e-Newsletter n°1

May 05
Published twice a year
Available at http://www.bright-eu.org

EDITORIAL

Welcome to the first Newsletter of the integrated project WWW.BRIGHT.EU, which started in July 2004. During the next two years, you will find news of the project and different technical topics in various fields, including health-care, telecom, security and environment. We hope you will enjoy the reading.

The Editors

Myriam Oudart
Alcatel Thales III-V lab
myriam.oudart@thalesgroup.com

Eric Larkins
University of Nottingham
Eric.Larkins@Nottingham.ac.uk

BRIGHT • EU

WWW.BRIGHT.EU

Wide Wavelength light for public Welfare: High-Brightness Laser Diode Systems for Health, Telecom and Environment Use

WWW.BRIGHT.EU is an integrated project supported by the European Commission's Information Society Technologies programme

CONTENT

GREETINGS FROM THE PROJECT COORDINATOR

Dear Reader,

Welcome to the first semi-annual *e-Newsletter* of the project ***Wide Wavelength light for public Welfare: High-Brightness Laser Diode Systems for Health, Telecom and Environment Use (WWW.BRIGHT.EU)***, a European Integrated Project on high-brightness laser diode technologies. **High brightness laser diode technology** is a key enabling technology for the information society of tomorrow, especially in the fields of **health-care, telecommunication, environment and security**.

The continued development of the information society relies on a smart use of the information for applications such as imagery or telecommunications. The electron and the photon are the two main information carriers, the latter having taken an increased role since the end of the seventies, when engineers demonstrated the efficiency of optical fibre transmission. Since then, the demand for high brightness sources their range of applications has increased continuously.

The WWW.BRIGHT.EU consortium is pursuing **a long-term vision** aimed at pushing the limits of the current laser diode technology towards higher brightness, and stimulating the development of new applications and markets. Our approach consists of mobilising the expertise of the main European actors of the laser diode core technology, and coupling it with highly innovative optical technologies. Industrialisation issues are being explored through packaging and reliability studies.

We hope that you find our e-Newsletter interesting and informative. If you are interested in exploring the advantages offered by high-brightness lasers for your applications or simply wish to comment upon or discuss any of the issues touched upon in the *e-Newsletter* in greater depth, please do not hesitate to contact us.

Dr Michel Krakowski
Project Coordinator
Alcatel Thales III/V Lab
Domaine de Corbeville
91404 ORSAY CEDEX

michel.krakowski@thalesgroup.com

OVERVIEW OF WWW.BRIGHT.EU

SIXTH FRAMEWORK PROGRAMME
INFORMATION SOCIETY TECHNOLOGIES

11 countries involved:

- **8 Industrial partners**
- **7 Universities**
- **8 Research Centres**

Duration: 2 years (01/07/04 – 30/06/06)

CHALLENGE

Strengthen the position of Europe in **High Brightness Laser Diode technology** and take a main share of the fast growing € 1 billion market foreseen by the end of the decade.

OBJECTIVE

Push the limits of current technology towards high brightness and demonstrate applications in the fields of **health-care, telecom, security** and **environment**. Develop new applications and open new markets for high-power, high-brightness laser diode technologies.

APPROACH

- Mobilise the European expertise in the field of **laser diode core technology** and couple it with innovative optical technologies (e.g. smart cavities, wavelength multiplexing).
- **Streamline the technical inputs through a coherent roadmap** relying on a systematic exploitation of their synergies. and leading to pre-industrial demonstrators
- Take into account the **industrialisation issues** in a continuous way (e.g. reliability, packaging).
- Reach out to new organisations and open new markets by promoting the awareness of high-power, high-brightness laser diode developments and opportunities in Europe.

PROJECT SUMMARY

High brightness laser diode technology is a **key enabling technology** for the **information society** of to-morrow, especially in the fields of health-care, telecommunication, environment and security.

The development and achievements of the information society rely on the smart use of information for applications such as imagery or telecommunications. The electron and the photon are the two main information carriers, the latter having taken an increased role since the end of the seventies, when engineers demonstrated the efficiency of optical fibre transmission.

Since then, the demand for high brightness sources has increased continuously. Laser diodes already offer extraordinary compactness at a reasonable cost and now play a central role in telecommunications. However, their brightness still needs to be improved to spread their large-scale uptake across the Information Society; **the main challenge is to couple more light power in smaller diameter fibres**.

The WWW.BRIGHT.EU consortium proposes a long-term vision aiming at pushing the limits of the current laser diode technology towards higher brightness, and at demonstrating applications such as:

- Medical imagery for cancer therapy
- Amplifiers for telecommunication networks

The approach consists of mobilising the expertise of the main European actors in the core laser diode core technologies, and coupling it with highly innovative optical technologies e.g. smart cavity concepts for higher efficiency and tuneability. Industrialisation constraints will be widely addressed through packaging and reliability studies.

This project is intended to be the initial phase (24 months) of a more long-term and ambitious project. This first phase will allow on one hand the full assessment of a few targeted applications corresponding to strong market needs such as **photodynamic therapy**. On the other hand, the first phase will also address the development of core technologies, the applications of which will be assessed in the second phase.

PARTNERS PARTICIPATING IN WWW.BRIGHT.EU

No.	Participant name & *Activities in the project*	Short name	Country
1	Alcatel Thales III-V Lab *Design, growth, fabrication and characterisation of high brightness laser diodes. Reliability studies*	**III-V Lab**	France
2	Alcatel-CIT *Design and implementation of Yb fibre laser using high brightness pumps.*	**ALCATEL**	France
3	Biolitec AG *System development of medical lasers for surgery & photodynamic therapy, medical application development.*	**BIOLITEC**	Germany
4	OSRAM Opto Semiconductors GmbH *Fabrication of red-emitting high power laser bars at 635nm. Packaging, reliability, strain, beam parameter, semiconductor material, laser characterisation.*	**OSRAM**	Germany
5	Thales Laser Diodes SA *Packaging of diodes and realisation of high-brightness fibre-coupled laser.*	**TLD**	France
6	The Chancellor, Masters and Scholars of the University of Cambridge *Laser modelling for optimal device geometry design. Design and implementation of etching for improved performance with focus ion beam etching.*	**CAM**	UK
7	Thales *Increasing brightness with external cavity wavelength multiplexing. Micro-photoluminescence. Toxicology*	**TRT**	France
8	FBH, Forschungsverbund Berlin e.V. *650nm high power diode lasers, 810nm tapered devices, gain media at 810nm for ECL applications, reliability investigations, technology of laser diode manufacturing.*	**FBH**	Germany
9	Fisba Optik AG *Laser, high-brightness, beam parameter, infrared, red, high power laser, laser characterisation, optical components, micro-optics.*	**FO**	Switzerland
10	Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung e.V. *Growth and fabrication of high-brightness laser diodes, advanced thermal management techniques.*	**FHG (ILT - IAF)**	Germany
11	High Pressure Research Center, Polish Academy of Sciences *Characterisation and wavelength tuning of laser diodes, using high pressure.*	**UNIPRESS**	Poland
12	Institut National d'Optique *High performance and low cost micro optics for fibre coupling.*	**INO**	Canada
13	Centre National de la Recherche Scientifique *Improving the brightness with external cavities.*	**LCFIO**	France
14	Lund University *Tissue fluorescence monitoring (spectroscopy and imaging). Defining protocols, specifying laser parameters and adapting lasers for biomedical applications.*	**LLC**	Sweden
15	MBI, Forschungsverbund Berlin e.V. *Device analysis with respect to reliability issues. Advanced characterization.*	**MBI**	Germany
16	University College Cork, National University of Ireland Cork *Laser, high brightness, strain, beam parameter, semiconductor material, high power laser, laser modelling, laser characterisation, optical components.*	**NMRC**	Ireland
17	Institute of Communication and Computer Systems *Development of imaging system for Photodynamic Therapy PDT and animal modelling. Fluorescence diagnostics (tissue).*	**ICCS**	Greece
18	Risø National Laboratory *Brightness of external cavity feedback system. Frequency doubling (810/405nm) Pulsed diodes. Clinical adaptation of lasers.*	**RISOE**	Denmark
19	Rainbow Photonics AG *Frequency doubled UV laser diodes for medical applications.*	**RB**	Switzerland
20	The University of Nottingham *Laser diode design/simulation, advanced characterisation, reliability studies, training/dissemination.*	**UNOTT**	UK
21	Universidad Politécnica de Madrid *Modelling and simulation of high brightness lasers to improve designs.*	**UPM**	Spain
22	Bayerische Julius-Maximilians Universität Würzburg *Growth of advanced high brightness laser materials, quantum dot lasers.*	**UWUERZ**	Germany

PRESENTATIONS OF SOME OF THE PARTNERS

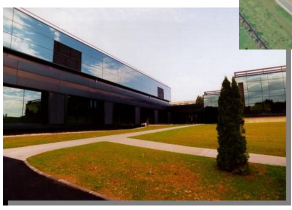
Partner 1- Alcatel Thales III-V Lab

Overall presentation

Alcatel Thales III-V Lab is a new private non-profit organisation jointly established by Alcatel and Thales on 1st July 2004, under the French "Economic Interest Group" (GIE) status. Relying on the expertise of "Alcatel CIT Research and Innovation" and "Thales Research and Technology," it concentrates in a single entity one of the most advanced industrial research groups in the field of III-V semiconductors in Europe. The staff numbers approximately 100 highly qualified people, most of them recognised experts in their area.

Alcatel Thales III-V Lab performs research on components, from the basic studies to the transfer for industrialisation, by exploiting the synergies between the technologies developed for various markets addressed by Thales and Alcatel, such as telecom, space, defence and security. The streamlining of the research work performed within the Group strengthens these efforts to exceed the critical mass and to increase the added value through the existing synergies.

Thales Research and Technology Palaiseau (June 2005)

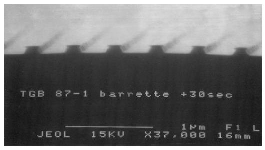


Alcatel Research and Innovation Marcoussis

Alcatel Thales III-V Lab is located in Marcoussis and Orsay and includes 4000 m^2 of clean rooms, advanced material synthesis (MOCVD, MBE), advanced material processing (RIE, ICP, CAIBE, IBE), measuring and modelling facilities. Some of the Orsay facilities will move to the new Thales Research and Technology facility in Palaiseau by June 2005.

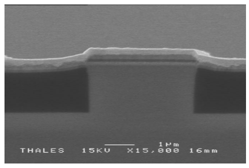
Main research topics

♦ Optical sources and detectors for telecom 10-40Gb/s
♦ Micro/nano-electronics circuits for telecom 40Gb/s (analogue and digital)
♦ N+2 generation telecom components,
♦ High data rate optical links
♦ High power and high brightness semiconductor lasers
♦ Quantum cascade semiconductor lasers
♦ Semiconductor lasers for atomic clocks and gas detection
♦ Quantum dot lasers
♦ High speed analogue optoelectronic components and functions for microwave photonics
♦ Microwave components based on GaN (high yield, wide band)
♦ High-resolution imaging

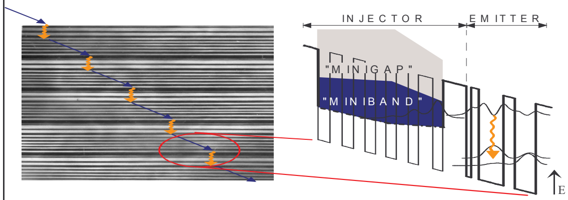


DFB gratings

Index guided tapered laser



Ridge laser

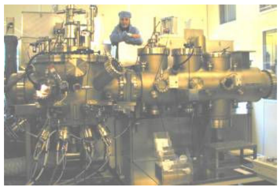


Quantum cascade laser (TEM photograph & design)

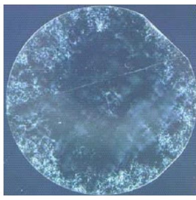
Technologies and facilities

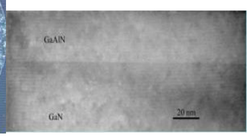
Epitaxial growth of III-V semiconductors
- Multi-wafer MBE, GS-MBE, MO-VPE reactors
- Complex heterostructures based on GaAs, InP, SiC and GaSb substrates

AlGaN/GaN HEMT on SiC substrates

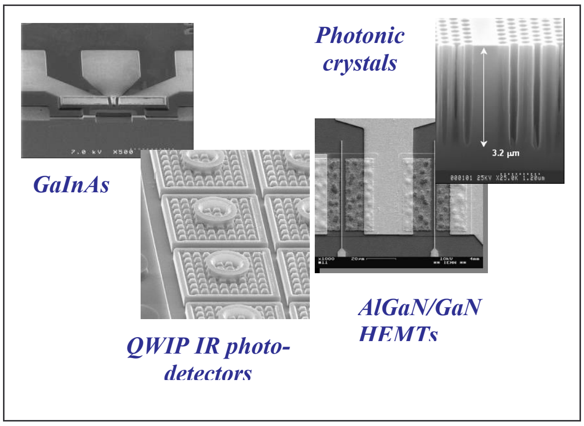


GS-MBE reactor



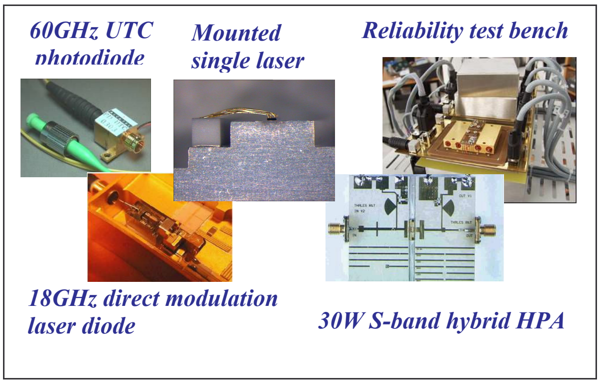


Clean room device processing
- Microelectronic technologies: lithography, metal and dielectric material deposition and etching, …
- Microwave and fast digital devices and circuits: InP HBTs, GaN HEMT, …
- Opto-electronic devices (lasers, modulators, photo-detectors, …)



Measurement, simulation and design
- Physical modelling of microelectronic and optoelectronic devices
- Linear and non-linear equivalent circuits
- Microwave and fast digital circuit design and simulation

Module and sub-system demonstrators
- Optoelectronic module demonstrators (40Gb/s transceivers…)
- Microwave amplifiers demonstrators
- Operational reliability evaluations



Partner 2 - Alcatel-CIT

Alcatel provides communications solutions to telecommunication carriers, Internet service providers and enterprises for delivery of voice, data and video applications. Alcatel brings its leading position in fixed and mobile broadband networks as well as applications and services, to help its partners and customers build a user-centric broadband world. With sales of 12.5 billion Euros in 2003, Alcatel operates in more than 130 countries. 13% of Alcatel's sales are dedicated to R&D.

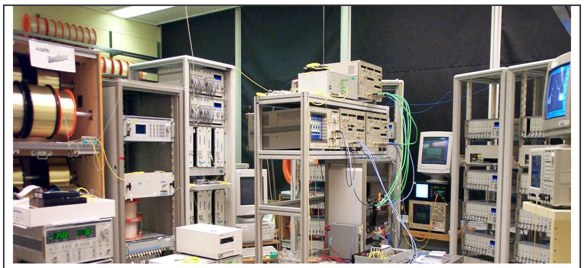
Alcatel is the optical networking worldwide leader. Its optical solution portfolio answers all the transmission needs: access, metro, terrestrial and submarine networks. Several world records and achievements in WDM amplifiers, Raman amplification, 40 Gbit/s DWDM transmission and 160Gbit/ field trials confirm Alcatel's leading research expertise in optical transmission technologies.

Alcatel R&I works to enhance Alcatel's existing portfolio, while at the same time it looks for disruptive concepts that will serve as the building blocks for the products and services of the future. This involves a balance between pragmatic short-term initiatives tied to relevant market issues and innovative long-term programs based on new concepts. Alcatel R&I also participates in global initiatives in basic science and technology on a national and worldwide basis, in connection with universities, research institutions and advanced technology providers. In addition, Alcatel R&I participates to numerous standardization bodies.

More specifically, Alcatel R&I has a research program on Optical Transmission Systems. The goal is to investigate the next generation optical transmission systems for long-haul terrestrial and sub-marine applications as well as for high-speed metro applications. This project includes work on the next generation of optical amplifiers, key elements to support future high capacity/low-cost/ backbone and metro networks.

Activities in WWW.BRIGHT-EU

Alcatel will specify and assess the sources developed by the project for the Telecommunication applications. The goal is to benefit from high brightness, reliable, low cost pump sources for fibre lasers (used to pump Raman amplifiers) and high power Er amplifiers. A first task is dedicated to the specifications of the sources provided by the project in order to be compatible with the Telecommunication applications. In a second task, a model will be developed to design the fibre lasers used to pump Raman amplifiers. Data measurements on fibres and validation of the models are planned as well. In a last task, the sources provided by the project will be assembled and tested as pumps of the fibre lasers.



Optical transmissions laboratory at Alcatel R&I Marcoussis, France

Partner 11- Institute of High Pressure Physics "Unipress"

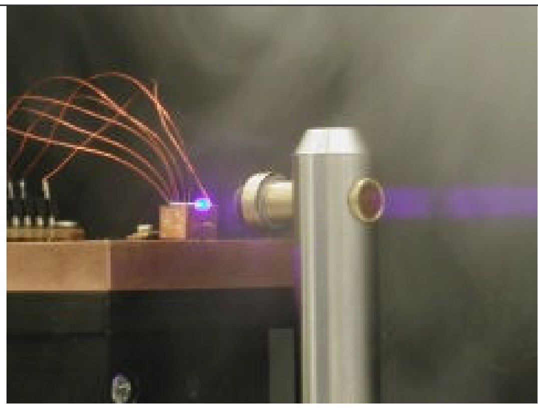
(created in 1972) specializes in the application of high-pressure techniques to various areas of material science. The materials studied include semiconductors, superconductors (HTC materials), metals, ceramics and biological materials. The research on semiconductors involves optical and transport experiments in gas and in liquid cells (up to 3 GPa) and in diamond anvils (up to 50 GPa). The semiconductor research also includes crystal growth under high pressure. The "Unipress" team was the first in the world to obtain bulk monocrystals of GaN, which is an important material for optical devices emitting in the blue and for high-temperature electronics. The epitaxial methods developed on GaN substrates (MBE and MOCVD) allowed us to obtain InGaN/GaN lasers (pulsed and cw).

"Unipress" manufactures high-pressure laboratory equipment and is recognized by the high-pressure community all over the world. Our director has been elected the President of AIRAPT (the International Association for Advancement of High Pressure Science and Technology).

Within its history, Unipress has spun off several companies, the last one (TopGaN Ltd founded in 2001) manufactures violet lasers.

Unipress' research has been recognized by the award of two Center of Excellence grants by the European Commission. In addition to these projects, we are engaged in many 5th and 6th Framework EU projects, NATO projects and other international cooperations. We have a "twinning agreement" with Montpellier University in France.

MBE laboratory



The violet laser manufactured at Unipress

The scientific staff of HPRC Unipress includes 10 Professors and 27 Research Associates and Postdoctoral fellows. We host 14 Ph.D. students.

Our main location is on Sokołowska 29/37, 01-142 Warsaw, but Unipress has another building on Prymasa Tysiąclecia 98 and a villa in the small town of Celestynów (40 km south-east of Warsaw). More information can be found on our webpage www.unipress.waw.pl

Activities in WWW.BRIGHT-EU

The Unipress team will develop wavelength tuning of laser diodes using hydrostatic pressure. We shall combine such tuning with external-resonator methods (WP3).

We shall use pressure for characterizing recombination mechanisms in laser diodes. In short wavelength lasers, we shall determine the barriers for leakage, since they are very sensitive to pressure (WP2).

Finally, we shall study laser diode reliability after multiple pressure cycles in WP5. This is important for pressure-tuning methods and for studying strain-induced degradation mechanisms. For further information, please contact: Prof. Witold Trzeciakowski (wt@unipress.waw.pl), Tel: +4822 8760346

Partner 12- Institute National d'Optique (INO) is a private, non-profit corporation founded in 1985. Over one hundred seventy-five (175) people are currently employed at its facilities in Sainte-Foy (Québec, Canada), a majority of them being engineers and technologists specialized in various branches of photonics.

INO's technological activities are grouped into three sectors: Microoptics and Microsystems (MOMS), Photonics, Fibres and Lasers (PFL) and Applied Optical Systems (AOS). INO's activities cover: Laser Technologies, Industrial Vision & 3D Sensors, Laser Micromachining, Telecom & Space Optics, Specialty Optical Fibers, Artificial Vision, Biophotonics, Bolometers, Fiber Sensors, MEMS, Microoptics, Optical Coatings, Optical Design.

Working in close partnership with industry, INO is a world class center of expertise in optics and photonics assisting companies in improving their competitive edge and developing their business. INO ensures its growth by creating intellectual property and drawing value from it through research and development contracts, fabrication of prototypes, volume production, and technology transfer.

Activities in WWW.BRIGHT-EU

INO is involved in the development of microoptics for fibre coupling of High Brightness Laser Diode (HBLD) bars into small diameter fibres. Due to their special beam characteristics, HBLDs require specially designed microoptics to make use of their increased brightness. The first task will involve the detailed optical design of an original device to produce a symmetric beam parameter product. The optical system will be designed using simulation tools such as Zemax, ASAP and OSLO. This task will be accomplished by one engineer of INO's optical design department. This department is composed of seven engineers and technologists, cumulating several years of expertise in the designing and simulation of optical systems in various fields of application. The second task will involve producing prototypes of microoptical coupling systems, as designed in the first task. Specific microprocessing techniques will be developed and applied for their fabrication. A dedicated team of four engineers and technologists of INO's MOMS group will apply their expertise in microprocessing techniques to produce the novel microoptics.

More specifically, techniques of photolithography, direct laser beam writing and replication in hybrid glass will be used to produce high performance and low cost microoptics. Finally, the prototypes will be thoroughly tested to confirm their performance and optimise the optical design of the fibre coupling microoptic. Previous expertise with laser systems using laser diode bars and arrays provides a strong background to conduct this task. Expertise in the optical collimation of laser diode bars and arrays, with and without further fibre coupling for direct use for illumination and material processing as well as for fibre laser and amplifier pumping will be used.

Developing High Brightness Laser Diodes will benefit the environment and security fields of application. For the past several years, INO has been working on these field-related projects, in particular the active imaging systems (ATV) and Lidar systems. The ATV system uses a collimated beam from a laser diode array to illuminate a remote scene (up to several km) allowing imaging and positive identification with a CCD camera combined with appropriate zooming optics. The ability to make active imaging (i.e. synchronized detection: time gating of the echo laser pulse coming from a specific volume of the region of interest/target) makes it possible to circumvent the difficulties of doing imaging in bad weather conditions. These characteristics are important in applications such as cost surveillance, and search and rescue operations. ATV applications benefit from the effectiveness, compactness, and reliability of laser diode bars. Development of HBLDs will benefit the ATV systems in lowering cost at improved or equivalent performance rating of the laser beam source

Lidar (Light Detection and Ranging) and derived techniques (multiple fields of view, Differential Absorption Lidar (DIAL) etc.) use laser light pulses to monitor atmospheric dust, pollutants or biological agents. Remote sensing (up to a few km) is accomplished by analysing the echo pulses from the interest region. Depending on the specific technique, the return intensity, scattering profile, and spectral characteristics will be analysed to obtain information on the particle's characteristics and composition. Such detection schemes require high peak power laser pulses. A selectable or tuneable wavelength is also important to a specific pollutant's or biological agent's sensitivity.

Therefore, diode-pumped pulsed fibre lasers and amplifiers are preferred laser sources for these applications as they are compact, robust, and well suited for field operations. Development of HBLDs will also benefit these applications as they will provide an efficient and economical ($ per Watt) pumping source for the fibre laser and amplifier.

Partner 15- The Max Born Institute (MBI) for Nonlinear Optics and Short Pulse Spectroscopy, founded in 1992, belongs to the "Forschungsverbund Berlin e.V." and is a member of the "Wissenschaftsgemeinschaft Gottfried Wilhelm Leibniz (WGL)". The MBI has about 180 staff, of which 90 are scientists (including PhD students).

The "Max Born Institute" was named in honour of one of the key scientists of modern physics. Max Born has been born on December 11, 1882 in Breslau. His professional career lead him to Professorships in Berlin, Breslau, Frankfurt/Main, Göttingen and Edinburgh (1936-1954). Finally, he came back to Germany, where he died on January 5 1970 in Göttingen. He received the Nobel prize in 1954 together with W. Bothe for his statistical interpretation of quantum mechanics and his lattice theory of crystals. His work includes groundbreaking research for describing atomic processes using quantum mechanics, important contributions to the development of formal quantum mechanics (together with his students W. Heisenberg und P. Jordan) and to modern optics. He conveyed these contributions in "Born and Wolf: Optics", which has remained a key textbook until the present day.

The MBI conducts basic research in the field of nonlinear optics and ultra-fast dynamics of the interaction of light with matter and pursues applications emerging from this research. For these investigations, it uses laser based short pulse light sources in a broad spectral range from the mid-infrared through the visible and down to the x-ray wavelength region. Our research focuses on new sources for ultra short and ultra intense light pulses, pulse shaping, pulse characterisation, and measurement techniques for ultra fast processes, with applications in basic research and in the development of newly emerging key technologies - with emphasis on physics, material sciences, photo chemistry, and photo biology.

With its research, the MBI fulfils a nationwide mission and is an integral part of the international science community. It offers its facilities and its scientific know-how also to external researchers within the framework of an active guest programme. The MBI is involved in a large number and variety of cooperative research projects with universities, other research institutions and industrial partners.

Partner 17 - Institute of Communication and Computer Systems (ICCS) is associated with the School of Electrical and Computer Engineering, of the National Technical University of Athens (NTUA). ICCS from 1989 has been carrying research and development activities in the fields of all diverse aspects of Telecommunications and Computer Systems and their applications in Biomedical Engineering, Electrical Power Systems, Control Systems and Software and Hardware Engineering.

Biomedical Optics and Applied Biophysics Laboratory of ICCS - NTUA, headed by professor D. Yova, works in basic and applied research. Its research has been and continues to be influential and attracts research institutes, universities, hospitals and providers, in the field of Bio-Photonics (medical lasers, PDT therapy and diagnosis, optical imaging, fluorescence spectroscopy, non-linear optical properties of biomolecules, optical biosensors). The Laboratory has many publications in prestigious scientific journals and conferences and coordinates or takes part to National and European Projects. PhDs and Master's theses are awarded in the field of Biophotonics

ICCS laboratory

Activities in WWW.BRIGHT.EU

ICCS' contribution will be in Medical Applications of Lasers (WP6) and specifically a first task will be the development of animal skin tumor models. A second task will be the definition of pre-clinical protocols ant test procedures to perform photodynamic therapy by using diode lasers and Fosgel. A third task will be the development of computer vision system and software to assess PDT therapy. A fourth task will be the contribution to the evaluation of diode lasers systems for PDT. The fifth task will be the evaluation of the diode laser system for IPDT, in preclinical studies.

For further information please contact: Professor Dido Yova (didoy@central.ntua.gr), Tel: +30 210 7722283, Fax: +30-210-7723894

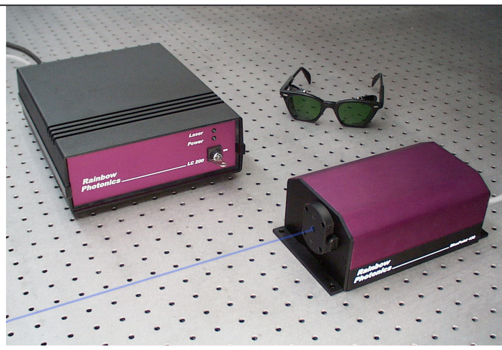
Partner 19- Rainbow Photonics AG, is a Swiss company founded as a spin-off of the Nonlinear Optics Laboratory at the Swiss Federal Institute of Technology (ETH) in 1997. Rainbow Photonics AG commercialises compact frequency-doubled blue lasers (BluePoint), and optical components: waveguides, organic and inorganic crystals for photorefractive and electrooptic applications, and Brillouin cells for optical phase conjugation. These products have been successfully introduced in the market. The fast developing field of optics and evolving market situation requires a dynamic growth both in research and development and in production.

We have cooperation programs with research groups and constant contact with our customers and they ultimate needs This allows us to follow the direction of the market, and we are able to react in advance to fast changes. We are present at the major laser exhibitions worldwide, and we have representation offices overseas.

Activities in WWW.BRIGHT-EU

Because of our experience in frequency doubled blue lasers, the role of Rainbow Photonics AG in the project is to bring their expertise in the realization of a frequency doubled UV laser for medical applications.

Carolina Medrano CEO



Blue lasers

High-Brightness Laser Diodes – An enabling technology for the 21st Century

Introduction

Information society technologies (IST) rely on using the electron and the photon as information carriers, the latter having taken an increased role since the end of the seventies, when engineers demonstrated the efficiency of optical fibre transmission. Since then, the demand for reliable compact low cost high brightness sources has increased continuously.

Laser diodes already offer extraordinary compactness at a reasonable cost and now play a central role in telecommunications. However, their brightness still needs to be improved to spread their large-scale uptake across a wider range of IST markets. Apart from telecommunications, other applications in the health-care, environment and security are targeted. Such technological improvements will, on the one hand, allow the replacement of existing cumbersome and expensive sources, and, on the other hand, enable the emergence of new applications, especially for cancer diagnosis and therapy.

In 2003, the world wide sales of commercial diode lasers experienced an increase of 16% to 3.1 B€. Especially for high power laser diodes, the same growth is expected to continue on the long-term. Fibre coupled laser bars will represent about 14% of the market for high power lasers by 2006, which would correspond to an annual market exceeding six hundred million Euro in 2006-2007. This market should undergo a rapid growth in the following years, mainly linked to the emergence of the health-care market, especially for cancer diagnosis and therapy. The market demand is clearly orientated on modules with increased brightness in order to couple more power in smaller fibres. The market price increases drastically with the output power. The price per Watt is rising for smaller fibre diameters. Therefore, in order to access this growing market, it appears important to satisfy the demand for extremely high brightness as well as to offer modules at reasonable prices.

What is the *brightness* of a laser?

The performance of commercial high power laser diodes sacrifices beam quality for raw power by using wide, multimode emitters. Their power is often combined by integration on a single chip (laser bars) or by use of external optics (both standard and micro-optics). Powers of 120 W (CW) have been obtained from a single 1cm laser bar and 1.5 kW stacks of linear bar arrays are on the market. Although laser bars have shown few

The advantages of laser diodes…

Laser diodes have many advantages over other types of lasers in terms of cost, size, efficiency, reliability, range of available wavelengths, and tunability. Laser bars with power levels of several tens of watts are available for wavelengths extending from the red to the near infrared, with wall-plug efficiencies above 50%. They are also available as fibre-coupled laser modules with fibre-coupling efficiencies up to ~50%. Whilst the cost of simple packaged bars is 80 €/W, the cost of fibre-coupled modules is < 200 €/W. By comparison, a CW Ti:sapphire laser (including pump laser) costs ~ 20-40 k€/W and is limited to powers of ? 10 W. With the advent of fibre lasers, the available power and cost per watt is currently ~ 500-1000 €/W for moderate powers (5-50W) and as low as 200 €/W for 1 kW. Diode laser modules can be as small as half the size of a matchbox for 40-50W uncoupled laser bars to the size of a cigarette box for a 10-30W fibre-coupled module. High-power laser diodes have excellent reliability, with typical lifetimes exceeding 10,000 hours.

Whilst there are many other compact solid-state lasers (e.g. solid state lasers, micro-chip lasers and fibre lasers) offering advantages in terms of beam coherence and brightness, diode lasers are still needed to pump them. Furthermore, advances in diode laser technology continues to improve the performance of these solid state lasers, thereby achieving further improvements in cost, reliability, power and the range of available wavelengths. New high-brightness laser diode concepts even promise to eliminate the need for the second-stage solid state laser for many applications.

Figure 1: Fibre-coupled diode laser module. *[Courtesy of Thales Laser Diodes]*

limitations towards the goal of high power, it is the optical power density P per emission Area A and unit of solid angle Ω in the output beam or beam "brightness" which determines their suitability for practical systems. High brightness sources are important because they allow the use of simple external optics to focus the beam to a small spot. Optical fibres are by far the most convenient beam delivery medium, but efficient fibre coupling requires a high quality beam. The brightness B of a laser beam can be described with the following terms:

$$B = \frac{P}{A \cdot \Omega} \propto \frac{P}{(w_0 \cdot \Theta_f)^2} = \frac{P}{Q^2} \propto P/(M^2)^2$$

by using either the "beam parameter product" Q which is the product of the beam's minimum diameter w_0 and its divergence θ_f, or the term "M^2", which is equal to the beam parameter product normalized to a fundamental Gaussian mode. The spot diameter and divergence angle of a focused higher order beam are always larger than that of a Gaussian beam (which defines the maximum quality or the "diffraction-limit") by a factor of M^2 (M^2 is defined in the International Standard ISO/DIS11146). The highest brightness is clearly obtained by maximising the output power and minimising the beam divergence. The problem is that commercial high power laser diodes have a beam divergence of ~8° along the "slow-axis" (see Figure 2), *which is far away from diffraction limit*. A first and decisive measure for the development of high-brightness diode laser systems is therefore the development of diode laser chips with divergences close to the diffraction limit.

How are high-brightness laser diode sources made?

High-brightness laser diode sources are comprised of several components (as shown in Figure 3): the laser diode(s); a heatsink; and fibre coupling optics. The design fabrication of a high-brightness laser diode source requires many technologies, with expertise ranging from crystal growth, laser processing, soldering/packaging techniques, optical engineering, reliability engineering and laser design/simulation.

The laser diodes themselves are often fabricated in the form of a 10mm wide linear bar array of typically 25-50 uncoupled emitters, in order to reach average powers of ~ 40W in commercial devices (and > 200W in research devices). Very high powers (up to 6 kW) can be obtained with stacks of laser bars.

Good thermal management is essential for the operation of laser bars and stacks at these power levels. Many heatsink technologies are available to remove the heat from the laser bars. Passive heatsinks are often suitable for low-power, low-cost applications, while water-cooled heatsinks (sometimes even micro-channel heatsinks) are required for higher power levels. The choice of heatsink also depends upon the reliability requirements of the target application. Expansion-matched heatspreaders and heatsinks can be used to reduce the mechanical strain on the bar arising from thermal expansion effects.

High-power laser sources also include optics for shaping the asymmetric and highly divergent output beams from the individual diode emitters and coupling them into an optical fibre with minimal loss of brightness and power. Typically, this involves separating the beams from the individual emitters, reshaping/repositioning them and then focusing them onto the end of a multimode fibre.

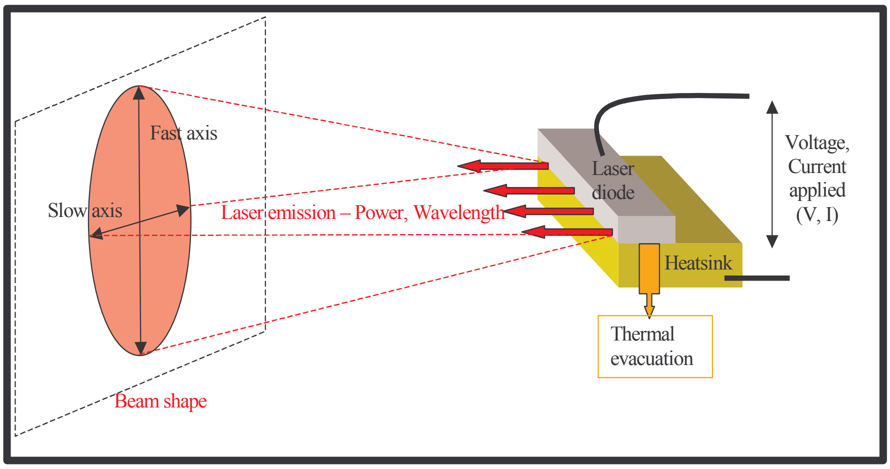


Figure 2: High-power laser diode in the form of a linear bar array mounted on a passively cooled heatsink (right). *[Courtesy of Thales Laser Diodes].* Asymmetric beam properties of a high-power diode laser, with fast vertical divergence and a slow in-plane divergence (left). Surprisingly, it is the focusing along the so-called "slow-axis" (which is not diffraction limited), which limits the brightness of a high-power laser diode. *[Courtesy of Thales Research and Technology]*

There are also problems associated with *maintaining* the brightness of the laser diodes when coupling their output beams to a multimode fibre. This requires that the output beams of each laser emitter are focused onto the end of the optical fibre. The spots from these beams must be positioned very close to each other in such a way that the pupil of the fibre is filled. The spot from a conventional high-power laser is very asymmetric (i.e. it is longer along the "slow-axis," since it is not diffraction limited in this direction). In order to exploit the

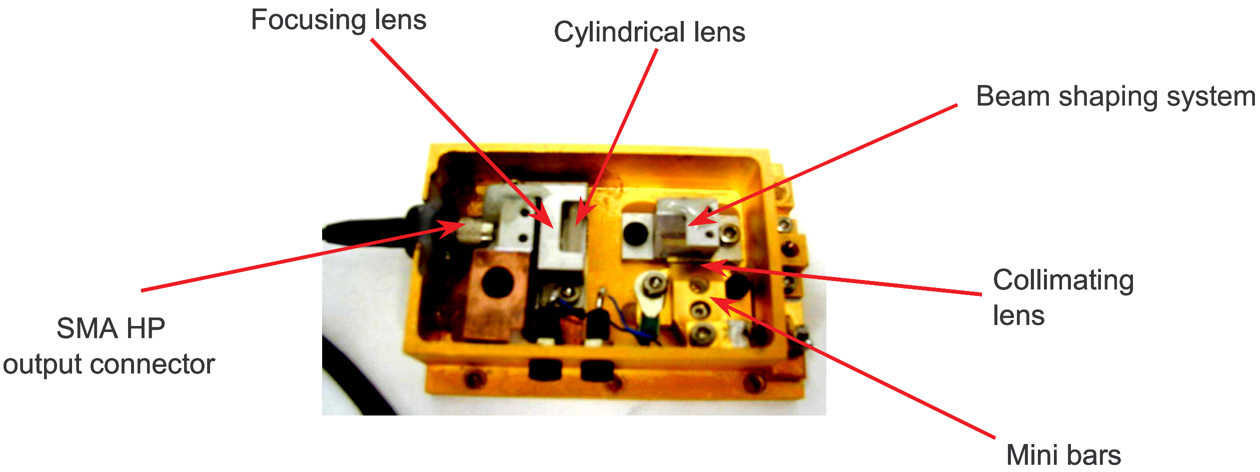


Figure 3: Components of a fibre-coupled diode laser module.
[Courtesy of Thales Laser Diodes]

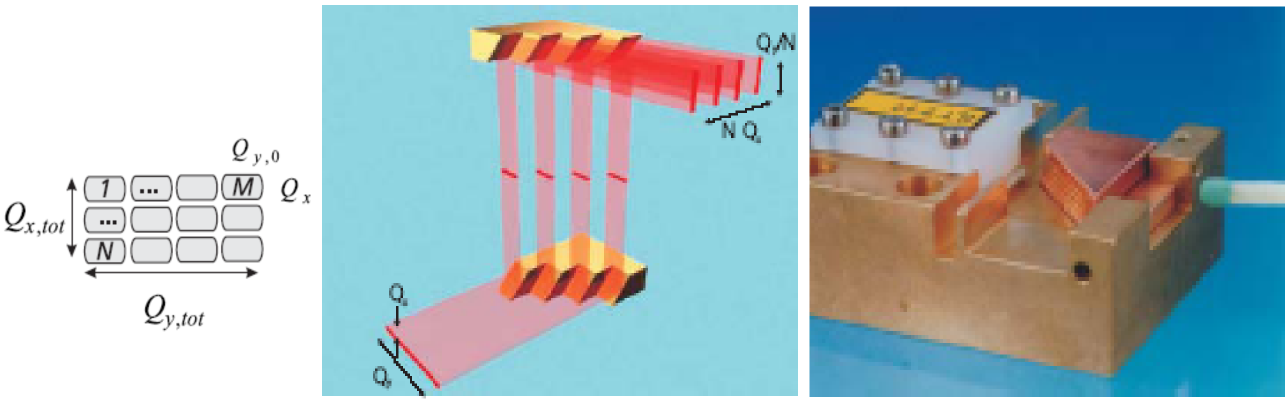


Figure 4: The images of the individual emitters of a high-power laser bar must be separated and re-positioned on the end of the delivery fibre to minimise the loss in brightness (left). A stepped mirror arrangement for reshaping the beam of a high-power laser bar (centre). An image of a high-power laser bar with stepped mirrors for beam shaping (right). *[Courtesy of Fraunhofer Institute for Laser Techology]*

Why is high brightness the main technical challenge for IST applications?

The beam parameter product Q is the key parameter which determines the performance of systems in IST applications - for both information transmission and materials processing. It controls the maximum energy density achievable by a laser diode, just as the gate length in CMOS technology determines the density or bandwidth of the information flow to be processed.

This can be easily understood in the case of the coupling of the light source into an optical fibre. In the ideal case, a diffraction limited source (Q= $4\lambda/\pi$) would be coupled into a mono-mode fibre with a matched numerical aperture, theoretically allowing us to couple of all (100%) of the source power into the fibre. If we use a source with the same power with a beam parameter equal to ten times the diffraction limit, we would couple only 1% of the source power into the fibre, resulting in a considerable penalty in the efficiency of the IST system.

advantages offered by high-power laser bars, the beams from each of the emitters must be separated and imaged onto the fibre with a different geometric coordination (see Figure 4). Conventional fibre coupling methods are not able to preserve the brightness of the individual emitters and limit the laser manufacturer's ability to maximise the power performance of the bar (i.e. the individual emitters have to be widely spaced).

State-of-the-art

The state-of the art is most conveniently represented by a diagram (see Figure 5) showing typical values for the output power and beam quality of commercial lasers used for industrial and health-care applications and for applications in optical telecommunications. The beam quality is measured with the beam parameter product Q: lower numbers mean higher quality and smaller focal spot sizes or fibre core diameters respectively. A straight forward technology to increase output power of diode laser systems is to combine as many diode laser emittersas needed to achieve the desired power. Simple side-by side combination however leads to a decrease of beam quality (or increase of Q) proportional to the square root of the output power. The diagram shows, that presently available diode laser systems (small grey dots in the upper-left part of the diagram) are far away from diffraction limit, indicated by the thick dotted horizontal line).

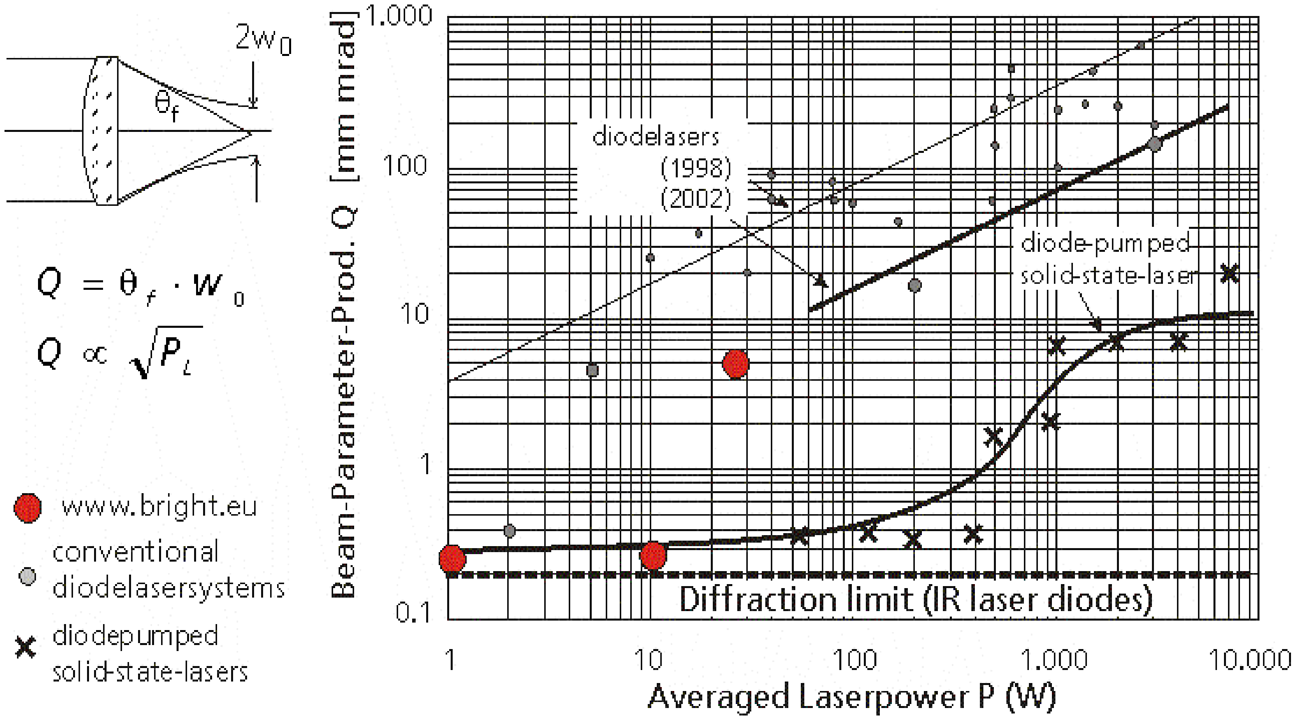


Figure 5: The performance of a high-power laser is described by its beam quality and overage output power. This diagram illustrates the typical performance of both laser diodes and diode-pumped solid state lasers. *[Courtesy of Fraunhofer Institute for Laser Techology]*

What are the applications of high-brightness laser diode sources?

High power and high-brightness laser diode systems are an enabling technology, with a wide variety of applications areas. They are used in telecommunications for pumping fibre-optic amplifiers (e.g. EDFAs, Raman amplifiers). Diode laser systems are experiencing particularly rapid growth in medicine (see inset) and the life sciences (e.g. surgery, opthalmology, urology, cancer therapy). They are used in materials processing (see inset) for applications such as marking, cutting and welding of plastics and metals. They are also used for printing, soldering, laser hardening and laser cleaning. Finally, diode lasers are the laser designer's first choice for pumping a variety of other lasers (e.g. solid state lasers, fibre lasers), which are designed to reach an even broader range of applications.

Telecommunications - cost reduction and high capacity networks drive the market

Raman and Erbium Doped fiber amplification require high power high brightness laser diode sources. They are key technologies for the telecommunication industry as they allow to support both the cost reduction trend and the effort to develop broadband access and transport networks.

Over the past years, Telecommunications transport networks have been using WDM technology, both for terrestrial and submarine networks. Faced with cost reduction issues, long haul carriers have already deployed Raman amplifiers for terrestrial routes with difficult conditions and submarine festoon links over 400km. Indeed, distributed Raman amplification allows the reduction of the effective noise figure of the transmission span, and consequently, minimizes the count of high-cost electrical regenerators used in the network. In the future, Raman amplifiers should be applied in ultra long links (above 1500km).

Metropolitan Area Networks (MAN) and cable TV (CATV) networks have similar economical constraints with CATV requiring higher power. In this context, cladding pumped EDFA is a well suited technology as it provides high power (>33dBm) at low cost and low electrical consumption.

In addition, evolution of the WDM systems from 10 Gbit/s line rate to 40 Gbit/s line rate will be motivated not only by cost of equipment itself but also by the evolution of the bit-rate handled in the routers. Due to the need for very high capacity at the router level, very-short-reach links between IP-routers and ATM-switch operating at very high bit rate are used (10 Gbit/s now and 40 Gbit/s soon at reduced cost). This is expected to happen between 2007 and 2008 if the required cost reduction technologies are made available in core-backbone equipments: Raman amplification using Raman fiber lasers and cladding-pumped EDFAs are well suited candidate technologies.

The additional margins required by 40-Gbit/s transmission will make necessary the implementation of new technologies. When Nx40-Gbit/s systems will be deployed over short and long-haul applications (several hundred km long), the Raman technology is likely to be used thanks to the significant margins provided by its low-noise characteristics. The output power of the EDFA will be also further increased when dispersion compensating fiber with reduced non-linear effects will be made available, like in submarine applications for instance.

In conclusion, the low-cost approach allowed by the cladding-pumped EDFA and the Raman fiber lasers implemented in the www.bright.eu project thanks to the use of high brightness laser diode sources will leverage the next 40-Gbit/s (r)evolution using Raman amplification. Such technologies have been already used at a low scale in some applications like unrepeatered submarine transmissions and CATV broadcasting.

Figure 6: From the laser diode to the telecommunication transport network
[Courtesy of Alcatel]

e-Newsletter n°1
May 2005

Materials Processing – a very large market, just waiting to be tapped...

Two of the most important parameters for laser materials processing are laser power and laser intensity. The beam intensity which can be achieved by a given laser can be linked to its beam-parameter product Q, once the numerical aperture of the focusing system is known. Figure 6 shows what values of beam-parameter product are needed for various materials processing applications for typical beam delivery optics with a typical numerical aperture of NA=0.12, which corresponds to a F#4 focusing system. A comparison of Figures 5 and 7 show what type of laser is most suitable for specific applications in materials processing - at least as far as laser power and beam quality are concerned.

Currently, the high-volume markets for materials processing are marking and cutting/welding of sheet metal. All three applications require relatively high beam quality, with high output powers (typically > 1 kW) needed for cutting and welding. Typical process intensities are in excess of 10^5 W/cm^2. Apart from these high-power and high-intensity applications, there also exist a broad range of “low intensity applications,” where the beam only needs to be focused to a moderate spot size, so that lasers with lower beam quality are adequate. Two examples of low-power and low-intensity applications are welding of plastics and soldering. In most cases, the two parts to be welded together are chosen from differently pigmented plastics, so that the laser penetrates through the transparent top layer and is fully absorbed at the surface of the layer underneath. The requirements on laser power are quite moderate, because the process power is applied very effectively - it only heats the joining zone and the melting energy for plastic is quite low. Advantages of welding by laser instead of conventional methods such as ultrasonic welding are e.g.: flexibility, high quality of the weld (important in the case of visible seams), controllability of the power input and the possibility of integration into automated quality control. These advantages also hold for the soldering of electronic components.

Considerably higher output powers are required for laser hardening, as illustrated in Figure 6 showing a side-cutter, whose cutting edges have been hardened with a diode laser system. Laser transformation hardening involves fast surface heating of steel to the austenitic temperature, followed by rapid self-quenching by heat conduction to the cold base material. Due to the relatively high temperatures required (approx. 750 - 1.000 °C) and the macroscopic geometry of typical parts, the laser power needed typically exceeds 1 kW. Diode laser stacks, which have recently been employed for these applications, are distinguished from classical lasers by the property of having already a rectangular beam, which usually is the most desirable geometry.

Whilst current diode laser systems are mainly used for low intensity applications, research is being conducted into the development of more advanced diode laser systems with significantly improved beam quality.

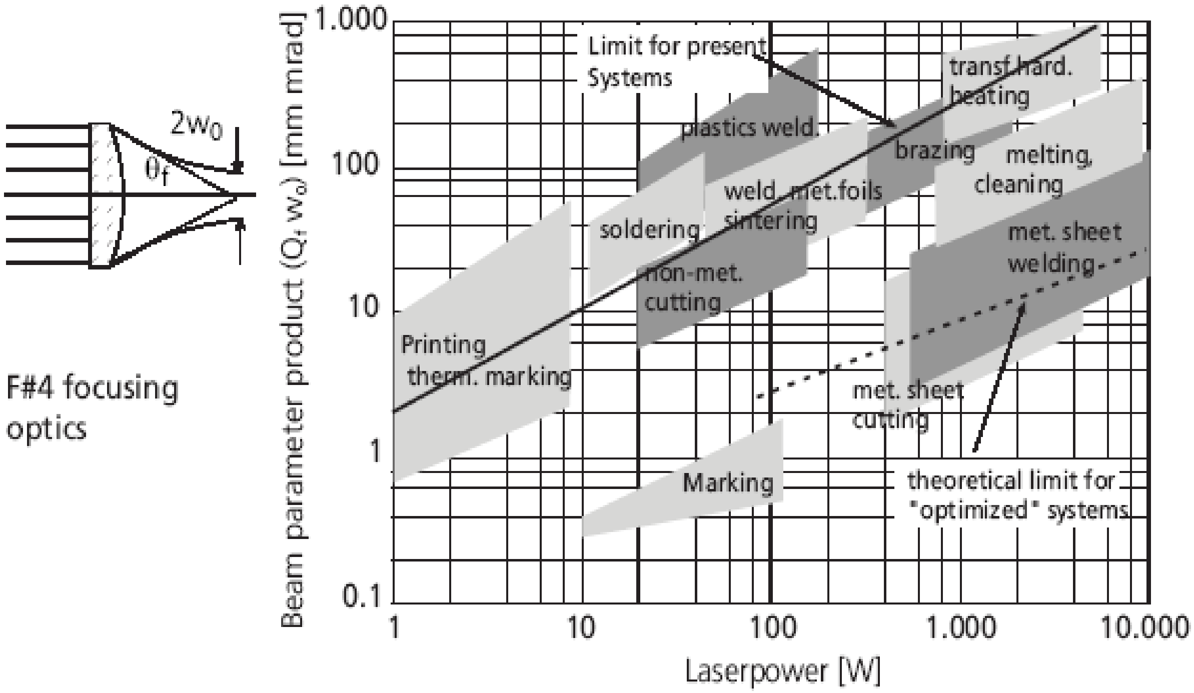


Figure 7: Laser beam quality (beam parameter product) and average power required for different materials processing applications, when the laser delivery optics has a numerical aperture of N.A. = 0.12.
[Courtesy of Fraunhofer Institute for Laser Techology]

Health-care - an important and growing market

The use of laser and optical technology in health care and biotechnology is a research field experiencing tremendous growth in terms of research activities, applications, and commercialisation - both Europe-wide and worldwide. The driving force is that laser and optical technologies have the potential of providing novel or improved non-invasive diagnostic and minimally invasive treatment procedures, which will have major impact on health care throughout the European community. The use of laser diodes for medical laser systems has the potential to reduce the unit equipment cost and increase their availability. (Portable laser diode-based photo-coagulators are already being produced allow the treatment of opthalmic disorders in children around the world.) Surgical lasers permit less invasive micro-endoscopic surgery, faster patient recovery times and reduce health care costs. One of the most recent and exciting applications for lasers is in Photodynamic Therapy (PDT) for localised cancer treatment. In PDT, unlike conventional chemotherapy, the cancer drug only becomes active when exposed to light with a specific wavelength. Consequently, PDT procedures are very localised and are expected to have fewer undesirable side-effects than chemotherapy, potentially offering cancer patients a greater chance for recovery and better quality of life during their treatment. Frequency doubled diode lasers are expected to find numerous diagnostic applications in the Health Care sector. Target applications include fluorophore tagging (e.g. of malignant tissue) and fluorescence spectroscopy/imaging, which has become an important tool in medicine, the pharmaceutical sciences and biotechnology.

The spread of laser-assisted treatment methods, such as photodynamic therapy (PDT), photo-stimulated wound or burn healing, and surgery in the European medical community is currently hampered by two central issues: a lack of reliable, high-power, though cost-efficient laser sources and a lack of on-line treatment monitoring systems which allow an immediate optimisation of the treatment process.

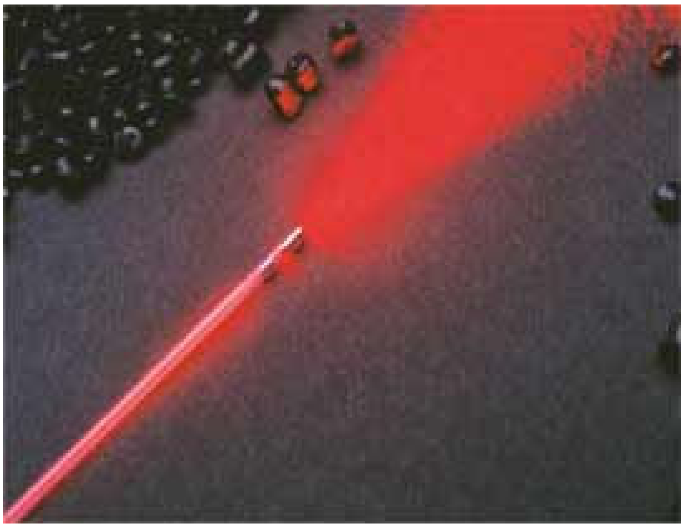


Figure 8: A medical laser system based upon high-power laser diode technology (left). A fibre delivery system with optical diffuser for photodynamic cancer therapy applications (right). *[Courtesy of Biolitec AG.]*

Where can I find out more?

• R. Diehl, R.D. Diehl, ***High-Power Diode Lasers: Fundamentals, Technology, Applications***, Springer-Verlag Telos: 2000.

• P. Loosen, *et al.* "High-power diode-lasers and their direct industrial applications", SPIE Vol. 2382 pp. 78-87.

• R. Szweda, ***Diode Laser Materials & Devices: Market Overview***, Elsevier, 2001.

• Laser Focus World: Laser Marketplace: Diode Lasers (Feb. 2002)

Prof. E.C. Larkins
School of Electrical and Electronic Engineering, University of Nottingham, Nottingham UK

Dr. K. Boucke *and* ***Dr. P. Loosen***
Fraunhofer Institute for Laser Technology, Aachen, Germany

D. Bayart and F. Leplingard
Alcatel, Research and Innovation Department, Marcoussis, France

Dr. T. Trebst [(1)], ***Prof. S. Andersson-Engels*** [(2)] ***and Dr. P. Andersen*** [(3)]
Biolitec, Bonn, Germany [(1)], *Lund University, Lund, Sweden* [(2)], *Risø National Laboratory, Copenhagen, Denmark* [(3)]

e-Newsletter n°1
May 2005

Spectroscopic analysis of external stresses in semiconductor devices

Jens W. Tomm

Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie Berlin
Max-Born-Str. 2 A, D-12489 Berlin, Germany,
tomm@mbi-berlin.de;
phone +49-30-6392-1453; fax +49-30-6392-1459; http://www.mbi-berlin.de/

INTRODUCTION

MBI performs research on the application of spectroscopic techniques developed or improved at the MBI to analytical purposes in optoelectronic devices. A primary objective is to improve insight into the microscopic nature of the mechanisms defining the limits of semiconductor device operation.

The following themes are presently in the focus of the research activities:

- defect creation and accumulation within the active region,
- mechanical stress as well as
- device and - particularly - facet heating

are quantitatively analyzed in very different device structures.

Together with our industrial partners new generations of optoelectronic devices with increased brightness and reliability are created, taking into account the analytical results of MBI.

Investigations of transient recombination processes (5 ps-10 ns) in optoelectronic materials and epitaxial structures such as quantum-well or quantum-dot structures complete these device-related analytical activities. Carrier transfer kinetics in self assembled or structured nanostructures such as stressors will be addressed (optical measurement of transport kinetics).

Furthermore, the group is involved into joint activities for the creation of novel classes of optoelectronic light sources such as mid-infrared light-emitting diodes or compact femtosecond emitters. Demonstrators are assembled and tested.

Within our common project WWW.BRIGHT.EU we coordinate the Workpackage WP5 “Reliability”. Reliability of optoelectronic devices is often influenced by external stresses, which are introduced by the packaging or during device operation. The quantification of these stresses is addressed in this article.

Semiconductor structures such as quantum-wells (QW) are frequently designed as strained systems. This kind of strain, called intrinsic or built-in strain, is created during epitaxial growth and is caused by the lattice mismatch between the different semiconductor materials.

During fabrication (processing, packaging) and operation, a quantum-well device such as a semiconductor laser might experience additional stresses of known or arbitrary symmetry. We refer to these as external stresses, which result in an additional strain contribution.

We present an approach for analyzing quantum wells experiencing built-in strain that allows for the quantification of external stresses of known symmetry, and of the externally-induced strains that arise due to these stresses. For special cases, the approach also provides results regarding the symmetry of the additional stresses and induced strains.

The approach is based on two main components. The first is the theoretical calculation of the strain-sensitivity of the spectral positions of the relevant quantum-confined optical transitions within a particular QW. These results are published separately [[i]] and are, in part, reproduced in the theory-section. Secondly, spectroscopic experiments are conducted, and the results are presented here. These experiments can be classified into two groups: those which are designed to check the theory, and those which employ the theory in order to translate spectroscopic data into quantitative information about strain in packaged, commercial high-power diode laser arrays, so-called cm-bars.

There are several experimental techniques suitable for spectroscopic strain analysis, such as Raman[[ii]], photoluminescence [[iii],[iv]], and photocurrent (PC) spectroscopy [[v]]. We use the PC-technique and introduce its background in the section on experimental details. Finally, we summarize our results and draw conclusions with respect to the applicability of our approach.

EXPERIMENTAL

Absorption and emission properties of certain species represent complementary information. Thus, the idea of employing both the emission properties of diode lasers for diagnostic purposes, and their absorption properties is self-evident. Unfortunately, an absorption measurement on a packaged device is rather difficult. However, a PC measurement that provides information about absorption properties is a rather simple and straightforward. PC has been widely used in basic research in the field of semiconductor physics. Application of this technique to regular optoelectronic devices also has been done routinely for many years. For example, the spectral-sensitivity-curve that is provided with a photodetector is nothing else but the PC spectrum of this device. Since diode lasers are also semiconductor diodes, it is clear that they will exhibit a characteristic PC-spectrum if they are measured like a photodetector, i.e. if the pn-junction is illuminated by light. To our knowledge Henry et al.[vi] were the first to carry out PC measurements on diode lasers and relate these results to reliability data.

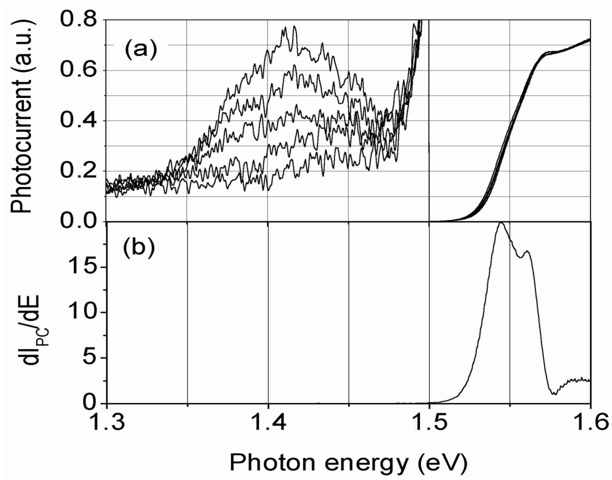


Figure 1. (a) Photocurrent spectra taken at different local positions from a cm-bar on a diamond heat spreader experiencing packaging-induced defects. Below 1.5 eV the data are multiplied by a factor of 1000, so that broad bands caused by packaging-induced defects are visible. (b) First derivative of a spectrum in a). The two peaks are associated with the spectral positions of the 1hh-1e and the 1lh-1e optical transitions of the QW.

It is worthwhile to provide a brief introduction to the microscopic mechanisms involved in the generation of PCs. Measurement of PC is among the very first techniques that have been applied to the investigation of semiconductors. Analysis of PCs, however, is sometimes difficult due to the fact, that there are two distinct processes involved in the generation of a photocurrent, namely absorption and transport. That is, both an optical and an electronic effect, respectively, are involved. In the first step, the excitation light must enter into the device and create non-equilibrium carriers there. In the simplest situation, when the excitation photon energy is larger than the energy gap of the material the absorption appears near the surface of the device. For smaller photon energies one has to consider light transmitted through the waveguide and cladding layers, and consider properties such as the optical mode structure of the waveguide. Depending on the absorption coefficient of a given material at a particular excitation wavelength, the light is absorbed after having passed a fixed distance into the structure, which determines the PC 'depth-resolution'. Absorption of photons generates non-equilibrium carriers that might be either free or localized in Coulomb wells, formed, e.g. by the QWs or defects. Even the ionization of defects by below-bandgap-energy photons is possible. At ambient temperature, i.e. the standard temperature for device testing, bound carriers can easily be freed by thermionic emission. Hence, we call these carriers quasi-free. The second step in the PC generation process is carrier motion, caused by either built-in or externally applied electric fields, resulting from the potential of the pn-junction or by external bias, respectively. This carrier motion is measured as the photocurrent after the electric circuit is closed by an ammeter. We should note that the exciting photons that are absorbed in device regions without potential gradients, e.g. in the substrate, cannot contribute to the PC. So, the PC technique has a self-focusing ability. Although one may illuminate the whole front facet of an edge-emitting laser, information revealed by the PC comes exclusively from the depletion region around the pn-junction, i.e. from the optically active region of the device. Since most edge-emitting diode lasers have comparable device architectures, the PC spectra also display an overall-shape that more or less reflect the absorption properties of the waveguide of the device.

Therefore, the PC technique is also a method for measuring the absorption spectrum of waveguides of devices. Figure 1 (a) shows 5 typical PC spectra from different locations along an 808 nm emitting cm-bar. At the laser emission energy there is a sharp edge that is formed by the energetically lowest optical transition within the QW. Higher quantum-confined transitions are detectable by differentiating the spectra, see Fig. 1 (b), and/or by making measurements while employing excitation with polarized light, cf. [v]. Furthermore, there are much weaker bands energetically below the QW absorption edge. These bands arise due to optical transitions involving energetic states that are caused by deep level defects. Thus, these data illustrate the ability of the PC-technique to detect and analyze defects in devices.

PC spectra can be measured with a standard apparatus that is also used for the characterization of photodetectors. Such devices consist of a lamp as a radiation source and a grating monochromator for dispersing the light. The light is usually focused on the front facet of the diode laser by a microscope and the signal generated by the mechanically chopped light is fed into a lock-in amplifier. A thermopile is used for measuring the intensity distribution of incident excitation light and, hence, to derive a spectral calibration function. For some investigations it is appropriate to introduce a polarizer into the light path in front of the laser. Otherwise care must be taken to avoid any polarization of the incident light beam. All measurements are done at stabilized room-temperature. This temperature control is important because the PC spectra exhibit the same temperature shift as the emission wavelength of the device. So, temperature stability is essential, especially if small energy differences, e.g. for strain measurements, are to be analyzed. The photocurrent is usually extracted from the device via the contacts through which the operation current is fed into device when it is in normal operation. Thus, preparation is not required and packaged devices can be easily measured.

Fourier-transform (FT) spectroscopy significantly improves the quality of PC spectra measured [i,v]. The setup remains the same as for a FT-based transmission measurement, but the regular sample is replaced by the laser diode that will be analyzed. Care must be taken to make sure that the light beam from spectrometer hits the front facet of the device, the window of the laser module, or gets properly fed into the pigtail of the attached fiber, for the case in which a fiber module is being inspected. The PC signal that is generated usually must be amplified by a broad-band preamplifier, and returned into the spectrometer. For this purpose minor electronic modifications of the spectrometer are required, which permit the connection of the exit of the external low-noise broad-band preamplifier with the signal input of the spectrometer, where, in the regular operation mode, the detector signal arrives. Typical measuring times are on the order of several minutes, whereas the spatial resolution is about 200 µm. By using a microscope objective the spatial resolution can be reduced to about 30 µm [vii].

The 808 nm emitting devices used in this study are fabricated on the basis of a standard InGaAlAs/GaAs QW structure, see Ref. [viii]. Two groups of samples of different geometry are investigated. First, there are the cm-bar arrays, which are 1 cm in width, 0.9 mm in cavity length, and 110 µm in thickness. These arrays consist of 25 segments and they are typically packaged with In on copper heat sinks. The different thermal expansion coefficients (α) of the device (α_{GaAs}=5.7×10^{-6}K^{-1}) and copper (α_{Cu}= 15.5×10^{-6} K^{-1}) create a compressive packaging-induced strain within the GaAs-based device when the packaged device is cooled down from soldering [T_m(In)= 156.6 °C] to ambient temperature (20 °C). Calculations based on the finite element method revealed that in consequence of the particular geometry of the cm-bars the packaging-induced strain along the lateral coordinate, i.e. along 110-direction, the long dimension of the array, is the main component of the packaging-induced strain [vii]. This primary strain component exceeds others, e.g. the component along the cavity axis, by over one order of magnitude, or more. The second group of samples involves so-called single-chip devices. In fact, these devices are 400 µm wide emitter segments of cm-bars, with the same general device architecture.

THEORY

The theoretical work presented here was carried out by Mark L. Biermann, Eastern Kentucky University, Richmond. A k·p, local pseudopotential theory [ix,x] is used to model packaging-induced strain in high-power, quantum-well diode lasers. The theory uses an empirical, local pseudopotential approach, combined with Löwdin perturbation theory with the k·p operator to simultaneously calculate the conduction, heavy-hole (hh), light-hole (lh) and spin-split-off bands of the constituent, bulk materials. QW states are found via an eigenvalue equation that is derived from the matching of the individual, bulk-material states at the material interfaces using the normal component of the current density operator. The effect of compressive strain on the bandstructure is modeled using deformation potentials that are determined empirically [xi]. A key result of the theoretical model is the piecewise linear nature of the 1hh-1e and the 1lh-1e interband-transition-energy shifts with compressive strain. This linear nature of the transition-energy shifts permits the characterization of the energy shifts as a function of strain using coefficients, or ‘strain sensitivities’, which represent the change in transition energy per change in packaging-induced strain. Table I summarizes strain sensitivities for relevant optical transitions and strain symmetries. Additional results, as well as details of the calculations are summarized in Ref. [i]. A clear trend can be discovered in the results in Table I. This trend holds only for situations under compressive intrinsic strain, and compressive, in-plane applied strains, and it can be observed by noting the ratio of the 1lh-1e- and the 1hh-1e-related strain sensitivities for various applied strain conditions.

These strain sensitivity ratios are in the bottom line in Table I. In the cases of a uniaxial stress applied along the 110-direction, a biaxially-symmetric, in-plane applied strain, and a hydrostatic applied strain, these ratios are, respectively, 2.7, 1.4, and ~1. It is clear that as the applied strain becomes more symmetric, changes in the 1lh-1e- and the 1hh-1e-related transitions as a function of applied strain become increasingly similar. This trend is consistent with the behavior of the zone-center states under the various applied strains.

TABLE I. Theoretical strain sensitivities for compressive strain in units of eV for the 1hh-1e and 1lh-1e optical transitions in the QW, for the laser structure investigated in this study.

	Strain symmetry		
Optical transition in the QW	Uniaxial stress, 110-direction	Biaxial	Hydrostatic
1hh-1e	-2.12	-10.2	-23.84
1lh-1e	-5.69	-14.1	-23.69
Strain sensitivity ratio lh/hh	2.7	1.4	~ 1

One can exploit this trend as long as one is able to measure the shifts in the energies with strain of both the 1lh-1e- and the 1hh-1e-related transitions. It is then straightforward to determine the ratio of these shifts. This ratio is then a rough indicator of the nature of the strain configuration in the structure. A value of the ratio close to 1 implies a highly symmetric strain configuration. A ratio increasingly different from one points to an increasingly lower-symmetry strain configuration.

RESULTS AND DISCUSSION

Comparison of theory and experiment

A series of experiments has been carried out in order to test the theoretical model and its applicability to device analysis. In these experiments, clearly defined strain configurations for single-chip devices are created and PC spectra are measured and analyzed. Figure 2 shows one example of such a comparison of theory and experiment, namely for the case of a uniaxial stress in the 110-direction. This particular case is of utmost relevance for spectroscopic analysis of cm-bars because the central emitters in cm-bars are expected to experience an overall strain symmetry which is very similar to the symmetry in this case. Thus, we have chosen for this experiment single-chip devices which are almost identical to the emitters in cm-bars. The uniaxial stress was applied by a special mini-bench vice-like setup, in which the device was compressed between two diamond bars. Note that the strain range with a clear linear relationship between deformation along the 110-direction and transition-energy shift is limited, especially for the 1hh-1e optical transition. Nevertheless, there is a remarkable agreement between theory and experiment. Data obtained for other well-defined experimental strain configurations, such as biaxially-symmetric, in-plane strain and hydrostatic stress, also yield remarkable agreement with our theory [i]. Consequently we draw the conclusion that the strain sensitivities given in Table I are suitable for strain analysis in the relevant diode laser devices.

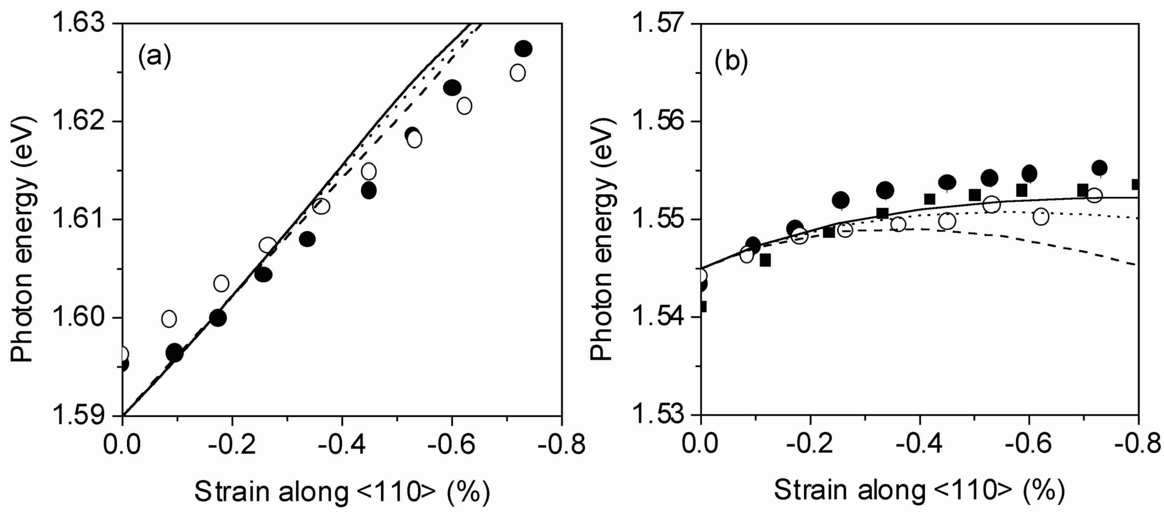


Figure 2. Spectral position of the 1lh-1e transition (a) and the 1hh-1e transition (b) versus induced strain in the 110-direction. The open and closed circles refer to different experiments with different devices (reproducibility test). The lines correspond to different model calculations that are described in detail in Ref. [i]. The three models are 1) no quantum-confined Stark effect, solid line; 2) quantum-confined Stark effect included, dashed line; 3) quantum-confined Stark effect with shielding included, dotted line. The shielding factor is 0.302.

<u>Strain analysis in cm-bars</u>

Figure 3 shows data obtained from a cm-bar array after several hundred hours of operation. From earlier studies, as well as from investigations carried out by other authors using other spectroscopic techniques on comparable samples [iii], we know the bow-like shapes of the plots of transition energy vs. local position to be typical for this kind of cm-bar array. In particular at the device edges (x=0 and 10 mm) there is a minimum of the transition energy. Several sets of experiments, see Ref. [xii], as well as calculations [vii] have shown that at the edge the device is almost unaffected by packaging-induced strain. Note that this statement holds exclusively for the use of In-based solder and low or moderate top pressure during the soldering process. Thus, the bowing represents the strain field along the device. From Figure 3 we obtain a maximum bowing of 1.2 and 3 meV for the 1hh-1e and the 1lh-1e transition energies, respectively. By using the strain sensitivities for uniaxial strain along the 110-direction from Table I, we find, concordantly, the center of the bar to be more compressed by -0.057 and -0.053% than the edge, repectively. The ratio 3/1.2=2.5 very nicely corresponds to the expected ratio of 2.7 for this strain configuration, as seen in Table I. This agreement indicates that our assumption about the symmetry of the overall-strain-field along the cm-bar is justified.

A striking feature can be seen in Figure 3 at about x=2 mm, at a location where 3 emitters failed. For both optical transitions a distinct peak is observed, with a transition energy about 2 meV above the background of the bow-like overall strain field, and associated strain-induced transition energies. One can infer that defect creation causes, on average, a hydrostatic compression of the semiconductor lattice. The uniform blue shift of the 1hh-1e and the 1lh-1e optical transitions confirms this assumption about the strain symmetry based on the hydrostatic

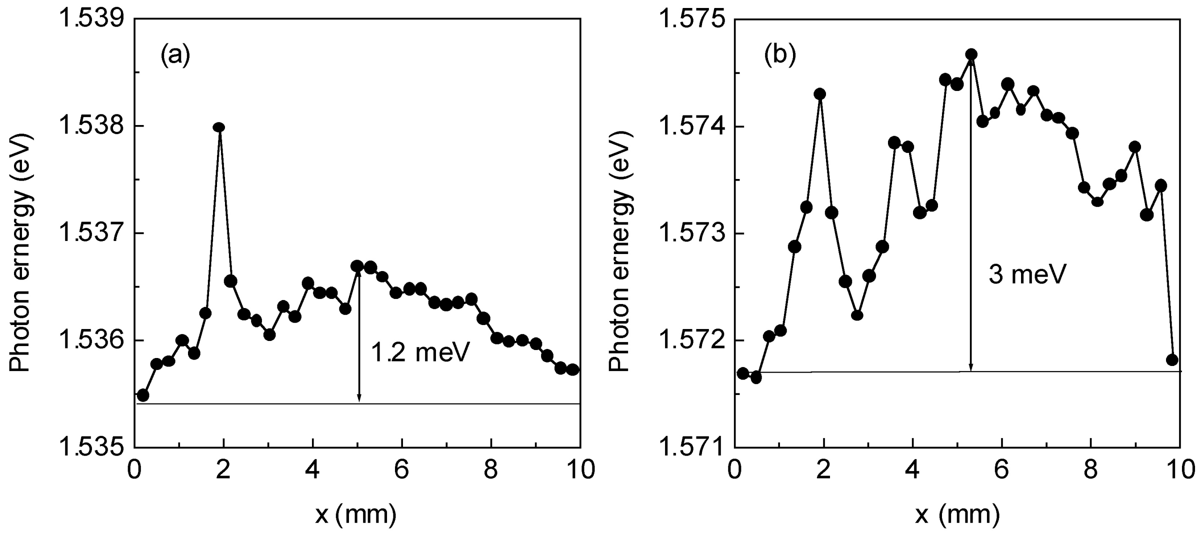


Figure 3. Spectral position of the 1hh-1e transition (a) and the 1lh-1e transition (b) versus local position along an aged cm-bar array which has become afflicted with defects. Around x=2 mm 3 of the emitters are affected by dark line defects.

strain sensitivities in Table I. By using the strain sensitivities from Table I the hydrostatic compression is quantified to about -0.008%.

Thus, our spectroscopic strain analysis of a cm-bar array clearly shows the potential of our approach. We are not only able to quantify the overall strain in the device, but also to obtain some information about the strain configuration.

Simulation of the strain caused by thermal cycling

In the previous sections we primarily discussed packaging-induced strains, which are created when devices are cooled down after the soldering process. It is obvious that this strain component is modified when lasers are heated, e.g. during operation. In pulsed operation such heating (and cooling) processes take place periodically. Hence, the packaging-induced strain also becomes, at least in part, modulated. In an earlier study we quantified this strain modulation and found for a pristine device strain values of up to 0.07% when the device is heated up by 18 degrees [[xiii]]. As one would expect, this maximum modulation appears in the center of a cm-bar, where the packaging-induced strain also shows its maximum.

In order to learn more about the gradual aging processes that are likely to be accompanied with this periodic load, we experimentally modelled the mechanical stress one central emitter in a cm-bar is expected to experience. This modelling was done by taking such an emitter, namely a single-chip-device from the same laser structure and applying pressure from the side. The pressure was applied via a mini bench vice setup that was powered by a piezo-electric force transducer. Two devices from the same batch were exposed to up to 2×10^6 mechanical cycles of a pressure corresponding to a mechanical strain of -0.07 or -0.2% along the 110 direction. The results of these experiments are presented in Figure 4.

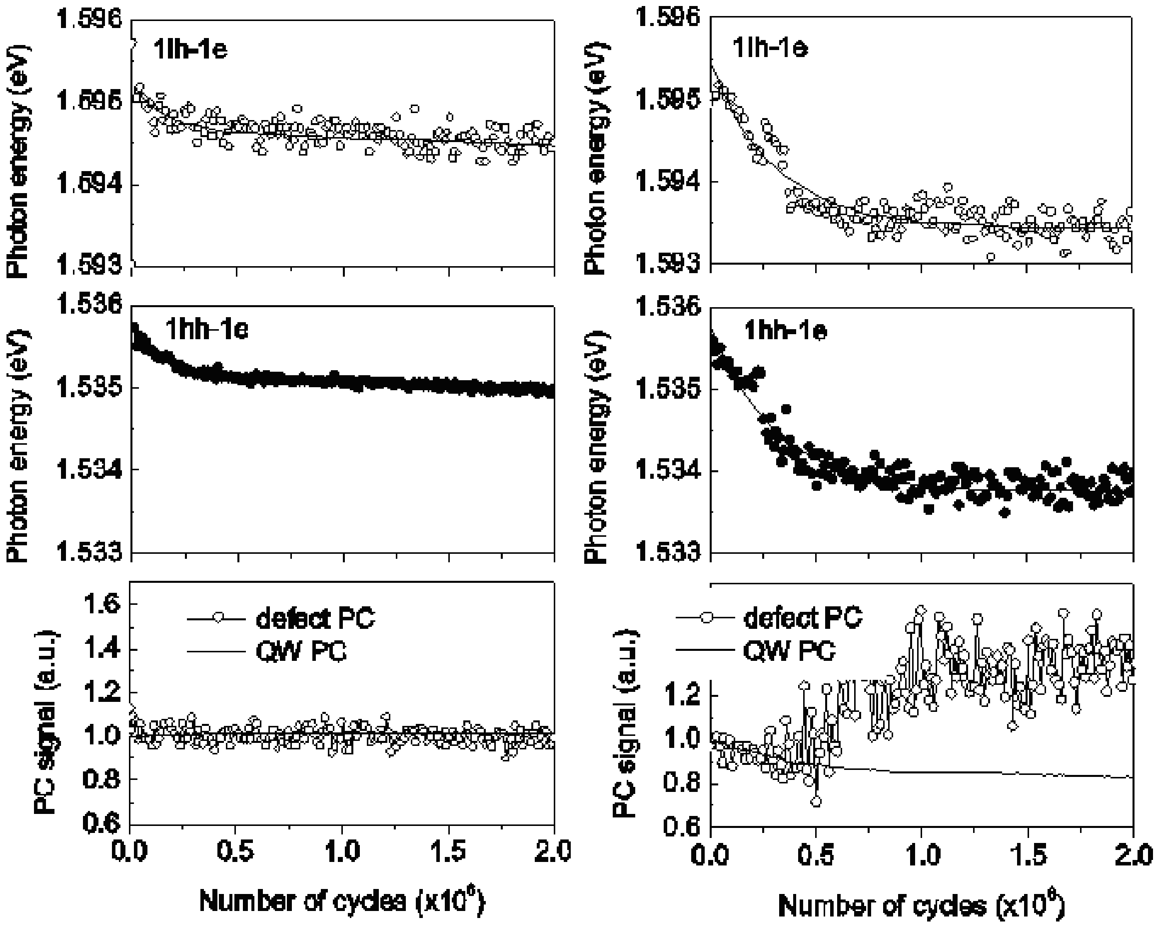


Fig. 4. Spectral positions of optical transitions within the QW (first and second row from top) and changes of the PC signal due to defect and QW absorption (row at the bottom) versus number of mechanical cycles. In each cycle the device is deformed by 0.07 and 0.2% along the 110 direction, see first and second column, respectively.

Before discussing Figure 4 we briefly return to the physics underlying the PC generation, earlier discussed in the section on experimental details. In a steady-state experiment, the population of non-equilibrium carriers in the QWs is proportional to the carrier lifetime. Since at ambient temperature thermionic emission is the mechanism that frees the non-equilibrium carriers from the QWs, and these free carriers are the ones that create the PC, there is a direct proportionality between the PC and the population of the QWs. Thus, finally, there is a direct link between QW PC and non-equilibrium carrier lifetime. The term 'defect PC' denotes PC contributions that are excited energetically below the QW absorption. Clear defect PC contributions are visible, e.g., in Figure 1 between 1.35 and 1.45 eV.

Figure 4 presents the energy positions of QW transitions as well as the QW and defect PCs for the two experiments. Obviously, there is again a uniform shift of hh- and lh-related optical transition energies that increases with the number of mechanical cycles as well as with the amplitude of the deformation. However, this shift is a red shift. Hence, in terms of strain this effect would correspond to a relaxation of hydrostatic compression, based on the strain sensitivities of Table I. Since the pristine devices are not hydrostatically compressed, and since defect annihilation (see discussion in the previous section) is not likely to be an aging-related effect, another mechanism must be responsible for this shift in the optical transition energies. This mechanism is found to be bandgap renormalization. The effect is driven by an increased equilibrium carrier population of the QWs due to the creation and ionization of insulated point defects and should cause almost uniform red shifts of the QW transitions. The 0.7 meV red shift observed with the smaller load corresponds to an increase in the 2×10^{11} cm^{-2} sheet carrier concentration of the QWs of about 10% [xiii]. Concordantly, the non-equilibrium carrier lifetime, represented by the QW PC, and defect concentration, represented by the defect PC, do not change in a noticeable way. In addition, we found that the device, which was packaged after the experiment did not show different electro-optical parameters compared to reference devices from the same batch, and no dark-line defects were observed in the active region. Thus, we observe a very early stage of device degradation. When increasing the stress amplitude, clear effects do become visible, including lifetime reduction and defect generation. One might note that a mechanical load resulting a -0.2% lattice compression is rather strong. This is, of course, true, especially if one considers global, packaging-induced strains across entire devices. However, local strains might reach this magnitude in practice.

SUMMARY AND CONCLUSIONS

We present the results of a spectroscopic study of packaging-induced strains in extended-width optoelectronic devices, namely high-power diode lasers and arrays with a width of up to 1 cm. After a detailed introduction to the experimental technique and a brief summary of the theory we discussed several experiments with externally stressed QW devices.

Our theory revealed that there is a piecewise linear relationship between the observed shifts of QW transitions and applied strain. In the case of uniaxial stress along the 110-direction, a case that is relevant when long devices are soldered onto heat sinks with different thermal expansion coefficients, this piecewise linearity holds for the lasing transition up to at least -0.2% compression. Based on the strain configuration (symmetry), there are different strain sensitivities for the different quantum-confined transitions. In practice this dependence of the strain sensitivities on strain symmetry can be employed to obtain information about the symmetry of observed strains. In a first set of measurements the theory was successfully compared to experiment.

Further experiments use the theory in order to obtain strain information from laser devices that have been subjected to external stresses. We analyzed the symmetry and magnitude of the packaging-induced, overall-strain in an aged cm-bar high-power diode laser array and found predominantly uniaxial compression in the 110-direction, reaching a value of -0.055%. At failed emitters, which are affected by dark line defects, a compressive strain field of hydrostatic symmetry is detected and the strain is quantified to about -0.008%.

Another set of experiments was undertaken in order to investigate the effects of periodic stress on laser structures. We observe very early stages of gradual ‘degradation’, which do not deteriorate any device properties. These pre-stages of device degradation are accompanied by point defect generation or accumulation in the active region, and result in weak red-shifts of the QW transitions assigned to bad-gap renormalization. In later phases of device degradation, this red-shift effect seems to be overcompensated by the compressive stress created by higher-dimensional defects, such as dislocations and dislocation networks resulting in dark line defects.

We have demonstrated that careful analysis of QW-transition-energy shifts, in particular spatially-resolved energy shift measurements in devices, allows for quantification of mechanical stresses. Furthermore, this kind of analysis allows the distinction between stress symmetries and the study of other effects that accompany device operation.

REFERENCES

[i]. Mark L. Biermann, Steven Duran, Kelsey Peterson, Axel Gerhardt, Jens W. Tomm, Witold Trzeciakowski, and Artem Bercha *J. Appl. Phys.* 96, 4056 (2004).

[ii]. W. C. Tang, H. J. Rosen, S. Guha, and A. Madhukar, *Appl. Phys. Lett.* 58, 1644 (1991).

[iii]. P. Martin, J. P. Landesman, J. P. Hirtz, and A. Fily, *Appl. Phys. Lett.* 75, 2521 (1999).

[iv]. A. Borowiec, D. M. Bruce, Daniel T. Cassidy, and H. K. Haugen, *Appl. Phys. Lett.* 83, 225 (2003).

[v]. J. W. Tomm, R. Müller, A. Bärwolff, T. Elsaesser, D. Lorenzen, F. X. Daiminger, A. Gerhardt, and J. Donecker, *Appl. Phys. Lett.* 73, 3908 (1998).

[vi]. C. H. Henry,P. M. Petroff, R. A. Logan, and F. R. Merrit, *J. Appl. Phys*. 50, 3721 (1979).

[vii]. Jens W. Tomm, Axel Gerhardt, Roland Müller, Mark L. Biermann, Joseph P. Holland, Dirk Lorenzen, and Eberhard Kaulfersch, *Appl. Phys. Lett.* 82, 4193 (2003).

[viii]. Martin Behringer, Marc Philippens, W. Teich, Alexis Schmitt, Stefan Morgott, Joerg Heerlein, Gerhard Herrmann, Johann Luft, G. Seibold, Jens Biesenbach, Thomas Brand, and Marcel Marchiano, *Proc. SPIE* 4993, 68 (2003).

[ix]. C. Mailhiot and D. L. Smith, *Phys. Rev. B* 33, 8360 (1986).

[x]. C. Mailhiot and D. L. Smith, *Phys. Rev. B* 35, 1242 (1987).

[xi]. I. Vurgaftman, J. R. Meyer and L. R. Ram-Mohan, *J. Appl. Phys.* 89, 5815 (2001).

[xii]. J. W. Tomm, A. Gerhardt, T. Elsaesser, D. Lorenzen, and P. Hennig, *Appl. Phys. Lett.* 81, 3269 (2002).

[xiii]. Axel Gerhardt, Fritz Weik, Tien QuocTran, Jens W. Tomm, Thomas Elsaesser, Jens Biesenbach, Holger Müntz, Gabriele Seibold, and Mark L. Bierm ann, *Appl. Phys. Lett.* 84, 3525 (2004).