OPTICAL SCIENCES

Mikhail A. Noginov

Solid-State Random Lasers

Springer

Random lasers are the simplest sources of stimulated emission without cavity, with the feedback provided by scattering in a gain medium. First proposed in the late 1960s, random lasers have grown into a large research field. This book reviews the history and the state of the art of random lasers, provides an outline of the basic models describing their behavior, and describes the recent advances in the field. The major focus of the book is on solid-state random lasers. However, it also briefly describes random lasers based on liquid dyes with scatterers. The chapters of the book are almost independent of one another. Scientists, engineers, or students interested in any particular aspect of random lasers can read directly the relevant section. Researchers entering the field of random lasers will find in the book an overview of the field of study. Scientists working in the field can use the book as a reference source.

Optical Sciences

Mikhail A. Noginov

Solid-State Random Lasers

ISSN 0342-4111

ISBN 0-387-23913-8

EAN

9 780387 239132 >

Noginov

Solid-State Random Lasers

Mikhail A. Noginov

Solid-State Random Lasers

With 131 Figures

Foreword by V.S. Letokhov

Springer

Mikhail A. Noginov
Center for Materials Research
Dept. of Physics
Norfolk State University
Norfolk, VA 23504
USA

Library of Congress Control Number: 2005924132

ISBN-10: 0-387-23913-8 e-ISBN 0-387-25105-7 Printed on acid-free paper.
ISBN-13: 978-0387-23913-2

Printed in the United States of America. (TC/MV)

9 8 7 6 5 4 3 2 1

springeronline.com

Springer Series in

OPTICAL SCIENCES **105**

Founded by H.K.V. Lotsch

Springer Series in
OPTICAL SCIENCES

The Springer Series in Optical Sciences, under the leadership of Editor-in-Chief *William T. Rhodes*, Georgia Institute of Technology, USA, and Georgia Tech Lorraine, France, provides an expanding selection of research monographs in all major areas of optics: lasers and quantum optics, ultrafast phenomena, optical spectroscopy techniques, optoelectronics, quantum information, information optics, applied laser technology, industrial applications, and other topics of contemporary interest.

With this broad coverage of topics, the series is of use to all research scientists and engineers who need up-to-date reference books.

The editors encourage prospective authors to correspond with them in advance of submitting a manuscript. Submission of manuscripts should be made to the Editor-in-Chief or one of the Editors. See also http://www.springer.de/phys/books/optical_science/

To Natalia, Maxim, and Julia

Foreword

This book reminded me of the unforgettable creative atmosphere in the late 1960s in the laboratory of my Ph.D. advisor N.G. Basov (at that time already a Nobel laureate in physics, who shared the prize in 1964 with A.M. Prokhorov and C.H. Townes). One of the experimental groups at that time included V.S. Zuev, P.G. Kryukov, and R.V. Ambartsumyan, who were working on an exceptionally important problem of amplifying nanosecond pulses in a cascade of ruby amplifiers to ignite a nuclear fusion reaction. I collaborated with this group trying to understand the challenging problems and questions that arose in the process of the experiments. One such problem, related to the strange behavior of a nanosecond pulse in a chain of amplifying crystals, led to the discovery of nonlinear propagation of a front of amplified pulse with a speed greater than the speed of light. A simpler problem, self-excitation of stimulated emission in a cascade of amplifiers by examination of its output with a paper white card, led to the concept of nonresonant intensity feedback without conservation of a phase. At the same time, I realized that this effect takes place in a medium with distributed amplification and scattering if the photon scattering length is significantly smaller than the gain length. In such a medium, there exists an effect of self-confinement of light, which is characterized by a stimulated emission threshold and many other properties of regular lasers, but without spatial coherence of radiation.

Today, I would call such a laser a *laser with incoherent feedback*. These early results and ideas were forgotten. However, 20 years later they were revived in laser-pumped powders of laser crystals. Today the achieved level of understanding of such lasers is high enough to have the results of numerous original publications reviewed in a book. This precise work was done by M.A. Noginov. I believe that this book, useful for many researchers working in the field of quantum electronics, will be a valuable addition to existing books describing different types of lasers.

Moreover, I foresee in the future important applications of random lasers including not only the search for novel laser materials and their express-testing, but also the development of random lasers based on thin scattering films excited by low-energy electrons produced by field-emission cathodes. In this way, one can anticipate the development of new high-brightness displays with an isotropic angular diagram of emission. Possibly, the progress will reach the level of designing thin-layer illumination systems, which can take different shapes on room and building walls, and so on. Future illumination devices probably will be based on controllable stimulated emission rather than noncontrollable or poorly controllable spontaneous emission. Any new effect sooner or later becomes very useful. This surely can be said about solid-state random lasers, and the book presented by M.A. Noginov will facilitate this progress.

Lund-Troitsk, Russia Professor V.S. Letokhov

Preface

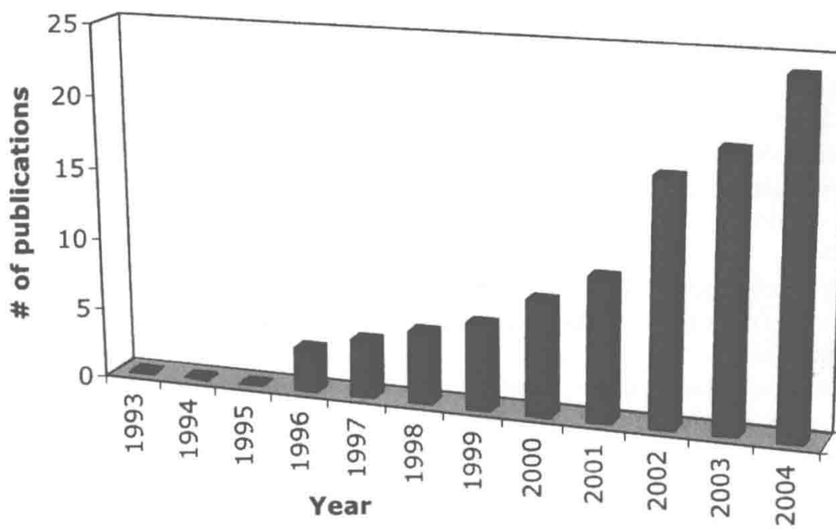
I turn the knob to increase the power of my pumping laser, I turn it further, I turn it a little bit more, and . . . Yes! A red splash crosses the screen of the streak camera. Another splash comes, one more pulse, again and again . . . . It is lasing! The beauty of this moment is irresistible. Those who experienced it will agree with me. Those who did not . . . well, come visit my lab (please, not all at once) and I will show it to you.

But wait a second. *What* is lasing? Does this small amount of powder the size of a cubic millimeter produce a laser emission without any cavity or mirrors? Is this possible?

Yes, it is possible, and the name of this miniature source of stimulated emission is the *random laser* or *powder laser*. First proposed by Letokhov in 1968, the effect of stimulated emission in a scattering medium with gain was studied by a large number of researchers. The wavelengths of random lasers span from ultraviolet to mid-infrared. Random laser materials (in the form of powders and polycrystalline ceramics) include inorganic dielectrics, semiconductors, polymers, and liquids. Some random lasers are based on liquid solutions of dyes with scatterers. The size of random lasers can vary from a cubic micrometer to hundreds of cubic millimeters, their radiation can be pulsed or cw, the coherence of emission can be high or low, and so on. The list of different varieties is long, and in a number of years it may become endless. Similar to the case of regular lasers, which range from semiconductor diode lasers to free electron lasers, various random lasers are extremely different from each other. So, what is a random laser? In this book I answer this question, emphasizing the similarities among various types of random lasers and discussing the differences.

The majority of random lasers are solid-state. Correspondingly, the focus of this book is on solid-state random lasers. However, random lasers based on liquid dyes with scatterers, which were discovered in the early 1990s initiating a renaissance in this field of study, are described as well. The discussion in this book is centered on experimental observations. A large number of extremely diverse theoretical models, which have been proposed over a number of recent years, indicate that the time for a conclusive review of theories describing random lasers has not yet come.

Over the last decade, random lasers have become a rapidly growing field of research. This is evidenced by the chart below showing the numbers of papers on random lasers published in different years. The search was done in INSPEC database using the keywords "random laser," "powder laser," and "plaser." (A number of articles, including nearly a dozen papers published between the late 1960s and mid 1990s, were not found by the search engine.) The review of such a field presents a challenge, inasmuch as interesting new publications appear every month in a constantly increasing rate. To get the book done, I had to finalize its scope at some point. However, I included the latest results that were published when the book was in proof stage.



The book is organized as follows. The early theoretical and experimental studies of random lasers are presented in Chapter 1. The stimulated emission experiments with neodymium-doped powders and ceramics, the materials of choice in our group, are described in Chapter 2. The propagation of pumping light in neodymium random lasers is studied in Chapter 3. The theoretical modeling of stimulated emission in neodymium random lasers, the results of which are applicable to most random lasers with incoherent feedback, is discussed in Chapter 4. Some engineering aspects of the random laser design are exemplified in Chapter 5. Chapter 6 is devoted to random lasers pumped with an electron beam. Random lasers based on semiconductor powders and films, primarily ZnO, are discussed in Chapter 7. Stimulated emission in liquid dyes with scatterers is described in Chapter 8. The rest of Chapter 8 is devoted to polymer film random lasers. Random lasers and relevant phenomena (including cooperative emission in scattering media), which do not fall in any of the categories above, are discussed in Chapter 9. Potential applications of random lasers are discussed in Chapter 10.

The references, which, I believe, include most of the important publications, are aimed to support the discussion of experimental results and theoretical concepts presented in the course of the book. The task of referring to all publications on random lasers has not been attempted. The omission of any particular reference should not be interpreted as a lack of my regard to its merit.

The chapters of the book are almost independent of one another. So, scientists, engineers, and students interested in any particular aspect of random lasers can read the relevant section directly. New researchers and students entering the field of random lasers will find in the book an overview of the research area. Scientists working in this and relevant fields can use the book as a reference source.

In conclusion, it is a pleasure to thank many friends and colleagues for their help and advice at different stages of the research and writing. First of all, I would like to acknowledge Prof. H. John Caulfield, my co-author on many papers and a permanent source of advice, who strongly encouraged me to write this book. I want to express my gratitude to Profs. Vladilen S. Letokhov, Vladislav V. Zolin, and Stephen C. Rand for reviewing the manuscript or its parts and returning comments to me. Prof. Stephen C. Rand contributed some of his unpublished results to Chapter 6. Prof. Letokhov, the founder of the field of random lasers, kindly accepted my invitation to write a foreword for this book. I would also like to thank Dr. Ch. M. Briskina, Prof. Alexander L. Burin, Prof. Hui Cao, Dr. Vladimir P. Drachev, Prof. George B. Loutts, Dr. Andrey K. Sarychev, and Profs. Vladimir M. Shalaev, Diederik S. Wiersma, and Vladisalav S. Zolin for many stimulating discussions.

Several chapters of this book are based on the original research of myself and my colleagues, collaborators, and students. I would like to acknowledge the help of many of my co-authors in different random laser-related papers, especially Dr. Messaoud Bahoura, Dr. Stephen U. Egavievwe, Ichesia N. Fowlkes, Dr. Milan R. Kokta, Prof. Sergey B. Mirov, Kaleem J. Morris, Jakub Novak, Dr. Joseph Paitz, Dr. Irina T. Sorokina, Starre M. Williams, and Guohua Zhu.

My special thanks are due to the editor, Dr. Hans Koelsch, for his great care and support in preparing this book.

This book could not have been possible without the help, advice, encouragement, love, and patience of my wife and co-author of many publications, Prof. Natalia Noginova.

Norfolk, Virginia
USA

Mikhail A. Noginov

Contents