IST – 035266

WWW.BRIGHTER.EU

World Wide Welfare: high-BRIGHTness semiconductor lasers for gEneric Use

IP - Integrated Project
IST - Information Society Technology

Publishable final activity report

Period covered from 01/10/08 to 31/03/10

Start date of project: 01/10/06 *Duration: 42 months*

Revision: Version 1

Project coordinator name: Michel Krakowski
Project coordinator organisation name: Alcatel Thales III-V Lab

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination level		
PU	*Public*	*x*
PP	*Restricted to other programme participants (including the Commission Services)*	
RE	*Restricted to a group specified by the consortium (including the Commission Services)*	
CO	*Confidential, only for members of the consortium (including the Commission Services)*	

CONTENTS

Partners

No.	Partner Name & *Main Responsibilities*	Acronym	Country
1	Alcatel-Thales III-V LAB ***Design, growth, fabrication & characterisation of high-brightness laser sources***	III-V LAB	France
2	Biolitec AG ***Design and implementation of medical laser systems for PDT and surgery***	BIOLITEC	Germany
3	Lund University ***Tissue fluorescence monitoring, Clinical study protocols***	LLC	Sweden
4	Institute of Communication and Computer Systems ***3D fluorescence imaging system for PDT monitoring, Clinical study protocols***	ICCS	Greece
5	DTU Fotonik ***FWM laser cavities, External feedback lasers, Wavelength multiplexing***	DTU	Denmark
6	OSRAM Opto Semiconductors GmbH ***Red-emitting laser bars at 635nm, Evaluation of lasers for display applications***	OSRAM	Germany
7	University of Cambridge ***Modelling, Post-processing using FIBE, Free-space communication systems***	CAM	UK
8	Keopsys ***Realisation of cladding-pumped EDFA's and Raman amplifiers***	KEO	France
9	Alcatel-CIT ***Design and realisation of cladding-pumped EDFA's and Raman amplifiers***	ALCATEL	France
10			
11	Bayerische Julius-Maximilians Universität Würzburg ***Realisation of tapered lasers with gratings for wavelength stabilisation***	UWUERZ	Germany
12	Fisba Optik AG ***Development & production of micro-optics, Module development & assembly***	FISBA	Switzerland
13	Rainbow Photonics AG ***Evaluation of non-linear crystals, Frequency doubling to 340 and 405nm***	RB	Switzerland
14	Thales Research and Technology ***Material characterisation, Reliability studies, Multiplexed external cavity lasers***	TRT	France
15	Universidad Politécnica de Madrid ***Modelling of high-brightness and high wall-plug efficiency laser diodes***	UPM	Spain
16	Ferdinand-Braun-Institute, Forschungsverbund Berlin e.V. ***Red-emitting laser bars at 650nm, Tapered lasers at 810 and 1060nm***	FBH	Germany
17	Fraunhofer-Gesellschaft (ILT, Aachen & IAF, Freiburg) ***Tapered lasers/amplifiers at 975 & 1060nm, Advanced packaging & modules***	FHG	Germany
18	Instytut Wysokich Cisnien PAN ***Temperature and pressure tunable lasers***	UNIPRESS	Poland
19	Universität Kassel ***Fabrication of high quality quantum dot material at 920 and 1060nm***	UKAS	Germany
20	Centre National de la Recherche Scientifique ***Self-organising cavity lasers, Extended cavity lasers with holograms & gratings***	LCFIO	France
21	Max-Born-Institute, Forschungsverbund Berlin e.V. ***Investigation of strain and defects in laser diodes, Reliability studies***	MBI	Germany
22	Tyndall National Institute ***Modelling and realisation of slab-coupled optical waveguide lasers (SCOWLs)***	TYN	Ireland
23	University of Nottingham ***Modelling external cavity lasers, Intracavity characterisation, Reliability studies***	UNOTT	UK

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1. Project objectives and major achievements during the reporting period

1.1. Overview of general project objectives

High brightness laser diode technology is a key enabling technology for the modern information society, especially in the fields of health-care, telecommunications, infotainment, environment and security.
Laser diodes offer high output power, compactness, robustness, and mass production capabilities. However their use in the above mentioned domains is often limited by the difficulty to reach satisfactory performances on power and beam quality simultaneously. The term "high brightness" indicates exactly the capability of a high power laser diode to provide high beam quality.
The brightness governs directly the performance of systems, such as the transmission span of an optical data link, the reliability of a diagnosis in fluorescence imaging of cancer, or the resolution of a laser projection display. Therefore, the need for high brightness laser diodes in these applications is currently strongly increasing.

The WWW.BRIGHTER.EU consortium proposes a long-term vision aiming at pushing the limits of the current laser diode technology towards higher brightness, and at demonstrating applications such as:
Laser sources for medical imagery for cancer diagnosis and intelligent therapy
Optical amplifiers for telecommunication networks
Compact source for projection display

The new project, WWW.BRIGHTER.EU, is based on a similar consortium than WWW.BRIGHT.EU led by the same Coordinator (Alcatel Thales 3-5 lab). It fully benefits of the know-how and results developed in WWW.BRIGHT.EU and offers a more comprehensive and ambitious approach, taking into account the recent market developments and evolution of the state-of-the-art. This approach, compared with the one of WWW.BRIGHT.EU, is summarised hereafter from the applications point of view:

1.1.1 Health-care application

It is a full validation of PDT lasers (with clinical tests), diagnostic and monitoring techniques for the assessment of PDT progress, introduction of 340 nm fluorescence imaging/diagnosis.

1.1.2 Telecom application

It is a full validation of the Raman amplifier, introduction of a new industrial Partner (Keopsys) for the component manufacturing and exploitation.
There is a free space communication: assessment of the improvement linked to the use of 980nm and 1060nm high brightness tapered laser diodes.

1.1.3 Display application

It did not exist in WWW.BRIGHT.EU, it fully benefits from the synergies with the 635nm and 650nm lasers developed for PDT and from the frequency doubling technique developed for fluorescence diagnosis; mid-term perspective.

The approach consists of mobilising the expertise of the core European players of the laser diode technology, and combining it with **original optical technologies** e.g. **smart cavity concepts for higher efficiency and tunability**. Leading European research centres and manufacturers participate in order to deploy the developed technology in new applications. Industrialisation constraints will be widely addressed through **packaging** and **reliability studies**.
The consortium includes major companies and SMEs that will exploit the developed technology commercially. WWW.BRIGHTER.EU therefore increases and strengthens existing European momentum within the laser diode industry and the Information Society.

1.2. Summary of Work performed and Main achievements

Partner	Summary of work performed	Main achievements
III-V Lab	• processing of QDots BA and IG tapered laser bars at 920 nm • processing of QW BA and IG bars at 975 nm • processing of two-sections tapered lasers at 1060 nm for free-space optical applications • Growth of 1060 nm laser structures including Large Spot Size and optimised structures • Coating and delivery of 975 nm laser arrays for ECL experiments at LCFIO • delivery of 920nm QDots and 975nm QW laser bars to ILT for telecom applications • delivery of two sections 1060nm QW tapered laser to ILT/UCAM for FSO applications • Aging tests of lasers from 5 different QW wafers and 1 QDots wafer achieved • delivery of tutorial on high brightness lasers to the consortium • update of project website including online deliverables • organisation of meetings and reviews, preparation of reports	• 20 W QDots IG tapered bar at 920 nm • 40 W Qdot BA laser bar at 920 nm • 40 W QW IG tapered bar at 975 nm • 120 W QW BA laser bar at 975 nm • Two-sections tapered laser at 1060 nm with 50 W/A modulation efficiency in static and 19 W/A at 700 Mbps, 20 dB Extinction Ratio and 1.6 W Optical Modulation Amplitude at 700 Mbps • Two-sections tapered laser at 1060 nm with 18 W/A modulation efficiency in static and 13 W/A at 1 Gbps, 11 dB Extinction Ratio, and 0.53 W Optical Modulation Amplitude at 1 Gbps • Two-sections tapered laser at 1060 nm with 5W output optical power together with beam quality parameter M^2 of 1.1 • Delivery of 975 nm laser arrays to LCFIO for ECL experiments, single lobe array in ECL configuration
BIOLITEC	• Detection unit was developed -> ID 6.2.2.1 • Finalized laser development -> CD6.2.3.1 • Usability evaluation of PDT system -> ID6.4.2.3	• PDT system with 4 laser ports and 4 detection ports
LLC	• Finalized a study protocol • Performed first test measurements with new laser in the clinical environment • Working on a clinical fluorescence imaging study • Evaluated fluorescence imaging data from joint WP6 preclinical study in Jena • Evaluated fluorescence tomography data from joint WP6 preclinical study in Jena • Developed a multispectral fluorescence tomography algorithm • Performed clinical fluorescence spectroscopy measurements for intraoperative brain tumour demarcation • Performed a study of novel upconverting nanocrystals as markers for fluorescence imaging	• Five scientific publications related to the project published during the period • One PhD thesis written (will be defended in Jan 2010) • Successful demonstration of clinical use of 355 nm laser developed within the project • Clinical usefulness of fluorescence spectroscopy for guiding surgical resection of brain tumours demonstrated. • Novel multispectral fluorescence tomography reconstruction algoritm presented • Novel nano-particle-based markers for fluorescence imaging demonstrated to have high potential for fluorescence imaging

Partner	Summary of work performed	Main achievements
ICCS	• Optimization of the fluorescence molecular imaging system. • Development of the software interface for user-system interaction. • Development of the streamline diffusion modification for the forward solver. • Accuracy assessment for the segmentation process for the inverse problem. • Development of the least squares fitting algorithm for the solution of the inverse problem. • Evaluation of the inverse problem solution through numerous phantom experiments • Last experiments of the evaluation process of IPDT treatment on prostate cancer animal model	• Final fluorescence molecular imaging system. • Automated synchronization between the scanning and image acquisition processes • Automated camera calibration • Increased accuracy of the forward solver model • Construction of a database, which corresponds to the image acquisition protocol, for the solution of the inverse problem. • Solution of the inverse problem with least squares fitting between the database and the acquired images. • Optimum therapeutic scheme of IPDT prostate cancer
DTU	• WP3 Investigation of carrier density changes in laser device in asymmetric external cavity • WP3 Phase conjugate feedback to segmented broad area diode laser • WP3 Off-axis spectral beam combining feedback to a broad area diode laser bar • WP3 Implementation of 670-680 nm tapered amplifiers in external cavity setups for SHG into 340 nm • WP3 Test of SHG in planar and ridge waveguide BBO crystals • WP3 Development of pulsed 355 nm laser system • WP3 Investigations of operation of 946 nm Nd:YAG laser under tapered laser pumping • WP6 Transfer of pulsed 355 nm laser system to LLC • WP8 Test and characterization of 1060 nm tapered amplifiers and lasers from FBH, IAF and III-V lab. • WP8 SHG of 1060 nm tapered lasers to green.	• WP3 Imaging of spontaneous emission from laser in asymmetric external cavity indicating spatial hole burning • WP3 Single frequency operation of segmented broad area laser with phase conjugate feedback • WP3 Broad area laser bar with 9 W output power, M2=6.4 and brightness = 79 MW/cm2-str • WP3 >1 W tunable output at 670-680 nm with M2<1.2 • WP3 Only very weak SHG signals are observed • WP3 >100 W peak power at 355 nm obtained with 5 kHZ repetition rate • WP3 High efficiency operation of 946 nm Nd:YAG laser (slope efficiency = 65 %) • WP6 Autofluorescence imaging using 355 nm laser system • WP8 > 9 W 1060 nm output power with narrow spectrum and good beam quality. • WP8 >1.5 W green light obtaind with 18.5 % conversion efficiency. • WP8 A modulation depth of 1:50 obtained in the green light.
OSRAM	• epitaxy and processing of laser emitting at 635 nm • implementation of a new non absorbing mirror • mounting of laser bars on CuDia • ageing experiments of laser bars	• Laser material with improved wall-plug efficiency • demonstration of a single emitter achieving > 0.9W • output from a passively cooled laser bar >5W • 2000 h lifetime for 3W output power achieved (80% criteria)

Partner	Summary of work performed	Main achievements
CAM	• WP2.1 Design of high beam quality emitters for tapered laser array • WP2.1 Design of optmised segmented tapered lasers for high bandwidth, low modulation current and high extinction ratio passed to 3-5 Lab for fabrication • WP2.2 Test of optimised tapered lasers under modulation • WP7.2 Demonstration of 1.25 Gb/s FSO link using BRIGHTER lasers • WP8 Demonstration of holographic projection display using BRIGHTER lasers	• 1.25Gb/s modulation with 10dB extinction ratio and <100mA modulation current swing • Demonstration of 1.25Gb/s FSO outdoors link over 60m operating error free • Demonstration of one and two (red and green) colour holographic displays using BRIGHTER laser modules
KEO	• CD7.1.4: The design (optical, mechanical & electrical) of the RFL has been finalized. The prototype has been manufactured and tested. • CD7.1.10: The design (optical, mechanical & electrical) of the Cladding Pump EDFA prototype has been finalized. The prototype has been manufactured and tested.	• CD7.1.4: The RFL prototype emitting 5.2W has been delivered in november 2009 to Alcatel Lucent. The final report has been issued in december 2009. • CD7.1.10: The Cladding Pumped EDFA prototype has an output power of 420mW with an input power of 10dBm. It has been obtained with the 3.2W (12W target) of the 975nm 50µm pump module delivered by Fraunhofer-ILT (CD4.3.8).
ALCATEL	• System experiment at 43Gbit/s with RFL • Raman Fiber Laser with 920nm Qdot module	• Up to 30dB of distributed Raman gain . Up to 55dB of span loss with error free operation • 7.3W of output power at 1117nm from the Yb laser with 48.5% efficiency versus the injected power at 920nm
INO		
UWUERZ	• Fabrication and Characterisation of gain and index guided tapered lasers with DBR gratings on quantum dot material. • Fabrication of tapered laser bars with DBR gratings.	• Stable single mode emission from gain guided tapered lasers on quantum dot material (920nm) up to 2 W. • 1W single mode output power from index guided tapered lasers at 920 nm. • 3W output power from 1060nm quantum dot tapered lasers with DBR gratings. • 4.2 W output power from 980 nm mini-bar with DBR gratings.
FISBA	• three coupling experiments of the SMF EDFA module WP4.3.2 • two mounting attempts of the red module WP8.1.6 • completing CD4.2.2, ID4.2.3, ID4.2.4, ID4.2.5	• first sport characterizations of the SMF EDFA module • completed delivery of optical components to requesting project partners

Partner	Summary of work performed	Main achievements
RB	• Waveguides implanted in borate materials for doubling 680 nm into 340 nm. • Development of structuring process process. • Calculations and modelling of implantation parameters. • Successful ridge waveguides implantation. • Optimization with angle- lithography for doubling at different wavelengths. • Process optimization based on experimental results. • First schematic set-up for a compact-relable UV laser @340 nm.	• New concept for the develompent of a compcat UV laser operating at 340 nm using nonlinear optics and BBO materials or waveguides implanted and structured in BBO. • Planar waveguides development for the first time in BbO for SHG of 680 nm into 340 nm. • Ridge waveguides implanted and structured according to first calculation in BBO, for efficient doubling of 680 nm into 340 nm.
TRT	•WP3: Wavelength multiplexing of a laser diode bar stack. Single emitters and bar characterizations. •WP5: • PL measurement of facet strain profiles of aged and degraded devices (line profiles and full-facet mappings). • Destructive analysis of degraded devices. •WP9: Tutorials presented at each meeting have been video recorded and the richmedia contents processed.	•WP3: Effective beam combining of three bars in the stack (ID3.4.4) •WP5: • Correlation of changes of the packaging-induced strain during operation with the use of In solder on p-side or n-side. Observation of processing-induced strain patterns extending over the whole thickness of the substrate. • Main degradation mechanisms identified are redistribution of In solder from n-side ribbon and formation of large solder voids in the spoiler regions close to the ridge/taper interface. •WP9: A Richmedia CD of the second set of tutorials has been prepared and delivered.
UPM	• Simulation and design of 1060 nm Gain Guided tapered lasers with high brightness • Simulation and design of 1060 nm tapered with separate contacts and high modulation efficiency • Simulation of red lasers based on new epitaxy • Development of QD laser model • Simulation of mirror heating in red lasers with Non-Absorbing Mirrors and comparison with experiments	• New epitaxial designs based on a asymetric structures provided to WP1 to improve brightness in 1060 nm tapered lasers • Optimised designs of 1060 nm Gain Guided tapered lasers with common and separate contacts provided to WP1 • Good agreement between experiments and a-priori simulations in 1060 nm tapered lasers • Analysis of reduced slope efficiency in QD tapered lasers and recommendations to WP1 • Good agreement between simulations and experiments in red lasers • 3D version of the QD laser model completed • Inclusion of tunnelling injection in QD laser model. • Determination of optimum parameters for Non-Absorbing Mirrors in red lasers.

Partner	Summary of work performed	Main achievements
FBH	• **Lasers for Medical Applications:** Development of 650 nm layer structures for the processing of broad area laser for photodynamic therapy completed Processed 650 nm broad area lasers and minibars Characterisation of processed devices Delivery to WP5 (aging tests) and WP6 Development of 680 nm layer structures for the processing of tapered gain media for external cavity lasers and tapered lasers completed Processed 680 nm tapered lasers and gain media Characterisation of processed devices Delivery to WP3, WP5 (aging tests) and WP6	• **Lasers for Medical Applications:** 650 nm broad area lasers with reliable output powers up to 1.2 W over 10,000 h 650 nm laser minibars with reliable output power up to 8 W over 10,000 h Project goals concerning the 650 nm broad area lasers and bars fulfilled 680 nm tapered gain media for output powers larger than 1 W in CW mode and good beam quality and 3 W in pulsed mode also with good beam quality Project goal fulfilled
	• **Lasers for Display Applications:** Development of 650 nm layer structures for the processing of tapered lasers with improved efficiency, small vertical far field, and good reliability completed Optimization of lateral device geometries towards high output power and good beam quality Processing of 650 nm tapered lasers with separated contacts Characterisation of processed devices Delivery to WP5 (aging tests) and WP8	• **Lasers for Display Applications:** 650 nm laser structure with an improved temperature stability of a T0 = 80 K and an internal efficiency better than 0.90 for tapered lasers. Devices with a maximal output power larger than 1 W together with more than 75% of the emitted power within the central lobe. Beam propagation ratio better than 2 at 1 W output power. Reliable operation at 15°C at an output power of 500 mW over 1,000 h with a stable beam quality. Decisive for reaching high output power is the efficient heat removal and the use of submount material with a small thermal resistance like diamond. Using structured AlN submounts, the output power is limited only due to the thermal properties. The project goal concerning the development of 650 nm tapered is fulfilled.
	Development of reliable 1060 nm layer structures for the processing of DBR-tapered lasers with a vertical divergence of only 15° (FWHM) Processing of 6 mm long 1060 nm DBR tapered lasers for output powers larger than 10 W Characterisation of processed devices Delivery to WP3, WP4, WP5 (aging tests), WP6, and WP7	1060 nm structure suitable for the manufacturing of DBR tapered lasers with a vertical far field angle of 15° (FWHM) Manufactured DBR tapered lasers with an output power larger than 12 W, a narrow spectral linewidth, and nearly diffraction limited beam quality in cw operation Devices with separated contacts for easy modulation of output power, modulation efficiency of 58 W/A obtained by temperature increase to 60°C Reliable operation over 1,000 h at an output power of 5 W without deterioration of beam quality or spectral properties. Project goals for the 1060 nm DBR tapered lasers fulfilled.

Partner	Summary of work performed	Main achievements
FHG	• Third tapered laser process finished • Introduction of diamond heat spreaders • Characterization of mounted devices in terms of output power and beam quality • Setup of a high fillfactor diode laser stack • Assembly and characterization of fibre coupled diode modules • Assembly and characterization of SHG pump module • Packaging of high power diode laser bars • Thermal and optical modeling of frequency conversion (SHG) of high power diode lasers • Setup of breadboard model for SHG	• M^2 = 2.78 @ 9W (976 nm) • Improvement in output power by 15% by use of diamond heatspreader • 25 W fiber coupled diode laser module • 15W quantum dot fiber coupled diode laser module (coolerless) • 250 mW SHG diode laser module
UNIPRESS	•Analysis of mounting-induced strains. •Pressure and temperature characterization of new batch of Osram 635 nm lasers. •Prototypes of pressure/temperature tuned lasers. •New results for pressure and temperature tuning in external cavity. •Reliability tests for different mounting schemes (temperature and pressure cycles).	•Photocurrent spectra reveal different strains for different submounts. Surface profile measurements reveal thermal strains for different submounts. Confirmed by Finite Element Calculations. •New Osram lasers have excellent properties at room temperature but low efficiencies at low temperature and high pressure. We reached 567 nm wavelength from a tuned 636 nm laser. •Temperature tuning for FBH 802 nm tapered laser and bent waveguide laser at 1520 nm revealed rapid narrowing of gain at low temperatures. Pressure tuning for 1050 nm tapered laser from Thales performed in the 142 nm tuning range. •Good reliability for GaAs submounts. 150 pressure cycles up to 15 kbar performed on one gasket. For Thales tapered lasers no degradation in case of gain guided lasers under pressure but degradation under pressure for index guided lasers. •4 our publications related to Brighter appeared in 2009 in international journals.
UKAS	• 920-nm quantum-dot laser development • 1060 nm QD laser structures • 1060 nm quantum dot laser structure with large spot size design	• High internal efficiency of 99%, low internal absorption of 1.1 cm^-1, low transparency threshold current density of 150 A/cm^2, wavelength stability of 0.21 nm/K. • Three QD laser structures were supplied to Wuerzburg and were processed into tapered QD lasers. Output power higher than 3 W, slope efficiency of 0.5 W/A, and WPE of 29 % in single cw mode were obtained by Wuerzburg. • The low-temperature (10 K) QDs emission exhibit a narrow linewidth of 24 meV (FWHM). The laser beam fast axis divergence measured by Tyndal is 28° (FWHM) and 59° (1/e^2), respectively.

Partner	Summary of work performed	Main achievements
LCFIO	• Identification of the power limitations observed at 960 nm for the self-organized cavities. No solution found. • Comparison of different extended-cavity configurations for passive coherent combination of tapered lasers (theory and experiment) • Coherent superposition of beams with a binary phase-grating.	• Systematic single mode operation up to 600 mW of the self-organized tapered extended-cavity laser. • Experimental demonstration of the positive influence of the spectral stabilization on the phase-locking process. • Measurement of the coherence of a phase-locked laser array in an innovant experimental setup.
MBI	• "By-emitter-analysis" and COMD analysis	• Microscopic models for gradual and catastrophic degradation
TYN	• CD1.2.28 Processed large spot size tapered lasers • MS2.2.21 Large spot size tapered laser with central lobe power of 2W • MS1.2.16 Large spot size tapered laser with >1.5W central lobe power. • MS9.1.7 Delivery of technical tutorials 5 • CD2.2.18 Comparison of large spot size laser based on quantum wells and dots. • ID2.1.1.15 Optimised tapered designs for large spot size 975nm Al-free SCOWLs. • ID2.2.38 Report on imaging of spontaneous emission in tapered and broad area quantum well and quantum dot structures.	• 2W of CW power in a mainly single lobe in a low divergence laser. • Characterised and compared the intra-cavity spontaneous emission of low divergence quantum dot and quantum well high power lasers and determined their internal temperature distribution. • Formulated a process for the fabrication of non absorbing mirrors in visible edge emitting lasers
UNOTT	**WP2.1 Laser Design and Simulation** • Investigated design parameters and performance of phase-coupled mini-arrays with integrated Talbot filter • Developed semi-analytical model to understand the asymmetric feedback mechanism • Developed numerical PR crystal model to investigate validity of analytical PR crystal model • Included spectral dependency of real index change in QW and improved ASE model of *Speclase* • Implemented power extrapolation and secant update scheme in *Speclase* to accelerate spectral simulations • Calibrated modelling parameters for 1060nm split contact tapered lasers and investigated design parameters to improve modulation efficiency • Developed *Barlase* to allow emulation of current competition (including effects of global temperature and strain distribution) and bar degradation • Benchmarking of *Speclase* against experiment (including intracavity spectral measurements) and ILDSP	**WP2.1 Laser Design and Simulation** • Carrier lensing predicted to affect the operation of the phase coupled array with integrated Talbot filter, suggesting the need for a non-absorbing Talbot filter • Asymmetric feedback operates by selective feedback of 2-4 lateral modes of the BA laser, limiting the beam quality to M-squared > 3 • The use of the analytical PR crystal model in the self-organizing cavity laser model justified • *Speclase* shows good agreement with experimental spectra of 975nm tapered lasers • Spectral simulations accelerated by a factor >2 with secant update scheme showing faster overall acceleration • *Speclase* reproduces experimental characteristics of 1060nm split contact lasers; lower Rf and longer RW found to increase modulation efficiency • *Barlase* shows that the interplay between current competition, thermal cross-talk and strain significantly influences the degradation of bars • Both *Speclase* and ILDSP show good agreement with experiments

Partner	Summary of work performed	Main achievements
	WP2.2 Laser Characterisation • Filter etalon calibrated for S-ELM/S-PLM system • Intracavity ELM experiments performed on external cavity laser in an asymmetric feedback configuration • Spectroscopic intracavity ELM measurements performed on a 975nm tapered laser with windowed contact **WP5 Reliability** • By-emitter measurements made on red BA laser bars, 980nm tapered lasers on standard & expansion-matched heatsinks and tapered mini-arrays • Software platform further developed for the emulation of bar degradation using simulation tools • Investigations of current competition, temperature and strain on the operation and degradation of laser bars **WP9 Training, Dissemination & Popularisation** • Organised tutorials and training exchange visits • Hosted 1 exchange visit • Prepared materials for and attended ICT-2008 event in Lyon • Edited and distributed 3 e-Newsletter editions • Role in organisation of HPDLS meeting at Photonex 2009 • Actively pursued popularisation opportunities and managed media requests	**WP2.2 Laser Characterisation** • Replacement etalon received and calibrated • Agreement in trends observed in simulations and experimental of carrier density far-field of asymmetric feedback laser • Good agreement between intracavity spontaneous emission spectra and simulations, but results show the need for non-equilibrium effects to be included **WP5 Reliability** • By-emitter measurements performed on 12 bars after 2 aging steps for each bar • Emulations of hypothetical bars used to understand the role of temperature, strain and current competition on emitter performance • Barlase shows hotter emitters draw more current and emit more power due to reduced turn-on voltage - this is contrary to expectations • Emulations of real bars show some agreement with the by-emitter experimental results **WP9 Training, Dissemination & Popularisation** • 5 technical tutorials and 11 exchange visits took place (7 more than planned) • One exchange visitor hosted from DTU • >200 slide presentation for ICT event in Lyon • Delivered technical tutorial on external cavity laser modelling • Wrote eNewsletter articles on external cavity laser and laser beam quality • 4th, 5th and 6th eNewsletters published and distributed (>600 recipients) • Popularisation articles written about BRIGHTer, including two by the ICT results service

2. Workpackages

2.2 WP1 and WP2.2: Devices realization and characterization

Red Lasers at 635 nm, 650 nm, and 680 nm

OSRAM

Broad area laser bars emitting at 635 nm have been developed for photodynamic therapy applications. Based on the epitaxial material, chip processing and mirror improvement realized in this project, the mounted laser bars demonstrate an optical output power of more than 5 W meeting the project requirement.

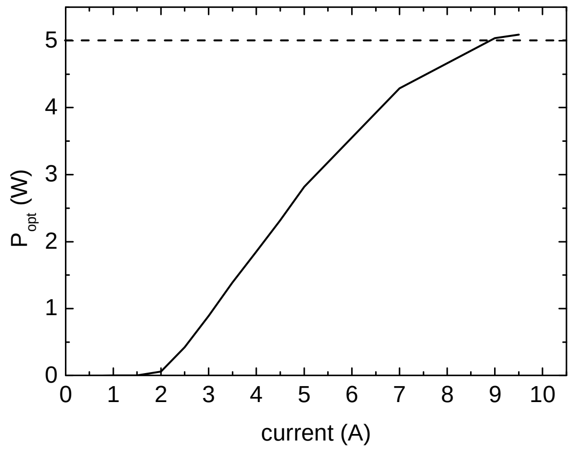


Fig. 1 Power characteristics for a broad area laser bar emitting at 635 nm at 20°C base temperature.

FBH

650 nm broad area laser with an output power up to 3.1 W and a reliable operation over 10,000 h at 1.2 W were developed for medical applications (WP6). 650 nm (for WP8) and 680 nm (for WP6) tapered lasers reached an output power up to 1.0 W with a nearly diffraction limited beam quality. They work reliable at 500 mW over 1,000 h. With the presented results the devices meet the project specifications.

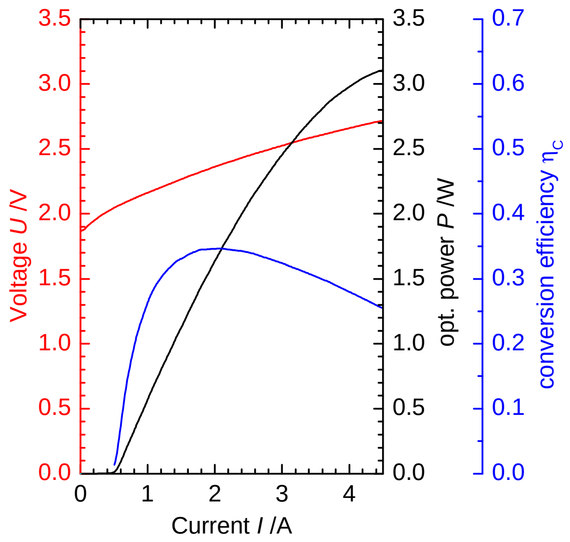


Figure 1: Power-voltage-current characteristics for a 100 µm x 1.5 mm 650 nm broad area laser at T = 15°C

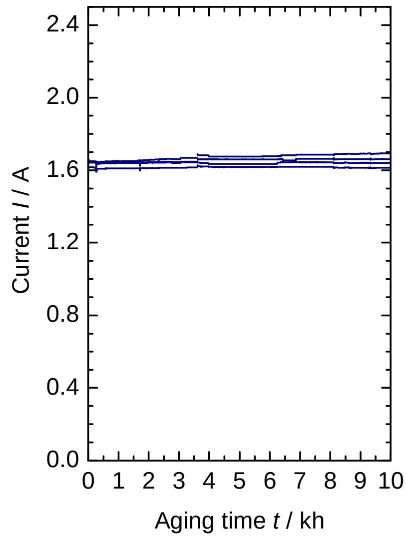


Figure 2: Reliability test for four 100 µm x 1.5 mm broad area lasers at T = 15°C and P = 1.2 W

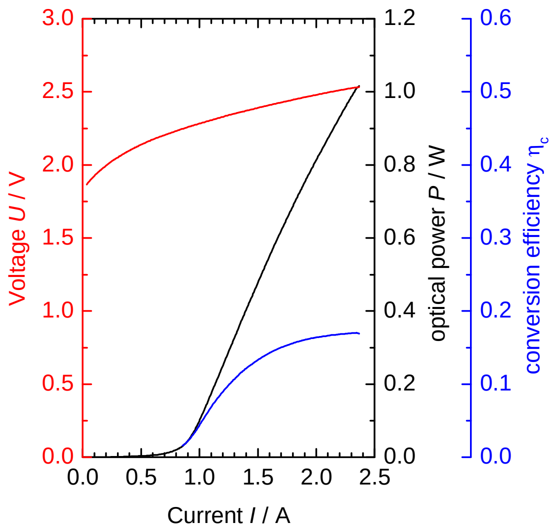


Figure 3: Power-voltage-current characteristics for a 2 mm long 650 nm tapered laser at T = 15°C

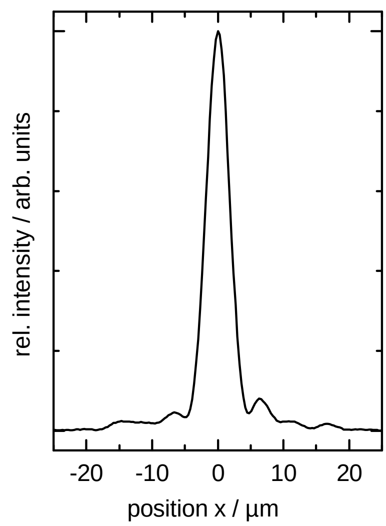


Figure 4: Beam waist for the device from Figure 3 at P = 1 W and T = 15°C – The beam waist width is 7.0 µm and more than 85% of the emitted power is in the central lobe. The beam propagation ratio M^2 = 1.3

TYN A low temperature intermixing process for 650nm AlGaInP quantum wells was developed. A 50 meV blue shift while maintaining reasonable photoluminescence intensity was achieved using a ZnO solgel as a promoter and a SiO2 layer as an inhibitor. The highest quality wafers show less shift implying a strong role for point defects incorporated during the growth.

810 nm tapered amplifiers

FBH 810 nm tapered gain media with small vertical far field angle below 15° (FWHM) were successfully developed within the first year of the project. In pulsed mode, tapered lasers reached an output power larger than 12 W and a nearly diffraction limited beam quality with $M^2 < 1.3$ within the central lobe. Herewith, the devices fulfil the target project specifications of the project.

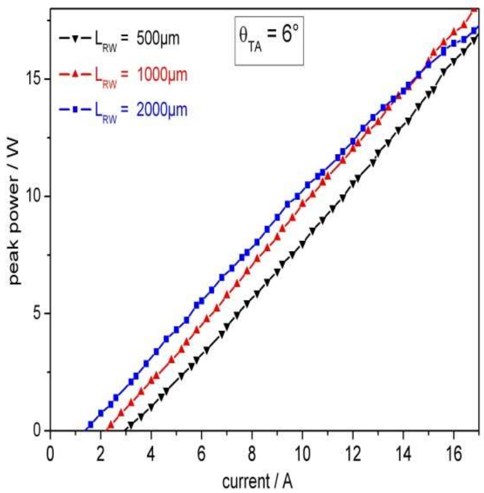


Figure 5: Power-voltage-current characteristics for a 4 mm long 810 nm tapered laser in pulsed mode (pulse length 100 ns, repetition rate 1 kHz) at T = 25°C

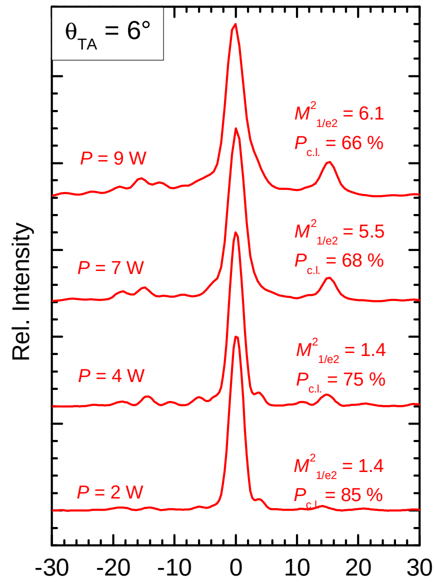


Figure 6: Beam waist for the 4 mm long 810 nm tapered laser with 1000 µm ridge length in pulsed mode (pulse length 100 ns, repetition rate 1 kHz) at T = 25°C

975 nm tapered lasers and bars

IAF The objective of IAF was to process and develop high power tapered diode lasers at 975 nm for various applications in the BRIGHTER project. In the third project year further improvement was made regarding the beam quality at high output power. Several single emitters were delivered to project partners ILT and FISBA. Single emitters with M2=2.8 at output power of 3W were demonstrated.

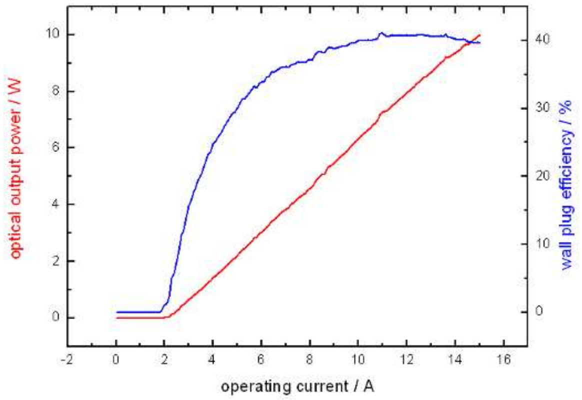


Figure 7: P-I-curve of a tapered diode laser with a tapered section length of 5 mm at a wavelength of 975 nm. Measurements were performed in cw operation at a heatsink temperature of 20°C.

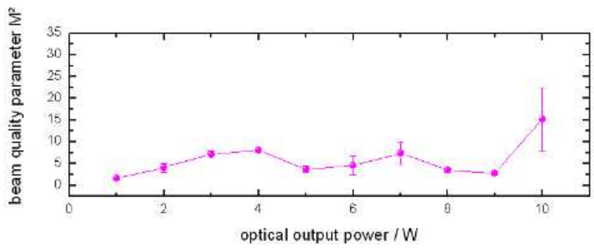
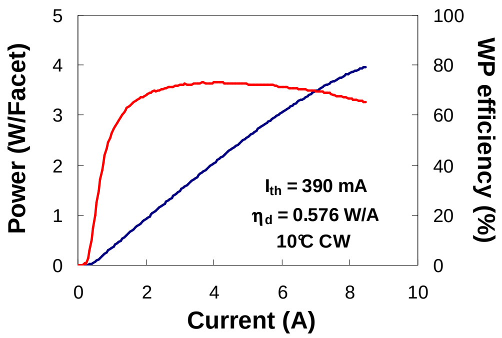


Figure 8: Beam quality parameter M2 as a function of the optical output for a tapered diode laser with 5mm tapered section length.

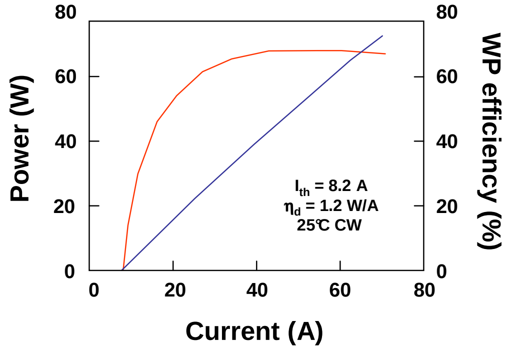
III-V Lab

975 nm high wall-plug efficiency lasers and bars

High wall-plug efficiency laser structures are useful in many applications, such as pump sources for telecom, when high optical output power together with low electrical input power are requested. In the BRIGHTER project, Alcatel-Thales 3-5 Lab has developed aluminum-free single emitter diode lasers that reach a high, state-of-the art wall plug efficiency of 71%, together with a high power of more than 3W per facet (uncoated laser). The project goal on these lasers was 70%. Based on these good results, we have also realised aluminum-free broad-area laser bars (1 cm wide) which deliver 70W optical power, together with a high wall-plug efficiency of 67%, which is higher than any commercial product available today. These good results have been made possible by close cooperation between 3-5 Lab and the other project partners, including Universidad Politecnica de Madrid for simulations and Fraunhofer ILT for bar mounting and characterisations. Further details are available in "High-Wall Plug Efficiency Broad Area Laser Bar with Strain-Compensated Quantum Well", IEEE International Semiconductor Laser Conference, 14-18 September 2008.



High wall-plug efficiency single emitter diode laser (uncoated, 200 µm x 2 mm)

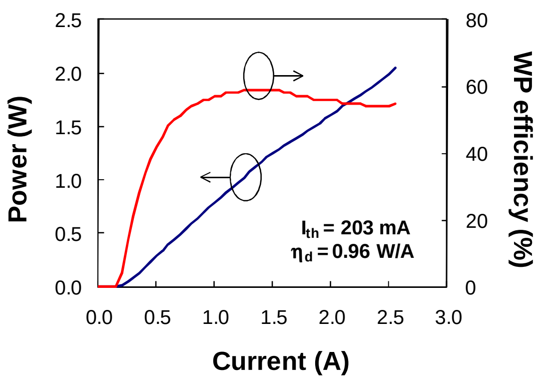


High wall-plug efficiency broad area laser bar (coated, 1 cm x 2 mm)

975 nm high brightness and high wall-plug efficiency index-guided tapered lasers

On the one hand, broad area lasers deliver high-power, but the large number of modes in their optical waveguide makes coupling into optical fibers more difficult. On the other hand, tapered lasers, which combine a single spatial mode section and a tapered section of increasing width, can deliver both high power and good beam quality. The quality of the beam is measured through the M^2 beam propagation ratio, which is higher or close to 1 for ideal beams. In cooperation with the Universidad Politecnica de Madrid for simulations, Alcatel-Thales 3-5 Lab has developed index-guided tapered lasers, which have a narrow output width (few tens of micrometers). On these aluminum-free active region lasers, we have obtained a high power of 2W, together with a good M^2 of less than 3, which matches the project goal. Moreover, the laser reaches a high maximum wall-plug efficiency of 56%, which is the highest reported for any kind of tapered laser.

Index-guided tapered laser waveguide geometry



High-power index-guided tapered laser output

1060 nm lasers

IAF The objective of IAF was to develop tapered diode lasers at 1064 nm for frequency doubling and display applications in WP8. Single emitter with P > 3W were developed with separated ridge- and taper-contacts to allow for high frequency modulation. All activities regarding this wavelength were finished in the second year.

FBH 1060 nm high brightness lasers for the efficient generation of 530 nm light with SHG for laser displays were successfully developed. An output power larger than 12 W (project goal 5 W) together with a small spectral line width Δλ ≤ 0.1 nm and more than 70% of the beam energy in the central lobe of the beam waist were developed. The vertical far field angle of 15° (FWHM) allows an easy beam shaping. The separate electrical excitation of ridge and tapered sections allows the easy modulation of the output power with small RW-currents. The modulation efficiency (up to 58 W/A) can be adjusted by proper selection of the maximum of the gain and DBR wavelength. The project goals for these devices are fulfilled.

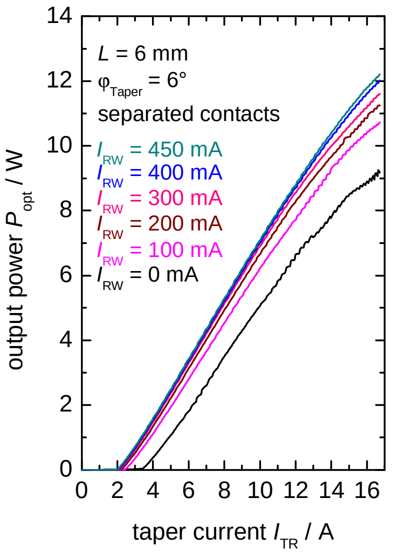


Figure 7: Power-voltage-current characteristics for 6 mm long DBR-tapered laser with separated RW and taper contact at $T = 15°C$

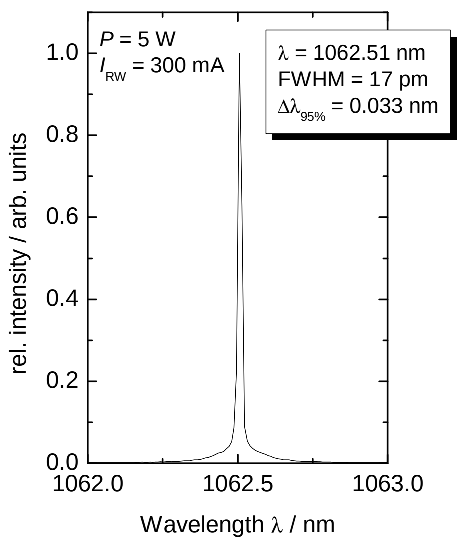


Figure 8: Spectrum at a power $P = 5$ W for the tapered laser from Fig. 7 and $I_{RW} = 300$ mA

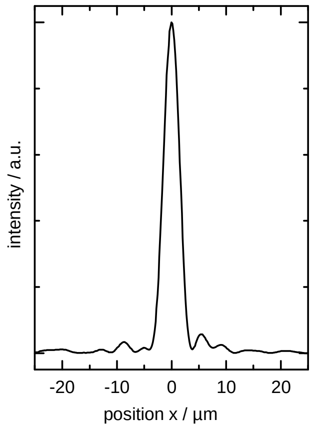


Figure 9: Lat. Beam waist for the tapered laser from Fig. 7 at P = 5 W and I_{RW} = 300 mA

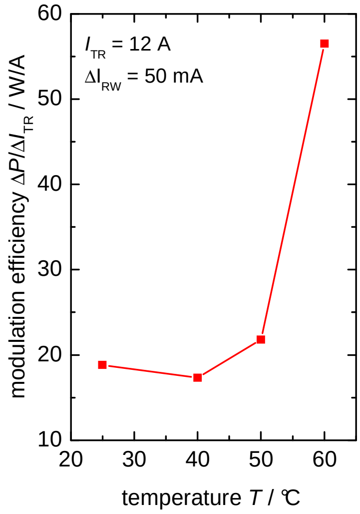
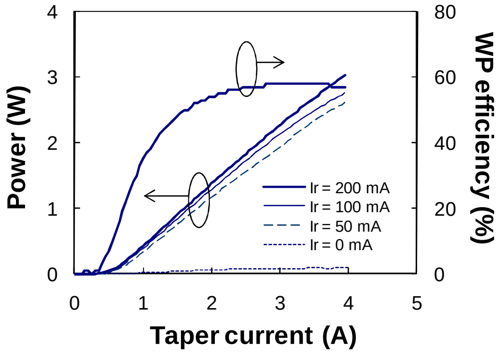


Figure 10: Modulation efficiency $\Delta P/\Delta I_{RW}$ versus laser diode temperature for ΔI_{RW} = 50 mA

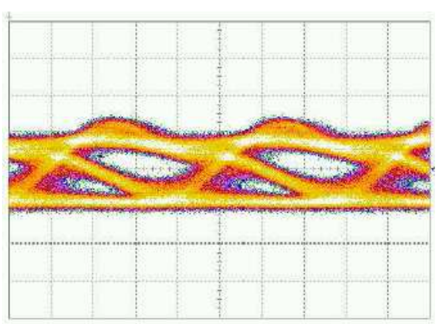
III-V Lab

1060 nm two-section tapered lasers for high-speed free-space optical communications

Free-space optical communications applications are useful from building to building or indoors. They require low-cost commercial diode laser drivers, which deliver a few tens of mA at high-speed (around 1 GHz). However, before the BRIGHTER project, such low current drive resulted in low power of tens of mW at the diode output, which required extra fiber or solid-state amplifiers. In the BRIGHTER project, we have developed two-electrode tapered lasers, which can deliver a high modulated output power without amplifier, together with a low drive current, which is the result of close cooperation between Alcatel-Thales 3-5 Lab, the Universidad Politecnica de Madrid, and the University of Cambridge. On these lasers, the ridge-waveguide section is operated with the high-speed low current driver, while the tapered section is operated with a constant DC bias of several Amps. In the dynamic regime at 700 Mbps, the output power of the laser moves from 22 mW to 1.68 W, while the control signal current moves from 22 mA to only 106 mA. This means that the modulation efficiency of the laser is of (1680-22)/(106-22) = 19 W/A, and the optical extinction ratio is of (1680/22) = 19 dB. Before the BRIGHTER project, the state of the art modulation efficiency of diode lasers was between 3 and 5 W/A using technologies such as Esaki Lasers or diode lasers connected in series. Further details are available in "High Modulation Efficiency and High Power 1060 nm Tapered Lasers with Separate Contacts", Electronics Letters, Vol. 45, n°2, pp. 103-104 (2009). Two-section lasers from Alcatel-Thales 3-5 Lab were packaged by Fraunhofer ILT, and were successfully used in a free-space optical communications experiments at 1 Gbps at Cambridge University.



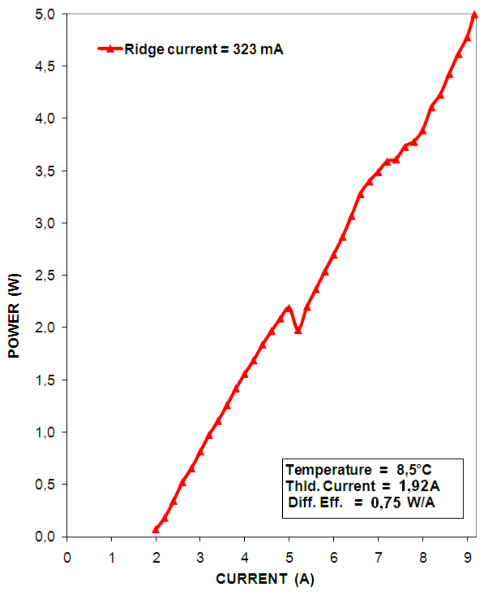
Two-section tapered laser power characteristics in the static regime.



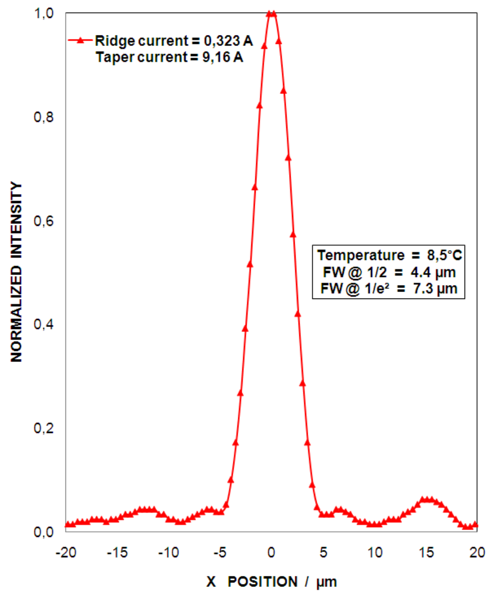
Open eye diagram at 700 Mbps (360 ps per division)

1060 nm high-brightness two-sections tapered laser

Based on an al-free active region, we have obtained two-sections high-brightness gain-guided tapered lasers at 1060 nmwhich deliver 5W CW with a very good M^2 beam propagation ratio of 1.1 at $1/e^2$, which matches our project target (5W with $M^2<3$). This result was obtained by increasing the current density in the ridge waveguide section. The total length of the laser is of 6 mm (1 mm ridge and 5 mm taper), with a taper angle of 4°. This result was made possible through cooperation between 3-5 Lab and the Universidad Politecnica de Madrid (for simulations).



Output power of the 1060 nm al-free active region gain-guided tapered laser



Near-field profile at waist, including with main Gaussian shape at 5W CW

920 - 1060 nm Quantum dot lasers

UKAS 920 nm and 1060 nm QD laser material were successfully developed and high device performance could be demonstrated. For 1060 nm also a new QW tunnel injection structure was investigated by UKAS demonstrating a strong improvement of the T0 value by doubling the value to about 200 K. Based on 920 nm QD material from UKAS broad area laser bars were processed by III-V Lab and characterized on the chip level by FhG ILT showing a WPE > 50% with a total output power of 38 W suitable for coolerless pump module (see critical path "Raman laser"), which allow a 15 W coupled fibre output power meeting the final project goal. Single mode emitting 1060 nm tapered lasers were developed by UWUERZ based on QD laser material from UKAS. 3 W single mode output power could be demonstrated meeting the final project goal.

We have applied the concept of tunnel injection QW to boost the temperature stability performances of our developed 1060-nm QD lasers for frequency doubling applications. The evaluation of the reciprocal external differential quantum efficiency and the threshold current density of lasers with different cavity lengths resulted in a high internal quantum efficiency, η_i, of 98 %, a relatively low internal absorption of $\alpha_i \cong 5$ cm^{-1}, and a modal gain coefficient Γg_0 of 33 cm^{-1}. The calculated transparency current density of the active material j_0 is 133 A/cm^2.

The temperature performance of the threshold current for a laser with cavity length of 982 μm is shown in Fig. 1. The insertion of QWs, which act as injectors for electrons, enhances the laser characteristics temperature of 197 K in the investigated temperature range 20-70 ^{o}C

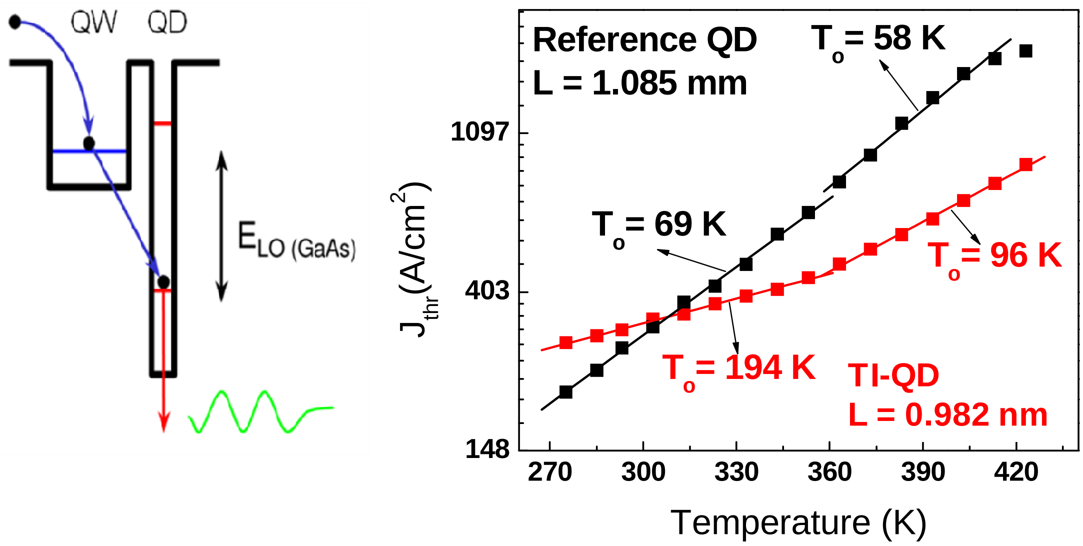


Figure 1. Left: Schematic conduction bandedge of a QW tunnel injection QD structure with LO phonon assisted electron tunneling. Right: dependence of threshold current density (logarithmic scale) on the operation temperature for a reference QD (black) and a tunnel injection QD laser (red). The continuous line represents a linear fit to the experimental points.

To our knowledge, these results show the first successful realization of the QW tunnel injection design in high power 1060 nm QD lasers and proves that this approach can be successfully utilized to boost the lasing performance and temperature stability (see also IEEE Photon. Technol. Lett. 21, 999 (2009)).

QD laser structures, based on a GRINSCH design show emission near 940 nm, low threshold currents in the range 200 to 400 mA and high slope efficiencies in the order of 0.5 to 0.6 WA^{-1}, depending on the cavity lengths. These structures have a high internal efficiency of 99%, a low internal absorption of only 1.1 cm^{-1}, and a low transparency threshold current density of 150 A/cm^2.The wavelength stability with temperature had a minimum of 0.25 nm/K.

Broad-area laser bars were processed at III-V Lab. The bars consist of 24 emitters, with a pitch a 400 µm, and an emitter width of 120 µm. The bars have a low reflectivity coating of 3%,on the front facet and a high reflectivity coating of 95% on the back facet. The laser bars were mounted on passively cooled submounts at FhG-ILT, and measured at 23°C CW (Figure 2) after device mounting. The bar allows a maximum output power of 39 W (30 W after 100 h burn-in) and a max. slope efficiency of 1.09 W/A. The wall plug efficiency is beyond 50%.

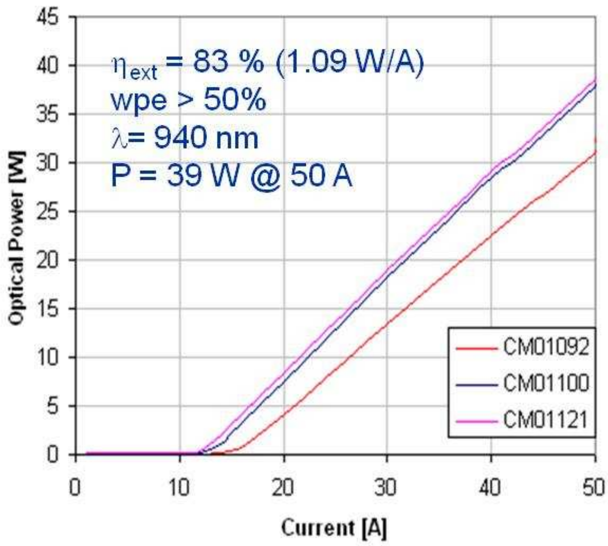


Figure 2 Power characteristics of several QDot broad area laser bars.

Tapered laser diodes with feedback gratings were fabricated by UWUERZ on 1060 nm quantum dot laser material grown by UKAS. The light output characteristics of the tapered lasers were measured in continuous wave operation. The corresponding light intensity curve of such a device is shown in figure 3.

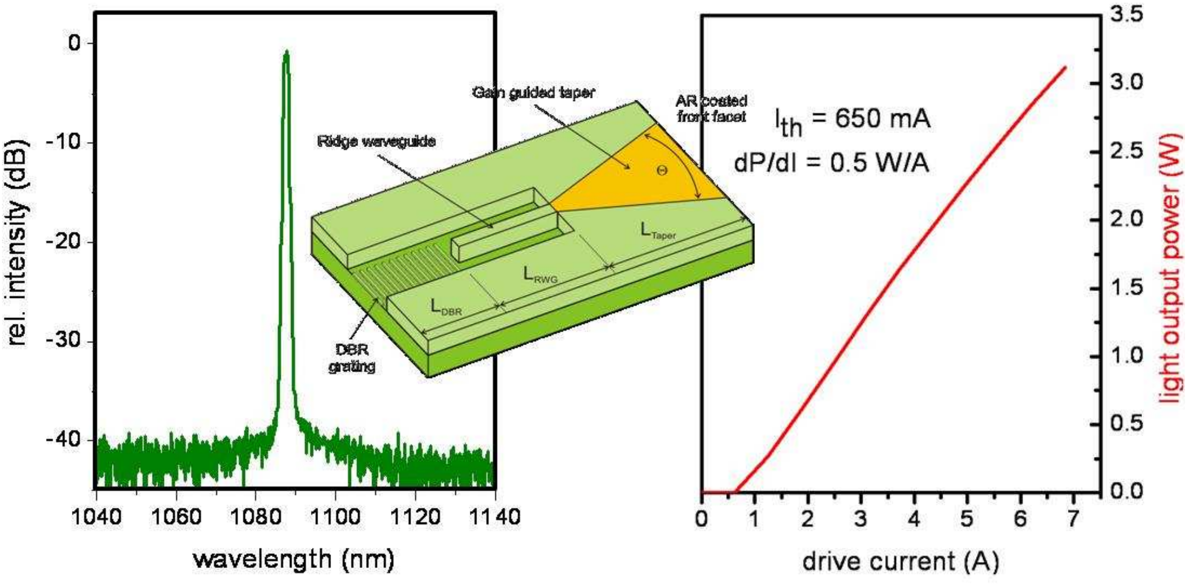


Figure 3. Left: single mode spectrum with SMSR = 38 dB at 3 W. Right: Light intensity curve for the tapered laser device with quantum dot active region showing an cw output power of 3 W. Centre: schematic drawing of tapered laser design with feedback gratings.

The 4.25 mm long single emitters show a threshold current of 650 mA. The light output power exceeds 3 W with a slope efficiency of 0.5 W/A. A maximum wall-plug efficiency of 29% could be measured. The emission spectrum at 3 W is single mode with a side mode suppression ratio of 38 dB.

Large spot size

TYN Large spot size designs (fast axis FWHM ~ 15°) for both quantum well and quantum dot active media emitting at 960 and 1060nm were grown achieving FWHM of 28°. A 4mm (1/3) long 6º flare large spot size flared laser based on a quantum well emitted >2.0 CW. Detailed 2D spatio-spectral characterisation was carried out.

2.3 WP2.1: Design and simulation of high-brightness laser diodes

During the first year, the modelling activities concentrated on the development of the modelling tools for advanced design activities and also on delivering the initial designs for the partners in WP1, WP3, WP7 and WP8. In particular, optimised design recommendations for 975 nm lasers diodes using asymmetric epitaxial design were delivered by UPM to III-V Lab. UPM delivered design recommendations for 920 nm QD lasers to UKAS. CAM and UNott provided the initial tapered laser phase coupled mini-arrays designs to III-V Lab. On 1060 nm tapered laser diodes with split contacts, UPM developed initial designs, UNott performed the first spectral simulations and CAM simulated the dynamic response for signals up to 1 Gbit/s OOK modulation. The design and simulation activities allowed TYN to design SCOWL lasers with beam divergence lower than 15 deg, while TRT developed large waveguiding structures, which effectively suppressed higher order modes. FHG-IAF improved the beam quality and efficiency of 975 nm and 1060 nm gain guided tapered lasers. CAM extended the dynamic model to simulate tapered laser diodes with Bragg gratings and tapered laser phase coupled mini-arrays. UNott improved the performance of the spectral laser simulation tool by reducing the simulation time and excess heat and also developed an initial steady state 2D model for tapered laser phase coupled mini-arrays. Furthermore, UNott developed a 1D steady state model and a 0D time domain model for self-adapting external cavity lasers. Work also started on the QD laser model (UPM), a model for current leakage in red lasers (UPM) and a model of an external cavity laser with asymmetric feedback (UNott). UPM extended the ILDSP to permit the simulation of split contact devices.

During the second year, the modelling activities concentrated on delivering laser designs for the partners pursuing the project objectives in WP1, WP3, WP7 and WP8. For WP1, UPM in cooperation with III-V Lab designed seven Al-free active region laser structures at 975 nm and 1060 nm, which contain two AlGaAs claddings two GaInAsP barriers, and one or two GaInAs quantum wells. UPM performed simulations of 1060 nm lasers with separated contacts, and proposed to III-V Lab the use of low front facet reflectivity to increase the modulation efficiency. These were fabricated and characterized showing agreement with predictions. UPM also delivered design recommendations for 920 nm QD lasers to UKAS, and studied the leakage current in red lasers, comparing the simulations with experiments by OSRAM. CAM and UNott provided new phase coupled mini-arrays designs based on tapered lasers to III-V Lab, including a design of phase-coupled mini-arrays with an integrated Talbot filter (UNott). TYN developed designs for 1060 nm large spot size laser diodes, based on epitaxies developed at UKAS and III-V Lab, which had a beam divergence lower than 20 deg and a confinement factor larger than 0.007. Furthermore, III-V Lab designed test electrical junctions for Esaki junction lasers. For WP3, UNott investigated the modal competition in external cavity lasers with asymmetric feedback. This analysis showed that the observed narrow far field patterns can be explained without the need to include four or two wave mixing effects. UNott also studied longitudinal mode competition in self-organising external cavity lasers. These simulations predicted self-consistent cavity modes with a single wavelength output spectrum. In collaboration with LCFIO, UNott performed a study of the optical filtering properties of external cavity lasers using the Talbot effect. For WP7 and WP8, UNott calibrated the spectral model against experimental results and performed a set of simulations for 1060 nm tapered laser diodes with split contacts. CAM performed isothermal dynamic simulations of 1060 nm tapered laser diodes with split contacts, which predicted up to 4 GHz bandwidth for these devices. Further simulations also showed that the bandwidth decreases by about 50% due to thermal effects. Significant effort was also invested during year 2 into the development of new models and the extension of existing modelling tools for the advanced design activities planned for the year 3 of the project. Here, CAM extended the dynamic model to permit the simulation of devices with multi-segmented contacts. UNott improved the performance of the spectral laser simulation tool by reducing the number of Fox-Li iterations needed to reach the solution. Furthermore, in collaboration with LCFIO, UNott developed a 2D steady state model for self-adapting external cavity lasers, and for an external cavity laser with asymmetric feedback (in collaboration with RISOE). In collaboration with LCFIO, UNott also developed a 2D model of an external laser cavity with Talbot effect. UPM introduced multiple conduction band valleys in the modelling tool to improve the simulation of red lasers. A new multi-population non-equilibrium model for QD lasers was implemented in 1D and extended to tapered lasers.

In the third year, the modelling activities continued to concentrate on delivering designs for partners pursuing the project objectives in WP1, WP3, WP7 and WP8. III-V Lab simulated three types of Al-free active region structures at 1060 nm for higher COMD (Catastrophic Optical Mirror Damage) and lower fast axis divergence angle. CAM performed isothermal dynamic simulations of 1060nm split contact tapered lasers to achieve good modulation performance. UPM compared simulations with experimental results of 1060nm single contact tapered lasers obtaining good agreement at low powers and differences in beam shape at high powers. The role of geometrical parameters was investigated and it was found that the beam quality improves using a higher index step. UPM also performed simulations to maximize the modulation efficiency of the 1060nm split contact tapered lasers. A larger taper angle and an asymmetric epitaxial structure were found to increase the modulation depth of the split contact lasers. UPM calibrated the internal parameters for 640nm lasers using experimental results provided by OSRAM. These were then used to simulate the mirror heating in the red lasers. UPM performed 3D simulations of SQD and DQD tapered lasers with identical geometry. A lower slope efficiency and higher threshold current was obtained for the SQD laser, which was interpreted as arising from a higher linear gain saturation. The use of designs with multiple QD layers, low taper angle and long cavities was recommended. In addition, tunnelling injection (TI-QD) lasers were simulated and the results were compared with experimental results of 1060 nm BA lasers provided by UKAS. Good agreement between simulation and experiment was obtained after adjusting the recombination and capture times of the QD and wetting layer. TYN developed designs for 1060 nm large spot size laser diodes based on a double anti-guiding layer in QD and QW epitaxies using low Al cladding to reduce the series resistance. For WP3, CAM and UNott performed further simulations on tapered laser phase coupled mini-arrays, including a design with an integrated Talbot filter (UNott). The simulations from UNott suggest that carrier lensing destroys phase locking at higher output powers. UNott developed and employed a simplified modal decomposition model, which revealed that the selective feedback of lateral modes is responsible for improving the beam quality of BA lasers using the asymmetric feedback technique and that 2-4 lateral modes participate in the lasing, limiting the minimum achievable beam parameter product to M^2~3. The intracavity imaging technique at UNott was applied to an asymmetric feedback laser and the spatial hole observed was in agreement with simulations. For WP7 and WP8, UNott improved the simulation parameters for 1060 nm split contact tapered laser diodes to obtain better agreement with experimental results. Further simulations using the improved parameters revealed an increase in the modulation efficiency for lower front facet reflectivities and longer RW section. Development of new models, improvement of existing tools and benchmarking activities were also performed during the third year. UNott improved the quasi-3D spectral laser diode model (Speclase) by employing the Kramers-Kronig method to calculate the real index change of the QW. The ASE model was also improved and verified against measured lasing spectra showing good agreement. The simulation efficiency of Speclase was improved by employing acceleration techniques based on extrapolating the fields forward in terms of roundtrips. Speclase was extended to allow the simulation of current competition, strain distribution and thermal crosstalk between emitters in a bar (Barlase). This provided a deeper understanding of the mechanisms affecting the degradation of emitters in a bar. For WP3, UNott developed a numerical solution of the Kukhtarev equations for photorefractive (PR) crystals to verify simple analytical models and to establish their range of validity. Both the ILDSP and Speclase were benchmarked against experimental results of a 975nm gain-guided tapered laser, with good agreement obtained for both models. The completed S-ELM system at UNott was used to image the spectrally resolved spontaneous emission distribution in a 975nm gain-guided tapered laser. The spectrally resolved images were found to be in agreement with simulations.

In summary, all activities have progressed towards the objectives set at the start of the project, mostly according to schedule.

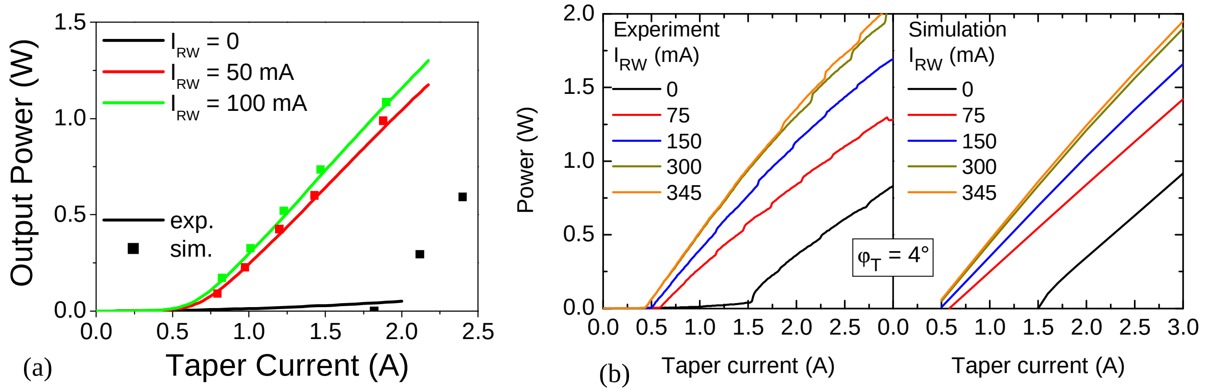


Fig. 1: (a) Simulated (using ILDSP) and experimental power-current characteristics of a 1060 nm 6 ° tapered laser (III-V Lab) with separate contacts. (b) Comparison of experimental and simulated (using Speclase) power - vs- taper current characteristics of a 4° split contact 1060nm DBR tapered laser (FBH) for different ridge waveguide (RW) currents.

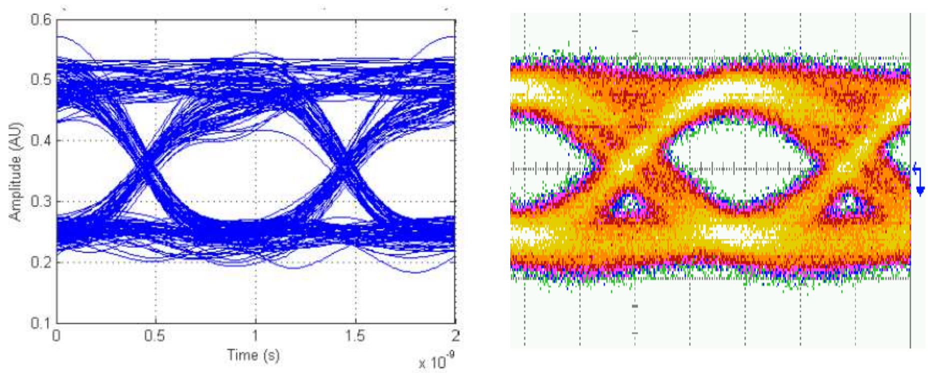


Fig. 2: Simulated (left) vs. experimental (right) output eye diagrams under data modulation for a 1060 nm twin-electrode tapered laser modulated at 1 Gb/s.

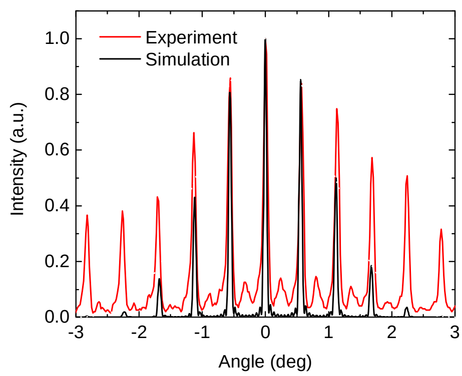


Fig. 3: Simulated vs. experimental far-field profile of the in-phase mode of a bar of 10 phase-locked 975 nm tapered laser emitters coupled by an external Talbot cavity.

2.4 WP3: External cavity approaches to high brightness and tunability

The objectives of the tasks in WP 3 are to improve the spatial and temporal coherence and the beam quality of high-power diode lasers to yield almost diffraction- limited tunable lasers that can be focused to a small spot. Furthermore, this work package focuses on the important development of compact, low-cost blue and UV frequency doubled lasers based on infrared and red external cavity laser diodes with high spatial and temporal coherence

In the project there have been three major initiatives: 1) improvement and optimization of the brightness in diodes with external feedback 2) development of blue and UV lasers based on nonlinear frequency conversion, and 3) development of a BBO waveguide for frequency doubling into 340 nm. The following main achievements have been obtained:

- DTU Fotonik has developed a pulsed 404 nm frequency doubled laser module with output power up to 720 mW

- DTU Fotonik has developed a pulsed 355 nm and 340 nm laser systems for the autofluorescence diagnostics module in WP 6. The specifications of the laser systems are so good that they exceed the specifications that originally were specified in the brighter project proposal. The 355 nm laser system has been transferred to LLC and has been used for clinical trials on autofluorescence imaging.

- DTU Fotonik has successfully brought an external cavity breadboard setup to UNOTT and used the setup for performing electroluminescence microscopy (ELM) measurements on a laser device from III-V lab with external feedback.

- LCFIO has investigated the origins of the power limitation of the single mode emission in the self-organizing extended cavities. It was found that around 980 nm an unexpected induced absorption of the photorefractive crystals is responsible for the multimode emission above an emitted power of about 600 mW. The experimental results are confirmed by the simulations.

- Coherent beam combining has been investigated at LCFIO both theoretically and experimentally with different bars provided by IAF-ILT and III-V Lab.

- Off axis spectral beam combining has been applied to a broad area diode laser bar and operated at a current of up to 35 A. The combined effect of spectral beam combining and off-axis feedback improved the slow axis beam quality from the free running value of approximately M^2 = 1580 to M^2 = 6.4. This resulted in a brightness of 79 MW/cm^2-str from the broad area laser bar system.

- Pressure cells allowing to combine pressure tuning, temperature tuning and external-cavity tuning have been developed by UNIPRESS. Osram lasers operating at 635 nm have been tested in these coolers and the commercial 734 nm high power laser. Furthermore, temperature tuning combined with external-grating tuning for the 802 nm tapered laser from FBH and for the commercial “bent waveguide” laser emitting at 1500 nm have been tested and pressure tuning has been combined with external grating tuning for the tapered 1050 nm laser from Thales.

- Red tapered diode laser systems based on external cavity feedback have been developed. One system tunable from 659 to 675 nm is demonstrated with a linewidth less than 0.07 nm. As high as 1.38 W output power is obtained, an M^2 value of 2.0 is achieved with an output power of 1.27 W. Another system tunable from 666 to 685 nm is developed with a linewidth below 0.07 nm. More than 1 W output power is obtained with an M^2 value less than 1.2.

- TRT has demonstrated effective multiplexing of a bar stack with 81% combining efficiency. The combined beam brightness is 12-16 times larger than the free-running diode laser bar.

- For the first time planar waveguides were implanted in BBO materials for doubling fundamental wavelength of 680 nm into 340 nm. Efforts to reduce the losses in the implanted material lead to an optimized planar waveguide with losses less than 10 dB/cm.

Below we outline in more details some of the important results obtained in WP 3.

Different tapered amplifiers at 670-680 nm have been tested in order to develop a pump source for the second harmonic generation in BBO waveguides. The lasers are tunable in the range 666-685 nm with a line width below 0.07 nm and the best M^2 value is <1.2. Power-current characteristics and tuning range for this laser is given in figure 1. This laser is suitable for coupling to BBO waveguides.

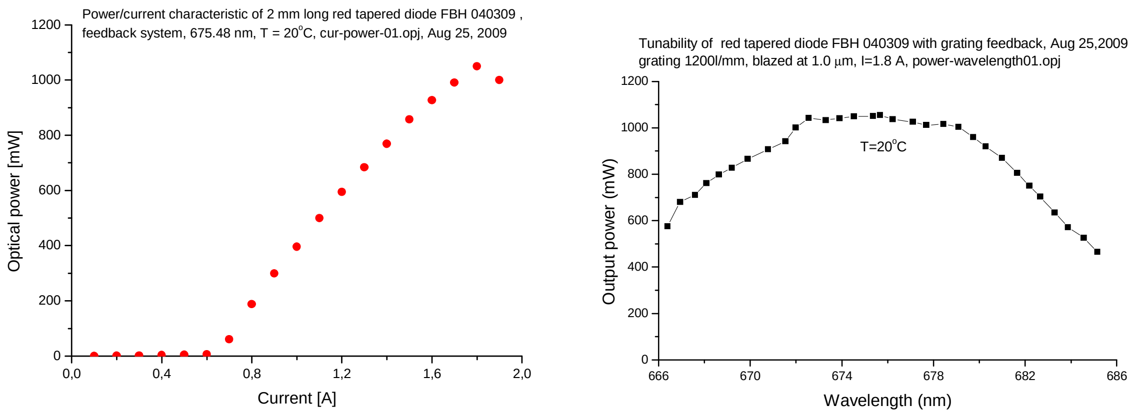


Fig. 1. (Left) Power current characteristics and (Right) tuning range for the 680 nm tapered laser system.

In brighter TRT have performed experiments on wavelength multiplexing of a laser diode bar stack. The wavelength multiplexing of the stack was performed in two steps:

- spectral locking of each diodes at different wavelength along the bars with a chirped Volume Bragg Grating (VBG)
- beam combining with a diffractive blazed grating.

The output beam is then beam-shaped with two cylindrical lenses to suppress astigmatism and symmetrise the focal spot.

At 10A, the output power is 13W. M^2 measurement has been performed for different number of bars (see figure 2 below). The fast axis M^2 increases steadily with the number of bars as expected. It is reduced while adding a “beam compressor” (from FHG-ILT) that reduces the spacing between the beams from the different bars. The slow axis exhibits almost the same M^2 for the first three bars (A to A+B+C) with a noticeable increase while adding the D bar. This reflects the good spectral locking and beam combining of the A, B and C bars and the ineffective one for the D bar, due to its collimated beam direction falling apart the acceptance angle of the VBG (out of specifications). The M^2 value for the three first bars is slightly higher than the M^2 value of single emitters.

While increasing the current (up to 25A), the M^2 remains stable in the fast axis direction but increases in the slow axis, accordingly with the increase of the M^2 of a single emitter.

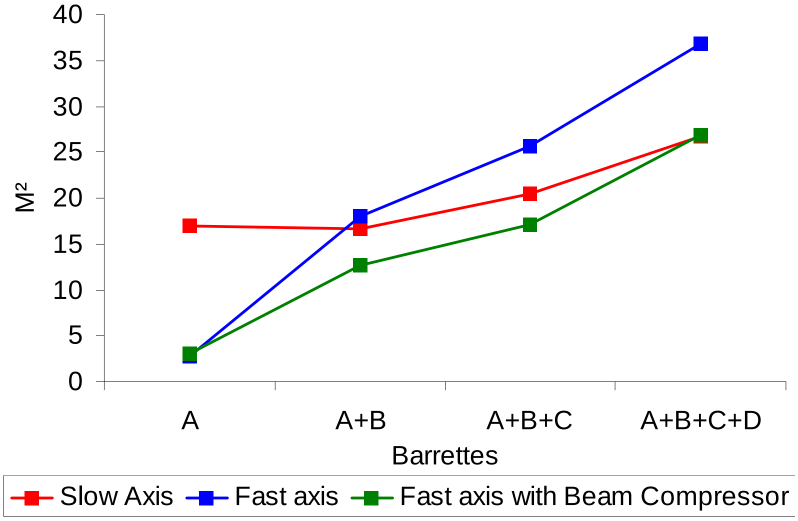


Figure 2. M² of the combined beam for 1 to 4 bars. Green : fast axis with beam compressor.

Coherent beam combining has been investigated at LCFIO both theoretically and experimentally with different bars provided by IAF-ILT and III-V Lab. We have focused our work on extended-cavity configurations, which result in a passive coherent combining of the lasers. Two extended-cavity designs have been studied: cavities based on the self-imaging Talbot effect, which induces a filtering in the near-field emission, and cavities using an angular-filtering (in the far-field).

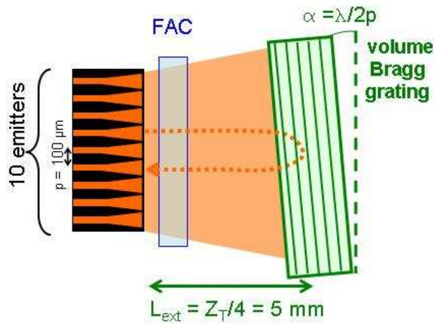


Figure 3 : Talbot extended-cavity diode laser array with a volume Bragg grating

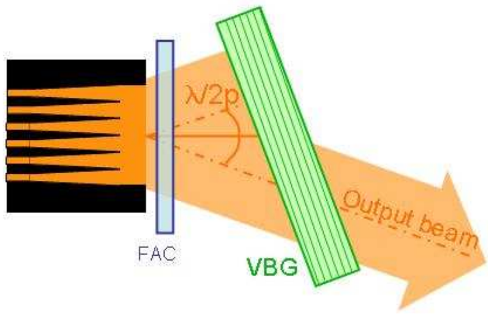


Figure 4 : Angular-filtering extended-cavity design for high fill-factor array

The angular-filtering extended-cavity has been studied in details during the last period; numerical modelling of the external-cavity operation, taking into account the angular selectivity of Bragg gratings, has been done. Experimentally, this configuration has been implemented with a bar of adjacent index-guided tapered lasers, with a ≅ 100% fill factor. Then the output beam is single lobe and close to the diffraction-limit ($M^2 < 2$), with up to 375 mW in the main lobe.

The Talbot extended-cavity configuration has resulted to date to the best results regarding the output power; different kind of bars have been used, either small index-guided arrays or wide gain-guided tapered bars.

The multilobed beam profile of a phase-locked laser array has been converted to a diffraction-limited, Gaussian-shaped, beam with the help of a diffractive optical element. This specific component has been designed and manufactured, and a simple optical setup has been realized . From the Talbot extended-cavity laser array, a maximum output power of 365 mW in a quasi-Gaussian beam with a M^2 of 1.7 has been obtained, corresponding to a conversion efficiency of 37%. We have also shown that this setup provides an effective measurement of the amount of optical power emitted into one supermode of the array; it is thus an actual evaluation of the coherence of the laser emission. This is the 1st demonstration of the coherent superposition of phase-locked diode lasers in an external-cavity setup.

In brighter we have developed a pulsed 355 nm laser system for an autofluorescence diagnostics module. The specifications of the laser system exceed the specifications from the beginning of the project. The laser system has been successfully transferred to LLC, implemented in an autofluorescence imaging module and used for clinical investigations. The laser system and the measured pulse train from the laser system are shown in figure 5.

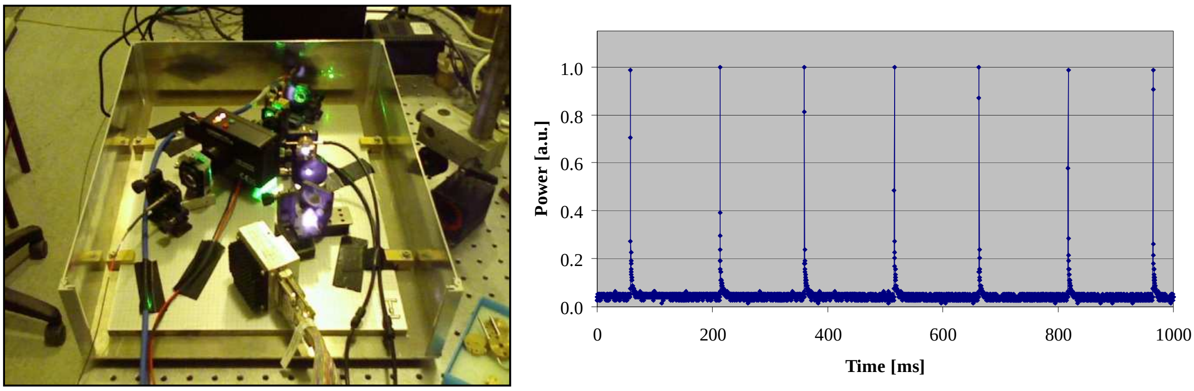


Fig. 5. (Left) Photo of the 355 nm laser system. (Right) Pulse train at 355 nm measured from the laser system.

The specifications of the laser system are given below.

Repetition rate 2 – 10 kHz

Average power 0 – 5 mW

Pulse duration 4 ns

Pulse energy 500 nJ

Peak power 100 W

In WP 3 we have furthermore successfully implemented a 404 nm frequency doubled laser module based on a tapered 808 nm pump laser diode with external feedback. The tapered diode is developed at the Ferdinand-Braun-Institute für Höchstfrequenztechnik in Germany. This laser pump source is operating in single mode with output power up to 1.2 W. Using a very compact cavity design shown in figure 6 (a) high efficient frequency doubling has been demonstrated. The external cavity consists of two reflecting concave mirrors and a nonlinear crystal (ppKTP) placed between the mirrors. One of the mirrors in the cavity is piezo-controlled and thus can be used to sweep the cavity in and out of resonance, which allows for pulsed second harmonic generation. The piezo mirror can either be externally controlled by a camera and a trigger system, or the camera can be controlled through the use of an arbitrary waveform generator. This feature allows using the system in fluorescence imaging applications where the blue laser pulses induce the fluorescence signal.

(a) (b)

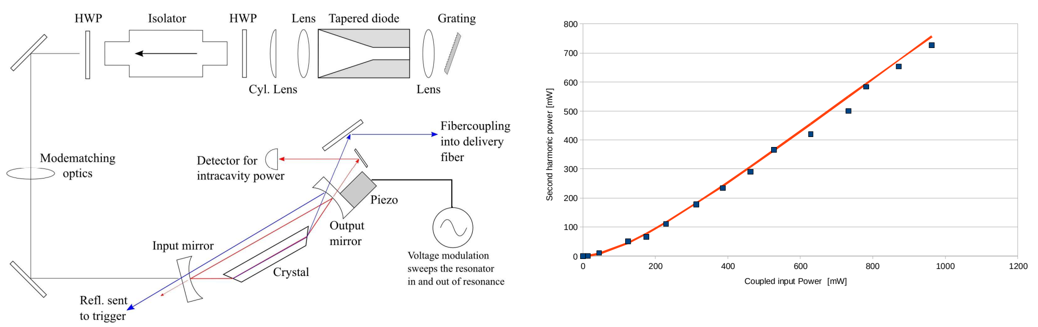


Figure 6. (a) *The experimental setup with SHG generation in an external cavity. (b) The experimental blue peak power at 404 nm versus fundamental couple pump power*

In Figure 6 (b) is shown the peak powers of the pulses versus the coupled input power in the external cavity. The pulses produced are up to 720 mW in peak power. This is to our knowledge the highest SHG power obtained in PPKTP at 404 nm. The new SHG laser module has been used for feasibility test in fluorescence diagnostics applications in WP 6.

The schematic setup for external cavity combined with pressure tuning is shown in Fig.7. If the pressure cell is placed in a cooler we can perform pressure and temperature tuning in external cavity. Cooling is necessary in case of pressure tuning of red InGaP/AlGaInP lasers.

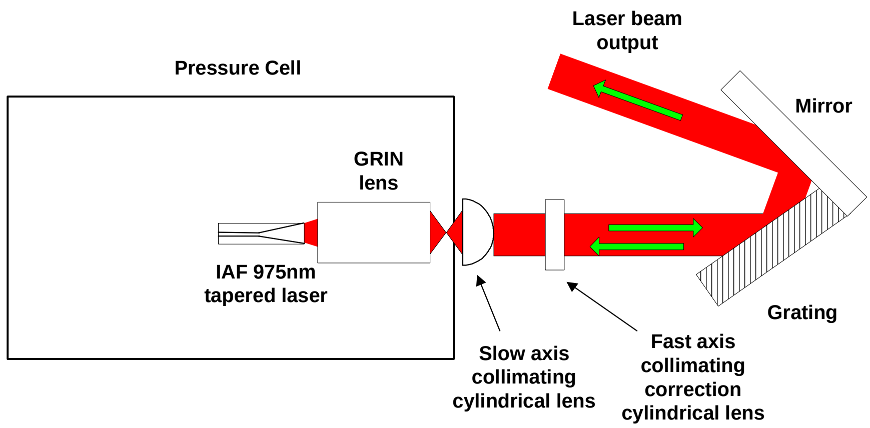


Figure 7 Setup of external cavity with grating in Littrow configuration combined with pressure tuning. The slow-axis profile is shown.

The results obtained in such setup for the tapered 975 nm laser from IAF are shown in Fig. 8. At ambient pressure the tuning range achieved with the grating is 20-25 nm while for a combined pressure+grating tuning we obtain 140 nm tuning range, with stable power above 600 mW and M^2=1.3 in the whole tuning range. These are the widest tuning ranges achieved for 975 nm laser diodes. In the visible range we demonstrated a 70 nm tuning range (from 643 nm down to 573 nm, as shown in Fig.9. These yellow-green wavelengths are the shortest ever achieved for InGaP/AlGaInP laser diodes.

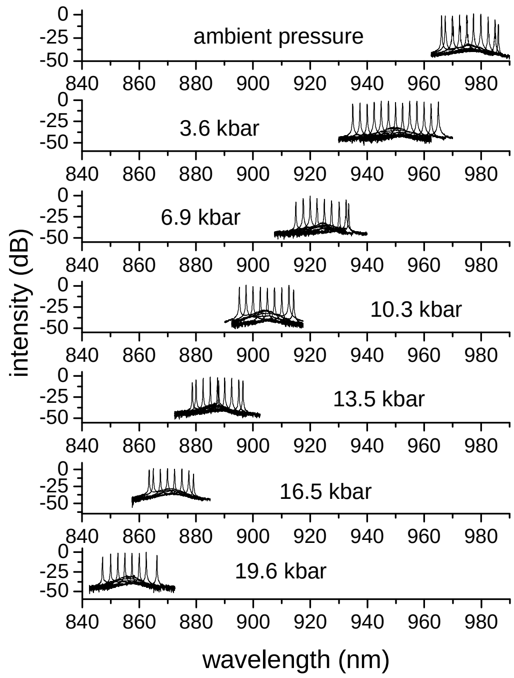


Fig.8 Emission spectra for the tapered laser coupled to external diffraction grating. At each pressure tuning with grating was performed (each emission line corresponds to a given position of the grating)

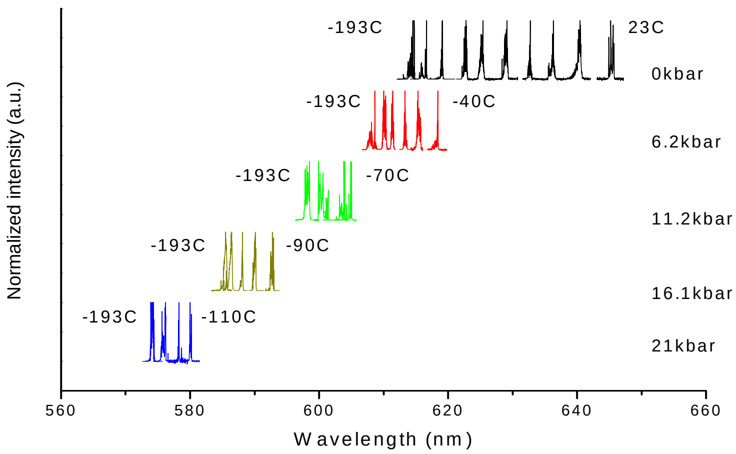


Fig.9 Emission spectra of the laser tuned by temperature at different pressures. The lowest temperature was -193°C and the highest depends on the pressure and is shown at the right-hand side of the spectra.

At RB for the first time, waveguides have been implanted in borate materials for doubling 680 nm fundamental light into 340 nm. The process consisted of: orientation of substrate crystal, first implantation to build a planar waveguide and photolithography processes in order to structure the channel waveguide. The waveguides were designed for efficient doubling of 680 nm pump laser with an $M^{2<}$<1.2.

Ridge waveguides were successfully implanted and submitted to the partners for further characterization with the pump lasers developed in the frame of this project. The waveguides were designed for efficient doubling of 680 nm pump laser with an $M^2<1.2$. A scanning electromicrograph of one of the produced waveguides is shown in figure 10.

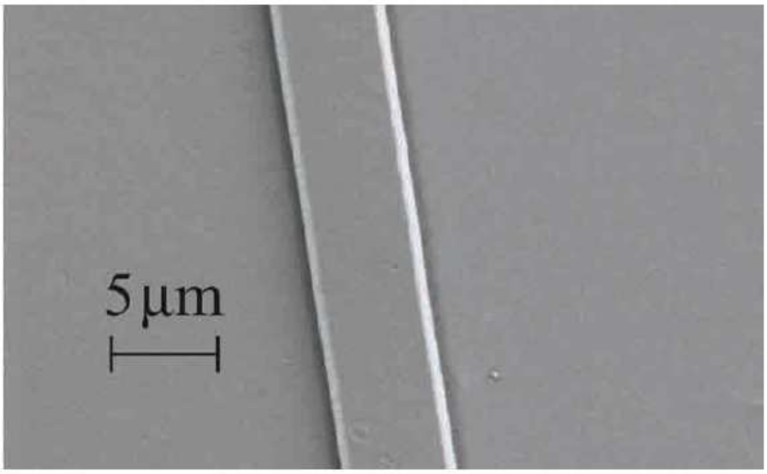


Fig. 10 Scanning electron micrograph (top view) of a BBO ridge waveguide with a width of 5 µm and a height of 1.7 µm fabricated by photolithography and Ar^+ ion etching.

2.5 WP4: Micro-optics and packaging

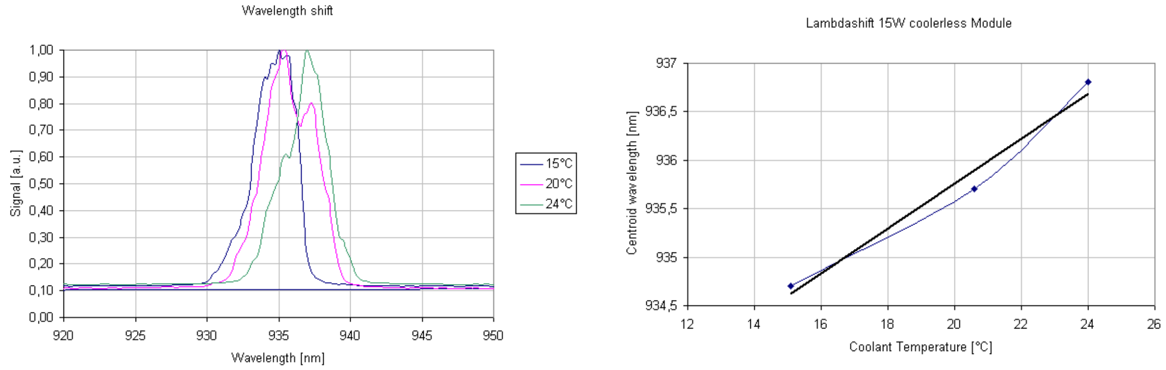
One of the objectives of WP 4 is the supply of tapered laser based pump sources for the telecom applications of WP 7. The following modules and devices are part of the work programme for WP4:

Module	Partner	Target Output Power	Fiber Coupling
ID4.1.5 Optical Stack for External Cavity Experiments	FHG-ILT	10 W	None
ID 4.3.1 30 W in 50µm Fiber Tapered Laser Module	FHG-ILT	30 W	50 µm NA 0.2
ID4.3.2 3.5 W SMF-Coupled Tapered Laser Module	FISBA	3.5 W	SMF
CD4.3.3 15W Coolerless Module with Quantum Dot Lasers	FHG-ILT	15 W	200 µm
ID4.3.5 20W in 200µm Fiber from 1 Tapered Laser Bar	FHG-ILT	20 W	200 µm
ID4.3.6 25W in 200µm Fiber from 1 Tapered Laser Bar	FHG-ILT	25 W	200 µm
ID4.3.8 12 W in 50µm Fiber Tapered Laser Module	FHG-ILT	12 W	50 µm NA 0.13
ID4.3.9 Modules for Free Space Communication	FHG-ILT	~0.5 W	100 µm

The optical stack for external cavity experiments (ID4.1.5) reached an output power of 10 W and a fill factor of 70%.

In SMF coupling experiments at ILT a coupled power of 1W was reached.

With CD4.3.3, the coolerless 15 W module, the first pump module based on a quantum dot laser bar has been built. The other 200 µm modules (ID4.3.5&4.3.6) also reached the required output power and were delivered to the project partners.



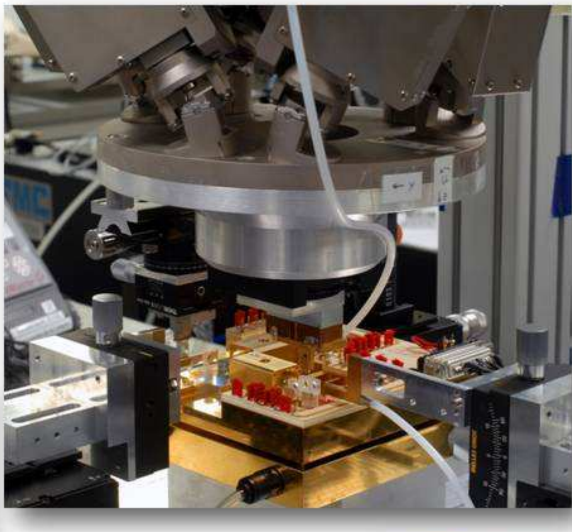
Wavelength Shift of the Quantum Dot Module CD4.3.3

For the 50 µm modules, the expected brightness per emitter was approximately reached (2.5 W compared to 3 W necessary to reach the specified output power), and the achieved brightness in the 50 µm NA 0.13 fiber exceeds the state of the art by 50%.

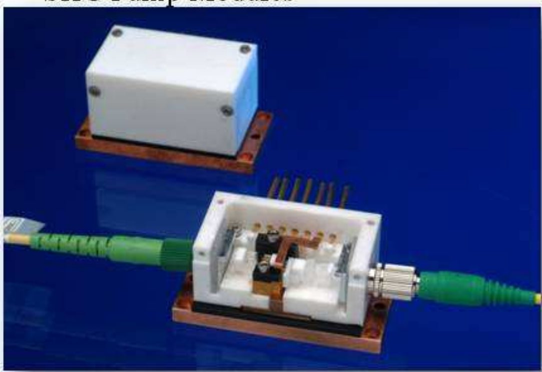
Two modules for FSO (ID4.3.9) were set up, one using a frequency stabilized Tapered DFB Laser from the FBH and one using a Tapered Laser from III-V Labs. Unfortunately the Module based on the III-V Tapered Labs Laser was damaged in transport to UCAM and could therefore not be used. A replacement module was set up at a later time, again using a III-V Labs Tapered Laser. For this last module UCAM requested the output power in a collimated beam instead of coupling it into a 100 µm fiber, as this seemed more promising for the free space communication experiments.

200 µm fiber coupled Module (IDs 4.3.3,4.3.5,4.3.6)

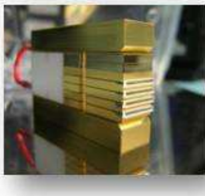
Work on 50µm fiber coupled Module (IDs 4.3.1&4.3.8)



Single Emitter module used for SMF coupling experiments, FSO Modules and SHG Pump Modules



Lensed Stack with high Fill Factor for External Cavity experiments



2.6 WP5: Reliability

An important part of this WP involves the reports on the achievement of certain lifetime goals. The achievement of these goals is verified in long-term aging experiments or accelerated aging experiments carried out by the device vendors. These results are used for lifetime estimates of the high-brightness devices. Such estimates are extremely important, because the end-users need this information for the qualification of their modules.

A second part of this WP involves own research, where the device vendors such as III-V lab, OSRAM, FHG, or FBH provide diode lasers, which are intentionally aged/degraded in order to understand the underlying mechanisms. By-emitter analysis and the research on the catastrophic optical mirror damage (COMD) process provide new insights.

- Consistent modelling of degradation processes and comparison with the experimental ‘by-emitter-results’ represent a completely novel approach to diode laser bar degradation and has the potential to become important for lifetime prediction.

- During the project the details of the COMD process are further investigated. The time resolution of the process was pushed from ms to µs, and finally to 1 ns. This allows seeing details in unsurpassed precision. Within the project, this particular work lead to 5 papers in Applied Physics Letters (2 are still in print) and 5 invited talks to international conferences.

Finally, the partners in WP5 concentrate core competencies in the field of semiconductor analytics, which are provided to all partners of the consortium. This mainly involves activities, which are not envisaged in the project planning such as extra photoluminescence or photocurrent measurements, which are necessary in order to clarify problems. Here the WP also provides service to the partners.

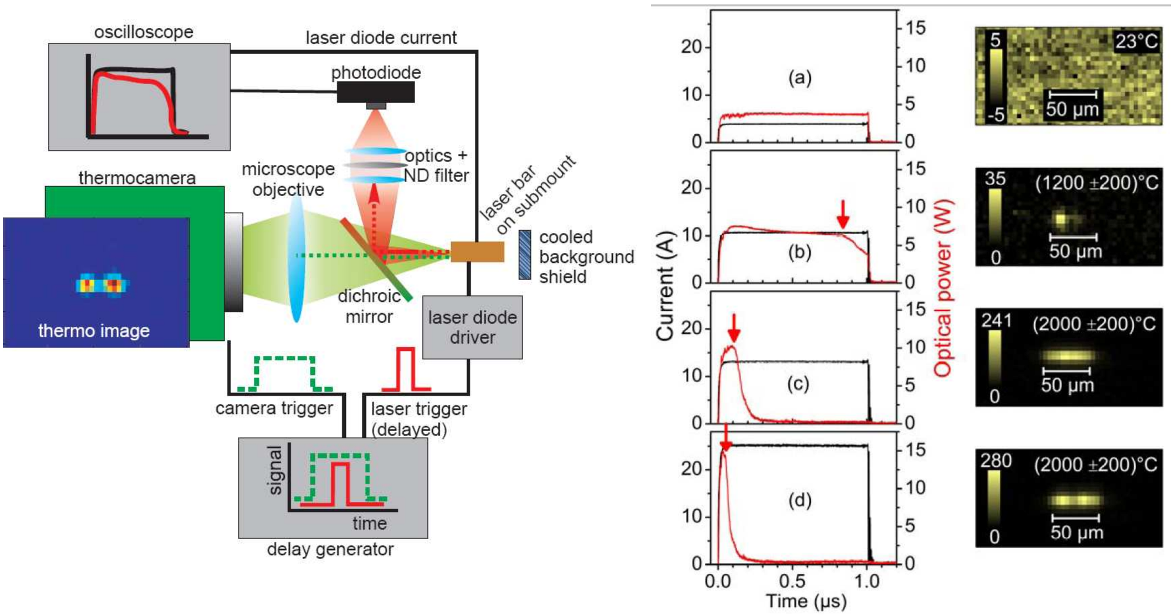


Figure 1: Setup for monitoring COMD events in 808 nm emitting high-brightness devices in single-shot operation. A dichroic mirror separates the emission spatially and spectrally. The primary emission is spatially integrated and detected by a fast photodiode (1 ns rise time). Planck's radiation is temporally integrated and displayed by a thermocamera. The right figures show typical current transients (black lines) and laser emission (red lines). The onset of COMD is marked by red arrows. The corresponding thermo-images are given in the right panel. Peak temperatures are estimated.

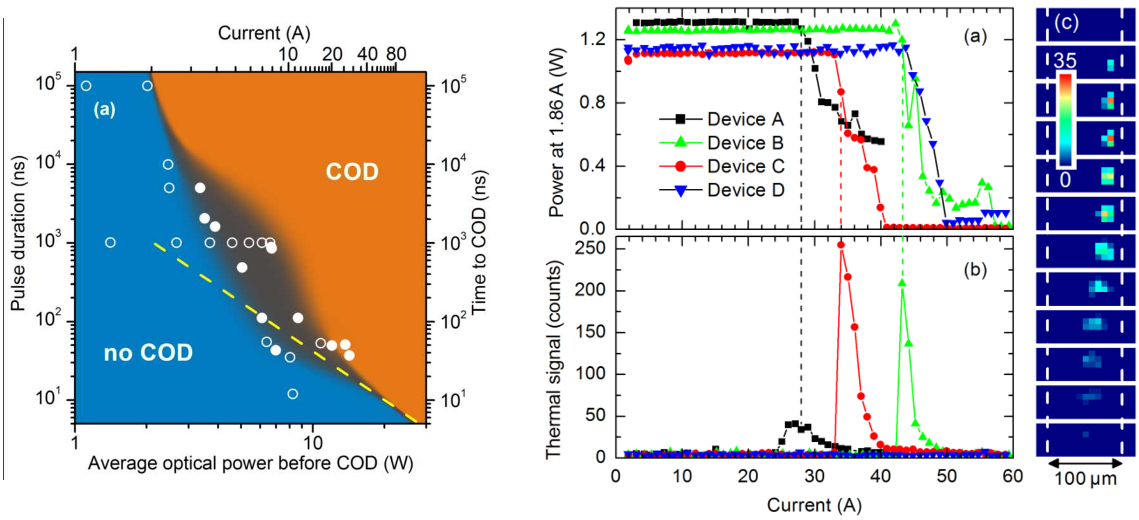


Figure 2: (left) COMD diagram showing the regions of COMD (filled circles) and no COMD (open circles) occurrence. The occurrence of COMD was derived from an analysis of thermo-images such as displayed in Fig. 1 (right panel). The borderline (colored gray) is blurred because of the randomness in filamentation and scatter in device properties. The dashed line shows the so-called "square-root law" determined earlier and shifted towards higher emission powers. (right) (a) Evolution of the optical output power from 975 nm high-brightness lasers during a current pulse of 1.86 A (as a measure of device degradation) after application of single current pulses with the amplitude given on the abscissa. (b) Thermal flash magnitude (intensity) as detected by the thermocamera. (c) Thermal images from device A taken during subsequent pulses with amplitudes from 24 to 35

A (from top to bottom, in counts). The emitter stripe width of 100 µm is indicated. These images clearly show the COMD process is re-ignited in subsequent pulses.

2.7 WP6: Medical applications

High-power, high-brightness laser system for interstitial PDT

A clinically adapted, high-power, high-brightness laser system for interstitial photodynamic therapy has been developed at Biolitec based on the red diode lasers developed by the partners FBH and Osram. Laser systems with different number of beam delivery channels and detection channels were targeted and thus a sufficiently modular and scalable system architecture had to be designed to address this requirement. The system allows the individual control of each port in an easily understandable and manageable interface. A user interface was developed and tested for its usability. The clinically adapted demonstrator incorporates the most essential safety and interface requirements stated in the medical devices directives.

Figure 1: The photo shows the iPDT system. It has 4 laser ports in the lower row of SMA connectors and 4 detection ports (upper row of SMA connectors).

Development of a pulsed 355 nm laser system for the autofluorescence diagnosis system

A pulsed 355 nm laser system for the autofluorescence diagnostics module has been developed by Risoe. The specifications of the laser system exceed the specifications from the beginning of the project. The laser system has been transferred to LLC, implemented in the autofluorescence imaging module and is currently used for clinical trials on autofluorescence imaging.

Furthermore, progress has been made in the development of a 340 nm laser system using two different approaches based on the contingency plan. This development resulting in more than 250mW peak power with a repetition rate of 5kHz is described in more detail in T3.6

Development and evaluation of the autofluorescence diagnosis system

A tissue autofluorescence imaging system is developed. A novel laser has been developed within the project for this purpose. A fruitful collaboration between several partners within two workpackages of the project led to this development. This laser with specifications meeting the requirements for this type of imaging is now integrated in the fluorescence imaging system developed. Successful collaboration between all the partners in the medical application WP also provided a possibility to evaluate this system in preclinical studies. The system has also been evaluated in clinical studies, well illustrating the possibility to utilize the system in the clinical environment. A data analysis program for absolute fluorophore concentration assessment has been developed and utilized in evaluation of data in scientific studies.

Development and evaluation of the fluorescence molecular imaging system

An epi-illumination fluorescence molecular imaging system has been designed and developed according to the specifications reported at the beginning of the project. The forward and inverse problem solvers have been encountered by developing sophisticated algorithms based on the coupled radiation transfer equation and diffusion approximation and on data fitting techniques. A software package, to control the system, to calibrate the fluorescence camera and to solve the inverse problem, has been developed. Moreover, through numerous phantom measurements the functionality of the fluorescence molecular imaging system has been evaluated, while the overall performance of the fluorescence molecular imaging system towards the solution of the inverse problem has been evaluated through phantom experiments (C.D. 6.4.2.4 – Evaluation of the Fluorescence Molecular Imaging System).

Preclinical evaluation of Interstitial Photodynamic Therary (IPDT)

The objective of this subtask was to preclinical evaluate IPDT treatment using the high brightness laser system, developed in BRIGHTER, and the special formulation of m-THPC encapsulated in liposomes in a murine model of prostate cancer.

The results demonstrated that IPDT with m-THPC encapsulated in liposomes and energy dose of 15J, not only effectively decreased the tumor growth rate (68%) but most significantly, managed to completely eliminate the tumor in 67% of the animals. Two months after complete tumor remission no tumor recurrence was observed. Also, the cosmetic outcome of the study was excellent.

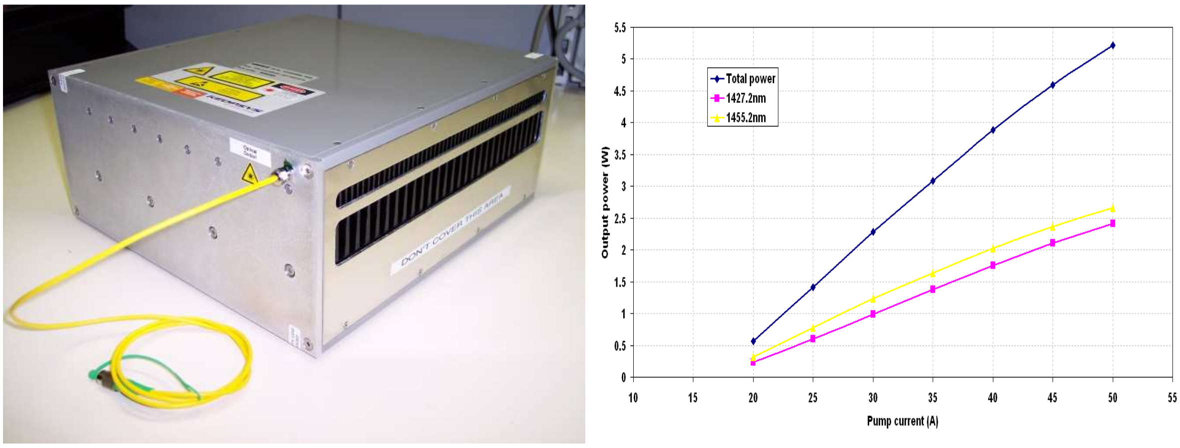
Another significant effect was the reduction of tumor growth rate (18%) at the animals that were treated with 30J IPDT. Although IPDT with 30J energy dose did not manage to cure the animals, it is considered effective, as it delayed significantly tumor growth rates.

In conclusion, the photodynamic therapy in prostate cancer animal model with the special formulation of m-THPC encapsulated in liposomes and the laser system at 652 nm that was developed in BRIGHTER has been shown to be an effective therapeutic option for the treatment of prostate cancer. These results are promising for further investigation of this laser and photosensitizer system and its clinical implementation.

2.8 WP7: Telecom applications

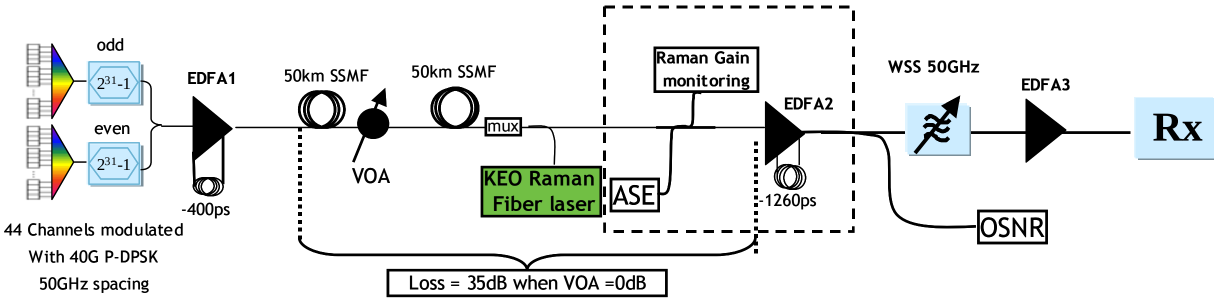
Telecom

Raman : Using the 25W 200µm module, **Keopsys** has built a 2λ Raman Fiber delivering up to 5.2W. The photo of the prototype is display below in the left, With this laser **Alcatel-Lucent** has achieved up to 30dB of distributed Raman gain achieving penalty free operation for 44 P-DPSK 43Gbit/s channels propagating though a span with equivalent loss of 55dB.

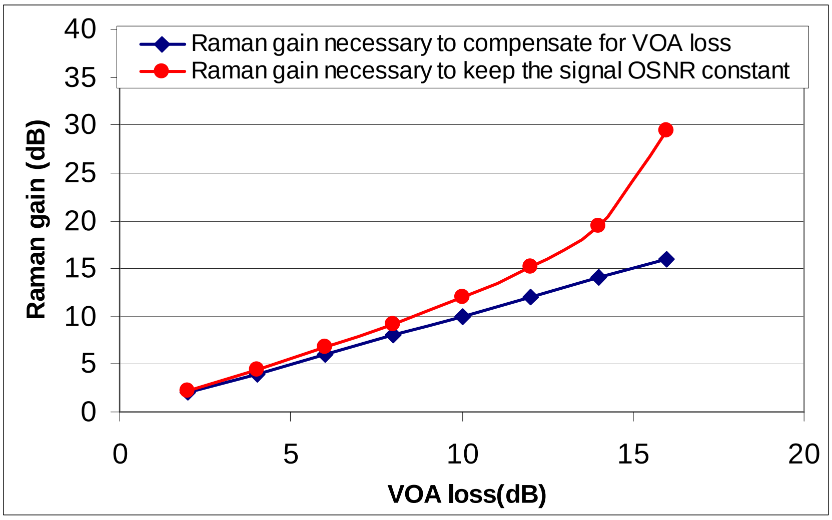


a) b)

a) 2 λ Raman Fiber Laser of **Keopsys***: photo of the prototype b) output power as a function of pump current*



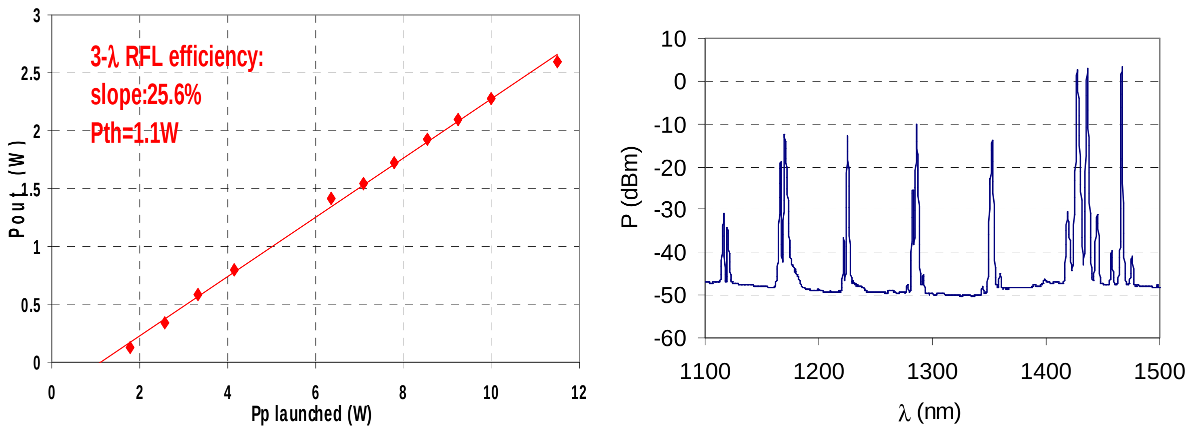
Alcatel-Lucent experimental set-up for system experiment



Distributed Raman obtained for two configuration

Alcatel-Lucent has also demonstrated a 3λ Raman Fibre delivering 2.6W using the 20W 200µm module. Moreover, the power of each output wavelength at 1427 nm, 1437 nm and 1467 nm is tuneable thanks to the output fiber Bragg gratings, which can be mechanically stretched. This tuneability is required in order to get a flat gain when the RFL is used as a pump for Raman amplification

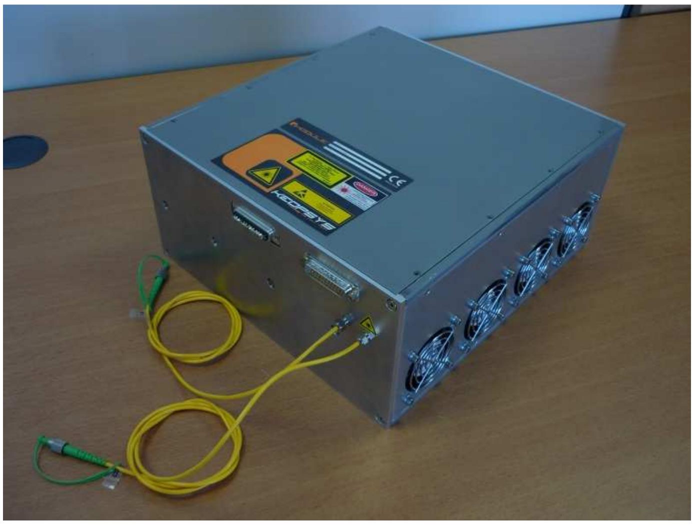
Alcatel-Lucent has developed a simulation tool for multi-output wavelength Raman Fiber lasers that enable predict accurately the performance and to design with such laser.



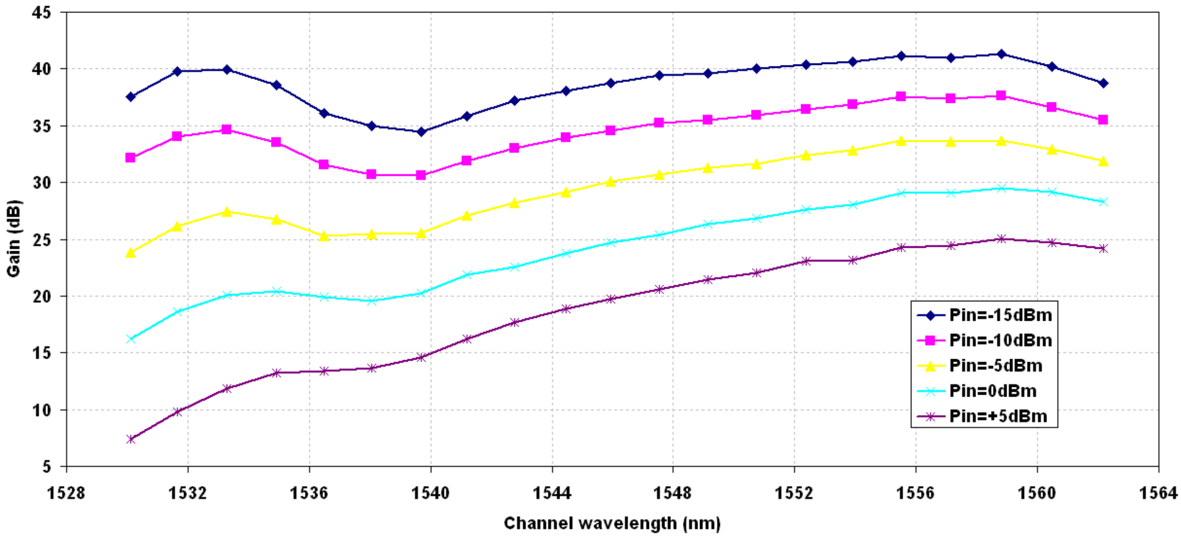
a) b)

a) output power of the Raman fiber laser, b) output spectrum of the Raman Fiber Laser

EDFA : **Cladding-pumped EDFA** Using the 50µm multimode module delivering 3.2W, **Keopsys** has built a cladding-Pumped EDFA using Fiber and Multiplexer of Alcatel-Lucent. This EDFA delivers 0.44W (26.4dBm). Calculus shows that with a 12W 50µm multimode module, 1.95W (32.9dBm) would have been obtained.



Kéopsys *Cladding Pumped EDFA prototype*



Gain versus channel wavelength, different input powers of **Keopsys** *Prototype*

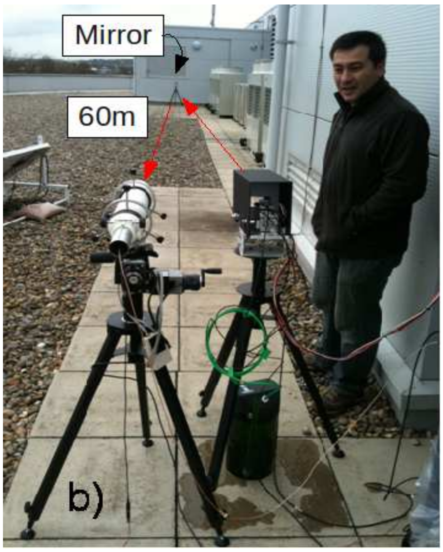
Alcatel-Lucent has developed a simulation tool for cladding-pumped EDFA. This tools enable to design EDFA and also to optimized cladding-pumped fiber parameters.

Single mode EDFA

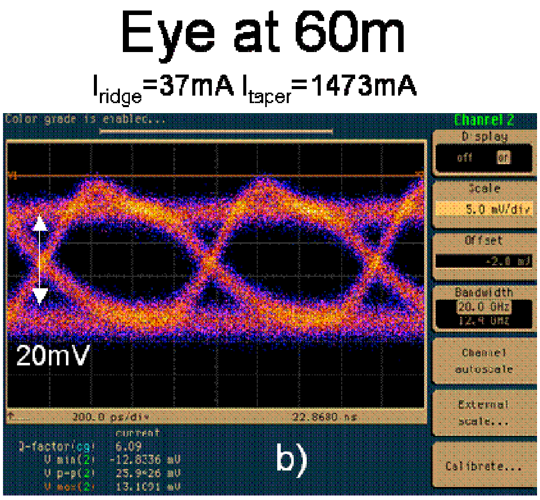
Alcatel-Lucent has made numerical study and defined optimized architecture for the high power single mode EDFA as well as optimized erbium doped erbium doped fiber high power application.

Free space Optics

UCAM has demonstrated a free space optical communication system that is capable of error free transmission over a 60m link at 1.25Gbit/s. The 1060nm twin contact laser achieved a modulation speed of 1 Gb/s with a record 0.95 W OMA using a 68 mA current swing at the ridge section and a constant 3 A tapered drive current corresponding to a record modulation efficiency of 14 W/A at 1 Gb/s under these drive conditions. The optimised devices operated error free with an extinction ratio of 11.5 dB at 1.25Gb/s. Transmission tests at 1.25Gb/s were carried out over a 60m outside path and a high quality received signal was demonstrated with a Q-factor of 6.09



Free space transmitter and receiver carrying out outside FSO link test on roof of CAPE building



Received 1.25Gb/s eye diagram after 60m link

2.9 WP8: Laser sources for display applications

The scope of this work package is the realization of a green and red laser module suitable for display applications (holographic projection and flying spot).

During the first two years of the project the different building blocks for laser modules have been developed. Evaluation of different IR laser sources, design of the optics and the two laser module concepts have been in focus of the work. Additionally modelling of the SHG process and corresponding experiments have been pursued. The main work of the final period focused on the integration of the different building blocks into working modules and the subsequent testing of the feasibility of the laser modules.

A red laser module could be demonstrated with an output power of ~300 mW in cooperation between partner FBH and FISBA. The green laser module provided by FBH-ILT shows an optical output power of ~500 mW under CW excitation together with good beam parameters. Additional high frequency modulation experiments have been pursued with this laser concept in a bread board setup at project partner DTU FOTONIK, showing the path for substantial improvement of the modulation depth of this laser concept.

According to the project plan, these lasers have been characterized as excitation sources for a two colour holographic display.

Holographic projection using tapered lasers

The tapered lasers developed in the Brighter project emit a high power single mode beam of narrow linewidth. The main advantage of three monochromatic laser sources in a laser projector is the extended colour gamut compared with a filtered halogen lamp. A warm white light can be created from the Red and Green lasers in the absence of the blue one. The taper amplifier integrated with the laser provides a single mode output beam, which can be propagated to the display device using anamorphic optics. The latter produces an elliptic spot profile which is well matched to the 16:9 aspect ratio of the HDTV screens used in the UCAM holographic projector. The optimum beam waist at the liquid crystal on silicon (LCOS) device is a trade off between overfilling and underfilling the device area. Overfilling results in loss of efficiency due to the light outside the display area being lost. Underfilling results in a less efficient holographic replay. The optics was designed so that the visible edge of the beam profile along the major axis filled the long axis of the display. The LCOS device displays an analogue phase hologram which is designed so that an image is displayed in the far field. A collimated laser beam is reflected from the device and the image appears at or near the focal plane of the lens which is used to collimate the light onto the device (Fig. 1). A mirror with a central hole of 1 mm diameter reflects the image and filters the zero order beam which would otherwise present a spot at the centre of the display. The reflected image is magnified onto a screen using a projection lens. The efficiency is that 24% of the input light is present in the projected display. A photograph of the screen is shown in Fig. 2.

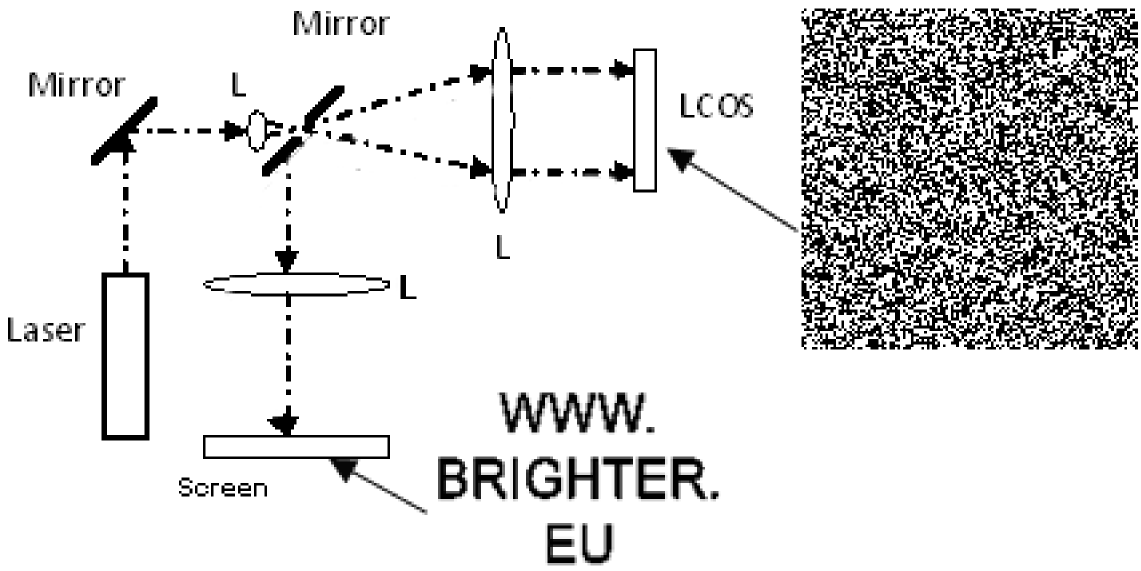


Fig. 1 Schematic layout of a monochromatic holographic projector

The important aspects for the laser source in this work are: ease of use; robustness; stability; controllability; beam conditioning; coherence; brightness; and sensitivity to environmental perturbations. The Brighter lasers could be developed into turn-key projects where a simple solution for display could be delivered. The robustness of the green laser allows multiple switch-on switch-off cycles during testing in the projection system. Some fluctuations at start-up disappear after one or two minutes warm-up. The digital control of the green laser has been tested up to 100 MHz. The beam profile of the green laser can be readily expanded up to the required shape for the LCOS device using a 4f optical system. Further beam shaping can be done to optimise the diffracted spot size at the screen for coherent light. The spatial coherence of both the green and red lasers are adequate for this application. The thermostatting of the key elements of the laser (diode, frequency doubling crystal) means that the lasing efficiency is independent of environmental factors.

Fig. 2 Replay of hologram in holographic projector using green laser from ILT

2.10 WP9: Training, Dissemination and Popularisation

Overview

The high level of sustained effort from the Consortium across the activities of Workpackage 9 “Training, Dissemination and Popularisation” has resulted in a broad range of achievements, which have all contributed to the dissemination of knowledge both within and outside of the Consortium. The main achievements include:

- 14 technical tutorials presented, filmed and available online
- 32 exchange visits (twice the number planned)
- Biophotonics Summer Schools in 2007 and 2009
- Development of a popular and informative website
- 6 e-Newsletters distributed to a wide audience (>600 recipients)
- Specific workshops organised at conferences and project meetings
    - High brightness laser sources workshop at CLEO Europe 2007
    - Organisation of the international DRIP-XII conference in 2007
    - Dedicated workshop on Toxicology and Safety in III-V Epitaxy
    - Organisation of the international NUSOD conference in 2008
    - Significant involvement in HPDLS meetings in2008 and 2009
- Project representation at EC ICT Event 2008
- Production and popularisation of a project film clip
- Learning materials in RichMedia CD format (17 video presentations online)
- Press release widely published – many further articles written about the project
- Scientific dissemination through more than 300 papers and presentations

Project Logo

The project logo (see Figure 1) was established at the very beginning of the project. It is used on all project documents, communications and the project website giving a clear identity to the project. The logo concept for BRIGHTER was based on the BRIGHT logo to indicate the clear link between the two projects and consortia.

Figure 1: BRIGHTER project logo

Website

The project website for BRIGHTER is available at http://www.ist-brighter.eu. The website has been continually updated over the course of the project and now contains more than 50 downloadable PDF documents (newsletters, tutorials, workshop presentations and press releases), 17 downloadable RichMedia presentations (tutorials and workshop presentations) and 28 video files that can be streamed online (film clips, tutorials and workshop presentations).

Since the launch of the website a wide range of daily, monthly and annual usage statistics have been collected. These demonstrate the popularity of the website, the visibility of the project, the importance of high quality downloadable materials and the effect of good publicity on the use of the website. Over the period from mid June 2008 to mid May 2010, the total number of visitors was 18,711 (from ~100 countries around the world), the total number of pages viewed was 43,458 and the total bandwidth was 525.16 gigabytes. This clearly indicates the need for a high capacity, resilient, web server. The link www.ist-brighter.eu is present on many different websites and the website was publicised in all project correspondence, press releases, e-Newsletters and at the ICT 2008 event.

The PDF documents, video files and RichMedia presentations have been viewed / downloaded more than 17,000 times. This represents 40% of the total number of pages viewed on the website. From these figures, it is clear that having documents to download and /or view online was extremely popular and the provision of such materials is very important for a good quality website. The most popular documents were the e-Newsletters followed by the tutorials. The online distribution of the e-Newsletters added significant numbers to the readership achieved by direct mailing alone.

The statistics for the opening / downloading of the PDF press release can be broken down further as there were several versions for different countries and languages. Of the ~2,500 views / downloads, ~70% were for non-English language versions while ~30% were for the English language versions. These figures demonstrate that viewers like to be able to read things in their own language and that the extra effort expended in preparing the translations was worthwhile.

Technical Tutorials

Technical tutorials formed a key part of the Consortium's training activities, particularly for the training of young researchers and technicians. These tutorials in specialised topics related to high-brightness laser technology were prepared and delivered by senior scientists within the Consortium. At each project meeting, two 1-hour tutorials were normally given and video recorded. Following their presentation within the Consortium, the tutorials were made available for public download on the website, (http://www.ist-brighter.eu/tutorial.htm). The video recordings were also processed to produce RichMedia format presentations (see below). The availability of the tutorials on the website was advertised in the project e-Newsletters. Over the course of the project 14 tutorials were delivered. The 11 tutorials that were presented during the BRIGHT project are still available from the BRIGHT website (http://www.bright-eu.org/bright-eu/publication/work/info/index.htm.

Exchange Visits

Training exchange visits, predominantly for younger researchers, were another key part of the Consortium's training activities. A total of 17 such exchanges were planned at the start of the project. However, during the project, further opportunities were identified for exchanges between partners and a total of 32 exchanges actually took place. These exchange visits supported interactions between collaborating partners and led to joint publications. Each exchange visit was reported upon at the next available project meeting. This took the form of a 5 minute presentation given to the Consortium by the exchange visitor and the preparation of a 1 page report. The exchange visits scheme was considered to be highly successful by all partners. This conclusion is supported by the large number of additional exchanges that took place.

e-Newsletters

One of the key dissemination and popularisation routes was through the Consortium's biannual e-Newsletter. Six e-Newsletters were published over the course of the project. At the start of the project, a template was established in order to create an easily identifiable brand for all editions of the e-Newsletter. Over the course of the project, the distribution increased significantly, from ~200 for edition 1 to >600 for edition 6. The increases in the distribution list resulted from the project press release and subsequent enquiries arising from it, requests through the project website and from contacts made during the ICT 2008 event. Following distribution, each e-Newsletter was made available for download from the project website (http://www.ist-brighter.eu/news.htm).

Each edition of the e-Newsletter contained 6 main sections as follows:

1. Welcome from Project Coordinator
2. Review of Latest Achievements
3. Partner Profiles (over the 6 editions, each partners published a 1 page profile)
4. Applications Articles (typically 2 per edition)
5. Technical Articles (typically 2 per edition)
6. Dissemination and Outreach (section containing reports of past events, adverts for coming events, lists of recent publications, publicity for the website, tutorials, film clip, RichMedia presentations, etc.)

Events

The Consortium originally planned to organise six events (workshops, conferences, summer schools) during the course of the project in order to expand the exploitation of project results and to further share the knowledge of the Consortium with the wider community. The Consortium completed these events relatively early in the project. Recognising the importance of these events, the Consortium also contributed to the organisation of several other high profile events in the latter part of the project. In total, 10 events were organised by the Consortium. More details on each of these events can be found below. Further information can be found on the website at http://www.ist-brighter.eu/workshop.htm. This page also provides links to external websites, detailed event programs and a selection of downloadable workshop presentations.

International Graduate Summer Schools on Biophotonics *(June 2007 & June 2009)*

The International Graduate Summer School on Biophotonics is a biennial event, begun in 2003, organised by project partners the Danish Technical University (formerly Risø National Laboratory) in Denmark and Lund University in Sweden. The BRIGHTER project provided sponsorship of the 3rd Summer School held in June 2007 and of the 4th Summer School held in June 2009.

The main purpose of the summer school is to provide education within biophotonics for students and young scientists at the highest international level. The format of the school is a combination of lectures, student poster presentations – and leisure time. However, the leisure time is also spent discussing, learning and exchanging new scientific ideas. The school targets graduate students and postdoctoral fellows with a limit of about 50 – 70 participants. Application to attend the summer school is by peer review of a summary of the participants' research and results or planned research project. During the school, successful applicants present their research during two poster sessions. The posters are evaluated by the lecturers and a best poster prize is awarded.

Biophotonics '07 had 57 participants from 19 different countries worldwide with 37 male and 20 female students mainly ranging in age from 25 to 35 years. Approximately 25% of the participants came from outside the EU – the majority (16%) of these coming from the US and Canada. The school had 11 lecturers representing 6 different countries – 5 lecturers from the US and 6 from the EU.

Biophotonics '09 had 74 participants from 21 different countries worldwide with 48 male and 26 female students mainly ranging in age from 25 to 35 years. As in 2007, approximately 25% of the participants came from outside the EU – the majority (16%) of these coming from the US and Canada. Once again the school had 5 lecturers from the US and 6 from the EU. The 2009 event was also organised in collaboration with Photonics for Life (P4L), a European network of excellence for biophotonics.

More details can be found on the project website at http://www.ist-brighter.eu/workshop.htm#biophotonics. External websites are available at http://www.biop.dk/biophotonics07 and http://www.biop.dk/biophotonics09. The Biophotonics websites provide details of the full programs and downloadable copies of the lectures and students presentations.

High Brightness Laser Sources Workshop *(June 2007)*

The Consortium organised and hosted a workshop entitled "High Brightness Diode Laser Sources" during the 2007 World of Photonics Congress and Laser Fair, which was held together with the CLEO-Europe Conference in Munich, Germany. The one-day workshop was attended by delegates from across Europe and beyond and included a program of 17 presentations – 8 of which were given by invited speakers from outside of the project. The full program, a selection of photos and 12 downloadable PDF presentations can be found on the website at http://www.ist-brighter.eu/workshop.htm#laser2007 and http://www.ist-brighter.eu/laser2007.htm.

Conference on Defects – Recognition, Imaging and Physics in Semiconductors – DRIP *(September 2007)*

The 12th International Conference on Defects – Recognition, Imaging and Physics in Semiconductors (DRIP-XII) was jointly organised and hosted 2 BRIGHTER partners, the Max-Born-Institute (MBI) and the Ferdinand-Braun-Institute (FBH). The conference was took place in Berlin from the 9th to the 13th September 2007 and was attended by 155 delegates from 28 countries. There were a total of 70 oral presentations (including 11 invited) and 70 poster presentations. The proceedings of DRIP-XII were published in a special issue of the Journal of Materials Science: Materials in Electronics.

Two special sessions which were supported by the BRIGHTER project and entitled "Defects in Devices" took place within the DRIP-XII conference. Of the 12 presentations given within these special sessions, 6 involved members of the project. Full details of the session can be found on the BRIGHTER project website at http://www.ist-brighter.eu/workshop.htm#drip. Extended information is also available on the conference website, http://www.drip12.de.

Toxicology and Safety Workshop *(February 2008)*

Nicole Proust, a clean technology expert from Thales Research and Technology, France, organised a workshop supported by the BRIGHTER project on "Toxicology and Safety". The workshop took place at Thales Research and Technology (TRT) in Palaiseau, France on 13th February 2008. The half-day workshop, attended by around 40 delegates from across Europe, included a program of 5 presentations – 3 given by invited speakers from outside the project. The workshop began with a screening of the 15 minute video introduction to the BRIGHTER project, its objectives and targeted applications. The entire workshop was video recorded and the presentations released in RichMedia format on the project website. Full details including the full program and 4 RichMedia presentations (to view online or download) are online at http://www.ist-brighter.eu/workshop.htm#toxico and http://www.ist-brighter.eu/toxicology.htm.

Conference on the Numerical Simulation of Optoelectronic Devices – NUSOD *(September 2008)*

In September 2008, the University of Nottingham, hosted the 8th International Conference on the Numerical Simulation of Optoelectronic Devices (NUSOD) at their University Park Campus in Nottingham, UK. The conference was attended by 76 delegates from 20 countries. The program was comprised of 7 invited papers, 44 regular papers, 7 postdeadline papers, 13 posters, 4 short courses and a software tutorial. One session was devoted to the subject of modelling high-brightness lasers, a topic that was a major part of the BRIGHTER project. Two of the five presentations in this session presented results from the project. Members of the project also contributed a post deadline paper and a poster. More details can be found on the project website at http://www.ist-brighter.eu/workshop.htm#nusod and the conference website at http://www.nusod.org/conf08, which includes downloadable copies of most of the presentations.

High Power Diode Lasers and Systems Meetings – HPDLS *(October 2008 & October 2009)*

The BRIGHTER partners made a major contribution to a topical meeting on High Power Diode Lasers and Systems. This inaugural meeting took place on 15th October 2008 in Coventry, U.K. as part of the Photonex 2008 exhibition. The meeting was organised by and chaired by Catrina Bryce (University of Glasgow), Eric Larkins (University of Nottingham) and Jim Ashe (Intense Ltd.) and was sponsored by the Scottish Chapter of IEEE LEOS. The meeting was attended by approximately 25 delegates from industry, research centres and academia. Partners from the project presented 4 of the 12 papers within the meeting.

Following the success of the 2008 event, the High Power Diode Lasers and Systems Meeting was organised again in 2009. Once again the event was held as part of the Photonex Exhibition in Coventry, U.K. The program was expanded to encompass an invited programme of 15 speakers, all leaders in High Power Diode Lasers from around Europe, followed by an evening poster session of contributed papers. The BRIGHTER project co-sponsored the 2009 event together with the IEEE Photonics Society, the Institution of Engineering and Technology (IET) and the European Photonics Industry Consortium (EPIC). The 2009 event was attended by >60 delegates from industry, research centres & academia, which represents a significant increase in attendance from the 1st event in 2008. Partners from BRIGHTER contributed significantly to the event, providing 4 invited talks (out of a total 15) and 3 posters (out of a total of 6). Full details of the 2009 event are available online at http://www.photonex.org/hpdls.php. There is growing industry interest in this meeting and preparations are being made for it to be held again in 2010.

European Commission ICT Event *(November 2008)*

Towards the end of 2008, the BRIGHTER Consortium took part in Europe's biggest ICT research event, with a booth at ICT 2008. The 2008 ICT Event, organised by the European Commission's Directorate General for the Information Society and Media, took place in Lyon, France from the 25th to the 27th of November 2008. The biennial ICT Event is the most important forum for discussing research and policy in information and communication technologies at European level. The event brings together researchers and innovators, policy and business decision makers working in the field of ICT. In 2008, more than 4,500 delegates attended the three day event. The 2008 ICT Event included more than 180 exhibits showcasing the latest breakthroughs in European research projects, including the BRIGHTER Project booth in the ICT for Wellbeing Village and a booth from project partner Biolitec in the SME Village.

The BRIGHTER exhibit was filled with demonstrations for visitors to see and interact with, including a state-of-the-art green laser source based on a frequency-doubled infrared laser, a range of laser diode samples and a dynamic simulation visualiser through which the internal workings of a laser diode could be investigated. Posters summarised the main application areas of the project – biomedical, communications and displays – whilst a rolling presentation gave more information about all topics related to the project. The final version of the project film clip was also premiered on the BRIGHTER booth. Visitors to the booth were able to talk with experts from the Consortium, read the project e-Newsletters and pick up a USB key containing information about the project (film clip, e-Newsletters, press release). Over 300 people visited the booth and >200 USB keys were handed out. Full details of the event are online at http://ec.europa.eu/information_society/events/ict/2008/index_en.htm.

European Conferences on Biomedical Optics – ECBO *(June 2009)*

The Consortium gave consideration to organising a workshop on medical applications in the final year of the project. However, as the European Conferences on Biomedical Optics (ECBO) were due to take place in June 2009, it was decided that an event organised by the project would require significant organisation and may not be well attended. Instead, several BRIGHTER partners contributed to the ECBO with major roles in 3 of the 7 conferences. Details are availble at http://www.osa.org/meetings/archives/2009/ECBO/ECBO2009Archive.pdf.

RichMedia CDs

RichMedia CDs have been developed by Thales Research and Technology (TRT) to facilitate knowledge sharing for workshops and training courses. They are an innovative way of attending a virtual presentation, which include the transparencies of the presentation, together with synchronised video and audio of the presenter. This novel format has a clear enhanced value for presentations that are used as teaching materials and also for independent learning (as compared to the presentation slides alone). The content can be distributed not only CDs, but also online (both as downloadable content and also as online streamed content). In a RichMedia presentation, the screen is divided in to three parts: (1) the presentation slides; (2) the video of the presenter; and (3) a content and navigation panel. The video, audio and slide changes are all synchronised and a PDF file of the presentation can also be opened from the main window.

The Consortium chose to adopt the RichMedia concept in order to distribute its technical tutorials and some workshop presentations. In total, 13 technical tutorials (http://www.ist-brighter.eu/tutorial.htm) and 4 workshop presentations (http://www.ist-brighter.eu/toxicology.htm) were recorded, processed into the RichMedia format and published online. On the website, users have 4 options to access the materials as follows:

1. Stream the full RichMedia presentation (slides, video and audio) from the website
2. Stream just the video recording of the presentation from the website
3. Download an ISO image file of the RichMedia presentation from which to make your own CD
4. Download a PDF copy of the presentation slides

Media Popularisation

A project press release (in English) was prepared at the end of the first year of the project describing the objectives of the project, the targeted applications and the achievements of the first year. The press release was titled “BRIGHTER lasers for tomorrow’s technologies”. A section of the press release was designed so that it could easily be modified to popularise the participation of the partners native to the country of publication. The Project Officer (at that time), Dr. Ronan Burgess, assisted the Consortium to obtain a quote from Mrs Viviane Reding, the EC Commissioner for Information Society and Media, for inclusion in the press release. Following the agreement on the text by the Consortium, partners from each country prepared translations of the press release, so that it could be issued in all countries involved in the project. The text was also modified as appropriate to represent the activities of the partners in that country. All country specific / language versions of the press release (18 in total) are available on the project website at http://www.ist-brighter.eu/publi.htm.

The principal English version of the press release was distributed in April 2008 to a wide range of local and national press in the UK and also to over 30 science / technology magazines and websites. Within 1 month, the full text of the press release appeared on many popular science / technology websites including www.laserfocusworld.com, www.compoundsemi.com and www.photonicsonline.com.

In addition, the Consortium was contacted several times for further information which led to articles in various magazines and on scientific and education websites as listed below.

- An article about BRIGHTER and the activities of the Ferdinand-Braun-Institute and the Max-Born-Institute appeared in *verbund journal* in December 2007. This journal is available at the scientific institutions in Berlin and is published by Forschungsverbund Berlin e.V.
- An article about BRIGHTER and UNIPRESS featured in *Sprawy Nauki* (News in Science) in March 2008. This publication is edited by the Polish Ministry of Science and distributed to scientific institutes (~1500 copies per month).
- An article about the medical applications of the project *“EU laser team readies cancer surgical strike”* was published in *Compound Semiconductor Magazine* in April 2008. The full article is online at

http://www.compoundsemiconductor.net/csc/news-details.php?cat=news&id=33871. The article was also later republished on the website www.optics.org.

- An article focusing on photodynamic therapy (PDT) systems *"EU takes a Brighter view"* was published in *BioOptics World* in July 2008. The article is available online (free registration required) at http://www.bioopticsworld.com/display_article/334510/131/none/none/Depar/EU-takes-a-Brighter-view.
- An article *"Brighter and better"* was published on the Science & Technology Website www.scenta.co.uk in August 2008. The site receives 500,000 visitors a month and part of their remit is to attract students to choose careers in Science, Engineering and Technology and then stay in that field. The full article is available at www.scenta.co.uk/gadets/cit/1727921/brighter-and-better.htm.
- The record green laser result of the project was widely publicised with the article *"Green laser diode generate record power levels"*, which was featured in the *OSA Newsletter* in May 2009 and in *Optics & Laser Europe* in June 2009.
- The BRIGHTER project featured on the ICT Results Website as a 2 part special feature published in June 2009. The first part *"Big impact from tiny semiconductor lasers"* gave an overview of the project and listed many of the major project results. It also contained a link to the BRIGHTER website. The second part *"New lasers drive powerful applications"* focussed on the project applications – medical, telecoms, and displays – and promoted the training and dissemination activities of the project. Both articles can be found online at http://cordis.europa.eu/ictresults.

Film Clip

The Consortium produced a short, 15 minute, film clip about the different aspects of the BRIGHTER project. The aim of the film was to raise awareness of the BRIGHTER project and its activities. The completed film was on display at the BRIGHTER booth at the ICT Event in Lyon and was also distributed to visitors to the booth (>200 USB keys containing the film clip and other project information were handed out). For online publication, the total film was divided into 11 short segments. These segments are available to view on the project website at http://www.ist-brighter.eu/clip.htm.

Scientific Publications

There was a strong effort on dissemination through scientific publications within the BRIGHTER project. In addition to publishing journal papers, the Consortium also attended all of the major conferences in fields related to the project. Many of the international conferences were co-located with trade fairs at which the industrial partners and research institutes have been represented. In total, there were 303 publications by the BRIGHTER Consortium. This total consists of 130 papers and 173 presentations (includes all types of conference, workshop, summer school, etc.). 50% of the publications were the result of joint work between two or more partner organisations and 34% of the publications had one or more female authors. (These numbers are correct as of the end of April 2010. Several further publications based on the work of BRIGHTER are in preparation and will be completed in the coming months.) A list of publications arising from the BRIGHTER project is available on the project website at: http://www.ist-brighter.eu/publi2.php.