

The Optics of Semiconductor Diode Lasers

Masud Mansuripur and Ewan M. Wright

Robert N. Hall, born in New Haven, Connecticut in 1919, joined General Electric's Research and Development Center after graduating from the California Institute of Technology. In 1962, having realized that a semiconductor junction could support population inversion, Hall built the first semiconductor injection laser. This device, based on a specially designed p-n junction, operated when an electric current injected the electrons directly into the junction, thus allowing for highly efficient generation of coherent light from a compact source. Today, diode lasers based on Hall's original idea are used, among other places, in CD and DVD players, laser printers, and fiber-optic communication systems.¹

In this article we describe the basic features of the beam of light emitted by a diode laser, and discuss methods to analyze and manipulate this beam. Collimation and beam-shaping with a pair of cylindrical lenses will be shown to be a simple and flexible method that may be applied not only to diode lasers but also to beams emerging from optical fibers.

Characteristics of diode lasers

A semiconductor diode laser shown schematically in Fig. 1 consists of a gain layer (only a few ten nanometers thick), surrounded by guiding layers for confining the laser mode. The guiding layers' index of refraction is somewhat greater than that of the surrounding regions (substrate and cladding), thus permitting confinement by total internal reflection. The electrical current is injected through the positive electrode, a metallic stripe several microns wide, and collected at the base plate on the opposite side of the junction (ground electrode). The population inversion and optical gain are strongest beneath the positive electrode, tapering off laterally with an increasing distance from the electrode's center line along Z . In gain-guided lasers, this tapering off of the gain is responsible for lateral beam confinement. (By contrast, in index-guided lasers the region adjacent to the guiding stripe are selectively etched away, then replaced by a lower-index cladding material.) In general, the gain layer is highly absorptive in regions that are not directly underneath the electrode and, therefore, experience weak pumping, or no pumping at all. The guiding layers are essentially transparent, except for losses due to scattering at impurities and at the interfaces. The substrate and the cladding are also highly transparent.

Figure 2 shows plots of intensity and phase at the front facet of a single-transverse-mode diode laser ($\lambda_0 = 980$ nm). The assumed beam divergent angles (full-width-at-half-maximum intensity



Figure 1. A semiconductor diode laser consisting of an active layer surrounded by guiding layers for confinement of the laser mode. The electrical current, injected through the positive electrode, is collected on the opposite side of the junction by the ground electrode.

or FWHM) are $\theta_x = 7^\circ$ in the plane of the junction and $\theta_z = 35^\circ$ perpendicular to the junction. In the top row of the figure, (a, b), where the assumed beam has no astigmatism, the phase distribution at the laser's front facet is uniform. In the middle row, (c, d), the astigmatic distance (defined as an equivalent distance in free space between horizontal and vertical beam waists) is $\Delta z = 10 \mu\text{m}$, resulting in a slightly wider beam along the X -axis, and a divergent phase front whose peak-to-valley variation (i.e., from the edge to the center of the beam) is $\sim 120^\circ$. In the bottom row, (e, f), the assumed astigmatism is $\Delta z = 25 \mu\text{m}$. Again the beam is broader (in the horizontal direction) than the one without astigmatism, and the phase distribution exhibits a peak-to-valley variation of $\sim 190^\circ$.

The elliptical cross-section of the beam emerging at the front facet of the laser is responsible (through diffraction) for θ_x being much smaller than θ_z . The cause of astigmatism is the non-uniform gain profile (along the X -axis) within the active region of the laser. As the gain is strongest near the cavity's central axis, the beam, while propagating in the cavity along Z , experiences a "gain focusing" effect toward this axis—a direct consequence of stronger amplification on-axis than in the wings.² Consequently, a divergent phase profile automatically evolves for counteracting this tendency of the beam to collapse to the center. We will have more to say about this property in the following section.

Another interesting property of a diode laser beam is its polarization state, which is typically linear, having E -field parallel to the plane of the junction. This property may be traced back to the fact that, for light polarized parallel to the junction (i.e., E_x) the gain is somewhat greater than that for perpendicularly polarized light (hereinafter E_z). The guided mode associated with E_x is slightly broader in the Y -direction than the mode associated with E_z . Since a broad mode has less overlap with the gain layer than a more compact mode, it stays behind while the compact mode surpasses the threshold and begins to lase. Moreover, confinement of electrons and holes to a thin (quantum well) active layer makes it easier for E_x (relative to E_z) to stimulate the excited electrons and holes into surrendering their photons and returning to the ground state. In practice a combination of both effects is responsible for promoting the selection of E_x polarization over E_z .

Origin of diode laser astigmatism

The non-uniformity of the gain profile along X has a focusing effect on the guided mode that is countered automatically by a divergent phase front imposed on the beam as it propagates along the Z -axis of the cavity. An easy demonstration is provided by

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Semiconductor Diode Lasers Volume I Progress In Lasers And Electro Optics:

Advances In Semiconductor Lasers And Applications To Optoelectronics (Ijhses Vol. 9 No. 4) Mitra

Dutta, Michael A Strosio, 2000-06-21 Foreword by Charles H Townes This volume includes highlights of the theories underlying the essential phenomena occurring in novel semiconductor lasers as well as the principles of operation of selected heterostructure lasers To understand scattering processes in heterostructure lasers and related optoelectronic devices it is essential to consider the role of dimensional confinement of charge carriers as well as acoustical and optical phonons in quantum structures Indeed it is important to consider the confinement of both phonons and carriers in the design and modeling of novel semiconductor lasers such as the tunnel injection laser quantum well intersubband lasers and quantum dot lasers The full exploitation of dimensional confinement leads to the exciting new capability of scattering time engineering in novel semiconductor lasers As a result of continuing advances in techniques for growing quantum heterostructures recent developments are likely to be followed in coming years by many more advances in semiconductor lasers and optoelectronics As our understanding of these devices and the ability to fabricate them grow so does our need for more sophisticated theories and simulation methods bridging the gap between quantum and classical transport **New Developments in**

Lasers and Electro-optics Research William T. Arkin, 2007 It is expected that ongoing advances in optics will revolutionise the 21st century as they began doing in the last quarter of the 20th Such fields as communications materials science computing and medicine are leaping forward based on developments in optics This new series presents leading edge research on optics and lasers from researchers spanning the globe Optical Fiber Telecommunications IV-A Ivan

Kaminow, Tingye Li, 2002-05-22 Volume IVA is devoted to progress in optical component research and development Topics include design of optical fiber for a variety of applications plus new materials for fiber amplifiers modulators optical switches light wave devices lasers and high bit rate electronics This volume is an excellent companion to Optical Fiber Telecommunications IVB Systems and Impairments March 2002 ISBN 0 12 3951739 Fourth in a respected and comprehensive series Authoritative authors from a range of organizations Suitable for active lightwave R D designers developers purchasers operators students and analysts Lightwave components reviewed in Volume A Lightwave systems and impairments reviewed in Volume B Up to the minute coverage **IEEE Circuits & Devices**, 1991 **Scientific and**

Technical Aerospace Reports, 1980 **Handbook of Laser Welding Technologies** S Katayama, 2013-06-30 Laser welding is a rapidly developing and versatile technology which has found increasing applications in industry and manufacturing It allows the precision welding of small and hard to reach areas and is particularly suitable for operation under computer or robotic control The Handbook of laser welding technologies reviews the latest developments in the field and how they can be used across a variety of applications Part one provides an introduction to the fundamentals of laser welding before moving on to explore developments in established technologies including CO2 laser welding disk laser

welding and laser micro welding technology Part two highlights laser welding technologies for various materials including aluminium and titanium alloys plastics and glass Part three focuses on developments in emerging laser welding technologies with chapters on the applications of robotics in laser welding and developments in the modelling and simulation of laser and hybrid laser welding Finally part four explores the applications of laser welding in the automotive railway and shipbuilding industries The Handbook of laser welding technologies is a technical resource for researchers and engineers using laser welding technologies professionals requiring an understanding of laser welding techniques and academics interested in the field Provides an introduction to the fundamentals of laser welding including characteristics welding defects and evolution of laser welding Discusses developments in a number of techniques including disk conduction and laser micro welding Focusses on technologies for particular materials such as light metal alloys plastics and glass

RF and Microwave Applications and Systems Mike Golio, Janet Golio, 2018-10-03 This volume RF and Microwave Applications and Systems includes a wide range of articles that discuss RF and microwave systems used for communication and radar and heating applications Commercial avionics medical and military applications are addressed An overview of commercial communications systems is provided Past current and emerging cellular systems navigation systems and satellite based systems are discussed Specific voice and data commercial systems are investigated more thoroughly in individual chapters that follow Detailed discussions of military electronics avionics and radar both military and automotive are provided in separate chapters A chapter focusing on FR microwave energy used for therapeutic medicine is also provided Systems considerations including thermal mechanical reliability power management and safety are discussed in separate chapters Engineering processes are also explored in articles about corporate initiatives cost modeling and design reviews The book closes with a discussion of the underlying physics of electromagnetic propagation and interference In addition to new chapters on WiMAX and broadband cable nearly every existing chapter features extensive updates and several were completely rewritten to reflect the massive changes areas such as radio navigation and electronic warfare

High Speed Diode Lasers Sergei A. Gurevich, 1998 This book is composed of seven invited papers which present the current status of high speed diode lasers Fast carrier and photon dynamics in directly modulated MQW lasers is analyzed and novel design approaches are considered which were critical for the demonstration and record of 40 GHz modulation bandwidth Attention is centered on the challenges in creation of high speed and low chirp single mode DFB lasers Recent progress in mode locked diode lasers is covered specifically by the examples of 160 fs pulse generation and appearance of microwave pulse repetition rates Future trends in increasing of high speed laser performance are also examined

Energy Research Abstracts , 1995 Advance Elements of Laser Circuits and Systems Ofer Aluf, 2021-03-09 This book on Advance Elements of Laser circuits and systems Nonlinearity applications in engineering addresses two separate engineering and scientific areas and presents advanced analysis methods for Laser circuits and systems that cover a broad range of engineering and scientific applications The book analyzed Laser circuits and

systems as linear and nonlinear dynamical systems and their limit cycles bifurcation and limit cycle stability by using nonlinear dynamic theory Further it discussed a broad range of bifurcations related to Laser systems and circuits starting from laser system differential equations and their bifurcations delay differential equations DDEs are a function of time delays delay dependent parameters followed by phase plane analysis limit cycles and their bifurcations chaos iterated maps period doubling It combines graphical information with analytical analysis to effectively study the local stability of Laser systems models involving delay dependent parameters Specifically the stability of a given steady state is determined by the graphs of some functions of which can be expressed explicitly The Laser circuits and systems are Laser diode circuits MRI system Laser diode circuitry Electron photon exchanges into VCSEL Ti Sapphire laser systems Ion channel and long wavelength lasers Solid state lasers Solid state laser controlled by semiconductor devices microchip solid state laser Q switched diode pumped solid state laser Nd YAG Mid Infrared and Q switched microchip lasers Gas laser systems copper vapor laser CVL circuitry Dual wavelength laser systems Dual wavelength operation of a Ti sapphire laser Diode pumped Q switched Nd YVO₄ yellow laser Asymmetric dual quantum well lasers Tm³ doped silica fibre lasers Terahertz dual wavelength quantum cascade laser The Book address also the additional areas Laser X guiding system Plasma diagnostics Laser Beam shaping Jitter and crosstalk Plasma mirror systems and High power Laser Target diagnostic system optical elements The book is unique in its emphasis on practical and innovative engineering and scientific applications All conceptual Laser circuits are innovative and can be broadly implemented in many engineering applications The dynamics of Laser circuits and systems provides several ways to use them in a variety of applications covering wide areas This book is aimed at electrical and electronics engineers students and researchers in physics as well It is also aimed for research institutes in lasers and plasma physics and gives good comprehensive in laser and plasma systems In each chapter the concept is developed from basic assumptions up to the final engineering and scientific outcomes The scientific background is explained at basic and advance levels and closely integrated with mathematical theory Many examples are presented in this book and it is also ideal for intermediate level courses at graduate level studies It is also ideal for engineer who has not had formal instruction in nonlinear dynamics but who now desires to fill the gap between innovative Laser circuits systems and advance mathematical analysis methods

Lasers Hans Joachim Eichler, Jürgen Eichler, Oliver Lux, 2018-11-19 This book provides a comprehensive overview of laser sources and their applications in various fields of science industry and technology After an introduction to the basics of laser physics different laser types and materials for lasers are summarized in the context of a historical survey outlining the evolution of the laser over the past five decades This includes amongst other aspects gas lasers excimer lasers the wide range of solid state and semiconductor lasers and femtosecond and other pulsed lasers where particular attention is paid to high power sources Subsequent chapters address related topics such as laser modulation and nonlinear frequency conversion In closing the enormous importance of the laser is demonstrated by highlighting its current applications in everyday life and

its potential for future developments Typical applications in advanced material processing medicine and biophotonics as well as plasma and X ray generation for nanoscale lithography are discussed The book provides broad and topical coverage of laser photonics and opto electronics focusing on significant findings and recent advances rather than in depth theoretical studies Thus it is intended not only for university students and engineers but also for scientists and professionals applying lasers in biomedicine material processing and everyday consumer products Further it represents essential reading for engineers using or developing high power lasers for scientific or industrial applications

A Quasi-optical Treatment of Integrated Optical Devices Daniel Wai-Cheong So,1995 **Collected Papers of Carl Wieman** Carl Edwin Wieman,2008

Carl Wieman s contributions have had a major impact on defining the field of atomic physics as it exists today His ground breaking research has included precision laser spectroscopy using lasers and atoms to provide important table top tests of theories of elementary particle physics the development of techniques to cool and trap atoms using laser light particularly in inventing much simpler less expensive ways to do this the understanding of how atoms interact with one another and light at ultracold temperatures and the creation of the first Bose Einstein condensation in a dilute gas and the study of the properties of this condensate In recent years he has also turned his attention to physics education and new methods and research in that area This indispensable volume presents his collected papers with annotations from the author tracing his fascinating research path and providing valuable insight about the significance of the works

Optoelectronic Technology and Lightwave Communications Systems Chinlon Lin,2012-12-06 Ever since the invention of the transistor semiconductor based microelec tronics has made a revolutionary impact on the information society as evi dent from the widespread application of microprocessor based technology in our modern society The next wave of modern information technology after transistors and microelectronics is that of lasers and micro optoelectronics Optoelectronics or optical electronics based on lasers and related modern optical technology has also become a very important field of science and technology in the past 20 years Electronics or microelectronics deals with micro electronic devices and components for generation transmission and processing of electronic sig nals In contrast in optoelectronics we deal with optoelectronic devices and components for the generation transmission and processing of lightwave signals It is the interaction of lightwaves photons with matter that shows the uniqueness of optoelectronic technology optical absorption and scat tering optical gain and amplification material and waveguide dispersion nonlinear optical effects etc are very much dependent on the material s intrinsic properties and the lightwave propagation effects

High Power Diode Lasers Friedrich Bachmann,Peter Loosen,Reinhart Poprawe,2007-05-26 This book summarizes a five year research project as well as subsequent results regarding high power diode laser systems and their application in materials processing The text explores the entire chain of technology from the semiconductor technology through cooling mounting and assembly beam shaping and system technology to applications in the processing of such materials as metals and polymers Includes theoretical models a range of important parameters and

practical tips **Solar Energy** United States. Energy Research and Development Administration. Technical Information Center, 1976

LED Lighting Malvin Carl Teich, 2025-04-14 LED Lighting is a self contained and introductory level book featuring a blend of theory and applications that thoroughly covers this important interdisciplinary area Building on the underlying fields of optics photonics and vision science it comprises four parts PART I is devoted to fundamentals The behavior of light is described in terms of rays waves and photons Each of these approaches is best suited to a particular set of applications The properties of blackbody radiation thermal light and incandescent light are derived and explained The essentials of semiconductor physics are set forth including the operation of junctions and heterojunctions quantum wells and quantum dots and organic and perovskite semiconductors PART II deals with the generation of light in semiconductors and details the operation and properties of III V semiconductor devices MQWLEDs microLEDs quantum dot devices QLEDs WQLEDs organic semiconductor devices OLEDs SMOLEDs PLEDs WOLEDs and perovskite devices PeLEDs PPeLEDs QPeLEDs PeWLEDs PART III focuses on vision and the perception of color as well as on colorimetry It delineates radiometric and photometric quantities as well as various measures of luminous efficacy and efficiency It also elucidates the significance of commonly used LED lighting metrics such as the color rendering index CRI color temperature CT correlated color temperature CCT and chromaticity diagram PART IV is devoted to LED lighting focusing on its history and salutary features and on how this modern form of illumination is deployed It describes the principal components used in LED lighting including phosphor conversion LEDs PCLEDs for generating cool and warm white light chip on board COB devices color mixing LEDs LED filaments retrofit LED lamps hybrid devices LED luminaires and OLED light panels It concludes with a discussion of smart and connected lighting that reviews plant centric lighting and highlights the roles of gamma and circadian brain rhythms in human centric lighting Finally the performance metrics for traditional and LED light sources are summarized Each chapter contains practical examples highlighted equations color coded figures and an extensive bibliography

Optical Communication Receiver Design Stephen B. Alexander, 1997 This tutorial text provides an overview of design principles for receivers based on courses for practising engineers Contents optical communications system performance photodetection photodetectors noise modelling front end design performance analysis

Laser Physics and Technology Pradeep Kumar Gupta, Rajeev Khare, 2014-11-06 The book Laser Physics and Technology addresses fundamentals of laser physics representative laser systems and techniques and some important applications of lasers The present volume is a collection of articles based on some of the lectures delivered at the School on Laser Physics and Technology organized at Raja Ramanna Centre for Advanced Technology during March 12-30 2012 The objective of the School was to provide an in depth knowledge of the important aspects of laser physics and technology to doctoral students and young researchers and motivate them for further work in this area In keeping with this objective the fourteen chapters written by leading Indian experts based on the lectures delivered by them at the School provide along with class room type coverage of the

fundamentals of the field a brief review of the current status of the field The book will be useful for doctoral students and young scientists who are embarking on a research in this area as well as to professionals who would be interested in knowing the current state of the field particularly in Indian context **Optical Fiber Technology** Detlef Gloge,1976

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






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