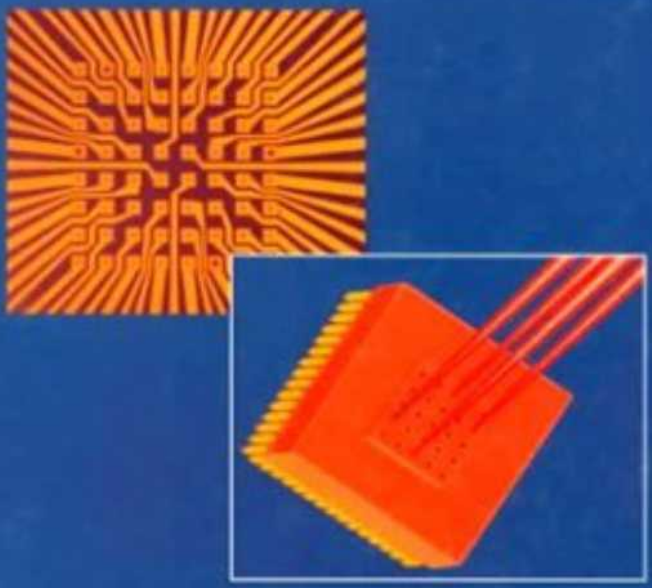
激光电子学

THIRD EDITION

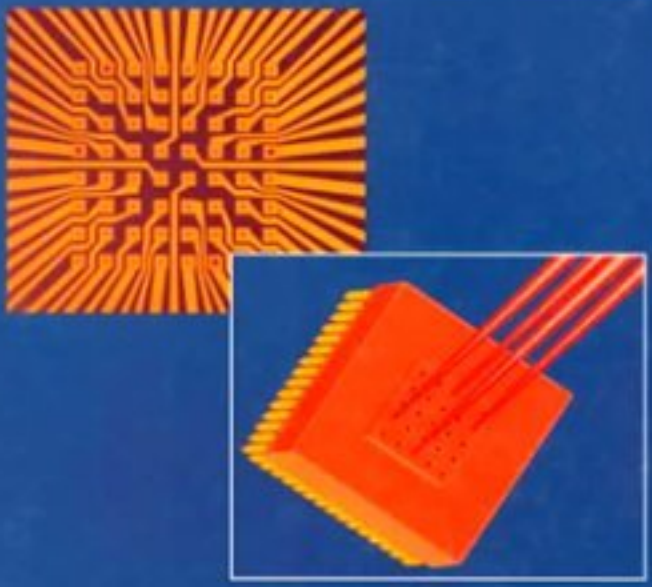


Joseph T. Verdeyen

PRENTICE HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS
Nick Holonyak, Jr., Series Editor

LASER ELECTRONICS

THIRD EDITION



Joseph T. Verdeyen

PRENTICE HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS
Nick Holonyak, Jr., Series Editor

版权免责声明

本文集内容均来源于网络，版权归著作方所有。广州基座光学科技有限公司仅做搜集整理工作，并供读者学习参考用途。在使用本文集内容时可能造成实际或预期的损失，读者转载时破坏电子文档的完整性，或以商业盈利目的复制和销售等行为，本公司概不承担任何责任。若原文版权方有异议，请联系我们删除。

Laser Electronics

THIRD EDITION

JOSEPH T. VERDEYEN

Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign, Urbana, Illinois

PRENTICE HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS
Nick Holonyak, Jr., Series Editor

PRENTICE HALL
Englewood Cliffs, New Jersey 07632

Oeabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

Library of Congress Cataloging-in-Publication Data

Verdeyen, Joseph Thomas
Laser electronics. / Joseph T. Verdeyen. – 3rd ed.
p. cm. — (Prentice Hall series in solid state physical electronics)
Includes bibliographical references and index.
ISBN 0-13-706666-X
1. Lasers. 2. Semiconductor lasers. I. Title. II. Series.
TA1675.V47 1995
621.36'61—dc20 93-2184
CIP

Acquisitions editor: ***Alan Apt***
Production editor: ***Irwin Zucker***
Copy editor: ***Michael Schwartz***
Production coordinator: ***Linda Behrens***
Supplements editor: ***Alice Dworkin***
Cover design: ***Design Solutions***
Cover illustration: ***Dr. R. P. Bryan of Photonics Research***
Editorial assistant: ***Shirley McGuire***

© 1995, 1989, 1981 by Prentice-Hall, Inc.
A Paramount Communications Company
Englewood Cliffs, New Jersey 07632

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

All rights reserved. No part of this book may be
reproduced, in any form or by any means,
without permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2

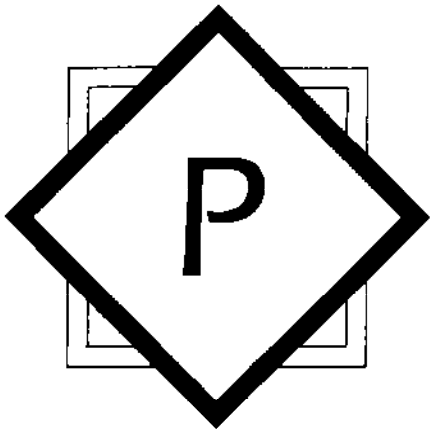
ISBN 0-13-706666-X

Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Simon & Schuster Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Oeabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

This book is dedicated to Katie,
my wife, constant companion, and best friend
for 40 years of marriage and courtship.
She is the loving mother of my children Mary, Joe, Jean, and Mike,
an exciting grandmother to their children,
and an understanding mother-in-law to Dennis, Pam, Jim, and Tammy.
She has demonstrated incredible patience and understanding
with the rather painful process of revising this book while maintaining
a most pleasant, cheerful and comforting home.
From my perspective, our marriage has had a storybook characteristic to it
with my love for her increasing daily.
With her enthusiasm, example, and love, it is easy to learn
to love God, to love our neighbors, and to keep His commandments.
Thank you honey for my life!

Oeabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方，如有侵权请联系kent@oeabt.com删除】



Preface

The underlying philosophy of this third edition of *Laser Electronics* is the same as in the previous two: lasers are very simple devices and are far simpler than the very complicated high frequency RF or microwave transistor circuits. The main purpose of the book is to convince the student of this fact. In one sense, lasers are a simple movement of the decimal point on the frequency scale three to five places to the right, but much of the terminology and all of the insight developed by the earlier pioneers of radio have been translated to the optical domain.

The potential of the many applications of lasers and optical phenomena has necessitated the formation of a new word to describe the field: *photonics*. One would be hard pressed to define all of its ramifications since new ideas, devices, and applications are frequently being added. In a very loose sort of way, the early history of radio is being repeated in the optical frequency domain, and this is a theme that will be employed throughout the book. Although both have a common basis in electromagnetic theory, there are special phenomena peculiar to the optical wavelengths.

For instance, a wave intensity of 10^{15}–10^{19} watts/m^2 would have been incomprehensible in 1960, but is now attainable with rather common lasers and comparatively cheap optics. Similarly, a 50 femtoseconds (50×10^{-15} s) pulse requires more frequency bandwidth for transmission than that which was installed in all of the telecommunications networks of 1960. Yet such a pulse is rather common with optical techniques.

The ability to generate such short pulses and transmit them over significant distances (many hundreds of kilometers) by using low loss fibers and erbium-doped fiber

Oeabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

amplifiers (EDFA) was a major impetus for the revisions incorporated into this third edition.

Chapter 4 has been changed to emphasize some of the more sophisticated aspects of guided wave propagation, such as dispersion in fibers, solitons, and perturbation theory. By necessity, the chapter is an introduction intended to encourage further investigation. While those are important topics for a communication system, they may be too involved for a first course in lasers. Thus, the entire chapter can be skipped if the focus of the course is on the *generation* portion of photonics.

Chapter 9 has been rewritten and reorganized to emphasize the dynamics of the laser: the approach to CW oscillation, Q switching, and various aspects of mode locking. The latter has been greatly expanded, but, even so, there are important topics not included.

Various additions have been included in Chapter 10 on specific laser systems. The example of a semiconductor laser pumping a YAG system was carried through in some detail so as to emphasize the application of the theoretical tools developed in the previous chapters and to indicate a significant application of the semiconductor laser. The *erbium doped fiber amplifier* (EDFA) is also discussed here, and a fairly long-winded simplified "problem" (with answers) is given to emphasize some of the unique considerations of the topic and to encourage further investigation of the literature. The multiplicity of levels of the EDFA serves as an introduction to gain/absorption between bands and to tunable vibronic lasers such as alexandrite, Ti:sapphire, and dye lasers.

Much of the expansion in photonics is being led by the improvements in the semiconductor laser, which has become the dominant laser for communication and control. Its use as a pump for the fiber amplifiers and solid-state lasers has also become most important. Chapter 11 has been expanded somewhat but is still intended to be an introduction to a course devoted entirely to that laser.

Most students have a fair grasp of the beauty and elegance of electromagnetic theory but have the mistaken view that the word *photon* somehow weakens its applicability. That is unfortunate. The lowest power laser generates literally billions of photons per second, and thus the classical field description of it is quite adequate. Even when the photon flux becomes small—say 10 to 100 s^{-1}, the classical field description will handle the practical cases. Many of the advances in semiconductor lasers, in particular, can be traced to classical electromagnetic theory of guidance of the modes by the heterostructures. Chapter 12 is included to introduce the student to some of the more advanced topics, possibly to be studied in a second course.

Chapters 13 and 14 are aimed at the student who wants a gradual transition to a quantum theory of the laser while the simple theory is fresh. Chapter 14 is an attempt to provide a bridge between the simple rate equation description of a laser and the more formal quantum theory using the density matrix. The two approaches agree, precisely, for the case of a CW two-level system, but the former is much easier and more akin to the student's background. The latter will handle the transient cases, scattering, two-photon phenomena, etc., at the expense of considerably more mathematics. The serious student should become aware of the transition between the two approaches, have confidence in both, and be aware of the pitfalls and limitations, again in a second course. One of the main conclusions is that

eabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

a simple rate equation of laser phenomena is quite adequate and accurate most of the time. A few cases that do not follow this rule are included.

Many more problems are included in this third edition with the primary purpose of convincing the student of the transparent simplicity of the rate equation approach. Rate equations are no more difficult than coupled circuit equations (or the differential equation describing the student's finances): There is always a source (a salary) and a loss (expenses) that may or may not be in steady state equilibrium.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge my present and former colleagues at the University of Illinois for their help, encouragement, and many discussions of the topics included here. I am particularly grateful to: N. Holonyak, Jr., for his ability and patience in communicating his masterful insight into semiconductor electronics; to J.J. Coleman for the initial encouragement to write the book and general discussions on semiconductor materials; to T.A. DeTemple, who has been most patient and helpful with my attempt to simplify some of the topics included here; to S. Bishop for his leadership as the Director of the Microelectronics Laboratory; and to P.D. Coleman who had a significant impact on my view of electrodynamics.

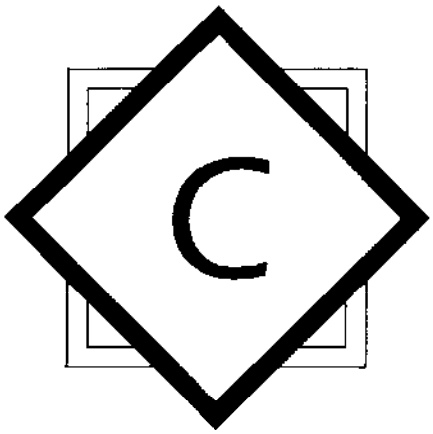
I would also like to thank the reviewers: Jorge Rocca of Colorado State University, Daniel Elliott of Purdue University, Raymond Rostuk of the University of Arizona, and Sally Stevens-Tammens of the University of Illinois at Urbana-Champaign.

I especially wish to thank the many students who have helped "write" and modify this book while keeping their good humor. Their enthusiasm for photonics has really been an inspiration to me. I hope that I have taught them as well as they have educated me. I am also grateful to Ms. Galena Smirnov who patiently checked much of the new material.

I am particularly grateful to Dr. Robert Bryan of Photonics Research, Inc. for his permission to use some of the figures on the cover.

Joseph T. Verdeyen

eabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】



Contents

List of Symbols xx

0 Preliminary Comments 1

Note to the students 3

References 6

1 Review of Electromagnetic Theory 8

1.1 Introduction 8

1.2 Maxwell's Equations 9

1.3 Wave Equation for Free Space 10

1.4 Algebraic Form of Maxwell's Equations 11

1.5 Waves in Dielectrics 12

1.6 The Uncertainty Relationships 13

1.7 Spreading of an Electromagnetic Beam 15

Oeabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

1.8 Wave Propagation in Anisotropic Media 16

1.9 Elementary Boundary Value Problems in Optics 20

1.9.1 Snell's Law, 20
1.9.2 Brewster's Angle, 21

1.10 Coherent Electromagnetic Radiation 23

1.11 Example of Coherence Effects 28

Problems 31

References and Suggested Readings 34

2 Ray Tracing in an Optical System 35

2.1 Introduction 35

2.2 Ray Matrix 35

2.3 Some Common Ray Matrices 37

2.4 Applications of Ray Tracing: Optical Cavities 39

2.5 Stability: Stability Diagram 42

2.6 The Unstable Region 44

2.7 Example of Ray Tracing in a Stable Cavity 44

2.8 Repetitive Ray Paths 47

2.9 Initial Conditions: Stable Cavities 48

2.10 Initial Conditions: Unstable Cavities 49

2.11 Astigmatism 50

2.12 Continuous Lens-Like Media 51

2.12.1 Propagation of a Ray in an Inhomogeneous Medium, 53
2.12.2 Ray Matrix for a Continuous Lens, 54

2.13 Wave Transformation by a Lens 56

Problems 57

References and Suggested Readings 62

3 Gaussian Beams 63

3.1 Introduction 63

3.2 Preliminary Ideas: TEM Waves 63

3.3 Lowest-Order $TEM_{0,0}$ Mode 66

oeabt 基座光学
optical experiment and basic teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方，如有侵权请联系kent@oeabt.com删除】

3.4 Physical Description of $TEM_{0,0}$ Mode 70

3.4.1 Amplitude of the Field, 70
3.4.2 Longitudinal Phase Factor, 71
3.4.3 Radial Phase Factor, 72

3.5 Higher-Order Modes 73

3.6 *ABCD* law for Gaussian beams 76

3.7 Divergence of the Higher-Order Modes: Spatial Coherence 79

Problems 80

References and Suggested Readings 84

4 Guided Optical Beams 86

4.1 Introduction 86

4.2 Optical Fibers and Heterostructures: A Slab Waveguide Model 87

4.2.1 Zig-Zag Analysis, 87
4.2.2 Numerical Aperture, 89

4.3 Modes in a Step-Index Fiber (or a Heterojunction Laser): Wave Equation Approach 90

4.3.1 TE Mode ($E_z = 0$), 92
4.3.2 TM Modes ($H_z = 0$), 94
4.3.3 Graphic Solution for the Propagation Constant: "R" and "V" Parameters, 95

4.4 Gaussian Beams in Graded Index (GRIN) Fibers and Lenses 96

4.5 Perturbation Theory 102

4.6 Dispersion and Loss in Fibers: Data 105

4.7 Pulse Propagation in Dispersive Media: Theory 109

4.8 Optical Solitons 116

Problems 122

References and Suggested Readings 127

5 Optical Cavities 130

5.1 Introduction 130

5.2 Gaussian Beams in Simple Stable Resonators 130

5.3 Application of the *ABCD* Law to Cavities 133

5.4 Mode Volume in Stable Resonators 137

eabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

Problems 139

References and Suggested Readings 142

6 Resonant Optical Cavities 144

6.1 General Cavity Concepts 144

6.2 Resonance 144

6.3 Sharpness of Resonance: Q and Finesse 148

6.4 Photon Lifetime 151

6.5 Resonance of the Hermite-Gaussian Modes 154

6.6 Diffraction Losses 156

6.7 Cavity With Gain: An Example 157

Problems 159

References and Suggested Readings 170

7 Atomic Radiation 172

7.1 Introduction and Preliminary Ideas 172

7.2 Blackbody Radiation Theory 173

7.3 Einstein's Approach: *A* and *B* Coefficients 179

7.3.1 Definition of Radiative Processes, 179
7.3.2 Relationship Between the Coefficients, 181

7.4 Line Shape 183

7.5 Amplification by an Atomic System 187

7.6 Broadening of Spectral Lines 191

7.6.1 Homogeneous broadening mechanisms, 191
7.6.2 Inhomogeneous Broadening, 196
7.6.3 General Comments on the Line Shape, 200

7.7 Review 200

Problems 201

References and Suggested Readings 205

8 Laser Oscillation and Amplification 207

8.1 Introduction: Threshold Condition for Oscillation 207

Oeabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

8.2 Laser Oscillation and Amplification in a Homogeneous Broadened Transition 208

8.3 Gain Saturation in a Homogeneous Broadened Transition 212

8.4 Laser Oscillation in an Inhomogeneous System 223

8.5 Multimode Oscillation 229

8.6 Gain Saturation in Doppler-Broadened Transition: Mathematical Treatment 230

8.7 Amplified Spontaneous Emission (ASE) 234

8.8 Laser Oscillation: A Different Viewpoint 238

Problems 242

References and Suggested Readings 258

9 General Characteristics of Lasers 260

9.0 Introduction 260

9.1 Limiting Efficiency 260

9.1.1 Factors in the efficiency, 260
9.1.2 Two, 3, 4 : : :, n level lasers, 261

9.2 CW Laser 263

9.2.1 Traveling Wave Ring Laser, 264
9.2.2 Optimum Coupling, 267
9.2.3 Standing Wave Lasers, 269

9.3 Laser Dynamics 274

9.3.1 Introduction and model, 274
9.3.2 Case a: A sub-threshold system, 276
9.3.3 Case b: A CW laser: threshold conditions, 276
9.3.4 Case c: A sinusoidal modulated pump, 277
9.3.5 Case d. A sudden "step" change in excitation rate, 280
9.3.6 Case e: Pulsed excitation → gain switching, 282

9.4 Q Switching, Q Spoiling, or Giant Pulse Lasers 284

9.5 Mode Locking 296

9.5.1 Preliminary considerations, 296
9.5.2 Mode locking in an inhomogeneous broadened laser, 298
9.5.3 Active mode locking, 304

9.6 Pulse Propagation in Saturable Amplifiers or Absorbers 311

9.7 Saturable Absorber (Colliding Pulse) Mode Locking 317

eabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

9.8 Additive-Pulse Mode Locking 322

Problems 324

References and Suggested Readings 344

10 Laser Excitation 347

10.1 Introduction 347

10.2 Three- and Four-Level Lasers 348

10.3 Ruby Lasers 351

10.4 Rare Earth Lasers and Amplifiers 358

10.4.1 General Considerations, 358
10.4.2 Nd:YAG lasers: Data, 359
10.4.3 Nd:YAG Pumped by a Semiconductor Laser, 362
10.4.4 Neodymium-Glass Lasers, 369
10.4.6 Erbium-Doped-Fiber-Amplifiers, 371

10.5 Broad-Band Optical Gain 376

10.5.1 Band-to-Band Emission and Absorption, 376
10.5.2 Theory of Band-to-Band Emission and Absorption, 377

10.6 Tunable Lasers 385

10.6.1 General Considerations, 385
10.6.2 Dye Lasers, 386
10.6.3 Tunable Solid State Lasers, 391
10.6.4 Cavities for Tunable Lasers, 395

10.7 Gaseous-Discharge Lasers 396

10.7.1 Overview, 396
10.7.2 Helium-Neon Laser, 397
10.7.3 Ion Lasers, 403
10.7.4 CO_2 Lasers, 405

10.8 Excimer Lasers: General Considerations 411

10.8.1 Formation of the Excimer State, 412
10.8.2 Excitation of the Rare Gas–Halogen Excimer Lasers, 415

10.9 Free Electron Laser 417

Problems 423

References and Suggested Readings 434

11 Semiconductor Lasers 440

11.1 Introduction 440

Oeabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

11.1.1 Overview, 440
11.1.2 Populations in Semiconductor Laser, 442

11.2 Review of Elementary Semiconductor Theory 444

11.2.1 Density of States, 445

11.3 Occupation Probability: Quasi-Fermi Levels 449

11.4 Optical Absorption and Gain in a Semiconductor 450

11.4.1 Gain Coefficient in a Semiconductor, 454
11.4.2 Spontaneous Emission Profile, 459
11.4.3 An Example of an Inverted Semiconductor, 460

11.5 Diode Laser 464

11.5.1 Homojunction Laser, 464
11.5.2 Heterojunction Lasers, 467

11.6 Quantum Size Effects 470

11.6.1 Infinite Barriers, 470
11.6.2 Finite Barriers: An Example, 476

11.7 Vertical Cavity Surface Emitting Lasers 482

11.8 Modulation of Semiconductor Lasers 486

11.8.1 Static Characteristics, 488
11.8.2 Frequency Response of Diode Lasers, 489

Problems 492

References and Suggested Readings 499

12 Advanced Topics in Laser Electromagnetics 502

12.1 Introduction 502

12.2 Semiconductor Cavities 503

12.2.1 TE Modes ($E_z = 0$), 505
12.2.2 TM Modes ($H_z = 0$), 507
12.2.3 Polarization of TE and TM Modes, 508

12.3 Gain Guiding: An Example 509

12.4 Optical Confinement and Effective Index 516

12.5 Distributed Feedback and Bragg Reflectors 517

12.5.1 Introduction, 517
12.5.2 Coupled Mode Analysis, 520
12.5.3 Distributed Bragg Reflector, 524
12.5.4 A Quarter-Wave Bandpass Filter, 525

eabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

12.5.5 Distributed Feedback Lasers (Active Mirrors), 528
12.5.6 Tunable Semiconductor Lasers, 531

12.6 Unstable Resonators 534

12.6.1 General Considerations, 534
12.6.2 Unstable Confocal Resonator, 540

12.7 Integral Equation Approach to Cavities 543

12.7.1 Mathematical Formulation, 543
12.7.2 Fox and Li Results, 547
12.7.3 Stable Confocal Resonator, 550

12.8 Field Analysis of Unstable Cavities 555

12.9 *ABCD* Law for "Tapered Mirror" Cavities 562

12.10 Laser Arrays 568

12.10.1 System Considerations, 568
12.10.2 Semiconductor Laser Array: Physical Picture, 568
12.10.3 Supermodes of the Array, 570
12.10.4 Radiation Pattern, 574

Problems 574

References and Suggested Readings 585

13 Maxwell's Equations and the "Classical" Atom 589

13.1 Introduction 589

13.2 Polarization Current 590

13.3 Wave Propagation With Active Atoms 592

13.4 The Classical A_{21} Coefficient 596

13.5 (Slater) Modes of a Laser 597

13.5.1 Slater Modes of a Lossless Cavity, 598
13.5.2 Lossy Cavity With a Source, 600

13.6 Dynamics of the Fields 602

13.6.1 Excitation Clamped to Zero, 602
13.6.2 Time Evolution of the Field, 603

13.7 Summary 609

Problems 610

References and Suggested Readings 615

eabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

14 Quantum Theory of the Field-Atom Interaction 616

14.1 Introduction 616

14.2 Schrödinger Description 617

14.3 Derivation of the Einstein Coefficients 621

14.4 Dynamics of an Isolated Atom 624

14.5 Density Matrix Approach 627

14.5.1 Introduction, 627
14.5.2 Definition, 628

14.6 Equation of Motion for the Density Matrix 633

14.7 Two-Level System 635

14.8 Steady State Polarization Current 639

14.9 Multilevel or Multiphoton Phenomena 643

14.10 Raman Effects 651

14.10.1 Phenomena, 651
14.10.2 A Classical Analysis of the Raman Effect., 654
14.10.3 Density Matrix Description of the Raman Effect, 660

14.11 Propagation of Pulses: Self-Induced Transparency 665

14.11.1 Motivation for the Analysis, 665
14.11.2 A Self-Consistent Analysis of the Field-Atom Interaction, 666
14.11.3 "Area" Theorem, 670
14.11.4 Pulse Solution, 673

Problems 676

References and Suggested Readings 679

15 Spectroscopy of Common Lasers 681

15.1 Introduction 681

15.2 Atomic Notation 681

15.2.1 Energy Levels, 681
15.2.2 Transitions: Selection Rules, 682

15.3 Molecular Structure: Diatomic Molecules 684

15.3.1 Preliminary Comments, 684
15.3.2 Rotational Structure and Transitions, 685
15.3.3 Thermal Distribution of the Population in Rotational States, 686
15.3.4 Vibrational Structure, 687

Oeabt 基座光学
optical experiment and basic teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

15.3.5 Vibration-Rotational Transitions, 688
15.3.6 Relative Gain on P and R Branches: Partial and Total Inversions, 689

15.4 Electronic States in Molecules 691

15.4.1 Notation, 691
15.4.2 The Franck–Condon Principle, 692
15.4.3 Molecular Nitrogen Lasers, 692*

Problems 693

References and Suggested Readings 695

16 Detection of Optical Radiation 697

16.1 Introduction 697

16.2 Quantum Detectors 697

16.2.1 Vacuum Photodiode, 698
16.2.2 Photomultiplier, 699

16.3 Solid-State Quantum Detectors 701

16.3.1 Photoconductor, 701
16.3.2 Junction Photodiode, 703
16.3.3 p-i-n Diode, 706
16.3.4 Avalanche Photodiode, 707

16.4 Noise Considerations 707

16.5 Mathematics of Noise 709

16.6 Sources of Noise 713

16.1.1 Shot Noise, 713
16.6.2 Thermal Noise, 714
16.6.3 Noise Figure of Video Amplifiers, 716
16.6.4 Background Radiation, 717

16.7 Limits of Detection Systems 718

16.7.1 Video Detection of Photons, 718
16.7.2 Heterodyne System, 722

Problems 725

References and Suggested Readings 728

17 Gas-Discharge Phenomena 729

17.1 Introduction 729

17.2 Terminal Characteristics 731

Oeabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

17.3 Spatial Characteristics 732

17.4 Electron Gas 734

17.4.1 Background, 734
17.4.2 "Average" or "Typical" Electron, 734
17.4.3 Electron Distribution Function, 741
17.4.4 Computation of Rates, 743
17.4.5 Computation of a Flux, 745

17.5 Ionization Balance 746

17.6 Example of Gas-Discharge Excitation of a CO_2 Laser 748

17.6.1 Preliminary Information, 748
17.6.2 Experimental Detail and Results, 748
17.6.3 Theoretical Calculations, 750
17.6.4 Correlation Between Experiment and Theory, 753
17.6.5 Laser-Level Excitation, 756

17.7 Electron Beam Sustained Operation 758

Problems 761

References and Suggested Readings 764

Appendices

I An Introduction to Scattering Matrices 765

II Detailed Balancing or Microscopic Reversibility 770

III The Kramers–Kronig Relations 774

Index 779

Oeabt 基座光学
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方,如有侵权请联系kent@oeabt.com删除】

文档篇幅过长，请跳转百度云盘下载：
链接：https://pan.baidu.com/s/1LiFZDFd40Qz5z0q5_VcbLQ
提取码：7pgr

Oeabt 基座光学
optical Experiment and Basic Teaching
《基座光学专业文集--激光篇》
www.oeabt.com【版权属于著作方，如有侵权请联系kent@oeabt.com删除】