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WWW.BRIGHT.EU

*Wide **W**avelength Light for Public **W**elfare: High-**Brig**htness Laser Diode Systems for **H**ealth, **T**elecom and **E**nvironment **U**se*

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

CONTENT

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GREETINGS FROM THE PROJECT COORDINATOR

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Dear Reader,

Welcome to the third and final e-Newsletter of the EC-IST Project WWW.BRIGHT.EU: Wide Wavelength Light for Public Welfare – High-Brightness Laser Diode Systems for Health, Telecom and Environment Use, 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, telecommunications, environment and security**.

The WWW.BRIGHT.EU consortium of 22 partners has pursued **a long-term vision** aimed at pushing the limits of current laser diode technology towards higher brightness, and stimulating the development of new applications and markets such as biophotonics (photodynamic therapy and fluorescence diagnosis). Our approach consisted of mobilising the expertise of the main European actors in laser diode core technology, and coupling this with highly innovative optical technologies. Industrialisation issues have also been explored through packaging and reliability studies. Although the WWW.BRIGHT.EU project concludes this month, we expect the excellent research partnerships to continue.

A lot of good results have been obtained as shown by the important list of publications and conference papers listed in this Newsletter. There are strong interactions and regular and various exchanges between the partners. This third Newsletter reports on the recent WWW.BRIGHT.EU workshop "High-Brightness Laser Diodes and their Applications" and presents five articles. These include two applications topics - cladding-pumped EDFAs in the telecommunications sector and the use of diode lasers and optical technology in medicine - and a technical paper on the pressure and temperature tuning of laser diodes. The medical topic includes three articles covering photodynamic therapy, optical coherence tomography and a binocular machine vision system for gauging very small objects.

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 or visit our website http://www.bright-eu.org.

EDITORIAL

Welcome to the third e-Newsletter of the integrated project WWW.BRIGHT.EU, which started in July 2004 and concludes this month.

If you wish to find out more about our project or would like to read our other Newsletters, please visit our website: http://www.bright-eu.org/

We hope you will enjoy the reading.

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High-Brightness Laser Diodes and their Applications

CAMBRIDGE UNIVERSITY - Friday 7th July 2006

Workshop hosted by two Universities: Nottingham and Cambridge

A one-day Workshop "High-Brightness Laser Diodes and their Applications" was organised by the Consortium and co-hosted by the Universities of Cambridge and Nottingham. The Workshop took place on the 7th July 2006 and was held in the William Gates Building of the University of Cambridge. A Workshop Dinner was held the preceding evening in Corpus Christi College, one of the ancient colleges of the University of Cambridge founded in 1352.

The Workshop, attended by 50 delegates from across Europe, included an extensive program of 25 presentations – 11 given by invited speakers from outside the Consortium and 14 given by members of the WWW.BRIGHT.EU project team. The program was divided into five topical sessions, each focussing on a particular aspect of laser design, type of laser or laser application. The full program is given on the following page. The high quality of presentations on state-of-the-art developments and techniques related to laser diodes stimulated many enthusiastic discussions, resulting in an extremely successful event. The presentations from the Workshop will shortly be available on the project website, http://www.bright-eu.org.






High-Brightness Laser Diodes and their Applications – Workshop Program

SESSION 1: Medical and Telecom Applications of High-Power Laser Diodes		
Katarina Svanberg	Lund University	Clinical PDT and pharmacokinetic studies using a novel photosensitiser
Steven Brown	National Medical Laser Centre, London	Interstitial photodynamic therapy
Dominic Robinson	Centre for Optical Diagnostics and Therapy	Fluorescence in cancer diagnostics and therapy
Florence Leplingard	Alcatel-CIT	The WWW.BRIGHT.EU project: Interest for telecommunication applications
SESSION 2: High-Power, High-Brightness Laser Diodes		
Hans Peter Reithmaier	University of Kassel	Quantum dot lasers
Bernd Sumpf	Ferdinand-Braun-Institute	Red lasers
Adrian Wonfor	Cambridge University	Integrated lensed lasers
Nicolas Michel	Alcatel Thales III-V Lab	915 nm tapered lasers
Stephen Najda	Intense Photonics	High-reliability, high-power laser arrays operating in wavelength range 800-1000 nm
Jennifer Hastie	Institute of Photonics, Strathclyde University	Visible and ultraviolet VECSELs
Jose Manuel García-Tijero	University of Madrid	Simulation and design of tapered laser diodes
Slawomir Sujecki	Nottingham University	Spectral modelling of high-power laser diodes
SESSION 3: Extended Cavity and Tunable Lasers		
Birgitte Thestrup	Risø National Laboratory	External feedback diodes
Peter Andersen	Risø National Laboratory	Frequency-doubled laser diode systems
Gaëlle-Lucas Leclin	CNRS - LCFIO	Extended-cavity tapered lasers with volume Bragg gratings for SHG at 405 nm
Witold Trzeciakowski	Instytut Wysokich Cisnien PAN	Pressure and temperature tuning of laser diodes
Wilhelm Kaenders	Toptica	Tunable single frequency diode laser solutions up to 1W in the UV to NIR spectral region
SESSION 4: Thermal Management, Packaging and Reliability		
Michael Leers	Fraunhofer Institute for Laser Technology	Expansion-matched packaging of laser bars
Jens Tomm	Max-Born Institute	Thermal management and thermal properties of high-brightness diode lasers
Maciej Bugaski	Institute of Electron Technology	Thermoreflectance study of the facet heating in high-power laser bars
SESSION 5: Test, Environment and Industrial Applications of High-Power Laser Diodes		
Joachim Sacher	Sacher Lasertechnik	Tunable diode lasers for test and measurement applications
Colin Mills	Domino UK Ltd.	Coding and marking with lasers
Frank Wilhelms	Alfred Wegener Institute	The physical properties of ice with respect to laser light for environmental applications
Guijun Bi	Nottingham University	Material processing with high-power diode lasers
Bill O'Neill	Institute of Manufacturing	Applications perspective of high-power semiconductor lasers

SELECTED RECENT PUBLICATIONS AND CONFERENCES

New Laser Technology: *Materials, Designs and Fabrication Processes for Improved Performance*

- F. K. Lau, C. W. Tee, X. Zhao, R. V. Penty and I. H. White, "Phase correcting element for intra-cavity laser Beam control," Optical Fibre Communications Conference (OFC 2006), Anaheim, Ca, USA, 5th – 10th Mar. 2006.
- N. Michel, I. Hassiaoui, M. Lecomte, O. Parillaud, M. Calligaro and M. Krakowski, "High-power, high-brightness tapered lasers with an Al-free active region at 915 nm," Photonics West 2006, San Jose, Ca, USA, 21st – 26th Jan. 2006, in Proc. SPIE, Vol. 6133, pp. 86-95.
- M. Zorn, B. Sumpf, U. Zeimer, H. Wenzel, G. Erbert and M. Weyers, "High-power red laser diodes grown by MOVPE," 13th International Conference on Metal-Organic Vapour Phase Epitaxy (IC-MOVPE XIII), Miyazaki, Japan, 22nd – 26th May 2006.
- B. Sumpf, M. Zorn, R. Staske, J. Fricke, P. Ressel, A. Ginolas, K. Paschke, G. Erbert, M. Weyers and G. Tränkle, "3 W – broad area lasers and 12 W – bars with conversion efficiencies up to 40% at 650 nm," 20th IEEE International Semiconductor Laser Conference (ISLC), Waikoloa Beach, Hawaii, USA, 17th – 21st Jan. 2006.
- F. Dittmar, A. Klehr, B. Sumpf, A. Knauer, J. Fricke, G. Erbert and G. Tränkle, "9 W output power from a 808 nm tapered diode laser in pulse mode operation with nearly diffraction-limited beam quality," 20th IEEE International Semiconductor Laser Conference (ISLC), Waikoloa Beach, Hawaii, USA, 17th – 21st Jan. 2006.
- C. Scholz, K. Boucke, R. Poprawe, M. T. Keleman, J. Weber, M. Mikulla and G. Weimann, "Comparison between 50 W tapered laser arrays and tapered single emitters," Photonics West 2006, San Jose, Ca, USA, 21st – 26th Jan. 2006, in Proc. SPIE, Vol. 6104, pp. 20-29.
- M. Leers, C. Scholz, K. Boucke and R. Poprawe, "Expansion-matched passively-cooled heatsinks with low thermal resistance for high-power diode laser bars," Photonics West 2006, San Jose, Ca, USA, 21st – 26th Jan. 2006, in Proc. SPIE, Vol. 6104, pp. 140-147.
- J. P. Reithmaier, S. Deubert, A. Somers, W. Kaiser, S. Höfling, A. Löffler, S. Reitzenstein, G. Sek, C. Hofmann, M. Kamp and A. Forchel, "Nanostructured semiconductors for optoelectronic applications," Photonics West 2006 (invited), San Jose, Ca, USA, 21st – 26th Jan. 2006.
- W. Kaiser, S. Deubert, J. P. Reithmaier and A. Forchel, "High power single mode lasers based on InAs/GaInAs quantum dot material with enhanced temperature stability," Conference of Lasers and Electro-optics (CLEO), Long Beach, CA, USA, 21st – 25th May 2006.

Design and Modelling: *Modelling Lasers, Design Optimisation and Advanced QW Gain Models*

- L. Borruel, I. Esquivias, J. M. G. Tijero, H. Odriozola, M. Krakowski, S. C. Auzanneau, N. Michel, S. Sujecki and E. C. Larkins, "Design and fabrication of high brightness semiconductor tapered lasers with a clarinet-like shape," Conference on Lasers and Electro-Optics (CLEO Europe), Munich, Germany, 12th – 17th Jun. 2005.
- S. Sujecki, "Modelling of high power semiconductor lasers," International Conference on Optical Transparent Networks (ICTON), Nottingham, U.K. (invited), Vol. 1, pp. 175-178, 18th – 22nd Jun. 2006.
- P. J. Bream, J. J. Lim, S. Bull, S. Sujecki and E. C. Larkins, "The impact of nonequilibrium gain in a spectral laser diode model," Numerical Simulation of Optoelectronic Devices (NUSOD) Conference, Singapore, 11th – 14th Sept. 2006.
- J. J. Lim, S. Sujecki and E. C. Larkins, "The influence of surface effects on the simulation of 1.3µm InGaAsN edge-emitting lasers," Numerical Simulation of Optoelectronic Devices (NUSOD) Conference, (post-deadline paper), Singapore, 11th – 14th Sept. 2006.
- P. J. Bream, S. Sujecki and E. C. Larkins, "Numerically efficient representation of anisotropic valence bands in semiconductor quantum-well optoelectronic devices," IEEE Photon. Tech. Lett., Vol. 18, pp. 1374-1376, 2006.
- S. Bull, J. J. Lim, P. J. Bream, S. Sujecki and E. C. Larkins, "Full spectral simulation of high-brightness laser diodes," European Semiconductor Laser Workshop (ESLW), Nice, France, 21st – 22nd Sept. 2006.
- R. MacKenzie, J. J. Lim, S. Sujecki and E. C. Larkins, "Thermal performance characteristics of passively cooled 1.3µm InGaAsN/GaAs double quantum well lasers," European Semiconductor Laser Workshop (ESLW), Nice, France, 21st – 22nd Sept. 2006.

Lasers in Medicine: *Imaging Systems, Analysis Methods and Clinical Studies*

- J. Svensson, A. Garofalakis, H. Meyer, F. Forster, J. Ripoll and S. Andersson-Engels, "Fluorescence spectroscopy in tissue phantoms for improved depth resolution in tissue imaging," Proc. SPIE, Vol. 5859, pp. 1-6, 2005.
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- E. Alexandratou, M. Kyriazis, D. Yova, S. Gräfe, T. Trebst, A. Johansson, J. Svensson, K. Svanberg, N. Bendsoe and S. Andersson-Engels, "Distribution studies of m-THPC after topical application of m-THPC thermogel in a murine non-melanoma skin cancer tumour model by fluorescence spectroscopic and imaging techniques," Proc. SPIE, Vol. 6139, pp. 91-100, 2006.
- D. Gorpas, K. Politopoulos, E. Alexandratou and D. Yova, "A binocular machine vision system for non-melanoma skin cancer 3D reconstruction," Multimodal Biomedical Imaging, Photonics West, BiOS 06, San Jose, Ca, USA, 21st – 26th Jan. 2006, in Proc. SPIE, Vol. 6081, 60810D.
- A. Johansson, J. Svensson, N. Bendsoe, K. Svanberg, S. Anderson-Engels, I. Bigio, S. Gräfe, T. Trebst, E. Alexandratou, M. Kyriazi and D. Yova, "Comparison of optical systems to measure photosensitizer concentration and pharmacokinetics," Optical Diagnostics and Sensing VI, Photonics West, BiOS 06, San Jose, Ca, USA, 21st – 26th Jan. 2006, in Proc. SPIE, Vol. 6094, 60940C.

External Cavities: *Achieving Wavelength Stabilisation and Superior Brightness*

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- V. Reboud, N. Dubreuil, P. Fournet, G. Pauliat and G. Roosen, "Spatial and spectral filtering effects induced by a photorefractive crystal inserted in a laser cavity," to be presented, European Optical Society (EOS) Annual Meeting, Paris, France, 16th – 19th Oct. 2006.
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Physics of Laser Diodes: *Strain, Defects, Temperature and Reliability Issues*

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Teaching outside the Consortium

- P. J. Bream, S. Sujecki and E. C. Larkins, "Nonequilibrium gain and nonlinear optical response of QWs for functional photonic devices," invited tutorial presented by E. C. Larkins at the 6th International Conference on the Numerical Simulation of Optoelectronic Devices (NUSOD), Singapore, 11th – 14th Sept. 2006.
- P. Adamiec, "The effect of pressure and temperature on laser diodes," PhD Thesis awarded with distinction by Warsaw University of Technology, Poland, Jun. 2006.
- P. M. Petersen, "High power diode lasers," tutorial presented by P.M. Petersen at the 2nd International Biophotonics Graduate Summer School, Hven Sweden, 24th Jun. 2005.
- N. Proust, "III-V safety and toxicology," short course given by N. Proust at EW MOVPE IX, Lausanne, Switzerland, 5th Jun. 2005.

PRESENTATIONS OF SOME OF THE PARTNERS

Partner 3 - Biolitec

biolitec AG was founded in 1986, in Bonn, Germany, and today is the world leader in specialty fibre and fibre optic-based products for medical, dental and industrial applications.

Based on our roots as a specialty fibre optics manufacturer (as CeramOptec GmbH), we continue to evolve everyday in a concerted effort to realise our vision – to innovate unique medical treatments, methods and products that will have a positive impact on the well-being of people worldwide.

Optical application fibre with cylindrical light diffuser

From the launch of our comprehensive line of advanced diode laser systems in 1996 to the establishment of our own biotechnology centre in Jena, Germany in 2000, biolitec continues to demonstrate its commitment to enhance the research and development of innovative techniques for the advancement of medical science.

Of particular importance to biolitec is the study of photosensitizers and their use in Photodynamic Therapy (PDT) applications. In addition to introducing products specifically designed for this, we are continually conducting several clinical trials and studies dedicated to the advancement of this exciting field.

Photosensitizer Foscan®

biolitec is an international corporation with facilities in several countries around the world. As a vertically integrated corporation, we are unique in that we make our own fibre optic preforms and manufacture the most advanced medical lasers on the market. We combine innovation with cost effectiveness to create the highest quality products for our customers.

Medical laser system

In addition, under the CeramOptec brand, we are the leading manufacturer of specialty fibre optics for industrial and scientific applications – setting the highest standards in the industry. For more information visit us at www.biolitec.com and www.ceramoptec.com.

Partner 4 - OSRAM Opto Semiconductors

OSRAM Opto Semiconductors GmbH is one of the two largest global manufacturers of opto-semiconductors in the lighting, sensor and visualisation sectors. The company has more than thirty years of experience in the development and manufacture of opto-semiconductor components, combining extensive know-how in semiconductors, converter materials and packages under one roof. Its expertise is evidenced by more than 3000 patents in various areas of semiconductor technology. The company, employing more than 3500 people, is headquartered in Regensburg, Germany with additional development and production sites located in San José (California) and Penang (Malaysia).

OSRAM Opto Semiconductors has a far-reaching presence in the opto-semiconductor market with lasers, detectors, visible and infra-red LEDs as well as organic LEDs (OLEDs). In addition to offering semiconductor components, OSRAM Opto Semiconductors provides support for system integration based on these components.

The company focuses on innovative light sources in growing markets such as external automotive lighting, LED backlighting for LCD displays, projection applications, sensors for mobile applications and organic as well as standard light emitting diodes.

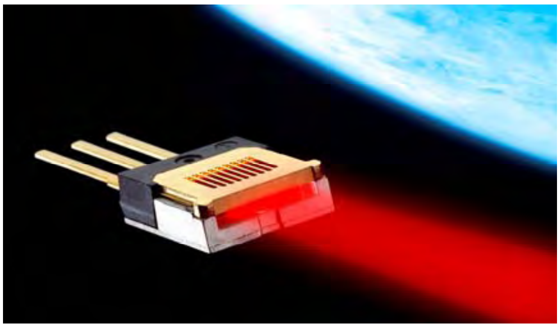
In the **automotive sector** OSRAM Opto Semiconductors is the world market leader with its pioneering lighting solutions. The company's LEDs can already be found in large numbers in dashboards, high-line brake lights, reading lights and other interior lights. At present, LEDs are used more and more in rear light clusters. Soon, LEDs will be used for daylight running lights. Headlights equipped entirely with OSRAM LEDs have already appeared in concept cars at automobile shows. Prototypes for headlights are expected to be ready before 2010.

OSRAM Opto Semiconductors is taking a dual approach to **display and projection technology** with its LEDs and lasers. Small and medium-size screens (for example for satnav systems, LCD monitors, mobile phones and other mobile terminals) are already available with LED and OLED backlighting. For projection applications, the company is using laser technology in addition to LED systems.

In the **general lighting** sector, illuminated advertising, effect lighting and marker lights are some of the typical areas of application for LEDs from OSRAM Opto Semiconductors. LED light sources are also taking over from traditional neon lights in the corporate lighting sector. As point light sources, light emitting diodes are being used in more and more different indoor applications, mainly in designer fittings. The range of use is rounded off by all types of signalling equipment such as traffic lights and railway signals. OLEDs will also be increasingly used in a variety of interesting applications in general lighting.

Our vast experience with **semiconductor lasers** is applied to devices addressing material processing, pumping solid-state lasers, medical applications and sensing. For example, a major contribution to road safety is the Night Vision System that OSRAM Opto Semiconductors is developing in conjunction with a series of partners. Infrared light from our high-power lasers is used in addition to conventional headlights.

As a technology driver with a high level of application know-how and considerable competence in system solutions, consultancy and problem-solving, OSRAM Opto Semiconductors will continue to expand its product portfolio and exploit synergy effects across all product groups.



Red-emitting laser bar

Activities within WWW.BRIGHT.EU

Within the WWW.BRIGHT.EU project OSRAM Opto Semiconductors develops multi-Watt 635 nm laser bars for photodynamic therapy (PDT). This comprises the epitaxial growth of laser structures, the fabrication of laser bars and finally the mounting into packages as shown in the preceding picture. Comprehensive characterisation after all fabrication steps is performed together with project partners Max-Born-Institute and Tyndall Institute. Project partner Biolitec integrates our red laser modules into systems ready to be deployed in the field.

For further information, please contact: Dr. Peter Brick (peter.brick@osram-os.com).

Partner 6 – University of Cambridge

The Centre for Photonic systems is part of the Electrical Engineering Division, one of six Divisions within the Department of Engineering. The Division has a staff of 21 academics, 80 post-doctoral researchers and 150 research students. It currently has a research grant portfolio in excess of £20M, plus a further £10M of funds for nanotechnology research. Members of the Division publish more than 100 journal papers each year. In the past 5 years, approximately 70 patents have been filed and 10 spin-out companies have been formed raising over €25M investment in the process.

The new Electrical Engineering Division building

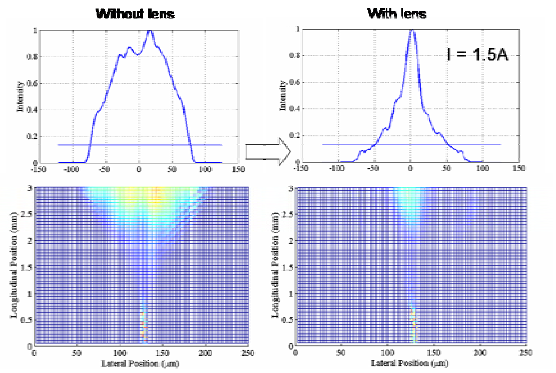
The Photonics Systems Research activity in Cambridge University Engineering Department has grown from approximately 15 people at its formation in 2000 to more than 40 people now. The three main research themes of the group are (i) ultrafast photonics, (ii) optical data communications and (iii) photonic switching.

The group has an output of approximately 50 publications and 2-3 patents per year, and has seen its level of invited papers at international conferences grow substantially to approximately 10 per year currently. Most recently, members of the group have chaired the sub-task-force of the channel modelling activity within the major IEEE 802.3aq standard and have co-founded with UCL a spin-out company, ZinWave Inc.

Activities within WWW.BRIGHT.EU

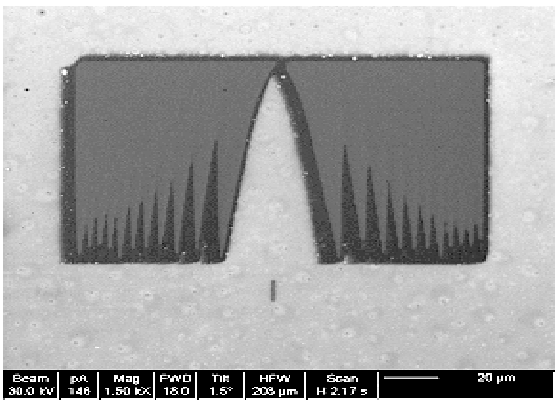
The Centre for Photonic Systems has two major areas of activity within the WWW.BRIGHT.EU project. A major modelling activity has developed a dynamic laser model which is well suited to investigate the performance of high-power broad area and tapered lasers. Of particular significance is the model's ability to simulate the effect of arbitrary cavity designs on laser performance.

There has been much modelling effort within the project on the optimisation of tapered lasers with etched Fresnel lenses. The introduction of such lenses is predicted to significantly improve the brightness of tapered lasers.



Typical model results showing the effect of inserting a FIB etched lens in a tapered laser

The other major effort within the project has been to post process lasers produced by other partners in order to improve performance. This has been accomplished by using the Cambridge focussed ion beam (FIB) etching facility. We can etch arbitrary structures in devices which have already been mounted and had their performance characterised. This FIB post-processing has been used to etch a number of designs of Fresnel lenses into tapered lasers, significantly improving their brightness.



Scanning electron microscope picture of a high order Fresnel lens etched into a tapered laser

In particular, the design and etching of a high order Fresnel lens has allowed improved laser performance with the removal of a very small amount of the laser material, making this a very promising technique.

Partner 8 - Ferdinand-Braun-Institut für Höchstfrequenztechnik

The Ferdinand-Braun-Institute explores cutting-edge technologies in microwaves & optoelectronics based on compound semiconductors. It develops high frequency devices and circuits for sensor and communications technologies. High-power diode lasers with excellent beam quality are produced for materials processing, laser technology, medical applications and high precision metrology.

The main building of the FBH on the campus of the research and technology centre Berlin-Adlershof

The FBH is an internationally recognized competence centre for III/V semiconductors. It operates industry-compatible and flexible clean room laboratories with equipment for epitaxial layer growth, different III/V-semiconductor process lines and an advanced mounting technology.

The work relies on comprehensive materials and process analysis equipment, a state-of-the-art device measurement environment, and excellent tools for simulation and CAD.

The FBH develops high-value products and services for its partners in the research community and industry which are tailored precisely to fit individual needs. The institute offers complete solutions and know-how as a one-stop agency – from design to ready-to-ship modules.

The FBH also succeeds in turning innovative product ideas into spin-off companies.

View into the clean room facility

Current Research Topics

Microwaves

- GaAs electronics with heterojunction bipolar transistors: MMICs up to 80 GHz and power amplifiers up to 10 GHz
- Gallium nitride electronics: microwave power transistors up to 10 GHz (power: >> 10 W)

Optoelectronics

- High-power, highly efficient diode laser and laser bars between 800 nm and 1060 nm
- High-brightness diode lasers up to 10 W single emitters
- Narrow linewidth lasers < 1 MHz
- Hybrid laser systems (compact MOPA systems)
- Non-linear frequency conversion with diode lasers as pump sources
- Semiconductor disc lasers
- Gallium nitride based LEDs and lasers

Technologies and Facilities

- Comprehensive III-V epitaxy equipment for homogenous semiconductor layer structures, not only for in-house requirements but also for customer-specific layer structures:
    - MOVPE for e.g. laser diodes, Schottky diodes, HBTs
    - HVPE and MOVPE for GaN based epitaxy
    - Characterisation in order to optimise processes and development
- Complete and industry-compatible process line: consists of all enabling technologies for chip manufacturing from structuring and deposition techniques to chip dicing
    - Wafers from 2" to 4"
    - Different types of substrates: GaAs, InP, Si, SiC, glass and others with high reproducibility

FBH offers complete processes up to small-scale series fabrication or transfers process modules to external partners.

- Mounting and packaging: a key competence for laser diodes as well as microwave transistors and circuits. For diode lasers:
    - Separation of wafers to chips by scribing and breaking
    - Soldering of lasers and laser bars
    - Wire bonding
    - Hybrid integration of diode lasers and electronic components
    - Active alignment of components and diode lasers: beam shaping and hybrid integrated MOPA systems

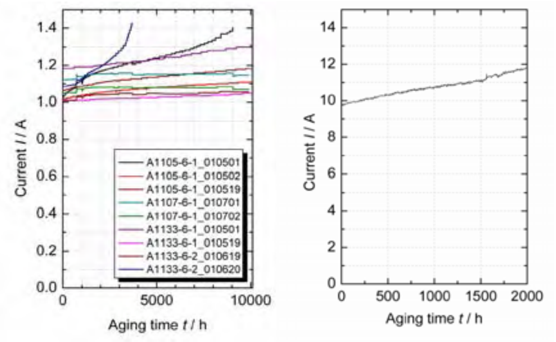
Activities within WWW.BRIGHT.EU

Within the project, the following topics were investigated:

1. High-power broad-area lasers and bars for medical applications at 652 nm

The manufacturing of high-power diode laser devices emitting in the red spectral range is very challenging due to some drawbacks of the laser material, like low barrier heights for carriers and low thermal and electrical conductivity. Research work is concentrated on layer design, growth procedure, device processing and mounting. As a result, reliable operation was demonstrated over 10000 h at 500 mW output power for 100 µm broad-area lasers and 2000 h at 5 W for 5 mm laser bars. These values exceed the lifetime demands for laser devices used in medicine (typically 1000 h). Now, 100 µm wide broad-area lasers with a maximum output power of 3 W and 5 mm bars with 12 W could be realised. The data represent record high output powers for devices at 652 nm. Reliability tests at higher output powers are started. The results also open perspectives for future research projects, including applications in display technology.

Mounted 650 nm laser



Reliable operation of 100 µm x 750 µm broad-area laser at T = 15°C and P = 500 mW (left), Reliable operation of a 5 mm wide bar with ten emitters 100 µm x 750 µm at T = 15°C and P = 5 W (right)

2. Tapered laser devices for the application in external cavities

The use of external cavities to improve the brilliance of high-power diode lasers is a common technique to open up new applications. The efficiency of feedback from external mirrors or gratings depends strongly on the divergence of the diode laser used as the gain medium. Within the project, 810 nm tapered gain media with very small vertical divergence $\Theta_{FA} \approx 18°$ (FWHM) were developed. Typically such structures suffer from quite low efficiency due to a very small optical gain. The structures designed and realized at the FBH have only a slight decrease in efficiency and combines herewith high output power with low vertical divergence. Using these well-suited devices in an external cavity, other partners achieved more then 2 W of nearly diffraction-limited optical power in a single spectral line.

Partner 10 - Fraunhofer Gesellschaft

The Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (FhG) is a link between science and industry, that is between the research and the application of its results. It was founded in Munich in 1949 as a non-profit registered association. The Fraunhofer-Gesellschaft is an autonomous organisation with a decentralised organisational structure. Whilst the administrative headquarters are in Munich, the legally non-independent research institutes operate from different locations throughout Germany. The Fraunhofer-Gesellschaft currently maintains 58 research institutes. A staff of approximately 13,000, with the majority being qualified scientists and engineers, work with an annual research budget of approximately one billion Euro.

Today, the Fraunhofer-Gesellschaft is the leading organisation of institutes of applied research and development in Europe. The employees carry out research and development projects on a contract basis on behalf of industry, the service sector and government. Future-oriented strategic research commissioned by the government and public authorities are carried out with the aim of promoting innovations in key technologies with an economic and social relevance in the next five to ten years. Working within the framework of the European Union's research and technological development programs, the Fraunhofer-Gesellschaft collaborates in industrial consortia on issues ultimately destined to improve the competitiveness of European industry. Commissioned by customers in industry, Fraunhofer scientists provide rapid, economical and immediately applicable solutions. Work focuses on specific tasks across a wide spectrum of fields including communications, energy, microelectronics, manufacturing, transport and the environment. When required, several institutes collaborate on an interdisciplinary basis to develop system solutions with a wide range of applications. The clients receive advanced technical know-how and very exclusive services.

Fraunhofer Institute for Laser Technology (ILT)

The Fraunhofer ILT, located in Aachen, is a development and contract research institute in the field of industrial laser technology. The activities cover the development of new laser beam sources and components, laser measurement and analysis technologies, laser-supported manufacturing and processing techniques, lasers in life science and lasers for telecommunication applications. One of the dominating activities is the development of diode laser based beam sources for a variety of applications ranging from industrial materials processing, graphics arts, and medicine to biotechnology and telecommunications.

In the field of high-power diode lasers, ILT is working on the cooling and packaging technology, micro-optics and waveguides, special beam shaping optics, fibre coupling, and wavelength multiplexing techniques as well as on module and system development. Furthermore, ILT is developing mounting and testing equipment for diode lasers and micro-optical elements. Currently, a staff of approximately 230 people is working at ILT, approximately 25 of them in the field of high-power diode lasers. The Institute is certified according to ISO 9001:2000.

Fraunhofer Institute for Applied Solid State Physics (IAF)

The Fraunhofer IAF is a leading research centre in the field of III-V compound semiconductors and their applications in micro-, nano- and opto-electronics. The IAF has the complete process technology from epitaxy to mounting and packaging, from the semiconductor wafer to integrated circuits and modules. The core competencies include the design of devices and integrated circuits, III-V epitaxy and technology. The R&D work is in close cooperation with industrial partners. The Institute is certified according to ISO 9001:2000.

In the field of semiconductor lasers, IAF focuses on the development and application of complete semiconductor processes for the manufacturing of optoelectronic semiconductor devices including high-power diode lasers, infrared diode lasers emitting at $\lambda > 2$ µm, and quantum cascade lasers for even longer wavelengths. Based on the III-V compound semiconductors GaAs, AlGaAs and GaInAs, high-power high-brightness diode lasers are realised. Based on new group III-antimonides such as GaSb and AlGaAsSb or in the material system InP, novel types of diode lasers are being developed.

Fraunhofer IAF is staffed with approximately 200 scientists including doctoral and diploma students, engineers, technical and administrative support, approximately 25 of them in the field of high-power diode lasers. Research work is performed in laboratories, clean rooms and offices with more than 8000 m^2 of floor space.

Partner 13 - Centre National de la Recherche Scientifique / Laboratoire Charles Fabry de l'Institut d'Optique

The **Centre National de la Recherche Scientifique** (CNRS, National Centre for Scientific Research) is a government-funded research organisation, under the administrative authority of France's Ministry of Research. Founded in 1939, the CNRS carries on its activities in all fields of knowledge from mathematics, high-energy physics, environmental sciences as well as humanities and social sciences. With 30,000 staff members, it is the largest fundamental EU research organisation. Its 1260 research units are spread throughout France.

The **Laboratoire Charles Fabry de l'Institut d'Optique** (LCFIO) is a joint laboratory partnered with the Institut d'Optique and the CNRS, in cooperation with the Université Paris-Sud. LCFIO is one major component of the Institut d'Optique together with the Engineering School, Ecole Supérieure d'Optique. Most faculty members of the School are active in research in the laboratory. Located on the premises of the University at Orsay, it enjoys a particularly active and rich scientific and technological environment in the Orsay / Saclay / Palaiseau area. LCFIO covers a broad range of optical research, both fundamental and applied, with emphasis on the experimental aspects. Skills covering essentially all of optics are highlighted by the timely research topics conducted by the six research groups:

- Atom Optics (Head: A. Aspect)
- Quantum Optics (Head: P. Grangier)
- Nanophotonics and Electromagnetism (Heads: H. Benisty and P. Lalanne)
- Lasers and Biophotonics (Heads: A. Brun and P. Georges)
- Non-Linear Materials and Applications (Heads: G. Roosen and G. Pauliat)
- Optical Components and Systems (Head: P. Chavel)

LCFIO has about 100 staff members, including 50 PhD students and post-doctoral researchers.

The two research groups involved in the WWW.BRIGHT.EU project are the Non-Linear Materials and Applications group (Manolia) and the Lasers & Biophotonics group (LasBio):

- The expertise of Manolia in optical nonlinearities runs from fundamental physics of light matter interaction to the design and development of novel optical functions and components. Manolia is currently studying optical nonlinearities in nanostructured materials (photonic crystals and photonic crystal fibres) and epitaxial ferroelectric films. Taking advantage of specific nonlinearities evidenced in basic studies, Manolia designs and develops novel optical functions for telecommunications, holographic storage and for novel devices such as the self-organizing laser cavities developed within WWW.BRIGHT.EU.
- The Lasers and Biophotonics group study new organic and inorganic materials, and use them in optical systems, lasers, and biosensors for various applications. The group has strong partnerships with laser companies, from fundamental studies to the development of commercial products (for instance, the picosecond laser DualChip developed with Nanolase). In particular the group develops new solid-state laser sources from the continuous to the femtosecond regime. In a close collaboration with laboratories involved in the growth of new materials, this group studies various diode-pumped solid-state gain media: crystals, fibres, and semiconductor structures. The association of these new materials with novel laser architectures, involving non-linear optical functions, allows one to design and investigate light sources with unprecedented characteristics. These activities trigger numerous applications in which the team is involved: biophotonics (fluorescence lifetime microscopy, eye surgery), metrology (optical frequency standards), solid-state physics (buried interface characterization, micromachining).

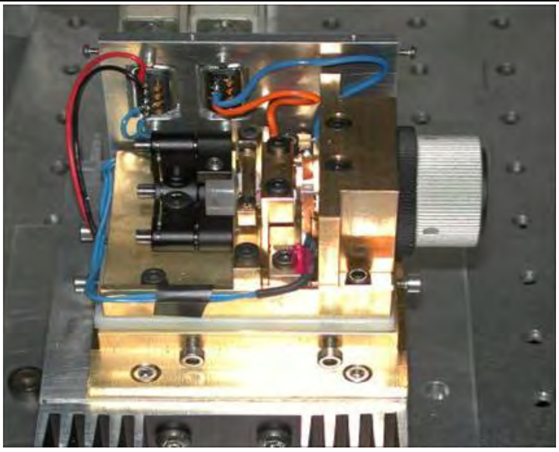
Chain of Raman transitions in a 120 m long single-mode fibre from a pulsed picosecond laser source emitting at 532 nm

Activities within WWW.BRIGHT.EU

In the scope of the WWW.BRIGHT.EU project, LCFIO takes part in developing novel external-cavity schemes for high-brightness, narrow-linewidth emission in WP3. Two designs have been investigated: self-organising laser cavities including a photorefractive crystal and wavelength-stabilized cavities with volume Bragg gratings.

A self-organizing cavity is an extended cavity in which a dynamic holographic medium, e.g., a photorefractive crystal, is inserted. The modes oscillating inside the cavity record a dynamic hologram that acts as a spectral and spatial filter. For a well-designed cavity, the result of this mutual interaction (i.e. modification of the hologram by the modes and vice-versa) leads to self-organization and thereby to an improvement of the spectral brightness of the laser with steady-state oscillation on a single longitudinal and transverse mode. The steady-state oscillation, being the result of a self-organization process, it is very robust to any cavity modifications: e.g. modifications originating during ageing, temperature or injection current changes, and slight cavity misalignments.

The photograph of a typical self-organized extended cavity developed within the WWW.BRIGHT.EU project is shown opposite. This cavity is built around a tapered device (either a device operating around 800 nm from the Ferdinand-Braun-Institute or a device operating at around 960 nm from the Fraunhofer IAF). Whatever the temperature and the injection current set within the operating range, the self-organization process always forces these devices to oscillate on a single longitudinal mode. Such laser sources have already shown their potential in some applications in which long coherence lengths are required with output powers ~ 1 W (typically interferometric applications, Optical Coherence Tomography, etc.).



Self-organizing cavity prototype designed at LCFIO

On the other hand, *volume Bragg gratings* are essential components for either brightness improvement or spectrum stabilization in external cavities. Within the WWW.BRIGHT.EU project, we have taken advantage of the spectrally narrow reflectivity of Bragg gratings, with a high reflection and limited wavelength shift, for the stabilization of high-brightness semiconductor sources. Tapered amplifiers in an external cavity including a Bragg grating have resulted in a high-power, good beam quality and narrow spectrum laser emission – an output power as high as 1.8 W, with a beam quality parameter $M^2 < 1.3$ and a linewidth narrower than 80 pm has been obtained at 810 nm. This laser source has been utilised as the pump source for the single-pass extracavity second-harmonic generation towards 405 nm in a periodically-poled KTP crystal, in collaboration with Risø and Rainbow Photonics. These promising results demonstrate the capabilities of extended-cavity laser diodes with Bragg gratings for non-linear conversion. The high-brightness and narrow linewidth of our extended-cavity tapered sources make them also suitable for the pumping of solid-state crystal lasers.

For further information, please contact: Dr. Gilles Pauliat (gilles.pauliat@iota.u-psud.fr) for self-organized laser cavities and Dr. Gaëlle Lucas-Leclin (gaelle.lucas-leclin@iota.u-psud.fr) for fixed grating extended-cavities. More information on CNRS and LCFIO can be found at www.cnrs.fr and www.institutoptique.fr.

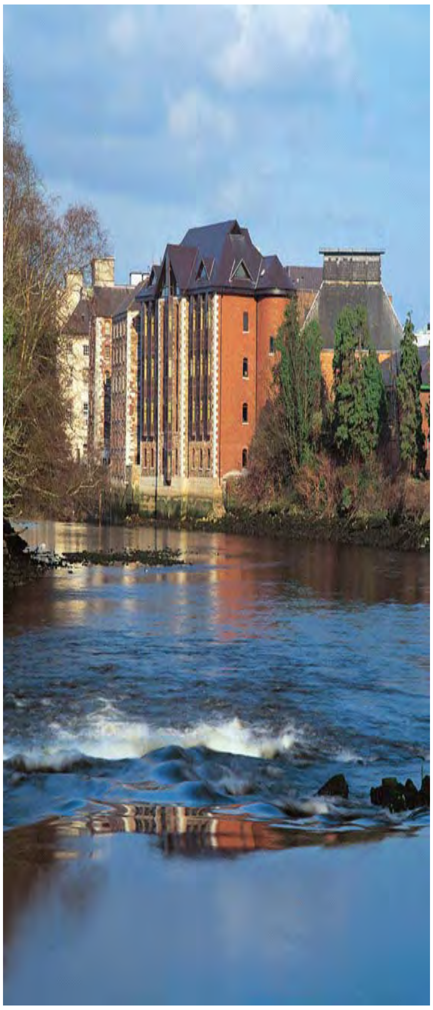
Partner 16 - Tyndall National Institute

The Tyndall National Institute was established in 2004 as an amalgamation of NMRC (National Microelectronics Research Centre) with other Information and Communication Technology (ICT) based scientific activities in the Cork region.

The Institute is named after the Irish polymath John Tyndall (1820-1893) who invented the light pipe, developed spectroscopy, sterilisation processes and studied the atmosphere and the ozone layer. There are 300 researchers at Tyndall with core competencies in Photonics, Nanotechnologies, Micro-technologies and ICT-Biotechnologies.

The fundamental mission of Tyndall is to develop new scientific knowledge and key technological capabilities in strategic ICT-related fields to successfully fuel the evolution of core technology platforms that will in turn enable Irish and European industry to develop next-generation products and applications. Tyndall (via NMRC) has a 20-year history of participation in advanced European research activities and is today a key European research hub.

The Photonics activities at Tyndall encompass basic physics to communication systems with research teams working in quantum optics, theory, nanostructures, non-linear dynamics, sources and photonic systems. Currently, Tyndall houses 6000 m^2 of state-of-the-art laboratory space including device fabrication facilities in III-V and silicon materials. A major expansion of these facilities is underway.

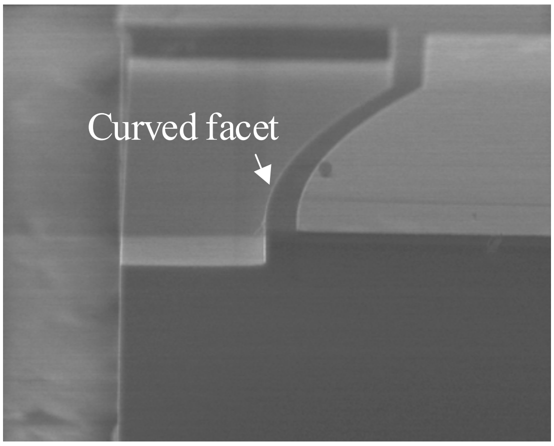


Tyndall is an autonomous research institute located on the grounds of University College Cork

The photonic sources group are investigating materials based on quantum wells and dots from the UV to the IR with resultant devices for applications such as (http://www.tyndall.ie/research/photonics-sources-group/index.html):

- High-power lasers
- Telecommunications lasers
- VCSELs
- GaN devices

Achievements include: watt level diffraction-limited power from curved facet lasers; a patented approach to low-cost, single frequency lasers; red-emitting VCSELs with high single mode power and temperature stability; and high extraction efficiency LEDs based on GaN. A number of spin-out companies have been established as a result of the photonics activities.



SEM Image of curved facet laser

Activities within WWW.BRIGHT.EU

The highest quality semiconductor laser beams are obtained with tightly confined waveguides resulting in limited output power and large beam divergences compromising the ability to use these beams. To address these issues, we are developing approaches for the transverse and lateral modes using quantum dot active regions (with Würzburg University), which are based on engineering large mode size lasers and using curved facet unstable resonators to improve lateral beam coherence. The objectives are to scale these devices to the watt level. We are also developing efficient models for the gain and spontaneous recombination and carrier capture in short-wavelength quantum well active regions. This information is supported by detailed measurements of the characteristics of quantum well structures grown by our partners OSRAM and FBH.

For further information, please contact: Brian Corbett (brian.corbett@tyndall.ie, Tel: +353 21 4904380)

Partner 18 - Risø National Laboratory

Risø National Laboratory is a government research institution under Denmark's Ministry of Science, Technology and Innovation. Risø's mission is to create new knowledge based on front-line research and to ensure that this knowledge is used to promote the development of an innovative and sustainable society. Risø's vision is to create:

- opportunities for energy systems of the future,
- technological possibilities for the diagnosis and treatment of diseases, and
- knowledge-based products and new business enterprises with growth potential

through close interaction with the business sector, the political system and the research community.

Risø possesses competencies within the following areas: the implementation of large projects, design, synthesis and prototypes, analysis techniques and characterisation methods, patenting and licensing, materials and nanotechnology, laser technologies, radioactivity and radiation and biosystems.

Within diagnostics and treatment of diseases, Risø develops technologies that improve diagnosis and medical treatment methods. In particular, Risø develops technologies for the early diagnosis and treatment of cancer and heart diseases, and possesses competencies within biomedical optics, biomedical tracers, and radiation dosimetry.

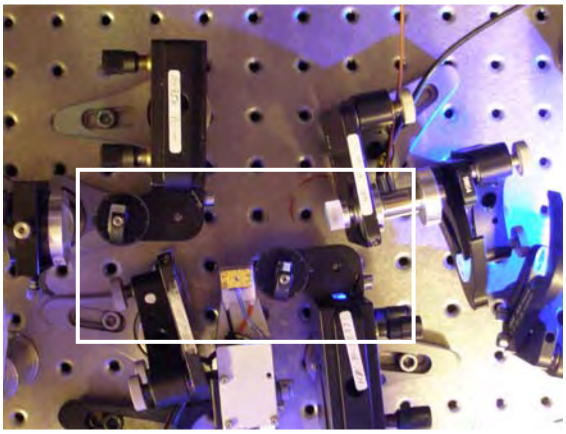
Risø takes an interdisciplinary approach, and our projects are part of both national and international networks. Training and education as well as innovative activities are naturally integrated with Risø's research activities, which are carried out concurrently with customer-driven activities.

The diode laser group caught outside the lab simultaneously on a cold and windy day in January 2005, which explains the sweaters.

Activities within WWW.BRIGHT.EU

Risø coordinates the activities within the work package "External cavity approaches to high brightness and tunability", where the goal is to improve the spectral characteristics and beam quality of high-power diode lasers to yield nearly diffraction-limited tuneable lasers.

As part of the research and development carried out, Risø develops new external laser architectures that significantly improve the temporal coherence properties, wavelength selectivity, wavelength tuning range, and brightness of high-power broad-area diode lasers, tapered lasers and laser bars. One recent example is the successful application of tapered amplifiers with external feedback providing virtually single-frequency operation of diode lasers with several Watts of output power. These laser systems have successfully been frequency-doubled into the blue wavelength region (400 nm).



Bow-tie cavity: the frame highlights the cavity, which produced 225 mW at 404 nm (CW) when pumped by 800 mW at 808 nm from a tapered amplifier with external feedback.

In WWW.BRIGHT.EU, Risø participates in the activity "Medical laser systems". Within this activity, one goal is to apply such blue lasers in fluorescence diagnostics of various cancer types. While Risø is capable of producing prototype systems for clinical testing, other partners within this activity are responsible for carrying out the clinical trials.

For further information, please contact: Paul Michael Petersen, Head of Laser Systems and Optical Materials Research Programme, E paul.michael.petersen@risoe.dk, T +45 4677 4512. Further information can also be found on the web: http://www.risoe.dk, http://www.risoe.dk/opl/ and http://www.risoe.dk/ofd/dlg/.

BRIGHT • EU

e-Newsletter n°3
September 2006

Prospects for Cladding-Pumped Erbium-Doped Fibre Amplifiers

Dominique Bayart, Alcatel-CIT, Marcoussis, France

Applications and markets of CP-EDFAs

Erbium-doped fibre amplifiers (EDFAs) are the pillars of current and future generations of WDM networks [1]. They remain the most cost-effective amplification solution for both metropolitan core networks and long-haul backbone networks. Independent of the link fibre type and characteristics, they are easy to control and preferred over Raman distributed amplification in most newly installed systems. In addition, EDFA technology is still showing impressive breakthroughs in terms of gain bandwidth, footprint, and power consumption due to the use of nanoparticles [2], micro-structured fibres [3] and cladding-pumping technologies [4].

0.98 µm pumping

0.98 µm pumping is now widely used since it minimises the EDFA noise figure (NF). It is ensured by single-mode pumps that can offer up to 500 mW power with reliability in line with the 15 years required lifetime for land-based systems. This leads to EDFA output powers close to +21 dBm accounting for a power conversion efficiency (PCE) of 35% when operated with a high average population inversion to keep a balanced gain spectrum. 1.48 µm pumps may be added for higher output powers. In contrast, only one multimode pump, which costs half, enables +23 dBm output power, avoiding extra-cost at system upgrade from 40 channels (20 dBm) towards 80 channels at full loading (23 dBm). This extra power-budget may also be used to improve the noise performance of current two-stage WDM amplifiers including dispersion-compensating modules (DCM) at mid-stage.

Noise figure increase caused by the DCM

As seen from Fig. 1, gain equalizing filters (GEQ) are used at amplifier mid-stages in order to flatten the amplifier gain spectrum and also to limit power excursion between channels at the first stage output. This is to limit the non-linear effects seen by the most amplified channels in the DCM and to ensure even powers for channels dropped by the optical add & drop module (OADM). This also imposes a maximum input power to the DCM (non-linear threshold), making NF of stage 2, although 0.98 µm pumped, impacts the total amplifier NF. The current trend is to use two different stand-alone single-stage amplifiers with R-OADM or DCM in-between paving the way to single-stage efficient cladding-pumped EDFAs.

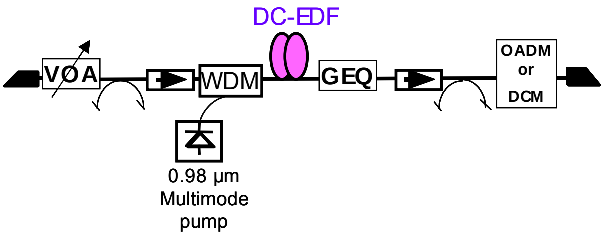


Fig. 2: *CP-EDFA gain block using with R-OADM.*

Characteristics of CP-EDFA

Rules of design to maximize the power performance of CP-EDFA are discussed here, with highlights on possible future improvements for WDM systems.

The double-clad fibre

Double-clad fibres consist of an inner single-mode core for the signal, an outer multimode core for the pump light and an over-cladding that imposes the numerical aperture (NA) for the multimode core (see inset in Fig. 5). Over-cladding made of silica glass gives NA up to 0.22 (much more, up to 0.8 with air-holes in over-cladding) and up to 0.4 if made of soft polymer (but this shows poor mechanical behaviour and may induce reliability issues). Since pump modes propagate in the multimode core, their overlap with the signal core is low. A first technique consists of increasing the likelihood of interaction with ions by using high erbium concentration and Yb co-doping (20 times more) in order to have a high absorption coefficient for the single-mode core (Co-doping with P is then required to ease the incorporation of Yb in the silica glass host and to favour interaction between Yb and Er through a closer arrangement for the ions). This technique first provides the advantage of efficiently absorbing the pump light even with a

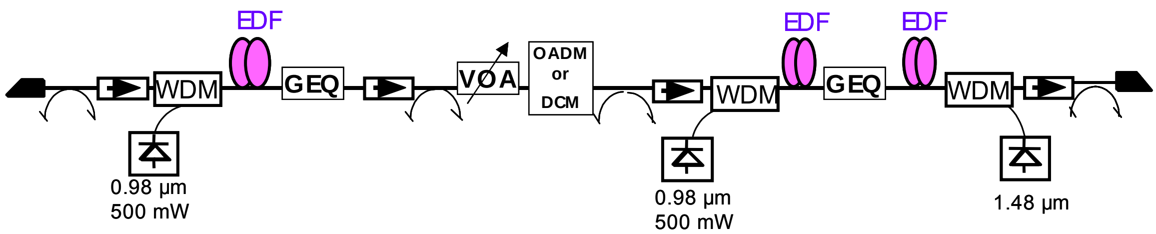


Fig. 1: *Current EDFA architecture for core networks.*

e-Newsletter n°3
September 2006

multimode core as wide as 100 μm, thus allowing the use of 100 μm stripe width pumps. In addition, this relaxes the tolerances on the pump wavelength making the future implementation of cooler-less pump technology easier. Operation with such high beam diameters also allows the use of the V-groove side-pumping technique (Fig. 3) [5] with high manufacturing yields. Coupling of the signal and several pumps can also be performed using specific fibre arrangements at the expense of increased loss for pump and signal lights. In the case of a fibre bundle, a low index polymer is also needed for the over-cladding to get a high NA.

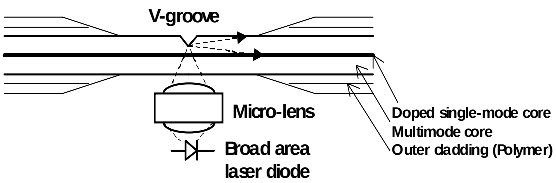


Fig. 3: *V-groove coupling technique for CP-EDFA.*

Two main applications for Yb-EDFAs can be highlighted as far as Telecom applications are concerned. The first one is single-channel CATV applications. Compared to polarization-beam multiplexed single-mode pumped EDFAs, CP-EDFAs provides a high cost-reduction by using only one pump, and improved NF due to the V-groove pump multiplexer, which is loss-free for the signal beam. The other application concerns unrepeated submarine systems [6], where high-power (up to 33 dBm) amplifiers are required in the land-based transmitter site in order to bridge large distances. Clearly, to place CP-EDFAs in the sea is not foreseen soon because the reliability requirement is much more stringent (25 years). Other niche markets also exist related to laboratories or military applications (although P-doping induces a high sensitivity to radiation [7]).

The Yb bottleneck

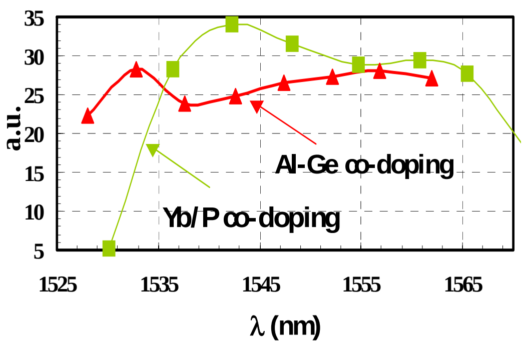


Fig. 4: *Gain spectra measured in the case of Yb-EDFA and of Al-EDFA showing the effect of P-doping.*

The drawback is that P-doping makes Yb/Er fibres unsuitable for WDM applications due to band narrowing at shorter wavelengths (Fig. 4). Using a highly inverted first stage made of a conventional EDFA in order to compensate for the lack of gain at shorter wavelengths in the Yb-EDFA second stage is not practical. The required contrast for the GEQ being much larger, almost no power budget is allowed at mid-stage to keep moderate the NF (meaning low loss range for VOA and no DCM/OADM). In addition, Yb-doped fibres show a five times higher non-linear coefficient compared to Er-doped fibres [8].

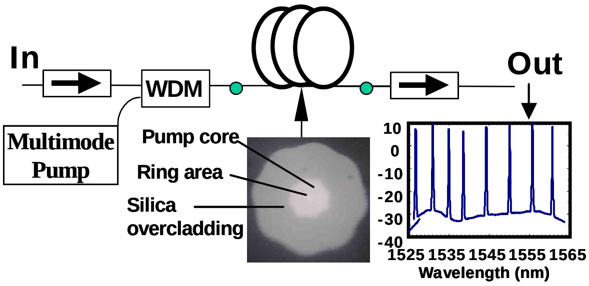


Fig. 5: *Set-up for cladding-pumped EDFA with pump coupling through a bulk multiplexer. Insets: All-silica octagonal ring-doping fibre section (44 μm, 0.18 NA) and WDM output spectrum.*

To take advantage of the cladding-pumping technology for WDM systems, it is necessary to increase the pump-to-signal-core overlap by using a reduced pump beam diameter in the double-clad fibre. Free-space bulk multiplexers should then be used (Fig. 5) with a price to pay in splice loss and a higher insertion loss for the pump and signal (compared to the V-groove technique), although these losses are then similar to single-mode bulk multiplexers used in conventional EDFAs [9].

Fibre design for WDM applications

Propagation of the optical modes

The multimode core exhibits a large count of allowed modes that can be excited or not depending if such modes are present in the input pump beam. In particular, the higher the numerical aperture of the guide is, the more numerous the excited modes are. After the coupling optics, it is therefore important to keep low the size and divergence of the beam to minimize the number of excited modes in the multimode core (for instance using low NA output fibre for the multiplexer). Then, only one part of the modes of the fibres will be excited by the input light (e.g. 44 over 77 estimated in [10]). Only these modes should be considered for the evaluation of the overlap of the multimode light with the erbium-doped area (see inset in Fig. 6). Specific measurements are required to enable accurate modelling of the power

e-Newsletter n°3
September 2006

performance of such amplifiers by properly accounting for the mode distribution of the input beam. During propagation along the fibre, only modes whose paths cross the erbium-doped area will be absorbed. Light contained in other modes will be unused unless their energy is transferred to the other modes through mode-coupling (which does not really happen over such short fibre lengths). Double clad fibres with a scalloped shape for the multimode core have been proposed to minimize such unabsorbed modes (but often require polymer over-cladding). Air-cladding with a specific distribution of the holes in the over-cladding can be useful to provide the multimode core with tailored shapes (like D-shape which gives best results [11]) while keeping the mechanical properties given by a silica-based over-cladding.

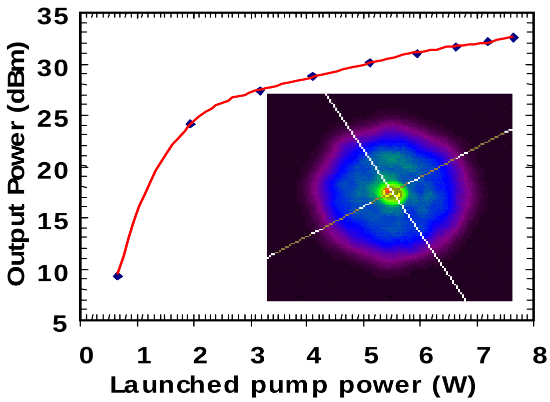


Fig. 6: *Signal power (dBm) vs pump power (W) for amplifier shown in Fig. 5. Inset: Measured pump mode distributions after 1m of fibre.*

Whatever the mode distribution, using reduced multimode core will necessarily increase the overlap of the pump light with the erbium doped area.

Impact for the pump technology

As far as single pump chip is concerned, an elliptical beam is provided whose shape and divergence are fixed by the manufacturing technology. The main parameter is therefore the maximum available power at a maximum bias current that guarantee long-term reliability. Hence, at a given reliability, a reduced stripe width means a lower maximum current and thus a lower available power. Significant progress has been made recently to increase this maximum current. Improvements may also come from the pump technology by providing high-brightness pumps (high power with both low size and low divergence for the pump beam). This can be provided by a spatial beam transformation of the elliptical optical beams of several pump chips in order to get a circular shape for the output beam. Hence, both low NA (0.12), low beam diameter (50 µm), and high power (>10 W) have been obtained in a small bulk package, enabling single-pump EDFA offering +33 dBm power [11] (Fig. 6). Progress is under way to provide integration of such pump sources using flared-laser bars [12, 13].

Applications in the C-band

With core-doped fibres, PCE at gain-peaks balanced was improved from a few % up to 15.7% when reducing the multimode core from 100 µm down to 50 µm, and further improved to 20% with a 30 µm core. These fibres exhibit both an octagonal shape for the multimode core and a silica over-cladding. This maximizes the number of propagating modes that cross the erbium-doped area. To reach high average inversion levels (around 60 % of ions being excited at gain-peaks balanced), it is efficient to reduce signal-induced gain saturation, thus the overlap of the signal with the erbium dopants. This can be achieved by locating erbium in a ring placed outside (but close to) the single-mode core. With a 44 µm multimode core, PCE exceeding 30% in saturation was shown [14] (28.7% with gain-peaks balanced). Such a CP-EDFA using the ring-doping technique for the fibre has been validated through 10-Gbit/s BER measurements [15].

Applications in the L-band

Operation in the L-band requires a lower average inversion (only 40% of ions being excited on average). Therefore, signal-induced gain saturation is welcome (ring-doping is no help) and pump absorption must not be too high in order to keep low the power wasted in amplified spontaneous emission occurring in the C-band. Hence, at a population inversion level giving a balanced gain spectrum between λ = 1570 nm and λ = 1603 nm, the PCE was improved from a few % up to 28.2% when the multimode core was reduced from 100 µm to 48 µm, while still providing +33 dBm output power [16]. Therefore, cladding-pumping offers a cost effective solution to provide a low NF and low power consumption for any desired output power.

Conclusions

Cladding-pumped EDFAs have shown dramatic improvements in last years leading to significant cost reductions over conventional technology. While multimode pump technology is still improving and micro-structured fibres are gaining in maturity, the time will come for the implementation of this technology in future WDM networks when DCM having high a non-linear threshold are used.

Special thanks

Results and knowledge displayed in this paper would not have happened without high team work involving C. Simonneau, P. Bousselet, C. Moreau, G. Melin, L. Gasca, L. Provost, F. Leplingard and many others.

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e-Newsletter n°3
September 2006

Medical Applications of Laser Diodes and Optical Technology

The use of lasers and optical technology in medicine and health care has experienced tremendous growth in recent years in terms of research activities, applications and commercialisation. In these articles, we explore the use of diode lasers and optical technology for both clinical treatments and medical imaging.

Photodynamic Therapy (PDT)

Stefan Andersson-Engels, Lund University, Sweden
Tilmann Trebst, Biolitec, Germany

Photodynamic therapy (PDT) is a local treatment for human malignancies and relies on the preferential uptake of various photo sensitizing agents or tumour localising substances with the interaction of light to achieve a selective treatment modality. When light of an appropriate wavelength interacts with the sensitized tumour tissue, a cytotoxic reaction is generated due to an energy transfer from the excited sensitizer molecules to the tissue oxygen [1].

A photodynamic treatment usually consists of several steps. Firstly, the photosensitizer is administered either topically, e.g. as a cream, or systemically, e.g. by injection. After a predetermined time, commonly called drug-light-interval, in which the photosensitizer is distributed in the tissue and may accumulate in the targeted cells, the targeted area or volume of tissue is then irradiated by light of an appropriate wavelength. The local activation of the photosensitizer triggers the photodynamic reaction and destroys the tissue. Finally, the treated tissue heals over a period of typically 4-12 weeks.

Fig. 1: *A typical single-port laser system for PDT.*

PDT has recently become a very popular treatment modality in dermatology for malignant skin lesions. The favourable properties of this modality have been fully utilised, while the limitations have been less challenging, as the drug uptake following topical application has been very selective, making the light dosimetry very simple and non-critical. For the treatment of solid tumours, PDT has the same potential, but the dosimetry is much more challenging, due the need for systemic administration of the photosensitizer with a presumable much lower specificity in the uptake. Topical application is not an option for solid tumours, since the drug will not be able to diffuse through the full thickness of a solid tumour.

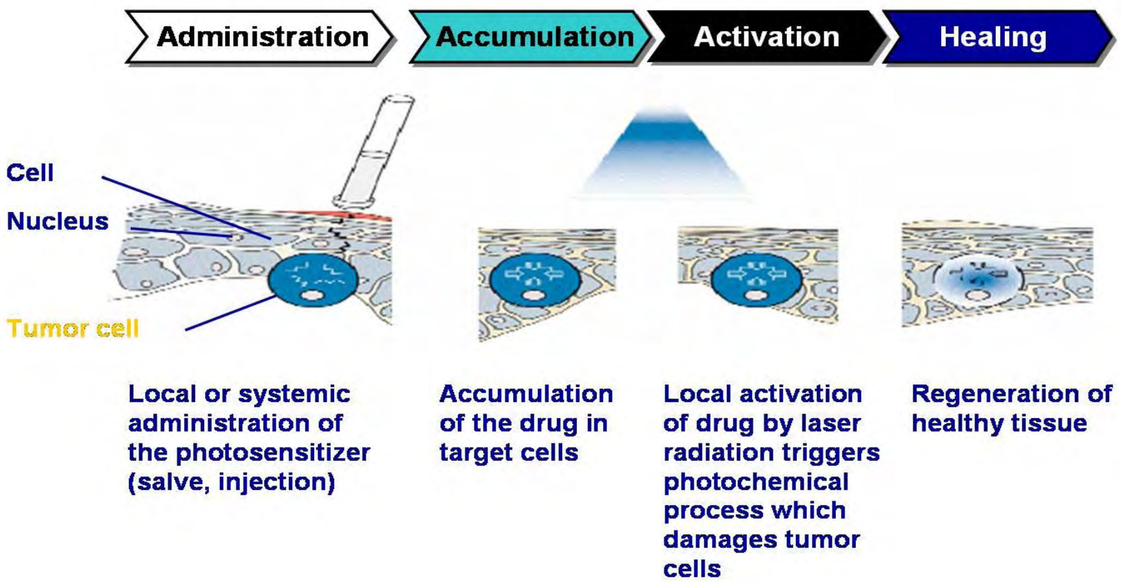

Fig. 2: *Treatment sequence for photodynamic therapy.*

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e-Newsletter n°3
September 2006

Photosensitizers

The first sensitizer used in clinical PDT was heamatoporphyrin derivative (HpD) and its purified fractions [4]. In Lund, we were performing the first clinical HpD-PDT procedures in Scandinavia in 1987 [5,19]. The investigations, both experimentally and clinically, with HpD have highlighted several criteria that an ideal photosensitizer should fulfil. The current efforts are aimed to produce a photosensitizer which:

- is a single compound
- has an absorption in the higher wavelength regions for better tissue light penetration
- gives a high quantum yield of triplet formation
- has good cytotoxic oxygen species generation
- shows high selectivity for malignant tumours over normal tissue

New photosensitizers, the so called "second generation" photosensitizers, have been produced with better biological and photophysical properties as compared to HpD [6]. The new sensitizers include modified phorphyrins, chlorins, bacteriochlorins, phtalocyanines, pheophorbides and purins. These substances exhibit increased efficacy in PDT mainly due to improved photophysical properties with absorption higher up in the red wavelength region.

Today there are four photosensitizers approved for at least one indication [partly from 20].

Chemical Name	Generic Name (Trade Name)	Date & Country of Approval	Indications	Activation Wavelength
Haematoporphyrin derivative (HpD)	Porfimer sodium (Photofrin®)	First in 1995, now >40 countries	Advanced and early lung cancer, superficial gastric cancer, oesophageal adenocarcinoma, cervical cancer, bladder cancer	630 nm
5-amino-levulinic acid → Protoporphyrin IX *	Amino-levulinic Acid	1999 USA	Actinic keratosis	635 nm
Methyl 5-amino-levulinate → Protoporphyrin IX *	Methyl-amino-levulinate	2001 Europe	Actinic keratosis, basal-cell carcinoma	
Methyl-tetrahydroxyphenyl-chlorin (mTHPC)	Temoporfin (Foscan®)	Approved 2001 EU, Norway, Iceland	Palliative head and neck cancer	652 nm
Benzoporphyrin derivative	Verteporfin (Visudyne®)	>70 countries (USA, Europe …)	Age-related macular degeneration	689 nm

** metabolised in the heme synthesis: http://en.wikipedia.org/wiki/Porphyrin*

PDT of Malignant Tumours

Thin malignancies, in particular skin tumours, lesions of Barret´s oesophagus and early lung- and urinary bladder cancers, have successfully been treated with PDT using various kinds of sensitizers, administered systemically as well as topically [7-10,20,21]. A limiting factor for treating thicker tumours is the light penetration into the tissue due to absorption and scattering [3]. A way to overcome this limitation is to apply PDT interstitially (IPDT) with optical fibres placed in the tumour mass in analogy with the concept of brachytherapy. IPDT, without dosimetry calculations, has been shown to be efficient for various malignancies, such as recurrent ENT-malignancies, non-resectable cholangiocarcinomas and cancer of the prostate glandular tissue [22-29]. However, it is noted in these studies, that a more precise treatment dosimetry is a prerequisite for developing IPDT to be the clinical treatment of choice [25]. Thus, with a dosimetry that takes into account efficient treatment of the tumour and sparing the surrounding normal tissue, IPDT can be developed to be an important cancer treatment modality for deep lying tumours embedded in the human body.

As the photosensitizing is selective to a certain degree due to a tumour-preferential uptake part of the safety is handled. The WWW.BRIGHT.EU project aims to further develop the compact, powerful and reliable light sources required for interstitial PDT using multiple fibres, thus allowing the dosimetry measurements required.

Fig. 3: *Nodular basal cell carcinoma on the lower arm of a patient. The tumour typically grows as nodules at the rim and can be relatively flat in the centre.*

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e-Newsletter n°3
September 2006

PDT Reactions

There are two types of PDT reactions [2]. Type I involves electron/hydrogen transfer directly from the photosensitizer. In this process, ions or free radicals are generated. These radicals can then react rapidly with the tissue triplet oxygen, which is transferred to reactive oxygen species causing damage to cellular targets. Type II reactions produce the electronically excited and highly reactive singlet oxygen. In this energy transfer process, the sensitizer falls down to its ground state. In the clinical situation, there is most probably a combination of the two types of reactions, indicating that the mechanism of tumour cell damage is dependent on oxygen tension and photosensitizer concentration in the tumour target tissue.

Photosensitizer-mediated cell destruction: PDT produces cytotoxic effects by causing photo damage to subcellular organells and bio-molecules. The damage sites reflect the localisation of the sensitizer in the cell. A variety of cellular components such as amino acids, cystein, histidine, tryptophane, tyrosine and methionin, nucleosides (in particular guanine) and unsaturated lipids react with the generated singlet oxygen, which has a short diffusion distance (about 0.1 μm) [11]. Due to this fact, the subcellular location of the sensitizer is probably as crucial as the total concentration of the sensitizer molecules in order to cause lethal damage.

Cellular location of photosensitizers: Many factors determine the cellular localisation of the sensitizers. Hydrophobic (lipophilic) agents bind preferably to membranes and will target structures such as the plasma membranes, mitochondria, lysosomes, endoplasmatic reticulum and to a smaller degree the nucleus [12-16]. In particular, the mitochondrion, which has a vital respiratory function in the cell with its ATP synthesis for energy requiring processes, has shown to be a critical target in PDT with necrosis formation. The damage to the mitochondrion can also induce chromatin condensation and has been linked to the induction of apoptosis. PDT is favoured compared to other treatment modalities, such as ionising radiation, as nuclear damage is not a dominant factor in PDT mediated cytotoxicity.

Tissue Localisation of Sensitizers

As most of the sensitizing agents exhibit high fluorescence yield, the uptake can be monitored by laser-induced fluorescence (LIF). Thus, the build-up in the tissue and the contrast between tumour and normal tissue can be followed *in situ*. For fluorescence excitation, UV or near-UV light is used and therefore only the superficial layers are monitored, as this light exhibits very shallow penetration. On the other hand, this can be utilised for early tumour/dysplasia localisation in combination with endoscopic procedures when only the surface mucosa is the target of interest. LIF has been developed both as a point-monitoring method as well as for imaging of larger areas. A lot of clinical research effort has been invested in the development of this technique [17,18]. In particular, skin has been used as a good model for the understanding of the sensitizer uptake in human tissue. A contrast of 1:2 up to 1:10 has been found in clinical as well as in experimental work [8,9]. Absorption spectroscopy is another spectroscopic technique for monitoring the tissue concentration of a sensitizer. For both LIF and absorption spectroscopy, a correlation between the real sensitizer concentration and the spectroscopic signal is needed using invasive methods, such as tissue sampling for HPLC-detection. We are involved in a project, Network for Translational Research: Optical Imaging, sponsored by NIH in collaboration with Boston University for these types of studies. Another ongoing project is within an EU collaboration in which LIF-imaging and absorption spectroscopy probes are used with the aim to develop algorithms for interpretation of the spectroscopic data in terms of "real" sensitizer concentration for PDT dosimetry modelling.

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e-Newsletter n°3
September 2006

Optical Coherence Tomography (OCT)

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Optical coherence tomography (OCT) has developed rapidly since its potential for applications in clinical medicine was first demonstrated in 1991 [1]. OCT performs high-resolution, cross-sectional tomographic imaging of the internal microstructure of materials and biological systems by measuring backscattered or back-reflected light, relying on broadband sources to obtain short coherence length light and thereby high axial resolution. Essentially, it is based on the well-known low-coherence interferometry technique sketched in Fig 1: The broadband source illuminates a fibre-optic Michelson interferometer and an interference pattern is detected when the sample and reference path lengths are matched to within the coherence length of the source. By appropriate scanning, ultra-high resolution two- or three-dimensional cross-sectional images of tissue may be obtained non-invasively and *in situ* with an axial resolution of around 2-3 μm [2] (or better).

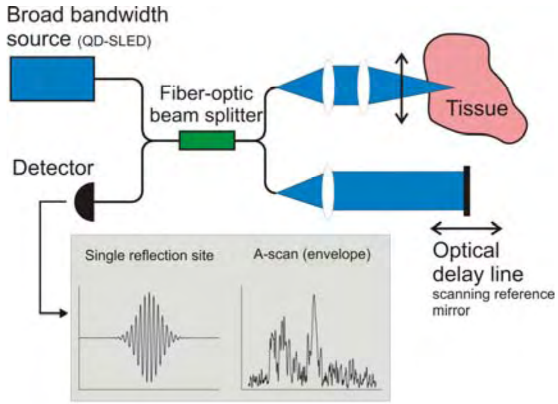
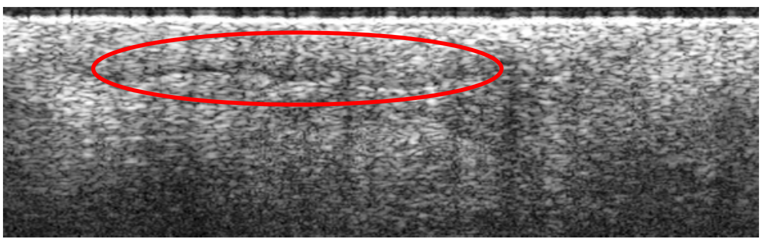


Fig. 1: *Optical coherence tomography layout. The inset shows the detected interference signal from a single reflection site and a full depth scan (A-scan; envelope).*

Tissue morphology (see Fig. 2 and Fig. 3) as well as functional information, e.g., blood flow using Doppler-OCT, can be obtained. In Fig. 2, an example of examining skin cancer is shown; basal cell carcinoma may be delineated using OCT. Small animal imaging is also feasible with OCT and Fig. 3 shows an example of the chick embryo heart [3]. The data was acquired in situ; the 3D rendering has been created by post-processing of the data. Today, commercial OCT systems are routinely used in ophthalmic clinics for examinations. In the near future, OCT could become an equally important tool for dermatological clinical applications.

Development of new light sources for OCT is also the subject of other European projects under FP-6. One such project is NANO UB-SOURCES and you can learn more about this on their project website [4].



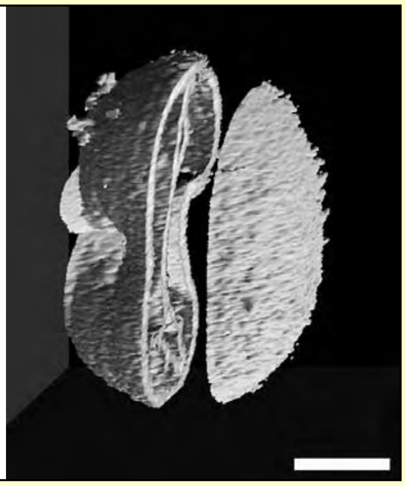


Fig. 2 (above): *Basal cell carcinoma (BCC) lesion from the back of a 67 year old woman imaged by OCT. The axial resolution is 8 μm penetrating approximately 1.4 mm into the skin tissue (width is 4 mm). Excision and histopathology confirmed the lesion as BCC.*

Fig. 3 (right): *Three-dimensional rendering of an embryonic heart (from [3]). The bar represents 100 μm.*

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e-Newsletter n°3
September 2006

Binocular Machine Vision System for Gauging Very Small Objects

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Rendering three-dimensional information of a scene from optical measurements is very important for a wide variety of applications. Although there are still no fully automatic commercial systems available, the problem of 3D reconstruction of relatively large objects has been solved [1]. Despite the recent advances in computer vision, close-range photogrammetry of very small objects has not yet been encountered.

The Binocular Machine Vision System, developed by ICCS during the WWW.BRIGHT.EU project, has succeeded in overcoming the major problems involved in gauging three-dimensional reconstruction of objects with a random and unknown geometry and with a maximum diameter of less than 1 cm [2]. The performed reconstruction achieved a high level of accuracy, of the order of 0.03 mm, while the software operation was fully automated.

The hardware configuration was strictly based on the nature of the problem, thus emerged into highest efficiency during image acquisition. Telecentric lenses provided the z-axis movement, so the system can achieve optimal focus, without further calibration, free from perspective error and distortion factors - a major advantage over the commonly used wide-angle lenses. In addition, stereo pair image acquisition was absolutely synchronized at the hardware level, minimizing reconstruction errors in the case of fast moving objects, as in the case of the breath rate of tumour bearing animal models.

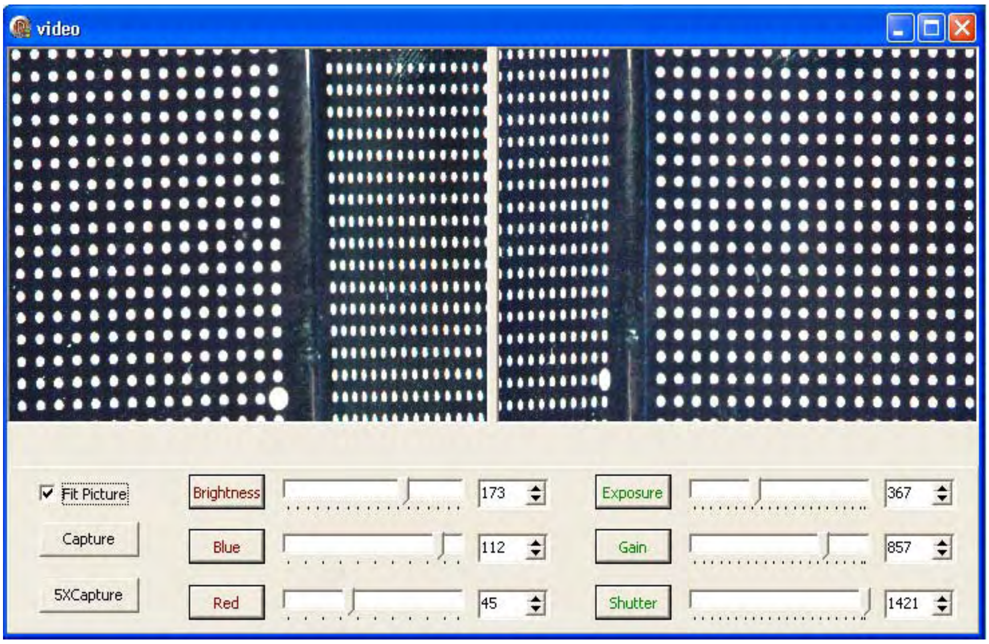

Fig. 1: Video preview snapshot. The displayed stereo pair is from the calibration object.

Fully automated algorithms with increased accuracy for the 3D reconstruction have been developed. More specifically, a pre-processing procedure, which included intensity adjustment, noise reduction and contrast enhancement algorithms, was applied to each one of the stereo pair images. This procedure, apart from highlighting the structured light features, also ensured the automated function of the Binocular Machine Vision software. At the second image-processing phase, the features of the structured light pattern were detected via a combination of a modified watershed algorithm and thresholding, uniquely labelled. That led to the successful confrontation of the well-known “matching” problem. The use and the successful detection of a custom coded structured light pattern [3] provided a large number of conjugate points, which made the three-dimensional reconstruction possible for any gauging application involving objects with a diameter of less than 1 cm, even if inherited object features, such as edges or colour variations, were absent [4]. Furthermore, a custom mathematical algorithm, based on surface contours and eccentricity alignment, has been applied in order to extract the object under inspection from the surrounding area, after the 3D reconstruction. This extraction is vital in gauging applications, where the possible curvature of the surrounding surface may be included in the geometrical characteristics calculation, increasing the accuracy of the system.

e-Newsletter n°3
September 2006

The developed system is a very useful tool for industrial quality control measurements, where accuracy and inspection are very important. Most of the modern machineries consist of a large number of very small parts and the need for automated three-dimensional reconstruction software is still urgent to control the successful construction of those parts [5]. Another field where the Binocular Machine Vision System would provide valuable assistance is Archaeology, where volume and surface geometry measurements of small items are essential [6]. In biology, there is also the need to observe and study the growth rates of various small species, like insects. Due to the absolute synchronization of image acquisition, the developed system can measure the growth rates of those fast moving specimens and provide all the necessary geometrical features. In addition to these applications, this system is the first CCD-based monitoring system providing 3D tumour imaging of very small skin tumours and monitoring their vanishing between photodynamic treatments.

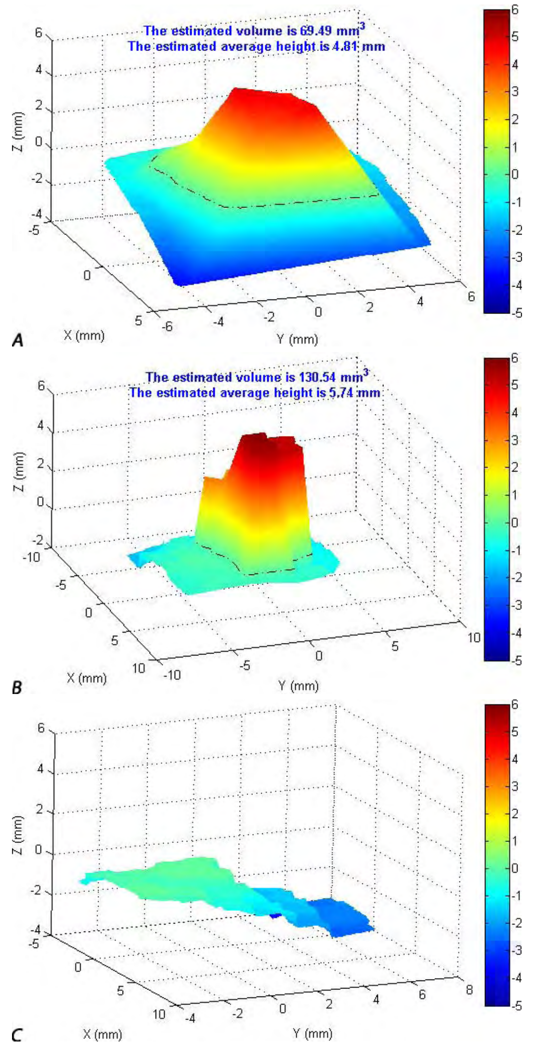

Fig. 2: Monitoring the vanishing of a tumour between PDT treatments. A: Before first treatment. B: Before third treatment. C: Two weeks after third treatment.

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e-Newsletter n°3
September 2006

Pressure and Temperature Tuning of Laser Diodes

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Pressure and temperature change the bandgap of III-V semiconductors and therefore shift the gain spectrum of laser diodes. With 20 kbar of pressure (achievable in a liquid pressure cell), we can increase the energy of the laser emission by ~ 200 meV for lasers grown on GaAs, InP or GaSb. The main physical limitation of pressure tuning for shorter wavelengths (i.e. between 600 nm and 800 nm) is the reduction of the indirect gap (Γ-X) in the barriers and claddings of the laser structure, which leads to a strong increase of leakage and threshold currents. In this wavelength range, temperature tuning seems more practical. By cooling down the laser from room temperature (300K) to about 100K, we should be able to increase the emission energy by ~ 80 meV. The combination of pressure/temperature tuning with tuning by an external grating turned out to combine the merits of both methods: wide spectral range, narrow linewidth, stable emission wavelength. This method seems promising, although several issues still have to be addressed, like the reliability of lasers and pressure cells after multiple pressure cycles, stability of coupling between the laser and fibre under high pressure, etc.

Introduction

Laser diodes have developed very rapidly in the last two decades. Commercial CW devices grown on GaAs, InP and GaSb are available in the 630 nm – 2400 nm spectral range and nitride devices in the 410 nm – 420 nm violet range. Single emitters achieve high powers of a few Watts and tapered lasers (developed within WWW.BRIGHT.EU) combine high power and high beam quality.

Numerous applications require wavelength tuning: spectroscopy (e.g. Tunable Diode Laser Absorption Spectroscopy), telecommunications (Dense Wavelength Division Multiplexing), and medicine (photo-dynamic therapy involving different photosensitizers). Diode lasers can be tuned by external or internal gratings, forcing the laser to oscillate at a frequency determined by the grating [1]. This method allows for tuning within the gain curve. The second possibility is to shift the whole gain curve of the laser. This can be achieved by high pressure or by low temperature (increased temperature is not practical for diode lasers because the threshold currents increase rapidly and the lifetime decreases). In the present paper, we shall review pressure and temperature tuning together with external cavity tuning. These activities have been developed by the UNIPRESS team within the WWW.BRIGHT.EU project (using the laser diodes grown by our partners).

Special requirements for pressure and temperature tuning

Pressure and temperature have been widely used for characterising laser diodes [2]. The most practical tool in such investigations has been the piston-cylinder liquid cell – a few experiments have been performed in the Diamond Anvil Cell [3], but the electrical connections to the laser are difficult to realise in this device. For a characterisation measurement, it is sufficient to make a few pressure cycles, pulsed operation of the laser can be applied (so that heatsinking is not a problem), efficient coupling of light out of the cell is not important, etc. When we want to develop pressure/temperature tuning, by which we mean high-power lasers operating CW, hundreds of pressure/temperature cycles without the degradation of the laser or of the pressure/temperature cell, efficient coupling of light out of the cell, good quality of the output beam, etc. are required. Safety issues are also important (in case of pressure tuning) if the device might be operated by non-specialists.

For edge-emitting lasers, we have closely spaced longitudinal modes and when we shift the gain by pressure or temperature, we observe mode-hops i.e. the tuning is not continuous but step-like. Moreover, there is some hysteresis when going up and down in energy. In order to avoid these mode hops, it is possible to deposit anti-reflection coatings on one laser facet and use the external cavity configuration so that the light is reflected back to the laser by an external grating or Bragg fibre. This reduces the linewidth of the laser (this is very important for spectroscopic applications [4]) and stabilizes the emission wavelength which can be fine-tuned by the grating.

The physical limitations of pressure tuning are related to the direct-indirect transition (Γ-X crossover) under pressure for materials like AlGaAs, GaAsP and AlGaInP. This is because the Γ-X separation decreases rapidly with pressure (10 – 14 meV/kbar) and the indirect barriers to the waveguide and cladding layers decrease as well. In other words, for indirect (X symmetry) waveguides and claddings, the quantum well becomes shallower at increased pressure. This leads to increased leakage of electrons from the well and to an exponential increase of

e-Newsletter n°3
September 2006

the threshold current with pressure. For longer wavelength lasers (above 900 nm), leakage is usually negligible and the pressure-tuning range is only limited by the available pressure range multiplied by the pressure coefficient of the direct bandgap (between 8 and 12 meV/kbar). For InGaN/GaN lasers, leakage to X minima does not occur, but the pressure coefficients are below 4 meV/kbar. Therefore, for wavelengths below 800 nm (including nitride lasers), temperature tuning may be a better alternative to pressure tuning. The combination of pressure and temperature tuning is possible, but not very practical – it involves cooling of the whole pressure cell and below the freezing point of the liquid in the cell pressure cannot be increased at low temperature.

Experimental

Let us first describe our piston-cylinder pressure cell (Fig. 1). As already mentioned, the cell should not exhibit plastic deformation effects after hundreds of cycles. We obtained very good results with tungsten carbide inserts. Such inserts have to be properly compressed by external (steel) cylinders because they are not resistant to tensile strain. The cells with tungsten carbide inserts did not show any plastic deformation (inside and outside) after 20 cycles to 20 kbar. The major problem remaining to be solved is multiple-use gaskets (on the piston). Another requirement for the gaskets is the long-term stability of pressure. For good gaskets, this requirement is fulfilled and in some cases we kept the laser for months under pressure and the emission wavelength stayed unchanged.

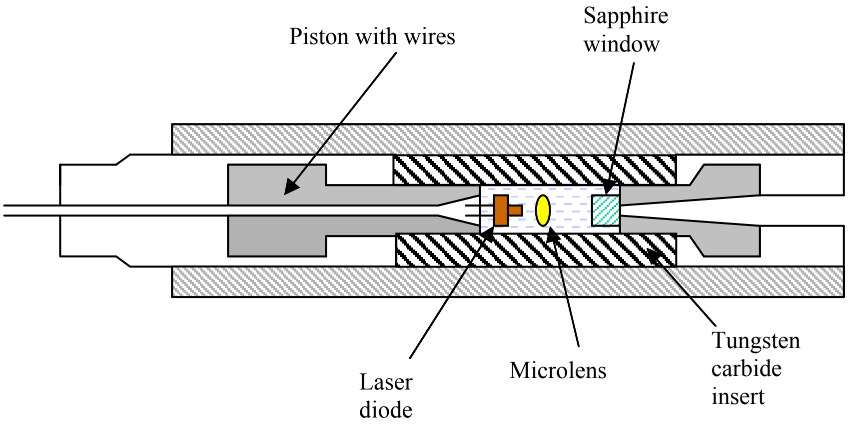

Fig. 1: *Schematic view of the pressure cell with tungsten carbide inserts.*

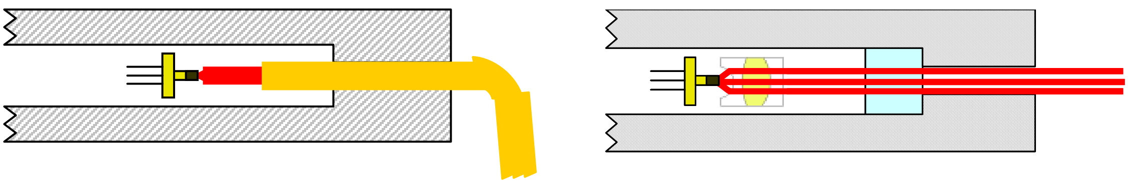

Fig. 2: *Two methods of extracting the laser light from the cell: butt coupling to fibre (left) and collimating with a microlens and passing through a sapphire window (right).*

In order to extract most of the laser light out of the cell, we used two solutions shown schematically in Fig. 2: direct butt coupling of the laser to an optical fibre or collimating with a microlens and passing through the sapphire window. Direct butt coupling is convenient, because many applications require light in the fibre. However, we could only use multi-mode fibres with 50 - 125 micron cores. Laser polarisation is scrambled in such fibres and speckles appear at the output. We were not able to achieve good (and stable with pressure) coupling to a single-mode fibre with a core of a few microns. The solution with the sapphire window required a collimating lens which is not sensitive to the changes of the refractive index of the pressure medium. The refractive index of gasoline increases from 1.35 up to 1.55 at 20 kbar pressure [5]. We designed a triplet consisting of two lenses from BK7 glass and one lens from ZnSe (see Fig. 2). This triplet was indeed insensitive to the index of the medium, but cracks appeared after a few pressure cycles and the lens was no longer transparent. We achieved better results with graded-index lenses. These lenses form the beam inside the lens due to the radial gradient of the index. We still observe some deterioration of the beam at the highest pressures, but further improvements of the microlens are possible. One more optical problem arises at wavelengths above 1 micron, where gasoline (and also pentane-hexane) starts to absorb strongly – especially in the band around 1700 nm and above 2250 nm (see Fig. 3). It is therefore important to keep the thickness of gasoline layer as small as possible. This is easy for butt coupling to a fibre, where we need only 50 – 100 micron distance from the laser to the fibre. However, with the microlens and the optical window, the layer of gasoline may be about 0.5 mm and this can reduce the emission power in the absorption bands.

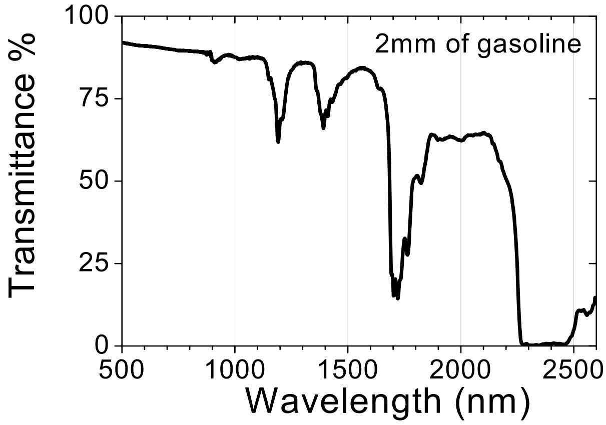

Fig. 3: *Transmittance of a 2 mm layer of gasoline measured by a spectrophotometer. Strong absorption bands occur around 1700 nm and 2300 nm.*

The pressure cell is placed under a small hydraulic press (see Fig. 4). With the light coming through the fibre, we can place the fibre anywhere in the optical system. When we use the window, the collimated beam is reflected at 45° from a mirror placed below the cell so that the output beam is parallel to the optical table. This solution is necessary if we couple the light to an external grating. We used the Littrow configuration, where the first order of the diffracted beam is sent back to the laser and the zeroth order is used as an output beam. The grating was connected to another mirror and they were rotated around the axis being the intersection of the plane of the grating and the plane of the mirror (following [5]). In this geometry, the output beam has a fixed direction while rotating the grating.

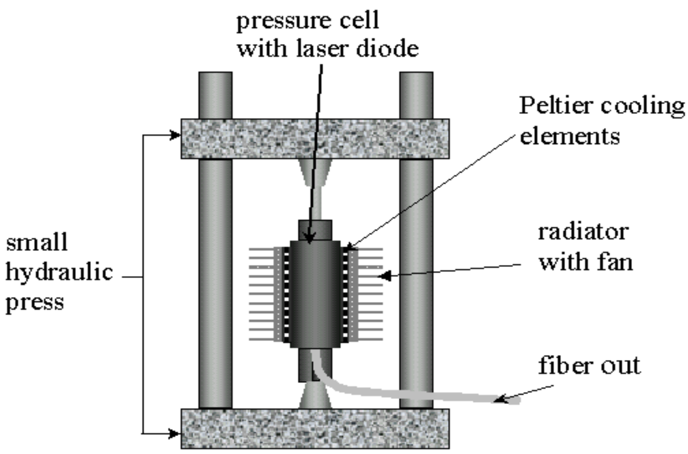

Fig. 4: *Pressure cell with Peltier cooling system placed under a hydraulic press. Laser light comes out through optical fibre. In the case of a window in the cell, the collimated output beam is reflected from a mirror at the bottom of the press.*

Let us now discuss laser diode mounting appropriate for pressure or temperature tuning. The semiconductor diode is usually soldered p-side down (with In or Au/Sn) to the submount, which is then mounted on a heatsink. In order to avoid soldering-induced strain, the submounts are chosen so that the thermal expansion is close to that of the semiconductor. The thermal conductivity of the submounts must be high – especially for high-power lasers. Typical submounts used commercially are AlN, SiC or diamond. As shown in Table 1, these submounts are much harder than GaAs (or InP), so that large tensile strain will be generated in GaAs lasers soldered to AlN or SiC and then pressurised. It is hard to find submounts with both thermal expansion and compressibility matched to GaAs. The closest is silicon, but its thermal conduction is not the best. For Cu and Ag heatsinks the strains generated by pressure compensate the strains generated by temperature (i.e. strains generated while cooling down after soldering). The strains depend on the solder (soft indium solder probably relaxes the strains) and on the size of the chip (for small chips the strains are relaxed). For indium solder after multiple pressure cycles, we found that it was often the solder which degraded, not the laser. After resoldering (heating up to 200°C), the laser recovered its initial characteristics. We found that the red InGaP/AlGaInP lasers were most fragile i.e. they degraded after pressure cycles much more than other lasers. This is why we used them for the mounting tests. We obtained the best results for lasers mounted with Au/Sn on Si and with In on Cu or Ag. Obviously it is also important to have solder without any voids, as under pressure these may cause cracking of the laser chip.

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e-Newsletter n°3
September 2006

Table 1

Material	GaAs	Cu	SiC	Ag	AlN	Si
Linear compressibility ΔL/L/Δp (%/GPa)	0.44	0.24	0.13	0.33	0.16	0.33
Thermal expansion coefficient (10^{-6}/K)	5.7	16.5	4	18.9	4.5	2.6
Thermal conductivity at 300K (W/m/K)	55	400	300	430	170	140

For temperature tuning, we constructed a small cryostat with the laser diode and the micro-optics in a vacuum chamber. We used Peltier cooling (reaching only -50°C) or liquid-nitrogen cooling (which should work down to 80K). However, in our first prototype, we only achieved 140K. Temperature tuning is much simpler experimentally than pressure tuning. Standard collimating optics can be used, as well as the standard mounting of the laser chip (since the submounts are thermal-expansion matched to the semiconductor chip). Moreover, the threshold currents usually go down and the lifetime of laser diodes is usually extended at low temperatures. There may be problems with p-type claddings at low temperatures because in some materials (e.g. nitrides), a high concentration of holes cannot be achieved and the carriers can be frozen on acceptors at low temperatures. Also, the expansion matching of the submounts can occur around room temperature, but at low temperatures the thermal expansions may become different which will cause strain. So far, we have only tested two types of red lasers and only a few temperature cycles have been performed. Thus, reliability issues remain to be studied in case of temperature tuning. Coupling to an external grating is straightforward and can be achieved from both facets of the laser, since the cryostat has two (or more) optical windows.

Results

For longer wavelength lasers, pressure tuning is only limited by the available pressure range. If we use a 20 kbar cell, we can achieve a tuning range of about 200 meV. For InGaAs/GaAs, lasers this means tuning from 960 nm to 830 nm, with almost constant output power over the whole tuning range [7,8]. This is shown in Fig. 5, where we plot the emission spectra from a pressure tuned 960 nm tapered InGaAs/GaAs laser (fabricated by IAF) and the threshold currents vs pressure at different temperatures.

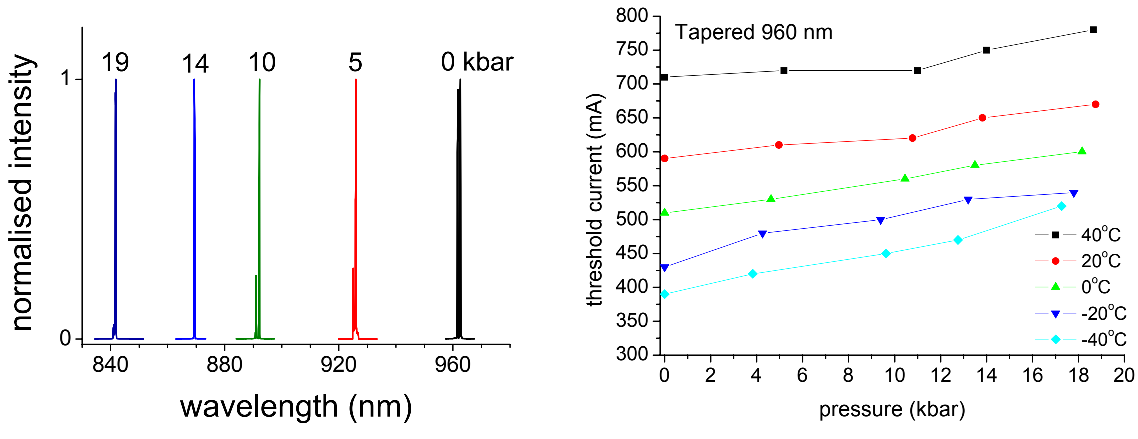

Fig. 5: *Emission spectra at different pressures (left) and threshold currents vs pressure and temperature (right) for a 960 nm tapered laser from IAF.*

The most spectacular tuning (over a 700 nm range) was achieved for a 2400 nm InGaAsSb/AlGaAsSb laser diode [9] obtained from our colleagues at Montpellier University (see Fig. 6). In this case, the thresholds went down and above 8 kbar started to increase. We suspect that this increase may be caused by electron leakage.

The results shown in Figs. 5 and 6 were obtained with optical fibres. Special fibres with high transmission in the mid-infrared can be found. For butt coupling to the fibre, the layer of gasoline between the laser facet and the tip of the fibre is only around 50 microns. Thus, the absorption of gasoline in such a layer is small up to a wavelength of 2300 nm (see Fig. 3).

e-Newsletter n°3
September 2006

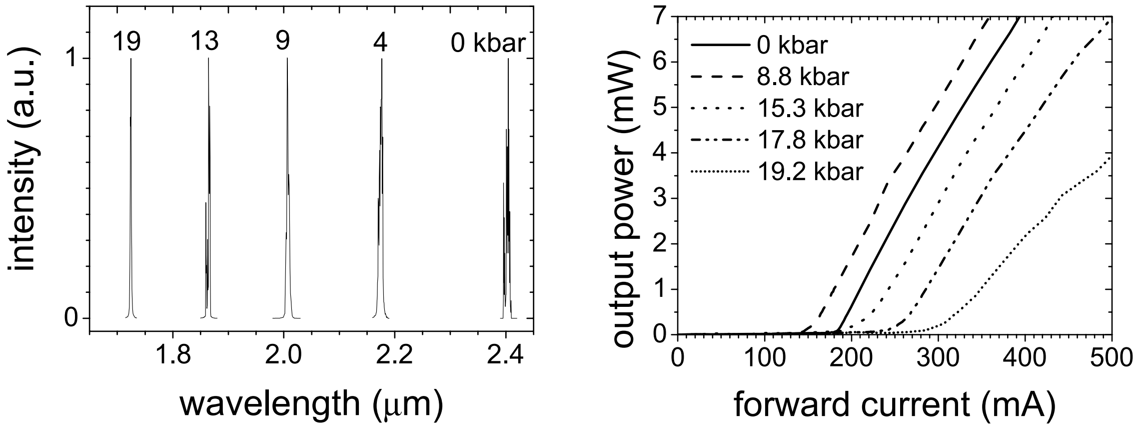

Fig. 6: *Emission spectra and light-current characteristics for a 2400 nm laser at different pressures.*

For wavelengths between 600 nm and 800 nm, the tuning range is limited by the increased leakage under pressure. In Fig. 7, we show the threshold currents vs pressure at a few temperatures for 800 nm InGaAsP/AlGaAs lasers and for 650 nm InGaP/AlGaInP lasers (grown by FBH). For these lasers, temperature tuning seems more appropriate.

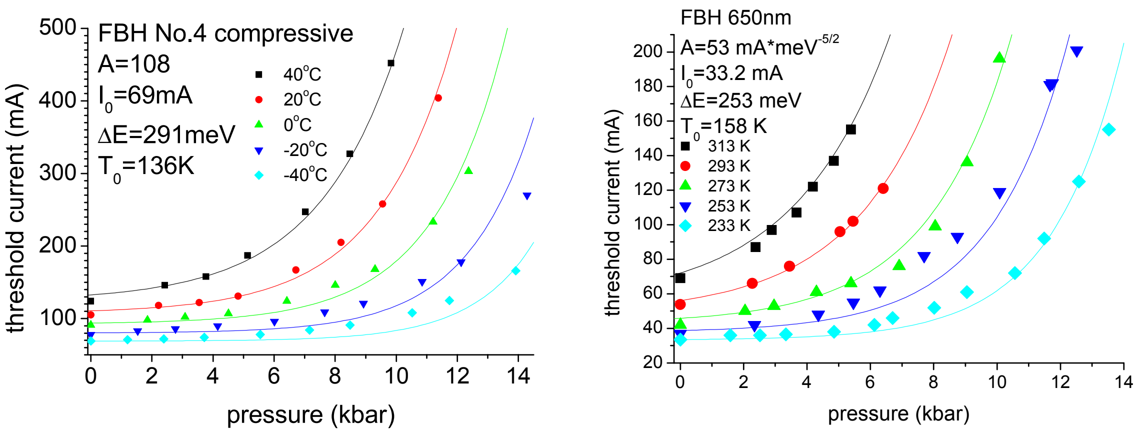

Fig. 7: *Threshold currents vs pressure at different temperatures for 800 nm and 650 nm lasers.*

The same concerns violet InGaN/GaN lasers. In Fig. 8, we show the emission spectra of a 410 nm InGaN/GaN laser (grown at Unipress), which shifted about 10 nm in the 20 kbar range [10]. The pressure coefficient of the lines was about 3.6 meV/kbar, which is a large shift for InGaN/GaN quantum wells and indicates that the built-in electric fields are screened.

For visible lasers, better tuning can be achieved with temperature. For the 650 nm and 635 nm high-power lasers, we tested our cryostat from 300K down to 140K and achieved about 28 nm tuning range, with reduced thresholds and increased efficiencies (see Figs. 9 – 11).

Let us finally show the combination of pressure tuning and the tuning by an external grating [11]. We chose the grating with 20% light diffracted in the first order and 70% in the zeroth order (in the Littrow configuration). A tapered laser fabricated by IAF was placed in the pressure cell with a GRIN collimating lens and sapphire window. A cylindrical lens for collimating the slow axis was placed outside the pressure cell. At each pressure, the tuning by grating has been performed (see Fig. 12). We achieved single-mode emission in the 100 nm tuning range, with powers between 200 and 300 mW (at a fixed current of 1.5 A).

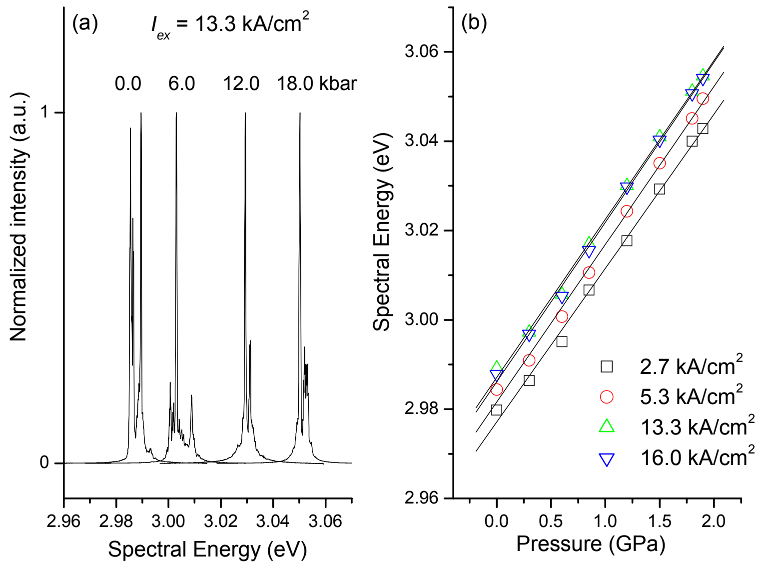

Fig. 8: *Emission spectra of a violet InGaN/GaN laser diode at different pressures [10]. The lines shifted by about 3.6 meV/kbar.*

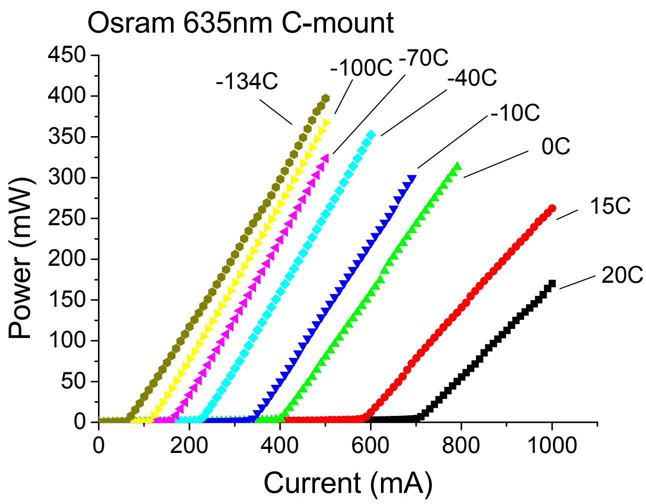

Fig. 9: *L-I characteristics of an Osram 635 nm laser diode at different temperatures.*

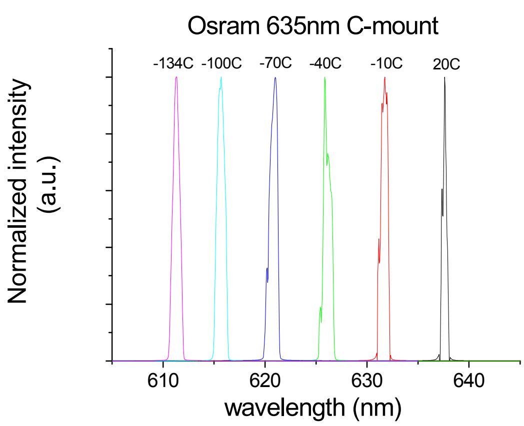

Fig. 10: *The emission spectra of an Osram 635nm laser diode at different temperatures.*

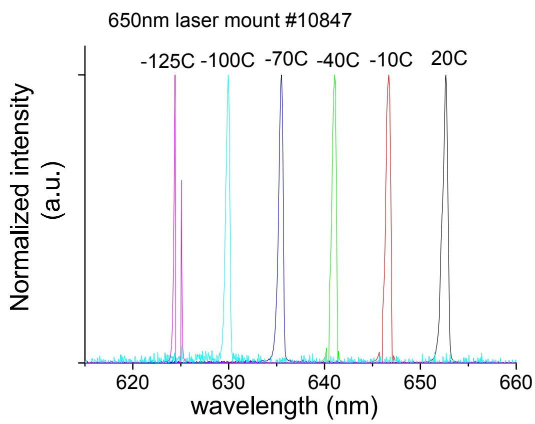

Fig. 11: *The emission spectra of a FBH 650nm laser diode at different temperatures.*

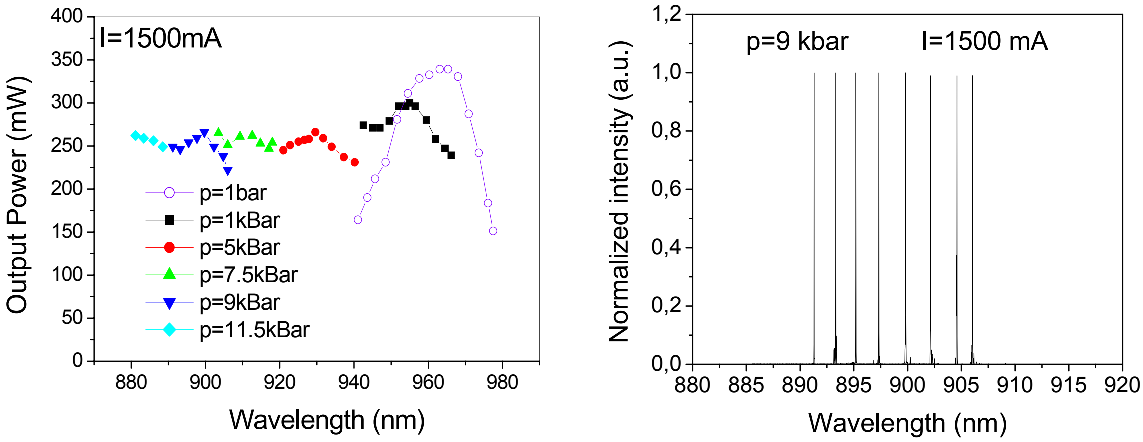

Fig. 12: *Output power of a tapered 960 nm laser (from IAF) tuned with grating at different pressures (left). The operating current was fixed at 1.5 A. Emission spectra tuned with the grating at 9 kbar pressure (right).*

Conclusions

Pressure tuning over a 200 meV range has been demonstrated for infrared laser diodes in the 800 nm – 2400 nm spectral region. The output beam can be passed by the optical window or by the fibre. For shorter wavelengths, temperature tuning seems more practical (including for violet lasers). The combination of pressure tuning with tuning by an external grating combines the merits of both methods: wide spectral range, narrow linewidth, single-mode emission and good quality of the beam.

Special care must be taken to ensure good reliability of the lasers and of the tuning module: reduced mounting strains, good heatsinking in the cell, special micro-optics, tungsten carbide inserts in the cell and multiple-use gaskets. Several improvements have to be made to create a user-friendly pressure-tuned module, which could be used by non-specialists.

Acknowledgments

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