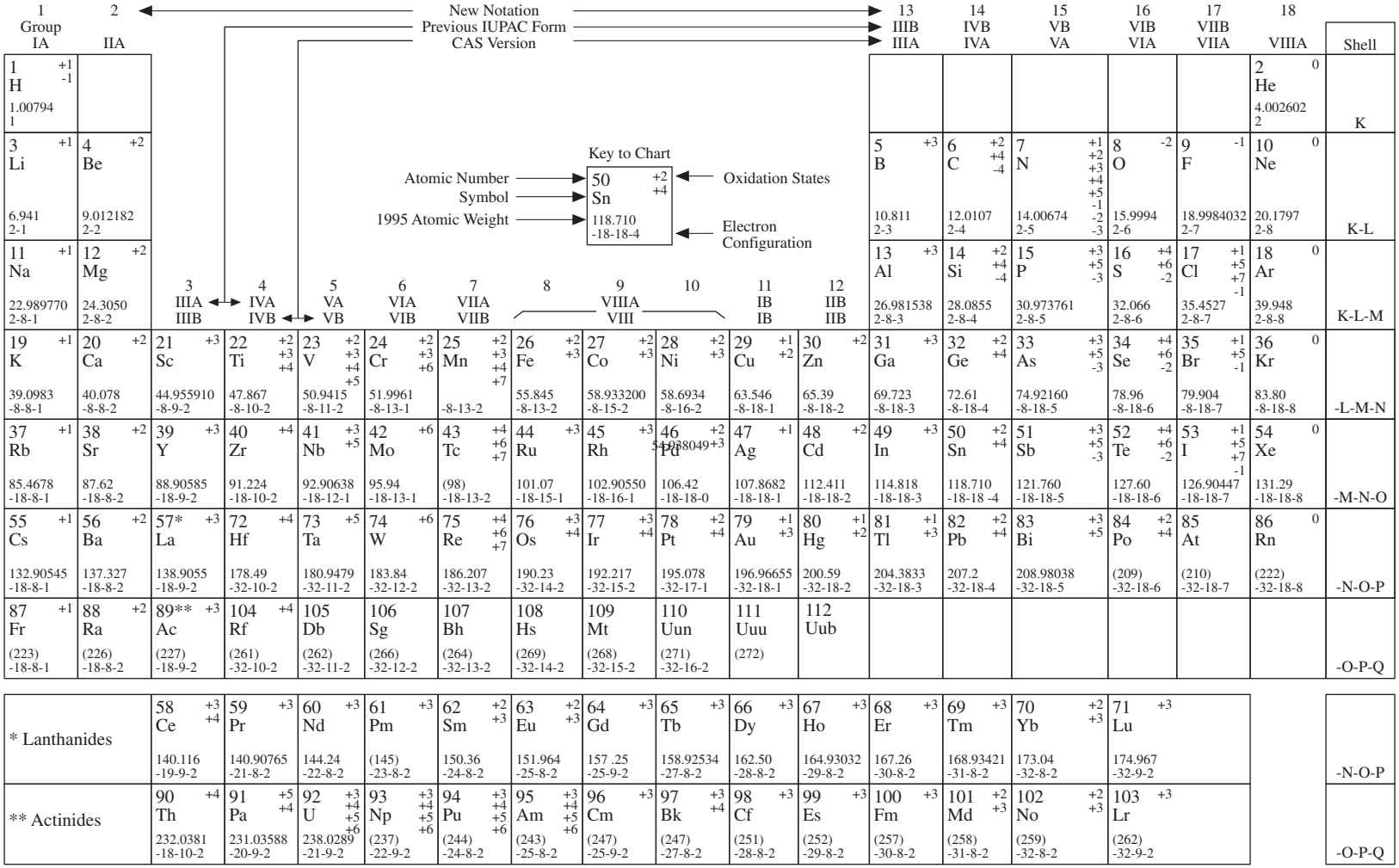
Weber, M. J. “Frontmatter”
Handbook of Laser Wavelengths.
Ed. Marvin J. Weber
Boca Raton: CRC Press LLC, 1999

PERIODIC TABLE OF THE ELEMENTS



The new IUPAC format numbers the groups from 1 to 18. The previous IUPAC numbering system and the system used by Chemical Abstracts Service (CAS) are also shown. For radioactive elements that do not occur in nature, the mass number of the most stable isotope is given in parentheses.

References

1. G. J. Leigh, Editor, *Nomenclature of Inorganic Chemistry*, Blackwell Scientific Publications, Oxford, 1990.
2. *Chemical and Engineering News*, 63(5), 27, 1985.
3. Atomic Weights of the Elements, 1995, *Pure & Appl. Chem.*, 68, 2339, 1996.

© CRC Press 1999 LLC

Handbook of Laser Wavelengths

Marvin J. Weber Ph.D.
Lawence Berkeley National Laboratory
University of California
Berkeley, California



CRC Press
Boca Raton London New York Washington, D.C.

© 1999 by CRC PRESS LLC

Library of Congress Cataloging-in-Publication Data

Weber, Marvin John, 1932–
Handbook of laser wavelengths / Marvin John Weber.
p. cm. -- (CRC Press laser and optical science and technology series)
Includes bibliographical references.
ISBN 0-8493-3508-6 (alk. paper)
1. Lasers--Handbooks, manuals, etc. 2. Laser materials--Handbooks, manuals, etc. 3. Light--Wave-length--Handbooks, manuals, etc. I. Title. II. Series.
TA1683.W43 1999
621.36'6—dc21

98-20095
CIP

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage or retrieval system, without prior permission in writing from the publisher.

The consent of CRC Press LLC does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from CRC Press LLC for such copying.

Direct all inquiries to CRC Press LLC, 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are only used for identification and explanation, without intent to infringe.

© 1999 by CRC Press LLC

No claim to original U.S. Government works
International Standard Book Number 0-8493-3508-6
Library of Congress Card Number 98-20095
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0

© CRC Press 1999 LLC

Foreword

It is really amazing how many laser transitions and how many laser wavelengths have been discovered. They cover nearly every class of material, from free electrons through gases, liquids, and solids. It is perhaps even more amazing that the comprehensive listing in this book could be compiled through the collaboration of leading experts in each of the fields.

Forty years ago, when Charles Townes and I were first trying to discover how lasers might be made, it seemed very difficult. We had always been taught that the world was pretty close to being in equilibrium, even though masers had shown that you could sometimes get away from it. As Ali Javan pointed out then, when discussing possible gas lasers, there are many processes tending to restore equilibrium. Moreover, since nobody had ever made a laser, we thought it might be very difficult. There might be some hidden problem that we had over-looked. But that turned out to be wrong and some kinds of lasers are quite easy to make once you know how.

When thinking of possible laser materials, I for one had plenty of blind spots and poorly based prejudices. For instance, I knew that the optical gain, for a given excess of excited atoms, would be inversely proportional to the spectral linewidth. Thus I felt that narrow lines were essential, overlooking the fact that some broad bands in things like organic dyes have large oscillator strengths and so make up for their large width. Also, for a time I couldn't see why anyone would want to use a laser to pump another, thereby compounding their inefficiencies.

Fortunately, lasers attracted the interest and stimulated the imagination of large numbers of very clever people. Some of them had specialized knowledge of things like crystal growing, very hot plasmas, or semiconductor luminescence. From their work have come the very many types of lasers listed in this book. Some of the discoveries resulted from careful study and planning, while others were serendipitous.

Many lasers have been discovered but never put to any practical use. In some cases, gases are too corrosive or too easily adsorbed on the walls. In others, crystalline materials are too difficult to grow in useful sizes, or are too hygroscopic. Sometimes, there just isn’t any obvious need for that kind of laser. Perhaps someone browsing in this book will find something for a new use, or will think of ways to overcome the apparent difficulties.

Perhaps also in the future, or even now, someone will recognize other blind spots and will see new approaches to yield still more types of useful lasers.

Arthur L. Schawlow
Stanford University

© 1999 by CRC PRESS LLC

Preface

Although we are well into the fourth decade since the advent of the laser, the number and type of lasers and their wavelength coverage continue to expand. One seeking a photon source is now confronted with an enormous number of possible lasers and laser wavelengths. In addition, various techniques of frequency conversion—harmonic generation, optical parametric oscillation, sum- and difference-frequency mixing, and Raman shifting—can be used to enlarge the spectral coverage.

This volume seeks to provide a comprehensive compilation of the wavelengths of lasers in all media in a readily accessible form for scientists and engineers searching for laser sources for specific applications. The compilation also indicates the state of knowledge and develop-ment in the field, provides a rapid means of obtaining reference data, is a pathway to the literature, contains data useful for comparison with predictions and/or to develop models of processes, and may reveal fundamental inconsistencies or conflicts in the data. It serves both an archival function and as an indicator of newly emerging trends.

The *Handbook of Laser Wavelengths* is derived from data evaluated and compiled by the contributors of Volumes I and II and Supplement 1 of the *CRC Handbook Series of Laser Science and Technology*. In most cases it was possible to update these tabulations to include more recent additions and new categories of lasers. For semiconductor lasers where in some instances the lasing wavelength may not be a fundamental property but the result of material engineering and the operating configuration, an effort was made to be representative rather than exhaustive in the coverage of the literature. The number of gas laser transitions is huge; they constitute nearly 80% of the over 15,000 laser wavelengths in this volume. Laser transitions in gases are well covered through the late 1980s in the above volumes. An electronic database of gas lasers prepared from the tables in Volume II and Supplement 1 by John Broad and Stephen Krog (Joint Institute of Laboratory Astrophysics) was used for this volume, but does not cover all recent developments.

In Section 1, a brief description of various types of lasers is given. Lasers are divided by medium—solid, liquid, and gas—each one of which is further subdivided, as appropriate, into distinctive types. Thus there are sections on crystalline paramagnetic ion lasers, glass lasers, color center lasers, semiconductor lasers, polymer lasers, liquid and solid-state dye lasers, rare earth liquid lasers, and neutral atom, ion, and molecular gas lasers. A separate section on "other" lasers covers lasers having special operating conditions or nature. These include extreme ultraviolet and soft x-ray lasers, free electron lasers, nuclear-pumped lasers, lasers in nature, and lasing without inversion. Brief descriptions of each type of laser are given followed by tables listing reported lasing wavelength, lasing element or medium, host, other experimental conditions, and primary literature citations. All lasers are listed in order of increasing wavelength.

The realm of tunable lasers has expanded and includes liquid and solid-state dye lasers, lanthanide and transition-metal crystalline lasers, color center lasers, and semiconductor and polymer lasers. Tuning ranges, when reported, are given for these broadband lasers. For most types of lasers, lasing—light amplification by stimulated

© 1999 by CRC PRESS LLC

emission of radiation—includes, for completeness, not only operation in a resonant cavity but also single-pass gain or amplified spontaneous emission (ASE).
The wavelengths of lasing transitions are of primary concern. No detailed descriptions of laser structure, operation, or performance are provided. These properties are covered in Volumes I and II and Supplement 1 of the *CRC Handbook Series of Laser Science and Technology*. Although laser performance data are not tabulated, a special section on commercially available lasers is included to provide a perspective on the current state-of-the-art and performance boundaries (although these are expected to change due to advances in technology). Further background information about lasers in general and about specific types of lasers in particular can be obtained from the books and articles listed under Further Reading in each section.

To cope with the continuing and bewildering proliferation of acronyms, abbreviations, and initialisms that range from the clever and informative to the amusing or annoying, two appendices are included—one for types and structures of lasers and amplifiers and one for solid-state laser materials. A third appendix provides a list of fundamental physical constants of interest to laser scientists and engineers.

Because lasers now cover such a large wavelength range and because researchers in different fields are frequently accustomed to using different units, there is also a "Rosetta stone for spectroscopists" on the inside back cover.

I wish to acknowledge the valuable help and expertise of the Advisory Board for this volume who reviewed the material, made suggestions about the contents, and in several cases contributed material (the Board, however, is not responsible for the accuracy nor thoroughness of the tabulations). We are all indebted to the contributors to Volumes I and II and Supplement 1 of the *CRC Handbook Series of Laser Science and Technology* who compiled the data from which most of this volume was derived. Others who have provided helpful comments, suggestions, and data include Eric Bründermann, Federico Capasso, Henry Freund, Claire Gmachl, Victor Granatstein, Eugene Haller, Stephen Harris, John Harreld, Thomas Hasenberg, Alan Heeger, Heonsu Jeon, George Miley, Michael Mumma, Dale Partin, Maria Petra, Jin-Joo Song, and Riccardo Zucca. Finally I appreciate the help of the CRC Press staff during the preparation of this volume—Tim Pletscher, Acquiring Editor for Engineering, Felicia Shapiro, Suzanne Lassandro, Gerry Axelrod—and especially Mimi Williams for her careful and excellent editing of the manuscript.

Marvin John Weber
Danville, California

© 1999 by CRC PRESS LLC

The Author

Marvin John Weber received his education at the University of California, Berkeley, and was awarded the A.B., M.A., and Ph.D. degrees in physics. After graduation, Dr. Weber continued as a postdoctoral Research Associate and then joined the Research Division of the Raytheon Company where he was a Principal Scientist working in the areas of spectroscopy and quantum electronics. As Manager of Solid State Lasers, his group developed many new laser materials including rare-earth-doped yttrium orthoaluminate. While at Raytheon, he also discovered luminescence in bismuth germanate, a scintillator crystal widely used for the detection of high energy particles and radiation.

During 1966 to 1967, Dr. Weber was a Visiting Research Associate with Professor Arthur Schawlow's group in the Department of Physics, Stanford University.

In 1973, Dr. Weber joined the Laser Program at the Lawrence Livermore National Laboratory. As Head of Basic Materials Research and Assistant Program Leader, he was responsible for the physics and characterization of optical materials for high-power laser systems used in inertial confinement fusion research. From 1983 to 1985, he accepted a transfer assignment with the Office of Basic Energy Sciences of the U.S. Department of Energy in Washington, DC where he was involved with planning for advanced synchrotron radiation facilities and for atomistic computer simulations of materials. Dr. Weber returned to the Chemistry and Materials Science Department at LLNL in 1986 and served as Associate Division Leader for condensed matter research and as spokesperson for the University of California/National Laboratories research facilities at the Stanford Synchrotron Radiation Laboratory. He retired from LLNL in 1993 but continues as a Participating Guest in the Physics and Space Technology Department. He presently does consulting and is a physicist in the Center for Functional Imaging at the Lawrence Berkeley National Laboratory.

Dr. Weber is Editor-in-Chief of the multi-volume *CRC Handbook Series of Laser Science and Technology*. He has also served as Regional Editor for the *Journal of Non-Crystalline Solids*, as Associate Editor for the *Journal of Luminescence* and the *Journal of Optical Materials*, and as a member of the International Editorial Advisory Boards of the Russian journals *Fizika i Khimiya Stekla* (Glass Physics and Chemistry) and *Kvantovaya Elektronika* (Quantum Electronics).

Among several honors he has received are an Industrial Research IR-100 Award for research and development of fluorophosphate laser glass, the George W. Morey Award of the American Ceramics Society for his basic studies of fluorescence, stimulated emission and the atomic structure of glass, and the International Conference on Luminescence Prize for his research on the dynamic processes affecting luminescence efficiency and the application of this knowledge to laser and scintillator materials.

Dr. Weber is a Fellow of the American Physical Society, the Optical Society of America, and the American Ceramics Society and has been a member of the Materials Research Society and the American Association for Crystal Growth.

© 1999 by CRC PRESS LLC

Advisory Board

John T. Broad, Ph.D.
Informed Access Systems, Inc.
Boulder, Colorado
(formerly of JILA)

Connie Chang-Hasnain, Ph.D.
Electrical Engineering/Computer Sciences
University of California
Berkeley, California

William B. Colson, Ph.D.
Physics Department
Naval Postgraduate School
Monterey, California

Christopher C. Davis, Ph.D.
Electrical Engineering Department
University of Maryland
College Park, Maryland

Bruce Dunn, Ph.D.
Materials Science and Engineering
University of California
Los Angeles, California

J. Gary Eden, Ph.D.
Electrical and Computer Engineering
University of Illinois
Urbana, Illinois

Alexander A. Kaminskii, Ph.D.
Institute of Crystallography
Russian Academy of Sciences
Moscow, Russia

David J. E. Knight, Ph.D.
DK Research
Twickenham, Middlesex , England
(formerly of National Physical Laboratory)

William F. Krupke, Ph.D.
Laser Program
Lawrence Livermore National Laboratory
Livermore, California

Brian J. MacGowan, Ph.D.
Laser Program
Lawrence Livermore National Laboratory
Livermore, California

Stephen Payne, Ph.D.
Laser Program
Lawrence Livermore National Laboratory
Livermore, California

Clifford R. Pollock, Ph.D.
School of Electrical Engineering
Cornell University
Ithaca, New York

Anthony E. Siegman, Ph.D.
Department of Electrical Engineering
Stanford University
Stanford, California

Richard N. Steppel, Ph.D.
Exciton, Inc.
Dayton, Ohio

Anne C. Tropper, Ph.D.
Optoelectronic Research Centre
University of Southhampton
Highfield, Southhampton, England

© 1999 by CRC PRESS LLC

Contents of previous volumes on lasers from the

CRC HANDBOOK OF LASER SCIENCE AND TECHNOLOGY

VOLUME I: LASERS AND MASERS

FOREWORD — Charles H. Townes

SECTION 1: INTRODUCTION
1.1 Types and Comparisons of Laser Sources — William F. Krupke

SECTION 2: SOLID STATE LASERS
2.1 Crystalline Lasers
2.1.1 Paramagnetic Ion Lasers — Peter F. Moulton
2.1.2 Stoichiometric Lasers — Stephen R. Chinn
2.1.3 Color Center Lasers — Linn F. Mollenauer
2.2 Semiconductor Lasers — Henry Kressel and Michael Ettenberg
2.3 Glass Lasers — Stanley E. Stokowski
2.4 Fiber Raman Lasers — Roger H. Stolen and Chinlon Lin
2.5 Table of Wavelengths of Solid State Lasers

SECTION 3: LIQUID LASERS
3.1 Organic Dye Lasers — Richard Steppel
3.2 Inorganic Liquid Lasers
3.2.1 Rare Earth Chelate Lasers — Harold Samelson
3.2.2 Aprotic Liquid Lasers — Harold Samelson

SECTION 4: OTHER LASERS
4.1 Free Electron Lasers
4.1.I Infrared and Visible Lasers — Donald Prosnitz
4.1.2 Millimeter and Submillimeter Lasers — Victor L. Granatstein, Robert K. Parker, and Phillip A. Sprangle
4.2 X-Ray Lasers — Raymond C. Elton

SECTION 5: MASERS
5.1 Masers — Adrian E. Popa
5.2 Maser Action in Nature — James M. Moran

SECTION 6: LASER SAFETY
6.1 Optical Radiation Hazards — David H. Sliney
6.2 Electrical Hazards from Laser Power Supplies — James K. Franks
6.3 Hazards from Associated Agents — Robin DeVore

© 1999 by CRC PRESS LLC

VOLUME II: GAS LASERS

SECTION 1: NEUTRAL GAS LASERS — Christopher C. Davis

SECTION 2: IONIZED GAS LASERS — William B. Bridges

SECTION 3: MOLECULAR GAS LASERS
3.1 Electronic Transition Lasers — Charles K. Rhodes and Robert S. Davis
3.2 Vibrational Transition Lasers — Tao-Yaun Chang
3.3 Far Infrared Lasers — Paul D. Coleman and David J. E. Knight

SECTION 4: TABLE OF LASER WAVELENGTHS — Marvin J. Weber

SUPPLEMENT 1: LASERS

SECTION 1: SOLID STATE LASERS
1.1 Crystalline Paramagnetic Ion Lasers — John A. Caird and Stephen A. Payne
1.2 Color Center Lasers — Linn F. Mollenauer
1.3 Semiconductor Lasers — Michael Ettenberg and Henryk Temkin
1.4 Glass Lasers — Douglas W. Hall and Marvin J. Weber
1.5 Solid State Dye Lasers — Marvin J. Weber
1.6 Fiber Raman Lasers — Roger H. Stolen and Chinlon Lin
1.7 Table of Wavelengths of Solid State Lasers — Farolene Camacho

SECTION 2: LIQUID LASERS
2.1 Organic Dye Lasers — Richard N. Steppel
2.2 Liquid Inorganic Lasers — Harold Samelson

SECTION 3: GAS LASERS
3.1 Neutral Gas Lasers — Julius Goldhar
3.2 Ionized Gas Lasers — Alan B. Petersen
3.3.1 Electronic Transition Lasers — J. Gary Eden
3.3.2 Vibrational Transition Lasers — Tao-Yuan Chang
3.3.3 Far-Infrared CW Gas Lasers — David J. E. Knight
3.4 Table of Wavelengths of Gas Lasers — Farolene Camacho

SECTION 4: OTHER LASERS
4.1 Free-Electron Lasers — William B. Colson and Donald Prosnitz
4.2 Photoionization-Pumped Short Wavelength Lasers — David King
4.3 X-Ray Lasers — Dennis L. Matthews
4.4 Table of Wavelengths of X-Ray Lasers
4.5 Gamma-Ray Lasers — Carl B. Collins

SECTION 5: MASERS
5.1 Masers — Adrian E. Popa
5.2 Maser Action in Nature — James M. Moran

© 1999 by CRC PRESS LLC

HANDBOOK OF LASER WAVELENGTHS

TABLE OF CONTENTS

FOREWORD

PREFACE

SECTION 1: INTRODUCTION

SECTION 2: SOLID STATE LASERS
- 2.1 Crystalline Paramagnetic Ion Lasers
- 2.2 Glass Lasers
- 2.3 Solid State Dye Lasers
- 2.4 Color Center Lasers
- 2.5 Semiconductor Lasers
- 2.6 Polymer Lasers

SECTION 3: LIQUID LASERS
- 3.1 Organic Dye Lasers
- 3.2 Rare Earth Liquid Lasers

SECTION 4: GAS LASERS
- 4.1 Neutral Atom, Ionized, and Molecular Gas Lasers
- 4.2 Optically Pumped Far Infrared and Millimeter Wave Lasers
- 4.3 References

SECTION 5: OTHER LASERS
- 5.1 Extreme Ultraviolet and Soft X-Ray Lasers
- 5.2 Free Electron Lasers
- 5.3 Nuclear Pumped Lasers
- 5.4 Natural Lasers
- 5.5 Inversionless Lasers

SECTION 6: COMMERCIAL LASERS
- 6.1 Solid State Lasers
- 6.2 Semiconductor Lasers
- 6.3 Dye Lasers
- 6.4 Gas Lasers

APPENDICES
- Appendix 1 Abbreviations, Acronyms, Initialisms, and Common Names for Types and Structures of Lasers and Amplifiers
- Appendix 2 Abbreviations, Acronyms, Initialisms, and Mineralogical or Common Names for Solid State Laser Materials
- Appendix 3 Fundamental Constants

© 1999 by CRC PRESS LLC