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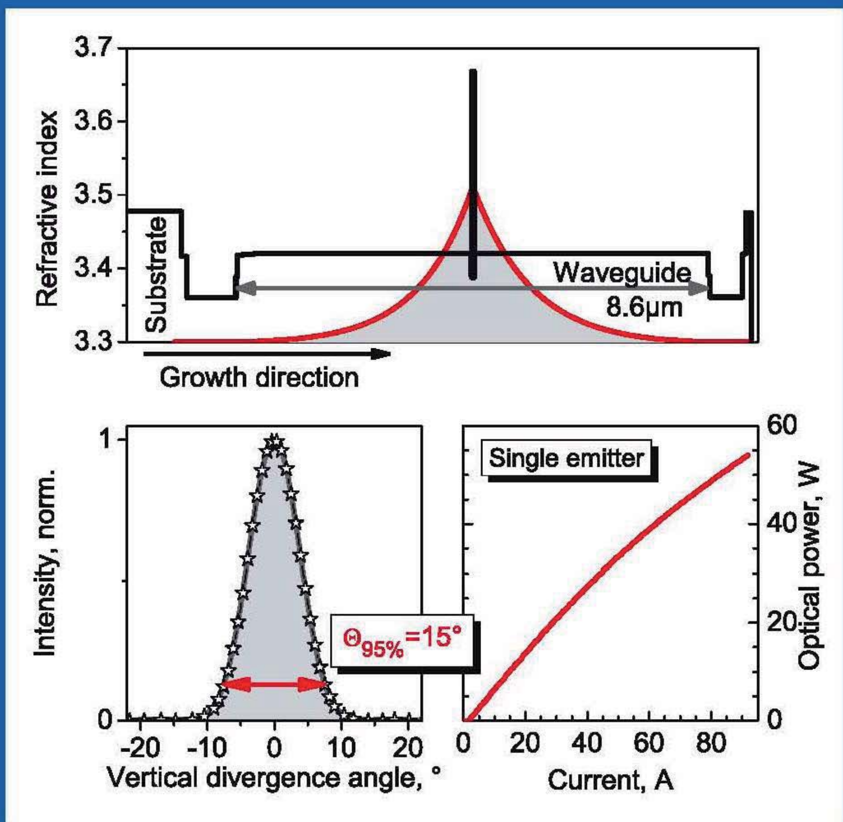
Realization of High Power Diode Lasers with Extremely Narrow Vertical Divergence



Agnieszka Pietrzak

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Realization of High Power Diode Lasers
with Extremely Narrow Vertical Divergence

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Innovations with Microwaves and Light

Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik

Preface of the Editors

Research-based ideas, developments and concepts are the basis of scientific progress and competitiveness, expanding human knowledge and being expressed technologically as inventions. The resulting innovative products and services eventually find their way into public life.

Accordingly, the *"Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik"* series compile the institute's latest research and developments. We would like to make our results broadly accessible and to stimulate further discussions, not least to enable as many of our developments as possible to enhance everyday life.

Diode lasers with ever-increasing brilliance are required for applications such as material processing, where they lead to faster and higher quality cutting and welding, for example. In this report, details are presented on the development of novel, near-infrared diode lasers that dramatically increase brilliance by emitting optical energy within particularly narrow angles. The narrow far fields were enabled by using new diode laser designs with extremely thick vertical optical waveguides. Sophisticated epitaxial designs were required to sustain narrow angle operation to the highest optical output powers and to enable the high power conversion efficiencies essential for industry. Based on the results of the studies, near-infrared (1064 nm) diode lasers were produced whose far field is threefold narrowed compared to typical commercial devices and that reach an overall brilliance higher than any other published source. Such devices are expected to find broad industrial use in material processing applications.

We wish you an informative and inspiring read.

Günther Tränkle

Prof. Dr. Günther Tränkle
Director

Wolfgang Heinrich

Prof. Dr.-Ing. Wolfgang Heinrich
Deputy Director

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The Ferdinand-Braun-Institut researches electronic and optical components, modules and systems based on compound semiconductors. These devices are key enablers that address the needs of today's society in fields like communications, energy, health and mobility. Specifically, FBH develops light sources from the visible to the ultra-violet spectral range: high-power diode lasers with excellent beam quality, UV light sources and hybrid laser systems. Applications range from medical technology, high-precision metrology and sensors to optical communications in space. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter wave frontends targeting energy-efficient mobile communications as well as car safety systems. In addition, compact atmospheric microwave plasma sources that operate with economic low-voltage drivers are fabricated for use in a variety of applications, such as the treatment of skin diseases.

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Realization of High Power Diode Lasers with Extremely Narrow Vertical Divergence

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Vor der Fakultät IV – Elektrotechnik und Informatik
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Abstract

The doctoral thesis deals with high power InGaAs/GaAsP/AlGaAs quantum well diode lasers grown on a GaAs substrate with emission wavelengths in the range of 1050 nm – 1150 nm.

The objective of this thesis is the development of diode lasers with extremely narrow vertical laser beam divergence without any resulting decrease in the optical output power compared to current state of the art devices.

The work is focused on the design of the internal laser structure (epitaxial structure), with the goal of optical mode expansion (thus reduction of the beam divergence), and the experimental investigation of the electro-optical properties of the processed laser devices. Diagnosis of the factors limiting the performance is also performed. The optical mode expansion is realized by increasing the thickness of the waveguide layers. Structures with a very thick optical cavity are named in this work as Super Large Optical Cavity structures (SLOC).

The vertical optical mode is modeled by solving the one-dimensional waveguide equation, and the far-field profiles are obtained from the Fourier transform of the electrical field at the laser facet (near-field). Calculations are performed by using the software tool QIP. The electro-optical properties (such as vertical electrical carrier transport and power-voltage-current characteristics, without self-heating effect) are simulated using the WIAS-TeSCA software. Both software tools are described in this thesis.

The lasers chips, grown by means of MOVPE and processed as broad area single emitters, are experimentally tested under three measurement conditions. First, uncoated and unmounted laser chips with various lengths are characterized under pulsed operation (1.5 μs, 5 kHz) in order to obtain the internal parameters of the laser structure. In the second part of the laser characterization, the facet-coated and mounted devices with large (4 - 8 mm long) Fabry-Perot resonators are tested under quasi-continuous wave operation (500 μs, 20 Hz). Finally, these devices are also tested under 'zero-heat' conditions (300 ns pulse duration, 1 kHz repetition rate). The 'zero-heat' test is performed in order to investigate the factors, other than overheating of the device, that limit the maximum output power. All measurements are performed at a heat-sink temperature of 25°C. The measurement techniques used to characterize the electro-optical properties of the laser and the laser beam properties are also described.

More specifically, the influence of the material composition and the thickness of the waveguide layers on the vertical beam divergence angle (perpendicular to the epitaxial structure) and on the electro-optical properties of the laser is discussed. It is shown that, due to the large cross section of the investigated laser chips, catastrophic optical mirror damage (COMD) is strongly reduced and that one of the major factors limiting the maximum optical power of the discussed diode lasers is weak carrier confinement in the active region leading to enhanced carrier and optical losses due to carrier accumulation in the thick waveguide. The reason for the vertical carrier leakage is a low effective barrier between the quantum well and the GaAs waveguide. Moreover, it is shown that the carrier confinement in the active region can be strengthened in three ways. Firstly, the QW depth is increased for lasers emitting at

longer wavelength (here ~ 1130 nm). Secondly, utilizing a higher number of QWs lowers the threshold carrier density per QW. In this case, the electron Fermi-level shifts towards lower energies for lower threshold currents and thus the effective barrier heights are increased. Thirdly, in lasers emitting especially at wavelengths shorter than 1130 nm (around 1064 nm, a wavelength commercially interesting) the quantum wells are shallower and thus the effective barrier is lower. It is shown that AlGaAs waveguides are required to improve the carrier confinement. The AlGaAs alloys provide higher conduction and lower valence band edge energies of the bulk material. Consequently, the potential barrier against carrier escape from the QW to the waveguide is increased.

Considering the mode expansion in the SLOC structures, it is shown, in simulation and experimentally, that the multi-quantum well active region, due to its high average refractive index, contributes significantly to the guiding of the modes. The optical mode is stronger confined in active regions with a higher number of quantum wells as well as in structures based on AlGaAs waveguides which are characterized by a lower refractive index compared to GaAs material. The increased mode confinement leads to a reduced equivalent vertical spot-size and results in a wider divergence angle of the laser beam. Moreover, by increasing the thickness of the waveguide layers the active region acts more and more as a waveguide itself thus preventing a further narrowing of the vertical far-field. As a new finding, it is presented that the introduction of low-refractive index quantum barriers (LIQB), enclosing the high-refractive index quantum wells, lowers the average refractive index of the multi-quantum well active region and thus reduces the beam divergence (the invention is content of a German Patent Application DEA102009024945).

Through systematic model-based experimental investigations of a series of laser diode structures, the vertical beam divergence was reduced from 19° to 8.6° at full width at half maximum (FWHM) and from 30° to 15°, at 95% power content. The achieved vertical far-field angle is smaller, by a factor of ~3, than state-of-the-art laser devices. The 8 mm long and 200 µm wide single emitters based on the investigated SLOC structures deliver more than 30 W peak-power in quasi-continuous wave mode. The large equivalent spot-size together with the facet passivation prevent COMD failure and the maximum measured power is limited due to the overheating of the device. Moreover, a 4 mm long and 200 µm wide single emitter tested under 'zero-heat' condition delivers 124 W power. The maximal measured power was limited by the current supply.

Kurzzusammenfassung

Diese Doktorarbeit handelt von Quantum-Well-Laserdioden höchster Leistung basierend auf einem InGaAs/GaAsP/AlGaAs-Materialsystem auf GaAs-Substrat. Die Laser emittieren in Wellenlängenbereich von 1050 nm bis 1150 nm.

Die Zielstellung dieser Doktorarbeit besteht in der Entwicklung von Laserdioden mit einer extrem geringen vertikalen Strahldivergenz ohne das dadurch die optische Ausgangsleistung gegenüber aktuellen Stand der Technik reduziert wird.

Der Fokus dieser Arbeit liegt auf dem Design der internen Laserstruktur mit dem Ziel, die Feldverteilung der optischen Mode aufzuweiten, um die Strahldivergenz zu reduzieren. Ein weitere Fokus der Arbeit liegt auf der experimentellen Untersuchung der elektro-optischen Eigenschaften der entwickelten Laserprototypen. Außerdem werden die Faktoren bestimmt, welche die maximal mögliche Ausgangsleistung limitieren. Die Ausweitung des optischen Modes wird durch die Verbreiterung des Wellenleiters erreicht. Strukturen mit einem breiten, vertikalen optischen Resonator werden in dieser Arbeit als Super Large Optical Cavity (SLOC) bezeichnet.

Der vertikale optische Mode wird durch die Lösung der eindimensionalen Wellenleitergleichung modelliert. Die Fernfeldprofile werden durch die Fourier-Transformation des elektrischen Felds an der Laserfacette (Nahfeld) bestimmt. Die Rechnungen wurden mit Hilfe der QIP Software durchgeführt. Die elektro-optischen Eigenschaften (wie vertikaler Ladungsträgertransport und Leistungs-Spannungs-Strom-Kennlinien ohne Eigenerwärmung) werden mit Hilfe der WIAS-TeSCA-Software simuliert. Beide Programme werden in der Arbeit näher beschrieben.

Die Laserdioden werden mittels Metal Organic Vapor Phase Epitaxy (MOVPE) hergestellt und als Breit-Streifen Einzelemitter prozessiert. Die Laser werden mit drei verschiedenen Messmethoden untersucht. Als erstes werden unter Pulsstrom Anregung (1.5µs, 5kHz) unbeschichtete Laser mit verschiedenen Resonatorlängen zur Bestimmung der internen Laserparameter untersucht. Folgend werden beschichtete Laser mit langen Fabry-Perot Resonatoren (4 – 8 mm) unter quasi-Dauerstrich (500 µs, 20 Hz) Anregung charakterisiert. Abschließend werden die Diodenlaser unter Verwendung sehr kurzer Stromimpulse (300 ns, 1 kHz) vermessen. Die letztgenannte Messmethode wird verwendet, um die Einflussfaktoren zu ermitteln, welche die Ausgangsleistung der Laserstruktur limitieren. Die Verwendung solch kurzer Pulse ist nötig da es hier zu keiner Eigenerwärmung der Laser kommt, was üblicherweise die Ausgangsleistung limitiert. Alle Messungen werden bei einer Wärmesenkentemperatur von 25°C durchgeführt. Alle Messmethoden für die Untersuchung der elektro-optischen Eigenschaften der Laser und der optischen Eigenschaften des Laserstrahls werden in der Arbeit näher beschrieben.

Insbesondere werden die Auswirkungen der Materialzusammensetzung und der Dicke des Wellenleiters auf die Laserstrahldivergenz in vertikaler Richtung, sowie auf die elektro-optischen Eigenschaften der Laserstruktur diskutiert. Es wird gezeigt, dass durch das große Modenbreite die Gefahr der katastrophalen optischen Facetten-Degradation (Catastrophic Optical Mirror Damage, COMD) reduziert ist. Außerdem wird gezeigt, dass die maximal erreichbare optische Leistung stark durch den schwachen Einschluss der Ladungsträger in der

aktiven Zone, limitiert ist. Dies führt zu erhöhten Ladungsträger- und optischen Verlusten auf Grund von Ladungsträgeransammlung in dem Wellenleiter. Der Grund für die Ladungsträgerverluste ist die niedrige effektive Barrierenhöhe zwischen Quantum Well und Wellenleiter. Es wird gezeigt, dass man den schwachen Ladungsträgereinschluss in der aktiven Zone auf drei Weisen verstärken kann. Erstens, durch Erhöhung der Quantum Well Tiefe. Hier gezeigt für Laser mit einer größeren Wellenlänge von ~ 1130 nm. Zweitens, durch Erhöhung der Anzahl der Quantum Wells dies reduziert die Ladungsträgerdichte pro Quantum Well an der Laserschwelle. Dadurch verschiebt sich das Fermi-Niveau für die Elektronen in Richtung niedrigerer Energien wodurch sich die effektive Barrierenhöhe vergrößert. Als Drittes, bei den Lasern, deren Emissionswellenlänge kleiner als 1130 nm ist (ca. 1064 nm, Wellenlänge kommerziell wichtig). Hier sind die Quantum Wells flacher und die effektive Barriere ist kleiner. Es wird gezeigt, dass um den Ladungsträgereinschluss zu verstärken, ein AlGaAs-Wellenleiter notwendig ist. AlGaAs als Wellenleitermaterial hat eine höhere Leitungsbandkante und niedrige Valenzbandkante im Vergleich zu GaAs al Wellenleiter. Im Resultat ergibt sich eine Barriere gegen vertikale Ladungsträgerverluste und damit wird der Einschluss der Ladungsträger in der aktiven Zone verstärkt.

Es wird sowohl in Simulationen als auch experimentell gezeigt, dass eine aktive Zone bestehend aus mehreren Quantum Wells, durch deren hohe mittlere Brechzahl, einen entscheidenden Einfluss auf die Wellenleitung hat. Der optische Mode ist bei Strukturen mit höherer Quantum Well Anzahl in der aktiven Zone stärker eingeschlossen, vergleichbar zu Strukturen mit einem erhöhtem Al-Anteil im Wellenleiter. Ein höherer Al-Anteil im Wellenleiter führt zu einer kleineren Brechzahl im Vergleich zu einem GaAs-Wellenleiter. Die erhöhte Beschränkung des Modes bewirkt eine geringere vertikale Modenbreite und hat dadurch einen breiteren Divergenzwinkel des emittierten Lichts zur Folge. Außerdem führt die Erhöhung der Wellenleiterdicke dazu, dass die aktive Zone mehr und mehr selbst wie ein Wellenleiter wirkt. Das wiederum verhindert eine weitere Verringerung des vertikalen Divergenzwinkels.

In dieser Arbeit wird erstmalig gezeigt, dass durch die Verwendung von Quantum Barrieren mit einer niedrigen Brechzahl (Low-Refractive Index Quantum Barriers, LIQB) die hohe mittlere Brechzahl der aktiven Zone reduziert wird und dadurch die Strahldivergenz vermindert werden kann. Aus dieser Entwicklung resultierte eine Anmeldung für ein deutsches Patent DEA102009024945.

Durch die systematische, modelgestützte und anschließende experimentelle Untersuchung der Laserdiodenstrukturen konnte die Strahldivergenz von 19° auf 8.6° (full width at half maximum, FWHM) bzw. von 30° auf 16° (95 % optischer Leistungsinhalt) reduziert werden. Die erreichten vertikalen Fernfeldwinkel sind um Faktor 3 kleiner als bei vergleichbaren Laserdioden. Einzelemitter mit einer Länge von 8 mm und einer Streifenbreite von 200 µm erreichten eine optische Leistung von 30 W im quasi-Dauerstrich Betrieb. Die große Modenbreite zusammen mit der Facettenpassivierung verhindern COMD und ermöglichen so höhere optische Leistungen. Dadurch ist die maximale Roll-Leistung hauptsächlich durch thermische Effekte begrenzt. Außerdem, erreichte ein 4 mm langer Einzelemitter mit einer Streifenbreite von 200 µm unter 300 ns Kurzpuls Anregung, eine optische Leistung von 124 W. Hierbei war die maximale Leistung durch die Stromquelle begrenzt.

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Publications

Parts of the work have been also presented in the following publications and during conferences:

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