Graduate Texts in Physics

K. Thyagarajan
Ajoy Ghatak

Lasers

Fundamentals and Applications

Second Edition

激光原理与应用 第2版

Springer

世界图书出版公司
www.wpcbj.com.cn

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图书在版编目(CIP)数据

激光原理与应用:第 2 版 = Lasers:Fundamentals and Applications Second Edition:英文/(印)西格若简(Thyagarajan,K.)著.—影印本.—北京:世界图书出版公司北京公司,2015.7

ISBN 978-7-5100-9847-5

Ⅰ.①激… Ⅱ.①西… Ⅲ.①激光理论—高等学校—教材—英文②激光应用—高等学校—教材—英文 Ⅳ.①O4

中国版本图书馆 CIP 数据核字(2015)第 153020 号

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激光原理与应用 第 2 版

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责任编辑: 刘 慧 岳利青
装帧设计: 任志远

出版发行: 世界图书出版公司北京公司
地　　址: 北京市东城区朝内大街 137 号
邮　　编: 100010
电　　话: 010-64038355(发行) 64015580(客服) 64033507(总编室)
网　　址: http://www.wpcbj.com.cn
邮　　箱: wpcbjst@vip.163.com
销　　售: 新华书店
印　　刷: 三河市国英印务有限公司
开　　本: 711mm×1245mm 1/24
印　　张: 28
字　　数: 538 千
版　　次: 2015 年 7 月第 1 版 2015 年 7 月第 1 次印刷
版权登记: 01-2015-4929
ISBN 978-7-5100-9847-5 **定价**: 99.00 元

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Graduate Texts in Physics

Graduate Texts in Physics publishes core learning/teaching material for graduate- and advanced-level undergraduate courses on topics of current and emerging fields within physics, both pure and applied. These textbooks serve students at the MS- or PhD-level and their instructors as comprehensive sources of principles, definitions, derivations, experiments and applications (as relevant) for their mastery and teaching, respectively. International in scope and relevance, the textbooks correspond to course syllabi sufficiently to serve as required reading. Their didactic style, comprehensiveness and coverage of fundamental material also make them suitable as introductions or references for scientists entering, or requiring timely knowledge of, a research field.

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ISSN 1868-4513 e-ISSN 1868-4521
ISBN 978-1-4419-6441-0 e-ISBN 978-1-4419-6442-7
DOI 10.1007/978-1-4419-6442-7
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2010930941

Reprint from English language edition:
Lasers: Fundamentals and Applications Second Edition
by K. Thyagarajan and Ajoy Ghatak

To: Abhinandan, Amitabh, Arjun, Divya, Kalyani, Kamayani and Krishnan

Preface

It is exactly 50 years since the first laser was realized. Lasers emit coherent electromagnetic radiation, and ever since their invention, they have assumed tremendous importance in the fields of science, engineering, and technology because of their impact in both basic research as well as in various technological applications. Lasers are ubiquitous and can be found in consumer goods such as music players, laser printers, scanners for product identification, in industries like metal cutting, welding, hole drilling, marking, in medical applications in surgery, and in scientific applications like in spectroscopy, interferometry, and testing of foundations of quantum mechanics. The scientific and technological advances have enabled lasers spanning time scales from continuous operation up to as short as a hundred attoseconds, wavelengths spanning almost the entire electromagnetic spectrum up to the X-ray region, power levels into the terawatt region, and sizes ranging from tiny few tens of nanometers to lasers having a length of 270 km. The range of available power, pulse widths, and wavelengths is extremely wide and one can almost always find a laser that can fit into a desired application be it material processing, medical application, or in scientific or engineering discipline. Laser being the fundamental source with such a range of properties and such wide applications, a course on the fundamentals and applications of lasers to both scientists and engineers has become imperative.

The present book attempts to provide a coherent presentation of the basic physics behind the working of the laser along with some of their most important applications and has grown out of the lectures given by the authors to senior undergraduate and graduate students at the Indian Institute of Technology Delhi.

In the first part of the book, after covering basic optics and basic quantum mechanics, the book goes on to discuss the basic physics behind laser operation, some important laser types, and the special properties of laser beams. Fiber lasers and semiconductor lasers which are two of the most important laser types today are discussed in greater detail and so is the parametric oscillator which uses optical nonlinearity for optical amplification and oscillation and is one of the most important tunable lasers. The coverage is from first principles so that the book can also be used for self study. The tutorial coverage of fiber lasers given in the book is unique and should serve as a very good introduction to the subject of fiber amplifiers and lasers.

Toward the end of the first part of the book we discuss quantization of electromagnetic field and develop the concept of photons, which forms the basic foundation of the field of quantum optics.

The second part of the book discusses some of the most important applications of lasers in spatial frequency filtering, holography, laser-induced fusion, light wave communications, and in science and industry. Although there are many more applications that are not included in the book, we feel that we have covered some of the most important applications.

We believe that the reader should have some sense of perspective of the history of the development of the laser. One obvious way to go about would be to introduce the reader to some of the original papers; unfortunately these papers are usually not easy to read and involve considerable mathematical complexity. We felt that the Nobel lectures of Charles H Townes, Nicolai G Basov, and A M Prokhorov would convey the development of the subject in a manner that could not possibly be matched and therefore in the third part of the book we reproduce these Nobel Lectures. We have also reproduced the Nobel lecture of Theodor W Hansch who in 2005 was jointly awarded the Nobel Prize for developing an optical "*frequency comb synthesizer*," which makes it possible, for the first time, to measure with extreme precision the number of light oscillations per second. The frequency comb techniques described in the lecture are also offering powerful new tools for ultrafast physics.

Numerical examples are scattered throughout the book for helping the student to have a better appreciation of the concepts and the problems at the end of each chapter should provide the student with gaining a better understanding of the basics and help in applying the concepts to practical situations. Some of the problems are expected to help the reader to get a feel for numbers, some of them will use the basic concepts developed in the chapter to enhance the understanding and a few of the problems should be challenging to the student to bring out new features or applications leading perhaps to further reading in case the reader is interested. This book could serve as a text in a course at a senior undergraduate or a first-year graduate course on lasers and their applications for students majoring in various disciplines such as Physics, Chemistry, and Electrical Engineering.

The first edition of this book (entitled LASERS: Theory & Applications) appeared in 1981. The basic structure of the present book remains the same except that we have added many more topics like Erbium Doped Fiber Lasers and Amplifier, Optical Parametric Oscillators, etc. In addition we now have a new chapter on Semiconductor Lasers. A number of problems have now been included in the book which should be very useful in further understanding the concepts of lasers. We have also added the Nobel Lecture of Theodor Hansch. Nevertheless, the reader may find some of the references dated because they have been taken from the first edition.

We hope that the book will be of use to scientists and engineers who plan to study or teach the basic physics behind the operation of lasers along with their important applications.

New Delhi, India

K. Thyagarajan
Ajoy Ghatak

Acknowledgments

At IIT Delhi we have quite a few courses related to Photonics and this book has evolved from the lectures delivered in various courses ranging from *Basics of Lasers* to *Quantum Electronics*, and our interaction with students and faculty have contributed a great deal in putting the book in this form. Our special thanks to Professor M R Shenoy (at IIT Delhi) for going through very carefully the chapter on Semiconductor Lasers and making valuable suggestions and to Mr. Brahmanand Upadhyaya (at RRCAT, Indore) for going through the chapter on Fiber Lasers and for his valuable suggestions. We are grateful to our colleagues Professor B D Gupta, Professor Ajit Kumar, Professor Arun Kumar, Professor Bishnu Pal, Professor Anurag Sharma, Professor Enakshi Sharma, and Dr. Ravi Varshney for continuous collaboration and discussions. Our thanks to Dr. S. V. Lawande (of Bhabha Atomic Research Center in Mumbai) for writing the section on laser isotope separation.

We are indebted to various publishers and authors for their permission to use various figures appearing in the book; in particular, we are grateful to American Institute of Physics, American Association of Physics Teachers, Institute of Physics, UK, Optical Society of America, SPIE, Oxford University Press, IEEE, Laser Focus World and Eblana Photonics for their permissions. Our sincere thanks to Elsevier Publishing Company for permitting us to reproduce the Nobel lectures. We are grateful to Dr. A.G. Chynoweth, Professor Claire Max, Professor Gurbax Singh, Dr. H Kogelnik, Dr. T.A. Leonard, Dr. D. F. Nelson, Dr. R.A. Phillips, Dr. R.W. Terhune, Dr. L.A. Weaver, Ferranti Ltd., and the United States Information service in New Delhi for providing some of the photographs appearing in the book.

One of the authors (AG) is grateful to Department of Science and Technology, Government of India, for providing financial support.

Finally, we owe a lot to our families – particularly to Raji and Gopa – for allowing us to spend long hours in preparing this difficult manuscript and for their support all along.

K. Thyagarajan
Ajoy Ghatak

Milestones in the Development of Lasers and Their Applications

1917: A Einstein postulated stimulated emission and laid the foundation for the invention of the laser by rederiving Planck's law

1924: R Tolman observed that "molecules in the upper quantum state may return to the lower quantum state in such a way to reinforce the primary beam by "*negative absorption*"

1928: R W Landenberg confirmed the existence of stimulated emission and negative absorption through experiments conducted on gases.

1940: V A Fabrikant suggests method for producing population inversion in his PhD thesis and observed that "*if the number of molecules in the excited state could be made larger than that of molecules in the fundamental state, radiation amplification could occur*".

1947: W E Lamb and R C Retherford found apparent stimulated emission in hydrogen spectra.

1950: Alfred Kastler suggests a method of "optical pumping" for orientation of paramagnetic atoms or nuclei in the ground state. This was an important step on the way to the development of lasers for which Kastler received the 1966 Nobel Prize in Physics.

1951: E M Purcell and R V Pound: In an experiment using nuclear magnetic resonance, Purcell and Pound introduce the concept of negative temperature, to describe the inverted populations of states usually necessary for maser and laser action.

1954: J P Gordon, H J Zeiger and C H Townes and demonstrate first MASER operating as a very high resolution microwave spectrometer, a microwave amplifier or a very stable oscillator.

1956: N Bloembergen first proposed a three level solid state MASER

1958: A Schawlow and C H Townes, extend the concept of MASER to the infrared and optical region introducing the concept of the laser.

1959: Gordon Gould introduces the term LASER

1960: T H Maiman realizes the first working laser: Ruby laser

1960: P P Sorokin and M J Stevenson Four level solid state laser (uranium doped calcium fluoride)

1960: A Javan W Bennet and D Herriott invent the He-Ne laser

1961: E Snitzer: First fiber laser.

1961: P Franken; observes optical second harmonic generation

1962: E Snitzer: First Nd:Glass laser

1962: R. Hall creates the first GaAs semiconductor laser

1962: R W Hellwarth invents Q-switching

1963: Mode locking achieved

1963: Z Alferov and H Kromer: Proposal of heterostructure diode lasers

1964: C K N Patel invents the CO_2 laser

1964: W Bridges: Realizes the first Argon ion laser

1964: Nobel Prize to C H Townes, N G Basov and A M Prochorov *"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"*

1964: J E Geusic, H M Marcos, L G Van Uiteit, B Thomas and L Johnson: First working Nd:YAG laser

1965: CD player

1966: C K Kao and G Hockam proposed using optical fibers for communication. Kao was awarded the Nobel Prize in 2009 for this work.

1966: P Sorokin and J Lankard: First organic dye laser

1966: Nobel Prize to A Kastler *"for the discovery and development of optical methods for studying Hertzian resonances in atoms"*

1970: Z Alferov and I Hayashi and M Panish: CW room temperature semiconductor laser

1970: Corning Glass Work scientists prepare the first batch of optical fiber, hundreds of yards long and are able to communicate over it with crystal clear clarity

1971: Nobel Prize: D Gabor *"for his invention and development of the holographic method"*

1975: Barcode scanner

1975: Commercial CW semiconductor lasers

1976: Free electron laser

1977: Live fiber optic telephone traffic: General Telephone & Electronics send first live telephone traffic through fiber optics, 6 Mbit/s in Long Beach CA.

1979: Vertical cavity surface emitting laser VCSEL

1981: Nobel Prize to N Bloembergen and A L Schawlow "*for their contribution to the development of laser spectroscopy*"

1982: Ti:Sapphire laser

1983: Redefinition of the meter based on the speed of light

1985: Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips develop methods to cool and trap atoms with laser light. Their research is helps to study fundamental phenomena and measure important physical quantities with unprecedented precision. They are awarded the Nobel Prize in Physics in 1997.

1987: Laser eye surgery

1987: R.J. Mears, L. Reekie, I.M. Jauncey, and D.N. Payne: Demonstration of Erbium doped fiber amplifiers

1988: Transatlantic fiber cable

1988: Double clad fiber laser

1994: J Faist, F Capasso, D L. Sivco, C Sirtori, A L. Hutchinson, and A Y. Cho: Invention of quantum cascade lasers

1996: S Nakamura: First GaN laser

1997: Nobel Prize to S Chu, C Cohen Tannoudji and W D Philips "*for development of methods to cool and trap atoms with laser light*"

1997: W Ketterle: First demonstration of atom laser

1997: T Hansch proposes an octave-spanning self-referenced universal optical frequency comb synthesizer

1999: J Ranka, R Windeler and A Stentz demonstrate use of internally structured fiber for supercontinuum generation

2000: J Hall, S Cundiff J Ye and T Hansch: Demonstrate optical frequency comb and report first absolute optical frequency measurement

2000: Nobel Prize to Z I Alferov and H Kroemer "*for developing semiconductor heterostructures used in high-speed- and opto-electronics*"

2001: Nobel Prize to E Cornell, W Ketterle and C E Wieman "*for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates*"

2005: H Rong, R Jones, A Liu, O Cohen, D Hak, A Fang and M Paniccia: First continuous wave Raman silicon laser

2005: Nobel Prize to R J Glauber "*for his contribution to the quantum theory of optical coherence*" and to J L Hall and T H Hansch "*for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique*"

2009: Nobel Prize to C K Kao "*for groundbreaking achievements concerning the transmission of light in fibers for optical communication*"

Ref: Many of the data given here has been taken from the URL for Laserfest: http://www.laserfest.org/lasers/history/timeline.cfm

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