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Editor-in-Chief

William T. Rhodes

Georgia Institute of Technology
School of Electrical and Computer Engineering
Atlanta, GA 30332-0250, USA
E-mail: bill.rhodes@ece.gatech.edu

Editorial Board

Ali Adibi

School of Electrical and Computer Engineering
Van Leer Electrical Engineering Building
Georgia Institute of Technology
777 Atlantic Drive NW
Atlanta, GA 30332-0250
Email: adibi@ece.gatech.edu

Toshimitsu Asakura

Hokkai-Gakuen University
Faculty of Engineering
1-1, Minami-26, Nishi 11, Chuo-ku
Sapporo, Hokkaido 064-0926, Japan
E-mail: asakura@eli.hokkai-s-u.ac.jp

Theodor W. Hänsch

Max-Planck-Institut für Quantenoptik
Hans-Kopfermann-Strasse 1
85748 Garching, Germany
E-mail: t.w.haensch@physik.uni-muenchen.de

Takeshi Kamiya

Ministry of Education, Culture, Sports
Science and Technology
National Institution for Academic Degrees
3-29-1 Otsuka, Bunkyo-ku
Tokyo 112-0012, Japan
E-mail: kamiyatk@niad.ac.jp

Ferenc Krausz

Ludwig-Maximilians-Universität München
Lehrstuhl für Experimentelle Physik
Am Coulombwall 1
85748 Garching, Germany
and
Max-Planck-Institut für Quantenoptik
Hans-Kopfermann-Straße 1
85748 Garching, Germany
E-mail: ferenc.krausz@mpq.mpg.de

Bo Monemar

Department of Physics
and Measurement Technology
Materials Science Division
Linköping University
58183 Linköping, Sweden
E-mail: bom@ifm.liu.se

Herbert Venghaus

Heinrich-Hertz-Institut
für Nachrichtentechnik Berlin GmbH
Einsteinufer 37
10587 Berlin, Germany
E-mail: venghaus@hhi.de

Horst Weber

Technische Universität Berlin
Optisches Institut
Straße des 17. Juni 135
10623 Berlin, Germany
E-mail: weber@physik.tu-berlin.de

Harald Weinfurter

Ludwig-Maximilians-Universität München
Sektion Physik
Schellingstraße 4/III
80799 München, Germany
E-mail: harald.weinfurter@physik.uni-muenchen.de

Walter Koechner

Solid-State Laser Engineering

Sixth Revised and Updated Edition

With 447 Illustrations and 45 Tables

 Springer

Dr. Walter Koechner
18496 Yellow Schoolhouse Rd.
Round Hill, VA 20141
U.S.A.

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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 description 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
May 2005

Walter Koechner

Contents

Preface	vii
Introduction	1
1. Energy Transfer Between Radiation and Atomic Transitions	11
1.1 Optical Amplification	11
1.2 Interaction of Radiation with Matter	12
1.2.1 Blackbody Radiation.....	12
1.2.2 Boltzmann's Statistics	13
1.2.3 Einstein's Coefficients	14
1.2.4 Phase Coherence of Stimulated Emission.....	17
1.3 Absorption and Optical Gain	18
1.3.1 Atomic Lineshapes	18
1.3.2 Absorption by Stimulated Transitions	22
1.3.3 Population Inversion	25
1.4 Creation of a Population Inversion	27
1.4.1 The Three-Level System	27
1.4.2 The Four-Level System.....	29
1.4.3 The Metastable Level	30
1.5 Laser Rate Equations.....	32
1.5.1 The Three-Level System	33
1.5.2 The Four-Level System.....	35
1.5.3 Comparison of Three- and Four-Level Lasers.....	36
2. Properties of Solid-State Laser Materials	38
2.1 Overview	40
2.1.1 Host Materials.....	40
2.1.2 Active Ions.....	45
2.2 Ruby.....	51
2.3 Nd:Lasers.....	54
2.3.1 Nd:YAG	54
2.3.2 Nd:Glass	61
2.3.3 Nd:Cr:GSGG.....	64
2.3.4 Nd:YLF.....	66
2.3.5 Nd:YVO ₄	69

2.4	Er:Lasers.....	73
2.4.1	Er:YAG.....	73
2.4.2	Er:Glass.....	75
2.5	Tunable Lasers.....	79
2.5.1	Alexandrite Laser.....	84
2.5.2	Ti:Sapphire.....	88
2.5.3	Cr:LiSAF.....	91
2.5.4	Tm:YAG.....	94
2.6	Yb:YAG.....	97
3.	Laser Oscillator.....	102
3.1	Operation at Threshold.....	103
3.2	Gain Saturation.....	108
3.3	Circulating Power.....	109
3.4	Oscillator Performance Model.....	111
3.4.1	Conversion of Input to Output Energy.....	112
3.4.2	Laser Output.....	118
3.5	Relaxation Oscillations.....	128
3.5.1	Theory.....	128
3.5.2	Spike Suppression.....	132
3.5.3	Gain Switching.....	133
3.6	Examples of Laser Oscillators.....	134
3.6.1	Lamp-Pumped cw Nd:YAG Laser.....	134
3.6.2	Diode Side-Pumped Nd:YAG Laser.....	139
3.6.3	End-Pumped Systems.....	148
3.7	Ring Laser.....	152
4.	Laser Amplifier.....	156
4.1	Single- and Multiple-Pass Pulse Amplifiers.....	157
4.1.1	Pulse Amplification.....	158
4.1.2	Nd:YAG Amplifiers.....	163
4.1.3	Nd:Glass Amplifiers.....	171
4.1.4	Multipass Amplifier Configurations.....	177
4.2	Regenerative Amplifiers.....	180
4.3	cw Amplifiers.....	188
4.4	Signal Distortions.....	190
4.4.1	Spatial Distortions.....	190
4.4.2	Temporal Distortions.....	193
4.5	Depopulation Losses.....	194
4.5.1	Amplified Spontaneous Emission.....	195
4.5.2	Prelasing and Parasitic Modes.....	198
4.5.3	Reduction of Depopulation Losses.....	199
4.6	Self-Focusing.....	200
4.6.1	Whole-Beam Self-Focusing.....	201

4.6.2	Examples of Self-focusing in Nd:YAG Lasers	203
4.6.3	Small-Scale Self-Focusing	206
4.6.4	Suppression of Self-Focusing	207
5.	Optical Resonator	210
5.1	Transverse Modes	210
5.1.1	Intensity Distribution	211
5.1.2	Characteristics of a Gaussian Beam	215
5.1.3	Resonator Configurations	217
5.1.4	Stability of Laser Resonators	221
5.1.5	Diffraction Losses	223
5.1.6	Higher-Order Modes	224
5.1.7	Mode Selection	227
5.1.8	Active Resonator	231
5.1.9	Examples of Resonator Designs	238
5.1.10	Resonator Modeling and Software Packages	254
5.2	Longitudinal Modes	255
5.2.1	The Fabry-Perot Interferometer	255
5.2.2	Laser Resonator with Gain Medium	259
5.2.3	Longitudinal Mode Control	263
5.2.4	Injection Seeding	268
5.3	Intensity and Frequency Control	271
5.3.1	Amplitude Fluctuations	271
5.3.2	Frequency Tuning	274
5.3.3	Frequency Locking	276
5.4	Hardware Design	278
5.5	Unstable Resonators	282
5.5.1	Confocal Positive-Branch Unstable Resonator	284
5.5.2	Negative-Branch Unstable Resonator	287
5.5.3	Variable Reflectivity Output Couplers	289
5.5.4	Gain, Mode Size, and Alignment Sensitivity	295
5.6	Wavelength Selection	297
6.	Optical Pump Systems	300
6.1	Pump Sources	300
6.1.1	Flashlamps	303
6.1.2	Continuous Arc Lamps	334
6.1.3	Laser Diodes	340
6.2	Pump Radiation Transfer Methods	366
6.2.1	Side-Pumping with Lamps	368
6.2.2	Side-Pumping with Diodes	393
6.2.3	End-Pumped Lasers	407
6.2.4	Face-Pumped Disks	418

7. Thermo-Optic Effects	423
7.1 Cylindrical Geometry	426
7.1.1 Temperature Distribution	426
7.1.2 Thermal Stresses	437
7.1.3 Photoelastic Effects	440
7.1.4 Thermal Lensing	442
7.1.5 Stress Birefringence	445
7.1.6 Compensation of Optical Distortions	449
7.2 Slab and Disk Geometries	457
7.2.1 Rectangular-Slab Laser	458
7.2.2 Slab Laser with Zigzag Optical Path	461
7.2.3 Disk Amplifiers and Lasers	469
7.3 End-Pumped Configurations	473
7.3.1 Thermal Gradients and Stress	473
7.3.2 Thermal Lensing	477
7.3.3 Thermal Fracture Limit	479
7.4 Thermal Management	481
7.4.1 Liquid Cooling	481
7.4.2 Conduction Cooling	485
7.4.3 Air/Gas Cooling	486
8. Q-Switching	488
8.1 Q-Switch Theory	488
8.1.1 Fast Q-Switch	490
8.1.2 Slow Q-Switching	493
8.1.3 Continuously Pumped, Repetitively Q-Switched Systems	494
8.2 Mechanical Q-Switches	498
8.3 Electro-Optical Q-Switches	499
8.3.1 KDP and KD*P Pockels Cells	502
8.3.2 LiNbO ₃ Pockels Cells	506
8.3.3 Prelasing and Postlasing	508
8.3.4 Depolarization Losses	511
8.3.5 Drivers for Electro-Optic Q-Switches	514
8.4 Acousto-Optic Q-Switches	514
8.4.1 Bragg Reflection	516
8.4.2 Device Characteristics	519
8.5 Passive Q-Switches	522
8.6 Cavity Dumping	529
9. Mode Locking	534
9.1 Pulse Formation	535
9.2 Passive Mode Locking	542
9.2.1 Liquid Dye Saturable Absorber	543

9.2.2	Coupled-Cavity Mode Locking	546
9.2.3	Kerr Lens Mode Locking	548
9.2.4	Semiconductor Saturable Absorber Mirror (SESAM)	556
9.3	Active Mode Locking	560
9.3.1	cw Mode Locking	561
9.3.2	Transient Active Mode Locking	564
9.4	Picosecond Lasers	568
9.4.1	AM Mode Locking	569
9.4.2	FM Mode Locking	572
9.5	Femtosecond Lasers	575
9.5.1	Laser Materials	575
9.5.2	Dispersion Compensation	576
9.5.3	Examples of Kerr Lens or SESAM Mode-Locked Femtosecond Lasers	579
9.5.4	Chirped Pulse Amplifiers	584
10.	Nonlinear Devices	587
10.1	Nonlinear Optical Effects	587
10.1.1	Second-Order Nonlinearities	589
10.1.2	Third-Order Nonlinearities	590
10.2	Harmonic Generation	592
10.2.1	Basic Theory of Second Harmonic Generation	594
10.2.2	Phase Matching	602
10.2.3	Properties of Nonlinear Crystals	611
10.2.4	Intracavity Frequency Doubling	618
10.2.5	Third Harmonic Generation	625
10.2.6	Examples of Harmonic Generation	629
10.3	Optical Parametric Oscillators	634
10.3.1	Performance Modeling	637
10.3.2	Crystals	649
10.3.3	Quasi Phase Matching	652
10.3.4	Design and Performance	655
10.4	Raman Laser	662
10.4.1	Theory	663
10.4.2	Device Implementation	666
10.5	Optical Phase Conjugation	669
10.5.1	Basic Considerations	669
10.5.2	Material Properties	671
10.5.3	Focusing Geometry	673
10.5.4	Pump-Beam Properties	673
10.5.5	System Design	676
11.	Damage of Optical Elements	680
11.1	Surface Damage	681

11.2	Inclusion Damage	684
11.3	Damage Threshold of Optical Materials	684
11.3.1	Scaling Laws	685
11.3.2	Laser Host Materials	688
11.3.3	Optical Glass	689
11.3.4	Nonlinear Crystals	690
11.3.5	Dielectric Thin Films	694
11.4	System Design Considerations	698
11.4.1	Choice of Materials	698
11.4.2	Design of System	699
11.4.3	System Operation	700
Appendix A	Laser Safety	702
Appendix B	Conversion Factors and Constants	708
Appendix C	Definition of Symbols	711
References		716
Subject Index		742