

Principles of Lasers
THIRD EDITION

Principles of Lasers

THIRD EDITION

Orazio Svelto

Polytechnic Institute of Milan
and National Research Council
Milan, Italy

Translated from Italian and edited by

David C. Hanna

Southampton University
Southampton, England

Plenum Press · New York and London

Library of Congress Cataloging in Publication Data

Svelto, Orazio.

Principles of lasers, 3rd ed.

Translation of: *Principi dei laser*.

Includes bibliographies and index.

1. Lasers. I. Hanna, D. C. (David C.), 1941 — . II. Title.

QC688.S913 1989

535.5'8

88-30671

ISBN 978-1-4615-7672-3

ISBN 978-1-4615-7670-9 (eBook)

DOI 10.1007/978-1-4615-7670-9

© 1989 Plenum Press, New York
A Division of Plenum Publishing Corporation
233 Spring Street, New York, N.Y. 10013

Softcover reprint of the hardcover 1st edition 1989

All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording, or otherwise, without written permission from the Publisher

*Laser . . . inter eximia naturae dona numeratum
plurimis compositionibus inseritur*

The Laser is numbered among the most miraculous gifts
of nature and lends itself to a variety of applications

Plinius, Naturalis Historia, XXII, 49 (first century A.D.)

*An Elaboration of the Quotation from Pliny the Elder:
The Laser during the Greco-Roman Civilization*

During the Greco-Roman civilization (roughly from the sixth century B.C. to the second century A.D.) the Laser was well known and much celebrated. Unlike its present-day homonym, it was actually a plant, but with no less wonderful properties. This plant, perhaps belonging to the *Umbelliferae*, grew wild over a large area around Cyrene, in present-day Libya. Sometimes also called *Laserpitium*, it was considered to be a gift of God because of its almost miraculous properties. It was used to cure a variety of diseases, from pleurisy to various epidemic infections. It was an effective antidote against the poison of snakes, scorpions, and enemy arrows. Its delicate flavor led to its use as an exquisite dressing in the best cuisine. It was so valuable as to be the main source of Cyrenaean prosperity and it was exported to both Greeks and Romans. During the period of Roman domination, it was the only tribute paid by the Cyrenaeans to the Romans, who kept the Laser in their coffers together with their golden ingots. What is perhaps the best testimony to the Laser of those days is to be found on the celebrated Arcesilao cup (now in the Cyrene Museum), where porters can be seen loading the Laser onto a ship under the supervision of King Arcesilao. Both Greeks and Romans tried hard, but without success, to grow the Laser in various parts of *Apulia* and *Ionia* (in the south of Italy). Consequently the Laser became more and more rare and seems to have disappeared around the second century A.D. Ever since then, despite several efforts, no one has been able to find the Laser in the deserts south of Cyrene, and so it remains the lost treasure of the Greco-Roman civilization.

Preface to the Third Edition

This third edition, motivated by the numerous and significant developments in the laser field since the publication of the second edition in 1982, is a substantially revised version of the previous edition. The basic philosophy has, however, remained the same, namely, to provide a broad and unified description of laser behavior at the simplest level that is compatible with a correct physical understanding. The basic organization of the book has also remained the same. The book is therefore aimed at both classroom teaching and self-study by students in electrical engineering, physics, and chemistry who have an interest in understanding the principles of laser operation.

The major additions to this edition are the following:

1. New sections dealing with laser types, in particular x-ray lasers and new solid-state lasers, including alexandrite devices, and a greatly extended description of semiconductor lasers.
2. A more extended treatment of laser mode-locking, including new sections on cavity dumping and pulse compression.
3. A more extended and greatly simplified description of the coherence and statistical properties of laser light as opposed to those of conventional light.
4. A greatly extended discussion of the physics of gas discharges.

Other important additions include a discussion of some topics from conventional optics (e.g., ray matrix methods, Fabry-Perot interferometers, and multilayer dielectric mirrors), Gaussian beam propagation (e.g., the ABCD law), and the theory of relaxation oscillations and active mode-locking.

Although the net result has been a considerable increase in the size of the book, I hope that this new edition can now better serve the need for a general introduction to the laser field.

I wish to acknowledge the following friends and colleagues, whose suggestions and encouragement have certainly contributed toward improving the book in a number of ways: Rodolfo Bonifacio, Ian W. Boyd, Richard K. Chang, Vittorio Degiorgio, Richard H. Pantell, Fritz P. Schäfter, Ian J. Spalding, and Boris Stoicheff. I wish also to acknowledge the critical editing of David C. Hanna, who has acted as much more than simply a translator. The careful reading of the manuscript and critical comments by P. Laporta were also helpful. Finally I wish to thank Dante Cigni for kindly providing me with the material concerning the history of the Laser during the Greco-Roman civilization.

Milan

Orazio Svelto

Contents

1. *Introductory Concepts*

1.1. Spontaneous and Stimulated Emission, Absorption	1
1.1.1. Spontaneous Emission	1
1.1.2. Stimulated Emission	2
1.1.3. Absorption	3
1.2. The Laser Idea	4
1.3. Pumping Schemes	6
1.4. Properties of Laser Beams	8
1.4.1. Monochromaticity	8
1.4.2. Coherence	8
1.4.3. Directionality	10
1.4.4. Brightness	11
1.4.5. Short Time Duration	12
1.5. Organization of the Book	12
<i>Problems</i>	13

2. *Interaction of Radiation with Matter*

2.1. Introduction	15
2.2. Summary of Blackbody Radiation Theory	15
2.3. Absorption and Stimulated Emission	24
2.3.1. Rates of Absorption and Stimulated Emission	24
2.3.2. Allowed and Forbidden Transitions	28
2.3.3. Line-Broadening Mechanisms	30
2.3.3.1. Homogeneous Broadening	30
2.3.3.2. Inhomogeneous Broadening	36
2.3.3.3. Concluding Remarks and Examples	40
2.3.4. Transition Cross Section, Absorption, and Gain Coefficient	42
2.4. Spontaneous Emission	44
2.4.1. Semiclassical Approach	44
2.4.2. Quantum Electrodynamical Approach	47
2.4.3. Einstein Thermodynamic Treatment	49

2.4.4. Relation between Spontaneous Lifetime and Cross Section	52
2.4.5. Concluding Remarks	52
2.5. Nonradiative Decay	53
2.6. Saturation	57
2.6.1. Saturation of Absorption: Homogeneous Line	58
2.6.2. Gain Saturation: Homogeneous Line	62
2.6.3. Inhomogeneously Broadened Line	65
2.7. Decay of a Many-Atom System	66
2.7.1. Radiation Trapping	66
2.7.2. Superradiance and Superfluorescence	66
2.7.3. Amplified Spontaneous Emission	68
2.8. Degenerate Levels	70
2.9. Molecular Systems	73
2.9.1. Energy Levels of a Molecule	73
2.9.2. Level Occupation at Thermal Equilibrium	78
2.9.3. Radiative and Nonradiative Transitions	79
2.9.4. Quantum Mechanical Calculation of the Radiative Transition Rates	82
<i>Problems</i>	85
<i>References</i>	88

3. Pumping Processes

3.1. Introduction	91
3.2. Optical Pumping	92
3.2.1. Pumping Efficiency	96
3.2.2. Radiative and Transfer Efficiencies	97
3.2.3. Pump Light Distribution	103
3.2.4. Absorption and Power Quantum Efficiencies	108
3.2.5. Concluding Remarks	110
3.3. Electrical Pumping	111
3.3.1. Physical Characteristics of Discharges	113
3.3.2. Electron Impact Excitation	116
3.3.2.1. Electron Impact Cross Section	117
3.3.2.2. Electron Energy Distribution	120
3.3.2.3. Spatial Distribution of the Pump Rate	124
3.3.2.4. The Ionization Balance Equation	126
3.3.2.5. Pump Rate Calculation	127
3.3.3. Excitation by (Near) Resonant Energy Transfer	129
<i>Problems</i>	132
<i>References</i>	134

4. Passive Optical Resonators

4.1. Introduction	137
4.2. Some Topics from Geometrical and Wave Optics	141
4.2.1. Matrix Formulation of Geometrical Optics	142
4.2.2. The Fabry-Perot Interferometer	148
4.2.3. Multilayer-Dielectric Coatings	155
4.3. Photon Lifetime and Cavity Q	159

4.4. Plane-Parallel Resonator	161
4.4.1. Approximate Treatment	161
4.4.2. Fox and Li Treatment	163
4.5. Confocal Resonator	170
4.6. Gaussian Beam Propagation and the ABCD Law	179
4.7. Generalized Spherical Resonator	184
4.7.1. Mode Amplitudes	184
4.7.2. Resonance Frequencies and Diffraction Losses	186
4.7.3. Stability Condition	188
4.8. Unstable Resonators	192
4.8.1. Geometrical-Optics Description	193
4.8.2. Wave-Optics Description	197
4.8.3. Advantages and Disadvantages of Hard-Edge Unstable Resonators	199
4.8.4. Variable-Reflectivity Unstable Resonators	200
<i>Problems</i>	203
<i>References</i>	206

5. Continuous Wave and Transient Laser Behavior

5.1. Introduction	207
5.2. Rate Equations	207
5.2.1. Four-Level Laser	207
5.2.2. Three-Level Laser	214
5.3. CW Laser Behavior	215
5.3.1. Four-Level Laser	215
5.3.2. Three-Level Laser	219
5.3.3. Optimum Output Coupling	220
5.3.4. Laser Tuning	221
5.3.5. Single-Mode Versus Multimode Oscillation	223
5.3.5.1. Reasons for Multimode Oscillation	223
5.3.5.2. Single-Mode Oscillation	225
5.3.6. Two Numerical Examples	232
5.3.7. Frequency Pulling and Limit to Monochromaticity	238
5.3.8. Lamb Dip and Active Stabilization of Laser Frequency	240
5.4. Transient Laser Behavior	243
5.4.1. Relaxation Oscillations in Single-Mode Lasers	244
5.4.2. Spiking Behavior of Multimode Lasers	248
5.4.3. <i>Q</i> Switching	248
5.4.3.1. Methods of <i>Q</i> Switching	250
5.4.3.2. Operating Regimes	256
5.4.3.3. Theory of Active <i>Q</i> Switching	258
5.4.3.4. A Numerical Example	263
5.4.4. Gain Switching	265
5.4.5. Mode Locking	266
5.4.5.1. Methods of Mode Locking	272
5.4.5.2. Mode-Locking Systems	278
5.4.6. Cavity Dumping	281
5.5. Concluding Remarks	283
<i>Problems</i>	284
<i>References</i>	285

6. Types of Lasers

6.1. Introduction	287
6.2. Solid-State Lasers	287
6.2.1. The Ruby Laser	288
6.2.2. Neodymium Lasers	290
6.2.2.1. Nd:YAG	290
6.2.2.2. Nd:Glass	292
6.2.2.3. Other Crystalline Hosts	293
6.2.3. Alexandrite Laser	294
6.3. Gas Lasers	296
6.3.1. Neutral Atom Lasers	297
6.3.1.1. Helium-Neon Lasers	298
6.3.1.2. Copper and Gold Vapor Lasers	302
6.3.2. Ion Lasers	304
6.3.2.1. Argon Laser	305
6.3.2.2. He-Cd Laser	308
6.3.3. Molecular Gas Lasers	309
6.3.3.1. The CO ₂ Laser	310
6.3.3.2. The CO Laser	323
6.3.3.3. The N ₂ laser	325
6.3.3.4. Excimer Lasers	327
6.4. Liquid Lasers (Dye Lasers)	331
6.4.1. Photophysical Properties of Organic Dyes	331
6.4.2. Characteristics of Dye Lasers	335
6.5. Chemical Lasers	339
6.5.1. The HF Laser	340
6.6. Semiconductor Lasers	342
6.6.1. Photophysical Properties of Semiconductor Lasers	343
6.6.1.1. Energy States in a Semiconductor	344
6.6.1.2. Level Occupation at Thermal Equilibrium	346
6.6.1.3. Radiative and Nonradiative Transitions	347
6.6.1.4. The Quasi-Fermi Levels	348
6.6.2. Semiconductor-Laser Pumping	350
6.6.2.1. The Homojunction Laser	350
6.6.2.2. The Double-Heterojunction Laser	352
6.6.3. Semiconductor Laser Devices and Their Performance	354
6.6.4. Semiconductor Laser Applications	358
6.6.5. Simplified Theory of a Semiconductor Laser	359
6.7. Color-Center Lasers	363
6.8. The Free-Electron Laser	366
6.9. X-Ray Lasers	370
6.10. Summary of Performance Data	372
Problems	374
References	376

7. Properties of Laser Beams

7.1. Introduction	379
7.2. Monochromaticity	379
7.3. Complex Representation of Polychromatic Fields	380

7.4. Statistical Properties of Laser Light and Thermal Light	381
7.5. First-Order Coherence	383
7.5.1. Degree of Spatial and Temporal Coherence	384
7.5.2. Measurement of Spatial and Temporal Coherence	387
7.5.3. Relation Between Temporal Coherence and Monochromaticity	390
7.5.4. Nonstationary Beams	391
7.5.5. Spatial and Temporal Coherence of Single-Mode and Multimode Lasers	392
7.6. Directionality	394
7.6.1. Beams with Perfect Spatial Coherence	394
7.6.2. Beams with Partial Spatial Coherence	397
7.7. Laser Speckle	400
7.8. Brightness	404
7.9. Comparison Between Laser Light and Thermal Light	405
7.10. Higher-Order Coherence	406
<i>Problems</i>	408
<i>References</i>	410

8. Laser Beam Transformation: Propagation, Amplification, Frequency Conversion, Pulse Compression

8.1. Introduction	411
8.2. Transformation in Space: Gaussian Beam Propagation	412
8.3. Transformation in Amplitude: Laser Amplification	418
8.4. Frequency Conversion: Second-Harmonic Generation and Parametric Oscillation	424
8.4.1. Physical Picture	425
8.4.1.1. Second-Harmonic Generation	425
8.4.1.2. Parametric Oscillation	432
8.4.2. Analytical Treatment	435
8.4.2.1. Parametric Oscillation	437
8.4.2.2. Second-Harmonic Generation	441
8.5. Transformation in Time: Pulse Compression	444
<i>Problems</i>	453
<i>References</i>	454

Appendixes

A Semiclassical Treatment of the Interaction of Radiation with Matter	459
B Space-Dependent Rate Equations	465
C Theory of Active Mode Locking for a Homogeneous Line	471
D Physical Constants	477

<i>Answers to Selected Problems</i>	479
---	-----

<i>Index</i>	487
------------------------	-----