Introduction to
Laser Diode–Pumped
Solid State Lasers
Tutorial Texts Series

- Modulation Transfer Function in Optical and Electro-Optical Systems, Glenn D. Boreman, Vol. TT52
- Fundamentals of Antennas, Christos G. Christodoulou and Parveen Wahid, Vol. TT50
- The Basics of Spectroscopy, David W. Ball, Vol. TT49
- Resolution Enhancement Techniques in Optical Lithography, Alfred Kwok-Kit Wong, Vol. TT47
- Copper Interconnect Technology, Christoph Steinbrüchel and Barry L. Chin, Vol. TT46
- Fundamentals of Contamination Control, Alan C. Tribble, Vol. TT44
- Evolutionary Computation: Principles and Practice for Signal Processing, David Fogel, Vol. TT43
- Infrared Optics and Zoom Lenses, Allen Mann, Vol. TT42
- Introduction to Adaptive Optics, Robert K. Tyson, Vol. TT41
- Fractal and Wavelet Image Compression Techniques, Stephen Welstead, Vol. TT40
- Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis, Valery Tuchin, Vol. TT38
- Design and Mounting of Prisms and Small Mirrors in Optical Instruments, Paul R. Yoder, Jr., Vol. TT32
- Basic Electro-Optics for Electrical Engineers, Glenn D. Boreman, Vol. TT31
- Optical Engineering Fundamentals, Bruce H. Walker, Vol. TT30
- Introduction to Radiometry, William L. Wolfe, Vol. TT29
- Lithography Process Control, Harry J. Levinson, Vol. TT28
- An Introduction to Interpretation of Graphic Images, Sergey Ablameyko, Vol. TT27
- Thermal Infrared Characterization of Ground Targets and Backgrounds, P. Jacobs, Vol. TT26
- Introduction to Imaging Spectrometers, William L. Wolfe, Vol. TT25
- Mounting Lenses in Optical Instruments, Paul R. Yoder, Jr., Vol. TT21
- Introduction to Wavefront Sensors, Joseph M. Geary, Vol. TT18
- Integration of Lasers and Fiber Optics into Robotic Systems, J. A. Marszalec, E. A. Marszalec, Vol. TT17
- Introduction to Optical Testing, Joseph M. Geary, Vol. TT15
- Diazonaphthoquinone-based Resists, Ralph Dammel, Vol. TT11
- Infrared Window and Dome Materials, Daniel C. Harris, Vol. TT10
- An Introduction to Optics in Computers, Henri H. Arsenault, Yunlong Sheng, Vol. TT8
- Digital Image Compression Techniques, Majid Rabbani, Paul W. Jones, Vol. TT7
- Aberration Theory Made Simple, Virendra N. Mahajan, Vol. TT6
Introduction to
Laser Diode–Pumped
Solid State Lasers

Richard Scheps

Tutorial Texts in Optical Engineering
Volume TT53

Arthur R. Weeks, Jr., Series Editor
Invivo Research Inc. and University of Central Florida
Introduction to the Series

The Tutorial Texts series was initiated in 1989 as a way to make the material presented in SPIE short courses available to those who couldn’t attend and to provide a reference book for those who could. Typically, short course notes are developed with the thought in mind that supporting material will be presented verbally to complement the notes, which are generally written in summary form, highlight key technical topics, and are not intended as stand-alone documents. Additionally, the figures, tables, and other graphically formatted information included with the notes require further explanation given in the instructor’s lecture. As stand-alone documents, short course notes do not generally serve the student or reader well.

Many of the Tutorial Texts have thus started as short course notes subsequently expanded into books. The goal of the series is to provide readers with books that cover focused technical interest areas in a tutorial fashion. What separates the books in this series from other technical monographs and textbooks is the way in which the material is presented. Keeping in mind the tutorial nature of the series, many of the topics presented in these texts are followed by detailed examples that further explain the concepts presented. Many pictures and illustrations are included with each text, and where appropriate tabular reference data are also included.

To date, the texts published in this series have encompassed a wide range of topics, from geometrical optics to optical detectors to image processing. Each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the processes and technologies under discussion.

The Tutorial Text series, which now numbers more than fifty titles, has expanded to include not only texts developed by short course instructors but also those written by other topic experts. It is my goal to maintain the style and quality of books in the series, and to further expand the topic areas to include emerging as well as mature subjects in optics, photonics, and imaging.

Arthur R. Weeks, Jr.
Invivo Research Inc. and University of Central Florida
“When we walked in fields of gold…”

– Sting
Contents

Preface / xiii
List of Symbols / xv

Part I. Fundamentals of Laser Diode Pumping

Chapter 1. Introduction / 3

1.1 Advantages of diode pumping / 4

Chapter 2. Basic Concepts / 7

2.1 Lasers / 7
2.2 Resonators / 8
2.3 Laser resonator transverse modes / 9
   2.3.1 TEM_{00} / 10
   2.3.2 Multimode operation / 12
   2.3.3 Advantages of single transverse mode operation / 12
   2.3.4 Longitudinal modes / 12
2.4 Laser diodes for pumping solid state lasers / 13
   2.4.1 Single-stripe diodes / 14
   2.4.2 Single-mode diodes / 15
   2.4.3 Pulsed and cw diode operation / 15
   2.4.4 Diode manufacturing terms / 16
   2.4.5 Laser diode arrays / 16
   2.4.6 Laser diode beam spatial properties / 17
2.5 Optical fiber concepts / 18
   2.5.1 Numerical aperture / 18
   2.5.2 Core size / 18
   2.5.3 Fiber-coupled single-stripe diodes: Advantages / 19
   2.5.4 Fiber-coupled laser diode arrays / 20
2.6 Light ducts / 21

Part II. Basic End-pumped Laser Design

Chapter 3. Design of a TEM_{00} Continuous-Wave Diode-pumped Nd:YAG Laser / 25

3.1 Considerations: End-pumped or side-pumped? / 26
3.2 Selecting the gain element / 29
3.2.1 Laser host crystals / 29
3.2.2 Laser rod specifications / 31
3.3 Selecting the laser diode / 32
  3.3.1 Pump diode center wavelength and spectral bandwidth / 32
  3.3.2 Temperature tuning / 32
  3.3.3 Bandwidth control / 33
  3.3.4 Current tuning and mode hop / 34
3.4 Selecting the resonator / 34
  3.4.1 Resonator length / 34
  3.4.2 Resonator configuration / 35
  3.4.3 Rod coatings / 36
3.5 Selecting the pump optics / 37
  3.5.1 Pump optics / 37
  3.5.2 Astigmatism correction / 38
  3.5.3 Focusing lens / 39
  3.5.4 Polarization combination of laser diodes / 41
  3.5.5 Diffraction-limited operation / 43

Chapter 4. Operation of the Continuous-Wave Diode-pumped Laser / 45

  4.1 Resonator gain and loss: Findlay-Clay analysis / 45
  4.2 Threshold / 47
  4.3 Optimum output coupling / 48
  4.4 Laser output, slope efficiency and bandwidth / 48
    4.4.1 Output / 48
    4.4.2 Slope efficiency / 49
    4.4.3 Bandwidth / 49
  4.5 Efficiency factors / 49
    4.5.1 Electrical-to-optical efficiency / 50
    4.5.2 Stokes efficiency / 50
    4.5.3 Geometric coupling efficiency / 50
    4.5.4 Laser quantum efficiency / 50
    4.5.5 Transfer efficiency / 51
    4.5.6 Extraction efficiency / 51
    4.5.7 Summary of efficiency factors / 51
  4.6 Dependence of the laser output power on the diode wavelength / 52

Part III. Advanced Concepts for Diode Pumping

Chapter 5. Power Scaling Considerations / 57

  5.1 Scaling the diode pump power / 58
    5.1.1 Diode arrays / 58
  5.2 Thermal effects / 60
Chapter 6. Side-pumped Designs / 67

6.1 Zig-zag slab laser / 68
6.2 Novel side-pumped design / 69

Chapter 7. Other Output Wavelengths for Nd-doped Lasers / 71

7.1 Operation at 1.3 μm / 71
7.2 Operation at 946 nm / 72

Chapter 8. Diodes for Pumping Other Gain Elements / 75

8.1 900-nm diodes / 75
8.2 670-nm diodes / 75

Chapter 9. Examples of Other Diode-pumped Lasers / 77

9.1 Yb-doped lasers / 77
9.2 Cr-doped tunable solid state lasers / 78
9.3 Dye lasers / 80


10.1 Acousto-optic Q-switch for high repetition rate / 83
10.2 Intracavity SHG for visible laser output / 85
10.3 Single-longitudinal-mode lasers / 86
10.3.1 Ring lasers / 87
10.3.2 “Microchip” lasers / 88

Chapter 11. Conclusion / 91

Bibliography / 93
References / 95
Index / 97
Preface

This book arose from a series of courses I presented on laser diode pumping. It covers a wide range of material, from the basics of laser resonators to advanced topics in laser diode pumping. The subject matter is presented in descriptive terms that will be understandable to the technical professional who does not have a strong foundation in fundamental laser optics. For the scientist or engineer with a more extensive background in laser design, the range and depth of the topics covered will provide a new and hopefully helpful perspective on development in this highly active area.

By presenting the material in courses to students from diverse backgrounds I have received numerous constructive comments that have been incorporated into the text. The modifications have enhanced the continuity of the technical material. As a result, this Tutorial Text represents an evolution from interactive classroom teaching to self-directed learning. I trust that the information presented will prove useful for those interested in diode pumping.

As the text is tutorial in nature, I have chosen not to include a comprehensive list of references. I have included a few general references and have cited papers that describe certain techniques in more detail than could be included in this book. In general, however, I have not provided the type of reference listing that one might expect in a review article on this subject and have therefore not been able to acknowledge much of the high-quality research that has been produced in this area over the past several decades.

Some of the material will become dated over time. The basic information presented in this book of course will not be affected by future developments, but for laser diodes the quoted costs and maximum output power levels will change. However, conclusions that are based on current (November 2000) numbers are readily modified when the relevant factors change. The book is generally explicit in terms of how these conclusions are reached, and the reader should have no problem including updated cost data using the paradigm provided in the text.

I want to end this section by thanking SPIE for offering me the opportunity to publish this book, and particularly Rick Hermann for helping overcome many of the difficulties that presented themselves. I also want to thank my family for their advice and support, my friends in France and the UK who made an important difference in my life, and my scientific colleagues, especially Joe Myers, who helped with the development of the concepts presented in the text.

Richard Scheps
San Diego, California
List of Symbols

A partial list of symbols used in the text:

\( \alpha = \) absorption coefficient
\( \alpha_m = \) maximum acceptance angle for TIR
\( \eta = \) wall plug efficiency
\( \eta_p = \) pump efficiency
\( \theta = \) divergence half angle
\( \lambda = \) optical wavelength
\( \ell = \) laser crystal length
\( \sigma = \) effective stimulated emission cross section
\( \sigma_{\text{em}} = \) stimulated emission cross section
\( \tau_c = \) cavity lifetime
\( \tau_f = \) fluorescence lifetime
\( \nu_p = \) frequency of pump radiation
\( \Delta \nu = \) separation between longitudinal mode frequencies
AO = acousto-optic
\( A_m = \) resonator mode area
\( A_p = \) pump mode area
AR = anti-reflective
ASE = amplified spontaneous emission
\( c = \) speed of light
cw = continuous-wave
dn/dt = change in refractive index with temperature
ESD = electrostatic discharge
\( f = \) focal length
\( f_{\text{nnq}} = \) resonator optical frequency, where \( n \) and \( m \) reference the transverse mode
\( f_i = \) relaxation frequency
\( f_2 = \) fraction of \( ^4F_{3/2} \) population in the \( R_2 \) upper laser level
\( g_o = \) small signal (unsaturated) gain
\( g_n = \) resonator parameter for the \( n^{\text{th}} \) mirror, useful for determining mode stability
HR = highly reflective
HT = highly transmissive
\( I = \) pump intensity
\( I_{\text{sat}} = \) saturation intensity
\( K = \) thermal conductivity
\( L = \) resonator length
\( L_p = \) resonator round-trip passive loss, including output coupling
\( L_u = \) round-trip passive loss, excluding output coupling
\( L_s = \) single-pass passive loss
MOCVD = metal organic chemical vapor deposition, a process for manufacturing laser diodes

MTBF = mean time between failure

\( n^* \) = upper laser level population

\( n_i \) = average refractive index along the optical path within the laser resonator

\( n_m \) = refractive index of the \( m^{th} \) optical component

\( n_o \) = dopant density

NA = numerical aperture

\( P \) = absorbed pump power

\( P' \) = excitation pump rate

\( P_e \) = excess energy, i.e., the pump power less the threshold pump power

\( P_h \) = fraction of pump power deposited as heat

\( P_{th} \) = threshold pump power

PBC = polarization beamsplitter cube

PFN = pulse-forming network

PPLN = periodically poled lithium niobate

ROC = radius of curvature

qcw = quasi-cw

\( R \) = reflectivity

\( R_n \) = radius of curvature of the \( n^{th} \) resonator mirror

SHG = second harmonic generation

SLM = single longitudinal mode

\( T \) = transmission of output coupler

\( T_{opt} \) = optimum output coupling

\( \text{TEM}_{nm} \) = transverse electric and magnetic mode \( n,m \)

TIR = total internal reflection

\( w_0 \) = resonator mode waist (1/e amplitude point)

\( w_n \) = resonator spot size on mirror \( n \)

\( z_n \) = location of resonator mode waist with respect to mirror \( n \)