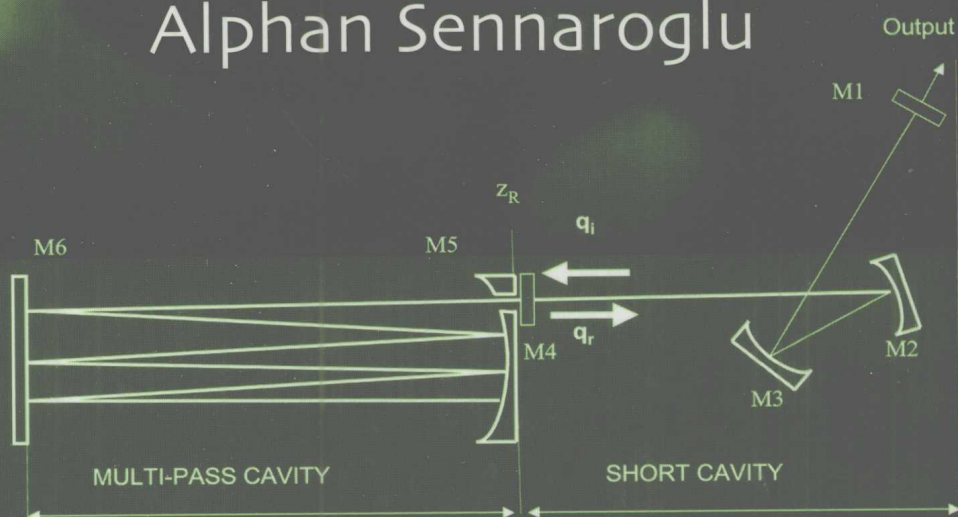


SOLID-STATE LASERS AND APPLICATIONS

edited by
Alphan Sennaroglu



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CRC Press

Taylor & Francis Group
Boca Raton London New York

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6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-3589-2 (Hardcover)
International Standard Book Number-13: 978-0-8493-3589-1 (Hardcover)

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Library of Congress Cataloging-in-Publication Data

Solid-state lasers and applications / Alphan Sennaroglu (editor).
p. cm. -- (Optical science and engineering ; 119)
Includes bibliographical references and index.
ISBN-13: 978-0-8493-3589-1 (alk. paper)
1. Solid-state lasers. I. Sennaroglu, Alphan. II. Series: Optical science and engineering (Boca Raton, Fla.) ; 119.

TA1705.S6748 2007
621.36'61--dc22

2006017534

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Preface

Since the invention of the first ruby laser in 1960, rapid progress has taken place in the development of solid-state lasers. In this class of lasers, optical amplification is produced by using insulating crystals or glasses doped with rare-earth or transition-metal ions. Many favorable characteristics such as chemical stability, mechanical durability, and long operational lifetime have put these laser systems among the most preferred candidates for a wide range of applications in science and technology, including spectroscopy, atmospheric monitoring, micromachining, and precision metrology, among others.

The field of solid-state lasers has become so diverse over the last nearly five decades that it is impossible to provide a complete, in-depth review of all of the developments. We will discuss some of the recent trends and the major directions in which active research continues. First, applications requiring lasers that operate at a specific wavelength prompted much interest in the development of new gain media. This has led to the emergence of many novel solid-state materials that produce laser light in different parts of the electromagnetic spectrum from the ultraviolet to the mid infrared. Second, studies have been directed toward achieving compact, cost-effective designs so that solid-state lasers operated in different regimes can be integrated into complete measurement and characterization systems. Examples include microchip solid-state lasers and multipass-cavity femtosecond lasers. Lastly, significant achievements have taken place in the generation and amplification of ultrashort optical pulses from the femtosecond to nanosecond time scales.

Solid-State Lasers and Applications aims at providing an in-depth account of the major advances that have taken place in the field with an emphasis on the most recent trends. For example, Chapter 2 to Chapter 5 discuss the most recent developments and applications of new solid-state gain media in different wavelength regions. Examples include cerium-doped lasers in the ultraviolet, ytterbium lasers near 1 μm , rare-earth ion-doped lasers in the eye-safe region, and tunable $\text{Cr}^{2+}:\text{ZnSe}$ lasers in the mid infrared. Other chapters focus on specific modes of operation of solid-state laser systems: pulsed microchip lasers (Chapter 1), high-power neodymium lasers (Chapter 6), ultrafast solid-state lasers (Chapter 7 to Chapter 10), amplification of femtosecond pulses with optical parametric amplifiers (Chapter 11), and noise characteristics of solid-state lasers (Chapter 12). A brief overview of each chapter is provided below. Comprising 12 contributed chapters, the handbook targets researchers, graduate students, and engineers who either work in the design of solid-state lasers or who use such systems in applications.

The handbook starts with the chapter on passively Q-switched microchip lasers. An in-depth overview of the basic characteristics of solid-state lasers in general and microchip lasers in particular is first given. Rate equations, energy-level structure of optical amplifiers, and output characteristics of solid-state lasers are discussed. Useful analytical formulas for output pulse energy, peak power, and pulsewidth are derived for passively Q-switched solid-state lasers. The chapter then describes practical demonstrations of passively Q-switched microchip lasers and examines some state-of-the-art applications such as ranging and laser-induced breakdown spectroscopy.

In recent years, ytterbium-doped materials have emerged as important tunable solid-state gain media near $1\text{ }\mu\text{m}$, owing to the development of high-power InGaAs-based pump diodes. Chapter 2 reviews the general characteristics of ytterbium-doped solid-state lasers and materials. Topics include crystal field effects, basic spectroscopic properties of the Yb^{3+} ion, structural effects, lasing efficiency, variation of quantum efficiency in different hosts, and the role of thermal loading. Finally, recent work in the development of Yb-based femtosecond lasers near $1\text{ }\mu\text{m}$ is discussed.

Chapter 3 provides a review of the recent work aimed at the development of $\text{Cr}^{2+}:\text{ZnSe}$ lasers operating in the mid infrared between 2 and $3\text{ }\mu\text{m}$. A brief historical review of tunable solid-state lasers is first given. Synthesis techniques are then discussed with a focus on diffusion doping. After a discussion of the absorption and emission spectroscopy of $\text{Cr}^{2+}:\text{ZnSe}$, pulsed, continuous-wave, and mode-locked operations of $\text{Cr}^{2+}:\text{ZnSe}$ lasers are described. Data showing the dependence of the passive losses, fluorescence lifetime, fluorescence quantum efficiency, and power performance on active ion concentration are presented. Finally, an intracavity-pumped $\text{Cr}^{2+}:\text{ZnSe}$ laser is described with an ultrabroad tuning range between 1880 and 3100 nm.

Tunable lasers in the ultraviolet have important applications in remote sensing, combustion diagnostics, spectroscopy of wide band-gap semiconductors, and medicine. Chapter 4 discusses all-solid-state cerium lasers which operate in the ultraviolet around 300 nm. Physical properties and tradeoffs of different hosts such as $\text{Ce}:\text{LLF}$, $\text{Ce}:\text{YLF}$, $\text{Ce}:\text{LiCAF}$, and others are discussed. Techniques of short pulse generation from Ce^{3+} -doped fluoride lasers are described. Finally, a $\text{Ce}:\text{LiCAF}$ -based chirped-pulse amplification system is described, capable of producing femtosecond pulses with 30-GW peak power near 300 nm.

Wavelengths longer than about $1.4\text{ }\mu\text{m}$ are strongly attenuated in the cornea and the vitreous humor of the eye before reaching the retina. Lasers operating above $1.4\text{ }\mu\text{m}$ hence provide enhanced eye safety and are commonly referred to as *eyesafe lasers*. Chapter 5 focuses on the characteristics of a particular class of eyesafe lasers based on bulk solid-state gain media doped with the rare-earth ions Er^{3+} , Tm^{3+} , and Ho^{3+} . Lasing performance of various Er^{3+} , Tm^{3+} , and Ho^{3+} lasers operating around the respective wavelengths of 1.6, 2.0, and $2.1\text{ }\mu\text{m}$ are reviewed. Energy transfer mechanisms via codoping, the quasi-three-level energy structure of the laser-active ions, and the role of

reabsorption are discussed. In addition, methods of diode pumping, activator-sensitizer pumping, and direct upper-state pumping are described.

High-power neodymium(Nd)-doped lasers are becoming widely used in several industrial applications such as welding. Chapter 6 reviews the state of the art in high-power Nd-based solid-state lasers. Important neodymium hosts such as YAG, vanadate, and YLF are compared. Possible crystal geometries (for example, rod and slab geometries) and pumping configurations are described. Recent developments in continuous-wave and pulsed Nd lasers at 1064 nm are reviewed. Lastly, wavelength conversion from 1064 nm to the visible and ultraviolet by using high-power Nd lasers is discussed.

Chapter 7 provides an in-depth review of ultrafast solid-state lasers. After a historical review of mode locking, progress in the development of pulsed solid-state lasers over the last 10 years is outlined. Requirements on the gain medium for ultrashort pulse generation, effects of dispersion and nonlinearity, and key design rules are discussed. Different mode-locking techniques are described with a particular emphasis on mode locking with semiconductor saturable absorber mirrors (SESAMs). Several examples of solid-state ultrafast laser systems are examined.

Chapter 8 provides a detailed account of the design rules of multipass cavities (MPC) and their application to pulse energy scaling in femtosecond solid-state lasers. Q-preserving multipass cavities are introduced and their analytical design rules are derived. In the case of MPCs with notched mirrors, use of compensating optics to restore the q-preserving nature of the multipass cavity is also discussed. Variation of the pulse repetition rates for different q-preserving configurations is investigated. Finally, experimental realization of MPCs in compact and/or high-energy mode-locked oscillators with different gain media is discussed.

An important route to femtosecond pulse amplification uses the technique of cavity dumping. Chapter 9 first provides a detailed theoretical description of cavity-dumped femtosecond lasers and investigates the output characteristics in various parameter ranges. Experimental realization of a femtosecond cavity-dumped Yb:KYW laser is then described. A very important emerging application of amplified femtosecond pulses is in the microfabrication of photonic devices. The second part of Chapter 9 discusses in detail the interaction of femtosecond pulses with transparent media through multiphoton absorption and other nonlinear processes. Then, application of the cavity-dumped Yb:KYW laser in waveguide writing and fabrication of waveguide lasers at the telecommunication wavelengths is described.

Chapter 10 is devoted to a discussion of octave-spanning Ti:sapphire lasers and their application in precision metrology. In particular, it is shown that besides their well-known importance for ultrafast time-domain spectroscopy, few-cycle Ti:sapphire lasers yield the highest-quality frequency combs for optical frequency metrology. Carrier-envelope phase-stabilization schemes, noise analysis, and pulse formation dynamics are described. The main technical challenges that must be overcome to enable the generation of ultra-broadband spectra are further discussed. An intriguing alternative to optical

clockworks based on difference frequency generation in the infrared spectral region is also presented.

Chapter 11 provides an in-depth review of the state of the art in femtosecond optical parametric amplifiers (OPA). The theory of optical parametric amplification is first reviewed and key design criteria are outlined. OPA systems operating in the visible, near-infrared, and mid-infrared ranges are then described. Use of OPAs in generating pulses shorter than the pump pulses and also their capability in generating pulses with constant carrier-envelope phase are discussed. Finally, an alternative route to petawatt-level peak power generation based on OPAs is presented.

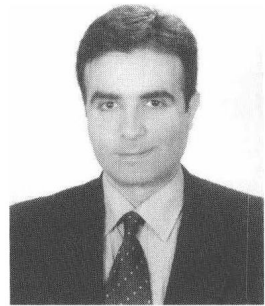
The final chapter of the handbook reviews the subject of noise in solid-state lasers. The authors start with the essential mathematical basics and explain some details of the notation, which often cause confusion in the literature. Then, the noise characteristics of single-frequency lasers are examined first, in order to facilitate the understanding of more complicated systems such as mode-locked lasers. Noise in multimode continuous-wave lasers, Q-switched lasers, and mode-locked lasers is then discussed. Each section begins with a discussion of the basic physics, and most of them end with an overview of experimental methods for measurement.

Many people contributed to the realization of this project. First, I would like to express my gratitude to all of the contributing authors without whose expertise and diligent work, none of this would have been possible. I would also like to thank the acquisitions editor, Taisuke Soda, from Taylor & Francis, for initiating the project. My thanks also go to project coordinator Jill Jurgensen, editorial assistant Jacqueline Callahan, and project editor Jay Margolis, all from Taylor & Francis, for carefully organizing and running the production process. During the preparation of the handbook, I greatly benefited from the support of the Turkish Academy of Sciences in the framework of the Young Scientist Award Program AS/TUBA-GEBIP/2001-1-11 and the NSF-Tubitak travel grant (TBAG-U/110-104T247). Finally, I am indebted to my wife, Figen Sennaroglu, and children, Canan and Özalp Demir, for their patience and never-ending support over the last 2 years.

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Editor

Alphan Sennaroglu was born on November 10, 1966 in Nicosia, Cyprus. He received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Cornell University in 1988, 1990, and 1994, respectively. In 1994, he joined Koç University in Istanbul, Turkey, where he is currently a Professor in the Departments of Physics and Electrical-Electronics Engineering. In 1994, he established the Laser Research Laboratory at Koç University. His research focuses on the development and modeling of solid-state lasers, ultrafast optics, spectroscopic investigation of novel laser and amplifier media, and nonlinear optics. He has authored or coauthored more than 80 journal and conference articles in these fields. He was a visiting researcher at the Massachusetts Institute of Technology during the 2002–2003 academic year and in the summers of 2005 and 2006. In 2004 and 2006, he served as the program chair for the conference on Solid-State Lasers and Amplifiers held as part of the Photonics Europe Meeting in Strasbourg, France.



In December 2005, Alphan Sennaroglu was elected as associate member to the Turkish Academy of Sciences (TUBA). He is a Senior Member of IEEE (Institute of Electrical and Electronics Engineers) and a member of OSA (Optical Society of America), SPIE (The International Society for Optical Engineering), and Optics Committee of Turkey. In 1999, he founded the Leos Turkish Chapter of the IEEE Lasers and Electro-Optics Society and served as the Chapter president between 1999 and 2003. He received the 2002 ICTP/ICO Award (ICTP: International Center for Theoretical Physics, ICO: International Commission for Optics), 2001 Werner-von-Siemens Award (Koç University), 2001 TUBA Young Scientist Award, 1998 Tubitak (Scientific and Technical Research Council of Turkey) Young Scientist Award, Sage Graduate Fellowship (Cornell University, 1989–1990), Sibley Prize of Electrical Engineering (Cornell University, 1988), and AMIDEAST (America-Mideast Educational and Training Services, Inc.) undergraduate scholarship (1984–1988). He married Figen Ecer Sennaroglu in 1995 and has two children, Canan and Özalp Demir.

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