

LASER FUNDAMENTALS

SECOND EDITION

WILLIAM T. SILFVAST

School of Optics / CREOL
University of Central Florida



ASML 1008

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa
<http://www.cambridge.org>

First published 1996
Reprinted 1999, 2000, 2003

First edition © Cambridge University Press
Second edition © William T. Silfvast 2004

This book is in copyright. Subject to statutory exception and
to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2004

Printed in the United States of America

Typeface Times 10.5/13.5 and Avenir *System* AMS-TeX [FH]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging in Publication data

Silfvast, William Thomas, 1937–

Laser fundamentals / William T. Silfvast. – 2nd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-521-83345-0

I. Lasers. I. Title.

TA1675.S52 2004

621.36'6 – dc21

2003055352

ISBN 0 521 83345 0 hardback

Contents

| | |
|--|-----------|
| <i>Preface to the Second Edition</i> | page xix |
| <i>Preface to the First Edition</i> | xxi |
| <i>Acknowledgments</i> | xxiii |
| 1 INTRODUCTION | 1 |
| OVERVIEW | 1 |
| Introduction | 1 |
| Definition of the Laser | 1 |
| Simplicity of a Laser | 2 |
| Unique Properties of a Laser | 2 |
| The Laser Spectrum and Wavelengths | 3 |
| A Brief History of the Laser | 4 |
| Overview of the Book | 5 |
| SECTION 1. FUNDAMENTAL WAVE PROPERTIES OF LIGHT | |
| 2 WAVE NATURE OF LIGHT – THE INTERACTION OF LIGHT WITH MATERIALS | 9 |
| OVERVIEW | 9 |
| 2.1 Maxwell’s Equations | 9 |
| 2.2 Maxwell’s Wave Equations | 12 |
| Maxwell’s Wave Equations for a Vacuum | 12 |
| Solution of the General Wave Equation – Equivalence of Light and Electromagnetic Radiation | 13 |
| Wave Velocity – Phase and Group Velocities | 17 |
| Generalized Solution of the Wave Equation | 20 |
| Transverse Electromagnetic Waves and Polarized Light | 21 |
| Flow of Electromagnetic Energy | 21 |
| Radiation from a Point Source (Electric Dipole Radiation) | 22 |
| 2.3 Interaction of Electromagnetic Radiation (Light) with Matter | 23 |
| Speed of Light in a Medium | 23 |
| Maxwell’s Equations in a Medium | 24 |
| Application of Maxwell’s Equations to Dielectric Materials – Laser Gain Media | 25 |
| Complex Index of Refraction – Optical Constants | 28 |
| Absorption and Dispersion | 29 |

| | |
|--|----|
| Estimating Particle Densities of Materials for Use in the Dispersion Equations | 34 |
| 2.4 Coherence | 36 |
| Temporal Coherence | 37 |
| Spatial Coherence | 38 |
| REFERENCES | 39 |
| PROBLEMS | 39 |
| SECTION 2. FUNDAMENTAL QUANTUM PROPERTIES OF LIGHT | |
| 3 PARTICLE NATURE OF LIGHT – DISCRETE ENERGY LEVELS | 45 |
| OVERVIEW | 45 |
| 3.1 Bohr Theory of the Hydrogen Atom | 45 |
| Historical Development of the Concept of Discrete Energy Levels | 45 |
| Energy Levels of the Hydrogen Atom | 46 |
| Frequency and Wavelength of Emission Lines | 49 |
| Ionization Energies and Energy Levels of Ions | 51 |
| Photons | 54 |
| 3.2 Quantum Theory of Atomic Energy Levels | 54 |
| Wave Nature of Particles | 54 |
| Heisenberg Uncertainty Principle | 56 |
| Wave Theory | 56 |
| Wave Functions | 57 |
| Quantum States | 57 |
| The Schrödinger Wave Equation | 59 |
| Energy and Wave Function for the Ground State of the Hydrogen Atom | 61 |
| Excited States of Hydrogen | 63 |
| Allowed Quantum Numbers for Hydrogen Atom Wave Functions | 66 |
| 3.3 Angular Momentum of Atoms | 67 |
| Orbital Angular Momentum | 67 |
| Spin Angular Momentum | 68 |
| Total Angular Momentum | 69 |
| 3.4 Energy Levels Associated with One-Electron Atoms | 70 |
| Fine Structure of Spectral Lines | 70 |
| Pauli Exclusion Principle | 72 |
| 3.5 Periodic Table of the Elements | 72 |
| Quantum Conditions Associated with Multiple Electrons Attached to Nuclei | 72 |
| Shorthand Notation for Electronic Configurations of Atoms Having More Than One Electron | 76 |
| 3.6 Energy Levels of Multi-Electron Atoms | 77 |
| Energy-Level Designation for Multi-Electron States | 77 |
| Russell–Saunders or <i>LS</i> Coupling – Notation for Energy Levels | 78 |
| Energy Levels Associated with Two Electrons in Unfilled Shells | 79 |
| Rules for Obtaining <i>S</i> , <i>L</i> , and <i>J</i> for <i>LS</i> Coupling | 82 |
| Degeneracy and Statistical Weights | 84 |
| <i>j-j</i> Coupling | 85 |
| Isoelectronic Scaling | 85 |

| | |
|---|-----|
| REFERENCES | 86 |
| PROBLEMS | 86 |
| 4 RADIATIVE TRANSITIONS AND EMISSION LINEWIDTH | 89 |
| OVERVIEW | 89 |
| 4.1 Decay of Excited States | 90 |
| Radiative Decay of Excited States of Isolated Atoms – Spontaneous Emission | 90 |
| Spontaneous Emission Decay Rate – Radiative Transition Probability | 94 |
| Lifetime of a Radiating Electron – The Electron as a Classical Radiating Harmonic Oscillator | 95 |
| Nonradiative Decay of the Excited States – Collisional Decay | 98 |
| 4.2 Emission Broadening and Linewidth Due to Radiative Decay | 101 |
| Classical Emission Linewidth of a Radiating Electron | 101 |
| Natural Emission Linewidth as Deduced by Quantum Mechanics (Minimum Linewidth) | 103 |
| 4.3 Additional Emission-Broadening Processes | 105 |
| Broadening Due to Nonradiative (Collisional) Decay | 106 |
| Broadening Due to Dephasing Collisions | 107 |
| Amorphous Crystal Broadening | 109 |
| Doppler Broadening in Gases | 109 |
| Voigt Lineshape Profile | 114 |
| Broadening in Gases Due to Isotope Shifts | 115 |
| Comparison of Various Types of Emission Broadening | 118 |
| 4.4 Quantum Mechanical Description of Radiating Atoms | 121 |
| Electric Dipole Radiation | 122 |
| Electric Dipole Matrix Element | 123 |
| Electric Dipole Transition Probability | 124 |
| Oscillator Strength | 124 |
| Selection Rules for Electric Dipole Transitions Involving Atoms with a Single Electron in an Unfilled Subshell | 125 |
| Selection Rules for Radiative Transitions Involving Atoms with More Than One Electron in an Unfilled Subshell | 129 |
| Parity Selection Rule | 130 |
| Inefficient Radiative Transitions – Electric Quadrupole and Other Higher-Order Transitions | 131 |
| REFERENCES | 131 |
| PROBLEMS | 131 |
| 5 ENERGY LEVELS AND RADIATIVE PROPERTIES OF MOLECULES, LIQUIDS, AND SOLIDS | 135 |
| OVERVIEW | 135 |
| 5.1 Molecular Energy Levels and Spectra | 135 |
| Energy Levels of Molecules | 135 |
| Classification of Simple Molecules | 138 |
| Rotational Energy Levels of Linear Molecules | 139 |
| Rotational Energy Levels of Symmetric-Top Molecules | 141 |
| Selection Rules for Rotational Transitions | 141 |

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts



Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research



With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips



Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.