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.

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.

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 X. In gain-guided lasers, this tapering off of the gain is responsible for lateral beam confinement. (By contrast, in index-guided lasers the regions 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 (λ_{vac} = 980 nm). The assumed beam divergence angles (full-width-at-half-maximum intensity or FWHM) are $\theta_{\perp} = 7°$ in the plane of the junction and $\theta_{\parallel} = 35°$ 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 $\Delta z = 10\,\mu$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 ~120°. In the bottom row, (e, f), the assumed astigmatism is $\Delta z = 25\,\mu$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 ~190°.

The elliptical cross-section of the beam emerging at the front facet of the laser is responsible (through diffraction) for $\theta_{\perp}$ being much smaller than $\theta_{\parallel}$. 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 countering 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., $E_{\perp}$) the gain is somewhat greater than that for perpendicularly polarized light (hereinafter $E_{\parallel}$). The guided mode associated with $E_{\parallel}$ is slightly broader in the Y-direction than the mode associated with $E_{\perp}$. 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 $E_{\perp}$ (relative to $E_{\parallel}$) 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 $E_{\perp}$ polarization over $E_{\parallel}$.

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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Advances In Semiconductor Lasers And Applications To Optoelectronics (Ijhses Vol. 9 No. 4) Mitra Dutta,Michael A Stroscio,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 **Optical Fiber Telecommunications IV** Ivan P. Kaminow,Tingye Li,2002 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 *Semiconductor Diode Lasers* William Streifer,Michael Ettenberg,1991 **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 Lasers Charles Blain,2002 Developments in lasers continue to enable progress in many areas such as eye surgery the recording industry and dozens of others This book presents citations from the book literature for the last 25 years and groups them for ease of access which is also provided by subject author and titles indexes *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 The Laser Literature Kiyo Tomiyasu,2013-11-09 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 **Energy Research Abstracts** ,1995 **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 **Lasers and Masers** ,1962 **Deep Space Optical Communications** Hamid Hemmati,2006-06-05 A quarter century of research into deep space and near Earth optical communications This book captures a quarter century of research and development in deep space optical communications from the Jet Propulsion Laboratory JPL Additionally it presents findings from other optical communications research groups from around the world for a full perspective Readers are brought up to date with the latest developments in optical communications technology as well as the state of the art in component and subsystem technologies fundamental limitations and approaches to develop and fully exploit new technologies The book explores the unique requirements and technologies for deep space optical communications including Technology overview link and system design drivers Atmospheric transmission propagation and reception issues Flight and ground terminal architecture and subsystems Future prospects and applications including navigational tracking and light science This is the first book to specifically address deep space optical communications With

an increasing demand for data from planetary spacecraft and other sources it is essential reading for all optical communications telecommunications and system engineers as well as technical managers in the aerospace industry It is also recommended for graduate students interested in deep space communications **Lasers and Masers: a Continuing Bibliography** United States. National Aeronautics and Space Administration,1965 Compact Blue-Green Lasers W. P. Risk,T. R. Gosnell,A. V. Nurmikko,2003-01-09 William Risk Timothy Gosnell and Arto Nurmikko have brought together their diverse expertise from industry and academia to write the first fully comprehensive book on the generation and application of blue green lasers This volume describes the theory and practical implementation of three techniques for the generation of blue green light nonlinear frequency conversion of infrared lasers upconversion lasers and wide bandgap semiconductor diode lasers In addition it looks at the various applications that have driven the development of compact sources of blue green light and reflects on the recent application of these lasers in high density data storage color displays reprographics and biomedical technology Compact Blue Green Lasers is suitable for graduate level courses or as a reference for academics and professionals in optics applied physics and electrical engineering 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 oflasers 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 **Nuclear Science Abstracts** ,1976 *Electrooptics* Jose Manuel Cabrera,Fernando Agullo-Rueda,2012-12-02 This comprehensive text provides an understanding of the physical phenomenon behind electrooptics It describes in detail modern electrooptic materials and operative physical mechanisms and devotes a full chapter tothe new materials engineering that is contributing to the development of low dimensional systems The book also reviews device applications in both bulk and waveguide technologies Provides extensive coverage in a self contained format and consequently useful to beginners as well as specialists Includes the most current information Features many tables and illustrations to facilitate understanding *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 Ill 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 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

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