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Walter Koechner

Solid-State Laser Engineering

Sixth Revised and Updated Edition

With 447 Illustrations and 45 Tables

Springer

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To my wife Renate

Preface to the Sixth Edition

This book, written from an industrial vantage point, describes the characteristics, design, and operation of solid-state lasers. As the title implies, the emphasis is placed on the technical aspects of these systems rather than on theoretical concepts. Lengthy mathematical derivations have been avoided because the theory is not treated as an end in itself, but rather serves to explain the experimental results observed in the laboratory. However, there is sufficient theoretical background provided in each chapter to make the book self-contained.

Solid-State Laser Engineering is mainly intended for the practicing scientist or engineer who is interested in the design or use of solid-state lasers. The response from readers has shown that the comprehensive treatment of the subject makes the work useful also to students of laser physics who want to supplement their theoretical knowledge with the engineering aspects of lasers. Although not written in the form of a college text, the book might be used in an advanced college course on laser technology.

After a historical overview, the book starts with a review of the basic concepts of laser physics (Chap. 1). Analytical expressions of the threshold condition, gain, and output of laser oscillators are derived in Chap. 3. An oscillator followed by one or more amplifiers is a common architecture in pulsed solid-state laser systems to boost output energy. Energy storage and gain of amplifiers is discussed in Chap. 4.

Four chapters deal with the basic subsystems of solid-state lasers. These are the active medium, the optical resonator, the pumping system, and the thermal management. Properties of solid-state laser hosts and active ions are reviewed in Chap. 2. Beam divergence and line width of an oscillator are strongly dependent on the spatial and longitudinal mode structure of the resonator. Resonator configurations and characteristics are presented in Chap. 5. Different pump sources and configurations for transferring pump radiation to the active material are discussed in Chap. 6. Thermal gradients set up as a result of heat removal from the active medium have a profound impact on beam quality and output power limitations. Thermal effects and cooling techniques are treated in Chap. 7.

Three chapters are devoted to techniques and devices that can alter the temporal or spectral output of a laser, i.e., Q-switching, mode-locking, and nonlinear devices. Electro-optical, acousto-optical, and passive Q-switches are employed for the generation of laser pulses with a pulsewidth on the order of nanoseconds (Chap. 8). Ultrashort pulses with pulsewidths in the picosecond or femtosecond regime are obtained from solid-state lasers by passive or active mode-locking (Chap. 9). Nonlinear optical devices, such as harmonic generators, parametric oscillators, and Raman oscillators, provide a means of extending the frequency range of available laser sources, and

Brillouin scattering offers the possibility of minimizing distortions in laser amplifiers (Chap. 10). The last chapter discusses the fundamental limit of the output energy or power of a laser system, which is determined by optical damage occurring at the surface or within the bulk of optical components (Chap. 11).

Following the demonstration of the first laser over 45 years ago, an extraordinary number of different types of lasers have been invented using a wide variety of active media and pump techniques to create an inversion. Laser research and engineering has developed into many specialized disciplines depending on the laser medium (solid state, optical fiber, semiconductor, neutral or ionized gas, liquid) and excitation mechanism (optical pumping, electric current, gas discharge, chemical reaction, electron beam).

For historical reasons, solid-state lasers describe a class of lasers in which active ions in crystal or glass host materials are optically pumped to create a population inversion. Other types of lasers that employ solid-state gain media are semiconductor lasers and optical fiber lasers and amplifiers. However, since these lasers employ very specialized technologies and design principles, they are usually treated separately from conventional bulk solid-state lasers.

The design and performance characteristics of laser diode arrays are discussed in this book because these devices are employed as pump sources for solid-state lasers. Fiber lasers, although similar to conventional solid-state lasers as far as the active material and the pump source is concerned, are radically different with respect to beam confinement, mode structure, coupling of pump and laser beams, and the design of optical components.

Gratified by the wide acceptance of *Solid-State Laser Engineering*, I have updated and completely revised the material for this sixth edition. Obsolete material has been deleted, the presentation and organization of the material has been streamlined in some places, and new information has been added to account for recent developments in the areas of diode laser pumping, laser materials, and nonlinear crystals. The sections dealing with the theory of mode-locking, femtosecond lasers, high-efficiency harmonic generation, passive and acousto-optic Q-switching, semiconductor saturable absorber mirrors (SESAM), and periodically poled nonlinear crystals have been greatly expanded. In particular

- the theory of second and third harmonic conversion has been expanded to describe high-efficiency conversion by taking into account pump depletion as well as phase mismatch.
- concave–convex resonators in the presence of strong thermal focusing have been analyzed in more detail compared to previous editions.
- the important technique of mode-locking via a semiconductor saturable absorber mirror (SESAM) is described in some detail.
- a description of the Pound–Drever–Hall (PDH) servo system employed to achieve absolute frequency stability from a laser oscillator has been added.
- the high gain that can be achieved in diode pumped cw Nd:YAG laser amplifiers required a section on cw amplifiers.

- the edge-pumped, conductively cooled slab laser concept is introduced in the section on thermal effects.
- a separate section dealing with multipass amplifiers in rod, slab, and thin disk geometries has been added.
- the threshold condition and slope efficiency of quasi three-level lasers, such as Yb:YAG, has been included in the oscillator performance model.
- an analysis has been added to the phenomenological descripiton of pulse formation in mode-locked lasers.
- the section on Bragg reflection that is fundamental to the operation of an acousto-optic-switch has been enlarged.

Solid-state lasers are a fascinating field to spend an entire scientific or engineering career, because working with these systems involves many scientific and technical disciplines, from solid-state physics and spectroscopy to laser physics, and to the engineering disciplines of optical and mechanical design and digital and analog electronic design.

The development of modern laser system represents a multidisciplinary effort. Based on the performance goals, the design of a new laser system typically starts with a laser physicist defining the system configuration and architecture. This conceptual effort is followed by a detailed optical and mechanical design of the laser components in parallel with the design of the analog and digital subsystems. In addition, manufacturing engineering and quality control play important roles in assuring producibility, reliability, and maintainability of the final product. These combined efforts result in highly reliable, computer-controlled turn-key laser systems employed in research, commercial, industrial, medical, and military applications. Solid-state lasers and systems represent a one-billion dollar industry, and they are the dominant class of lasers for the applications mentioned above.

The material presented in this book reflects the author's experience gained in directing solid-state laser R&D over a 35-year period. This book would not have been possible without the many contributions to the field of laser engineering that have appeared in the open literature and which have been used here as the basic source material. I apologize to any of my colleagues whose work has not been acknowledged or adequately represented in this book.

It is impossible to describe all the new materials, laser configurations, and pumping schemes which have been developed over the last several years. In doing so, the book would merely become a literature survey with commentaries. Readers interested in specific devices are referred to the original literature. Very good sources of information are the *IEEE Journal of Quantum Electronics*, *Optics Letters*, and the conference proceedings of the CLEO and solid-state laser conferences.

My wife Renate not only typed most of the new material for this edition, but without her patience and understanding this book could not have been written.

Great Falls, VA *Walter Koechner*
May 2005

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