

[15] Dey S 2021 *PhD Thesis* (IIT Madras)

[16] Ali A 2013 *PhD Thesis* (IIT Madras)

Chapter 22

[1] Wilson J and Hawkes J F B 1989 *Optoelectronics: An Introduction* 2nd edn (Englewood Cliffs, NJ: Prentice-Hall, Inc.)

[2] Stredman B G 2006 *Solid State Electronic Devices* (Englewood Cliffs, NJ: Prentice-Hall)

[3] Holonyak N and Bevacqua S F 1962 Coherent (visible) light emission from $Ga(As_{1-x}P_x)$ junctions *Appl. Phys. Lett.* **1** 82–3

[4] Hino I, Gomyo A, Kobayashi K, Suzuki T and Nishida K 1983 Room-temperature pulsed operation of AlGaInP/GaInP/AlGaInP double heterostructure visible light laser diodes grown by metalorganic chemical vapor deposition *Appl. Phys. Lett.* **43** 987–9

[5] Holonyak N 1997 The semiconductor laser: a thirty-five-year perspective *Proc. IEEE* **85** 1678–93

[6] Sands D 2004 *Diode Lasers* (Boca Raton, FL: CRC Press)

[7] Aspnes D E, Kelso S M, Logan R A and Bhat R 1986 Optical properties of $Al_xGa_{1-x}As$ *J. Appl. Phys.* **60** 754–67

[8] Weber M 1998 *Handbook of Laser Wavelengths* (Boca Raton, FL: CRC Press)

[9] Koyama F, Kinoshita S and Iga K 1989 Room-temperature continuous wave lasing characteristics of a GaAs vertical cavity surface-emitting laser *Appl. Phys. Lett.* **55** 221–2

[10] Faist J *et al* 1994 Quantum cascade laser *Science (80)* **264** 553–6

[11] Faist J 2013 *Quantum Cascade Lasers* (Oxford: Oxford University Press)

[12] Gmachl C *et al* 2001 Recent progress in quantum cascade lasers and applications *Rep. Prog. Phys.* **64** 1533

Chapter 23

[1] Snitzer E 1961 Optical maser action of Nd^{+3} in a barium crown glass *Phys. Rev. Lett.* **7** 444–6

[2] Stone J and Burrus C A 1973 Neodymium-doped silica lasers in end-pumped fiber geometry *Appl. Phys. Lett.* **23** 388–9

[3] Townsend J E S *et al* 1987 Solution-doping technique for fabrication of rare-earth-doped optical fibers *Electron. Lett.* **23** 329–31

[4] Krupke W F 2000 Ytterbium solid-state lasers. The first decade *IEEE J. Sel. Top. Quantum Electron.* **6** 1287–96

[5] Mears R J, Reekie L, Poole S B and Payne D N 1986 Low-threshold tunable CW and Q-switched fiber laser operating at 1.55 μm *Electron. Lett.* **22** 159–60

[6] Okayasu M *et al* 1989 High-power 0.98μm GaInAs strained quantum well lasers for Er^{3+}-doped fiber amplifier *Electron. Lett.* **25** 1563–5

[7] Hasegawa A and Tappert F 1973 Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. I. Anomalous dispersion *Appl. Phys. Lett.* **23** 142–4

[8] Mollenauer L F, Stolen R H and Gordon J P 1980 Experimental observation of picosecond pulse narrowing and solitons in optical fibers *Phys. Rev. Lett.* **45** 1095–8

[9] Sindhu T G, Bisht P B, Rajesh R J and Satyanarayana M V 2000 Effect of higher order nonlinear dispersion on ultrashort pulse evolution in a fiber laser *Microw. Opt. Technol. Lett.* **28** 196–8

[10] Duling I N 1991 Subpicosecond all-fiber erbium laser *Electron. Lett.* **27** 544–5

[11] Richardson D J, Nilsson J and Clarkson W A 2010 High power fiber lasers: current status and future perspectives [invited] *J. Opt. Soc. Am.* B **27** B63–92

[12] Russell P 2003 Photonic crystal fibers *Science (80–).* **299** 358–62

[13] Hill K O and Meltz G 1997 Fiber Bragg grating technology fundamentals and overview *J. Light. Technol.* **15** 1263–76

[14] Grubb S G *et al* 1995 High-power 1.48 μM Cascaded Raman laser in germanosilicate fibers *Optical Amplifiers and Their Applications 18, SaA4* (Washington, D.C.: Optical Society of America)

[15] Agrawal G P 1989 *Nonlinear Fiber Optics* (New York: Academic)

Chapter 24

[1] Kogelnik H and Shank C V 1972 Coupled-wave theory of distributed feedback lasers *J. Appl. Phys.* **43** 2327–35

[2] Scifres D R, Burnham R D and Streifer W 1974 Distributed-feedback single heterojunction GaAs diode laser *Appl. Phys. Lett.* **25** 203–6

[3] Sailaja R and Bisht P B 2007 Tunable multiline distributed feedback dye laser based on the phenomenon of excitation energy transfer *Org. Electron. physics, Mater. Appl.* **8** 175–83

[4] Huang S *et al* 2017 Dual-cavity feedback assisted DFB narrow linewidth laser *Sci. Rep.* **7** 1185

[5] Attwood D S 1999 *X-Rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge: Cambridge University Press)

[6] Popov V S 2004 Tunnel and multiphoton ionization of atoms and ions in a strong laser field (Keldysh theory) *Phys. Usp.* **47** 855

[7] Augst S, Strickland D, Meyerhofer D D, Chin S L and Eberly J H 1989 Tunneling ionization of noble gases in a high-intensity laser field *Phys. Rev. Lett.* **63** 2212–5

[8] Corkum P B 1993 Plasma perspective on strong field multiphoton ionization *Phys. Rev. Lett.* **71** 1994–7

[9] Corkum P B, Burnett N H and Ivanov M Y 1994 Subfemtosecond pulses *Opt. Lett.* **19** 1870–2

[10] Rudawski P *et al* 2013 A high-flux high-order harmonic source *Rev. Sci. Instrum.* **84** 73103

[11] Sokolov A V, Walker D R, Yavuz D D, Yin G Y and Harris S E 2000 Raman generation by phased and antiphased molecular states *Phys. Rev. Lett.* **85** 562–5

[12] Strickland D and Mourou G 1985 Compression of amplified chirped optical pulses *Opt. Commun.* **56** 219–21

[13] Durfee C G *et al* 1999 Phase matching of high-order harmonics in hollow waveguides *Phys. Rev. Lett.* **83** 2187–90

[14] Trebino R 2000 *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* (New York: Academic)

[15] Mourou G and Tajima T M 2011 Intense, shorter pulses *Science (80–)* **331** 41 LP–2

[16] Gibson E A *et al* 2004 High-order harmonic generation up to 250 eV from highly ionized argon *Phys. Rev. Lett.* **92** 33001