An Introduction to Photonics and Laser Physics with Applications

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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.

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

Dedicated to people all over the world.

Contents

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.

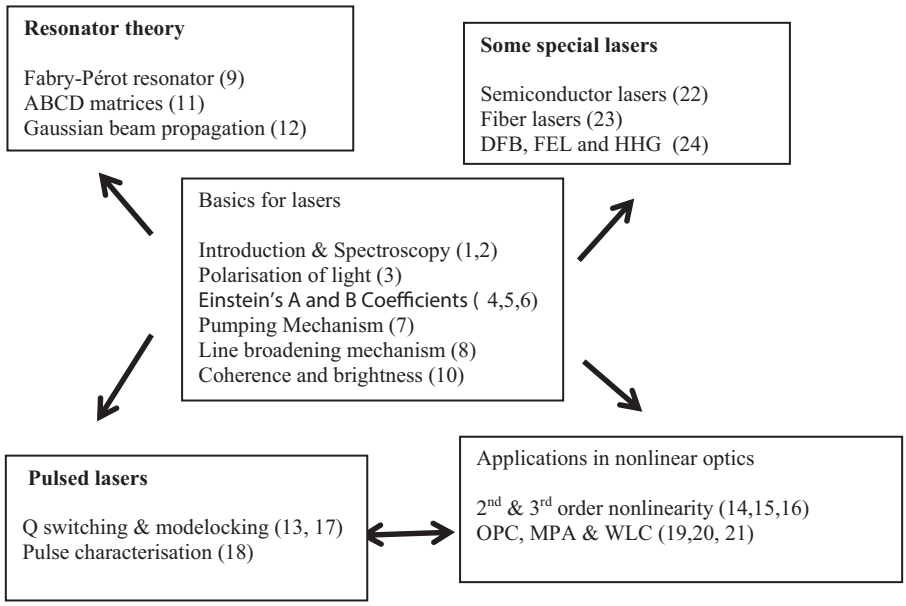

Chart: Schematic of the theme of the book. The chapter numbers are given in parentheses. Arrows indicate the interconnections between the chapters and the subsections.

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

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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

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