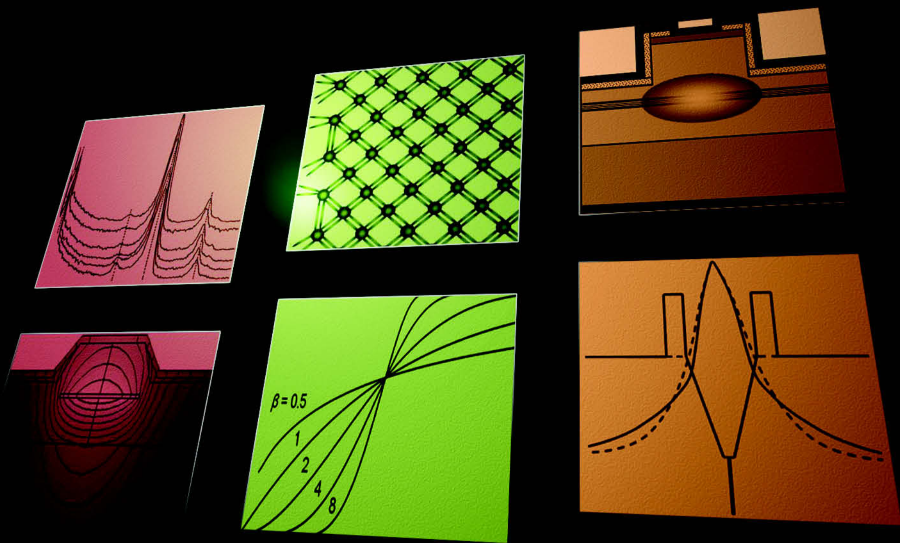
Semiconductor Laser Engineering, Reliability and Diagnostics



A Practical Approach to High Power and Single Mode Devices

Peter W. Epperlein

WILEY

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To Eleonore

My beloved wife and closest friend

With deep gratitude and affection

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Preface

Scope and purpose

Semiconductor diode lasers have developed dramatically in the last decade as key components in a host of new applications, with optical fibre communications and data storage devices as the original and main driving forces behind the enormous progress in diode laser technologies. The increase of laser output power, accompanied by improved laser reliability and widened laser wavelength range in all single-emitter and multi-element emitter devices, gave rise to the penetration of diode lasers into other mass-markets and emerging applications, such as laser pumping, reprographics, data recording, displays, metrology, medical therapy, materials processing, sophisticated weaponry, and free-space communications. As a consequence, diode lasers continue to represent a high percentage of the worldwide commercial laser revenues, 51% of the $6.4B in 2010 with 10% growth forecasted for 2011 (Laser Focus World, 2011)[1]. Huge progress has been made in high power, single transverse mode lasers over recent years, followed by new applications and along with increased requirements for device engineering, reliability engineering and device diagnostics.

This book is a fully integrated novel approach, covering the three closely connected fields of diode laser engineering, reliability engineering and diagnostics in their development context, correlation and interdependence. It is exactly the blend of the underlying basic physics and practical realization, with its all-embracing, complementary issues and topics that has not been dealt with so far in the current book literature in this unique way. This includes practical, problem-related design guidelines as well as degradation-, reliability- and diagnostic-related aspects and issues for developing diode laser products operating in single transverse mode with high power and reliability. And it is this gap in the existing book literature, that is, the gap between device physics in the all-embracing context, and the practical issues of real device exploitation, which is going to be filled by the publication on hand. Research and practical experience gained in industry and higher level education have provided a lot of empirical evidence that the market is in need of a book to fill this gap.

[1] Laser Focus World, (2011). *Laser Markets - Annual Review and Forecast*: in *eNewsletter*, February 8, 2011

The book provides a novel approach to the development of high power, single transverse mode, edge-emitting (in-plane) diode lasers, through addressing the complementary topics of device engineering (Part I), reliability engineering (Part II) and device diagnostics (Part III) in altogether nine chapters. Diode laser fundamentals and standard material, fabrication and packaging issues are discussed first. In a subsequent section a comprehensive and elaborate account is given on approaches and techniques for designing diode lasers, emitting high optical power in single transverse mode or diffraction limited beams. This is followed by a detailed treatment of the origins of laser degradation including catastrophic optical damage and an exploration of the engineering means to address for effective remedies and enhanced optical strength. The discussion covers also stability criteria of critical diode laser characteristics and key laser robustness factors. Clear design considerations are discussed in great detail in the context of reliability-related concepts and models, and along with typical programs for reliability tests and growth. A final extended third part of advanced diagnostic methods covers in depth and breadth, for the first time in book literature, functionality-impacting factors such as temperature, stress and material instabilities. It also presents the basics of those diagnostic approaches and techniques and discusses the diagnostic results in conjunction with laser product improvement procedures.

Main features

Among the main features characterizing this book are, that it is:

1. Providing a novel approach of high power, single transverse mode, in-plane diode laser development by addressing the three complementary areas of device engineering, reliability engineering and device diagnostics in the same book and thus closes the gap in the current book literature.
2. Addressing not only narrow stripe lasers, but also other single-element and multi-element diode laser devices, such as broad area lasers, unstable resonator lasers, tapered amplifier lasers, phase-locked coherent linear laser arrays and high power incoherent standard 1 cm laser bars, designed by applying the various known principles to achieve high power emission in a single transverse mode or diffraction-limited beam.
3. Furnishing comprehensive practical, problem-oriented guidelines and design considerations by taking into account also reliability related effects, key laser robustness factors, and functionality impacting factors such as temperature, stress and material instabilities, and dealing with issues of fabrication and packaging technologies.
4. Discussing for the first time in depth and breadth diagnostic investigations of diode lasers, and using the results for improving design, growth and processing of the laser device in the development phase.

5. Covering in detail the basics of the diagnostic approaches and techniques, many of which pioneered by the author to be fit-for-purpose, and indicating the applicability of these techniques and approaches to other optical and electrical devices.
6. Demonstrating significance of correlations between laser operating characteristics and material parameters, and showing how to investigate and resolve effectively thermal management issues in laser cavities and mirrors.
7. Providing in-depth insight into laser degradation modes including catastrophic optical damage, and covering a wide range of concepts and technologies to increase the optical robustness of diode lasers.
8. Discussing extensively fundamental concepts and techniques of laser reliability engineering, and providing for the first time in a book details on setting up and operating a typical diode laser reliability test program used in industry for product qualification.
9. Representing an invaluable resource for professionals in industry and academia engaged in diode laser product R&D, for academics, teachers and post-graduates for higher educational purposes, and for interested undergraduates to gain first insights into the aspects and issues of diode laser technologies.
10. Featuring two hundred figures and tables illustrating numerous aspects of diode laser engineering, fabrication, packaging, reliability, performance, diagnostics and applications, and an extensive list of references to all addressed technical topics at the end of each of the nine chapters.

Addressed niche markets

The underlying synergetic laser development approach will make this much needed guidebook, a kind of vade mecum of high practical relevance, a great benefit to a broad worldwide readership in industry, higher education, and academic research. Professionals including, researchers and engineers in optoelectronics industries who work on the development of high quality, diode laser products, operating in single transverse mode with high optical output power and high reliability, will regard this book as an invaluable reference and essential source of information. The book will also be extremely useful for academics, teachers and post-graduates for higher educational purposes or satisfying their requirements, if they are just interested in gaining first insights into the aspects and issues associated with the optimization of these diode laser products.

Book context

The book is based primarily on the author's many years of extensive and complex experience in diode laser engineering, reliability and diagnostics. The author accumulated his highly specialized knowledge and skills in hands-on and managerial roles both in global and start-up companies in cutting-edge optoelectronics industries, including IBM, Hewlett-Packard, Agilent Technologies, and IBM/JDSU Laser Enterprise (today part of Oclaro) – starting in the early nineties with his decisive and formative collaboration, as core member of the Laser Enterprise team, the spin-out of IBM Research, pioneering and commercializing its pre-eminent 980-nm pump laser technology for applications in terrestrial and submarine optical communications networks.

The inspiration to write exactly this book has come from the author's extensive semiconductor consulting experience, providing a realistic insight into the very obvious need for a practical, synergetic approach to diode laser development, along with the realization that there has not been any such publication available yet to meet these needs - both at industry and higher educational level. The author is confident, therefore, that the book on hand will be welcomed worldwide by the addressed, specialized readership with high, and growing demand, so that further editions are required much earlier than expected.

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About the author

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He looks back at a thirty year career in cutting-edge photonics and electronics industries with focus on emerging technologies, both in global and start-up companies, including IBM, Hewlett-Packard, Agilent Technologies, Philips/NXP, Essient Photonics and IBM/JDSU Laser Enterprise. He holds Pre-Dipl. (B.Sc.), Dipl. Phys. (M.Sc.) and Dr. rer. nat. (Ph.D.) degrees in physics, magna cum laude, from the University of Stuttgart, Germany.

Dr. Epperlein is a well-recognized authority in compound semiconductor and diode laser technologies. He accumulated the broad spectrum of his professional competencies in most different hands-on and managerial roles, involving design and fabrication of many different optical and electrical devices, and sophisticated diagnostic research with focus on the resolution of issues in design, materials, fabrication and reliability, and including almost every aspect of product and process development from concept to technology transfer and commercialization. He has a proven track record of hands-on experience and accomplishments in research and development of optical and electrical semiconductor devices, including semiconductor diode lasers, light-emitting diodes, optical modulators, quantum well devices, resonant tunneling devices, field-effect transistors, and superconducting tunneling devices and integrated circuits.

His extensive investigations of semiconductor materials and diode laser devices have led to numerous world-first reports on special effects in laser device functionality. Key achievements and important contributions to the improvement of development processes in emerging semiconductor technologies include his pioneering development and introduction of novel diagnostic techniques and approaches. Many have been adopted by other researchers in academia and industry, and his publications of these pioneering experiments received international recognition, as demonstrated by thousands of references, for example, in Science Citation Index and Google, advanced search exact phrase for ‘PW or Peter W Epperlein’. Many of those unique results added high value to the progress of new product or emerging technology development processes.

Dr. Epperlein authored or co-authored more than seventy peer-reviewed journal and conference technical papers, has given more than thirty invited talks at international conferences and workshops, and published more than ten invention disclosures in the IBM Technical Disclosure Bulletin. He has served as reviewer of numerous proposals for publication in technical journals and he was awarded five IBM Research Division Awards for achievements in diode laser technology, quality management and laser commercialization.

Dr. Epperlein started his career in emerging superconductor technologies in the late seventies, with sophisticated design, modelling and measurements on superconducting materials, tunneling effects, devices and integrated circuits in his more than five years collaboration in the then revolutionary IBM Josephson Junction Superconducting Computer Project (dropped by IBM end of 1983), which included a two-year International Assignment from the IBM Zurich Research Laboratory to the IBM Watson Research Center, N.Y., USA until the mid-eighties.

This term was followed by a fundamental career re-orientation from emerging superconductor to emerging semiconductor technologies, comprising more than twenty-five years in the fields of semiconductor technologies, optoelectronics, fibre-optic communications, and with his first role to start as core member of the pioneering IBM Laser Enterprise (LE) Team, to become a spinout of IBM Research in the early nineties. He contributed significantly to research, development and commercialization of the pre-eminent pump diode laser technology for applications in optical communication networks in the early nineties along with the transition of the LE-Research Team into a competitive market leader IBM/JDSU LE some five years later.

Part I

DIODE LASER ENGINEERING

Overview

The impressive technological advances that resulted in semiconductor diode laser technologies in the last decade can be grouped roughly into four areas: higher optical output power, higher single transverse mode and diffraction-limited output, increased range of lasing wavelengths, and significantly improved reliability (see Part II). Most noteworthy commercial demonstrations in high-power continuous wave (cw) outputs of single-emitter and multi-element emitter laser products, for example, in the 980 nm band, include 0.75 W ex-fiber for single spatial mode, narrow-stripe emitters, 12 W for tapered master oscillator power amplifier emitters with single-mode, diffraction-limited operation, 25 W for standard 100 μm wide aperture single-emitter devices, and 1000 W quasi-cw for standard 1 cm multi-element linear laser arrays with nearly diffraction-limited beams.

The development of novel design approaches including strained quantum wells and quantum cascade structures, as well as the advanced maturity of material systems such as compounds based on GaN, CdS, and GaSb, have significantly extended the operating wavelength range of semiconductor lasers throughout the visible spectrum into the ultraviolet regime down to about 0.375 μm on the short-wavelength side and far into the infrared regime with cw operation within 3–10 μm at room temperature, and beyond 10 μm up to 300 μm at operating temperatures around 77 K on the very long wavelength side. Compressively-strained InGaAs/AlGaAs quantum well lasers emitting in the 980 nm band are typical examples of lasers with wavelengths, which lattice-matched quantum well structures cannot deliver.

This part consists of two chapters. Chapter 1, on basic diode laser engineering principles, includes elaborate descriptions of relevant basic diode laser elements, parameters, and characteristics, aspects of high-power laser design, diode laser structures, materials, fabrication, and packaging technologies, and practical laser performance figures. Chapter 2 is on the design considerations for high-power single spatial mode operation. It provides an extensive account of various approaches and techniques for the development of high-power semiconductor lasers emitting in a single spatial mode or diffraction-limited beam. The discussion is mainly on design issues and operating parameter dependencies of narrow-stripe, in-plane lasers, but also on other single- and multi-element diode laser devices. This includes broad-area lasers, unstable resonator lasers, tapered amplifier lasers, phase-locked coherent linear laser arrays, and high-power incoherent standard 1 cm laser bars designed by applying the various known principles to realize high-power emission in a single transverse mode or diffraction-limited beam.

Chapter 1

Basic diode laser engineering principles

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Introduction

This chapter starts with a brief recap of the fundamental aspects and elements of diode lasers, including relevant features of the standard device types, with an emphasis on the advantages of quantum heterostructures for their effective use as active regions in the lasers. Common laser material systems are then discussed, along with lasing wavelength-dependent applications and best output power levels achieved in each individual high-power diode laser category for illustration and comparison. Various aspects of high-power issues are presented, including power-limiting factors and reliability tradeoffs. To develop a good understanding of diode laser operation, key electrical, optical and thermal parameters and characteristics are described. The chapter concludes with a description of the basic aspects of diode laser fabrication and packaging technologies.

1.1 Brief recapitulation

1.1.1 Key features of a diode laser

The basic device structure consists of a rectangular parallelepiped of a direct bandgap semiconductor, usually a III–V compound semiconductor such as GaAs, incorporating a forward-biased, heavily doped p–n junction to provide the optical gain medium in a resonant optical cavity, as illustrated schematically in Figure 1.1.

Further basic elements include the optical confinement in the transverse vertical direction perpendicular to the active region and transverse lateral confinement of injected current, carriers and photons parallel to the active layer. Further details of these features will be illustrated below.

1.1.1.1 Carrier population inversion

The operating principle of a semiconductor laser requires the gain medium to be pumped with some external energy source, either electrical or optical, to build up and maintain a nonequilibrium distribution of charge carriers, which has to be large enough to enable a population inversion for the generation of optical gain. Pumping realized by optical excitation of electron–hole pairs is usually only important for the rapid characterization of the quality of the laser material without electrical contacts. The more technologically important technique, however, is direct electrical pumping using a forward-biased semiconductor diode with a heavily doped p–n junction at the center of all state-of-the-art semiconductor injection lasers, that is, diode lasers. The