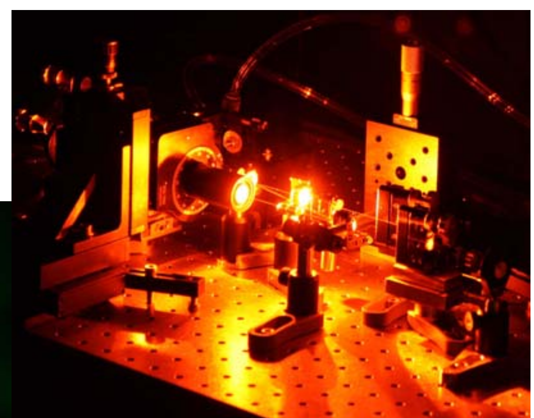
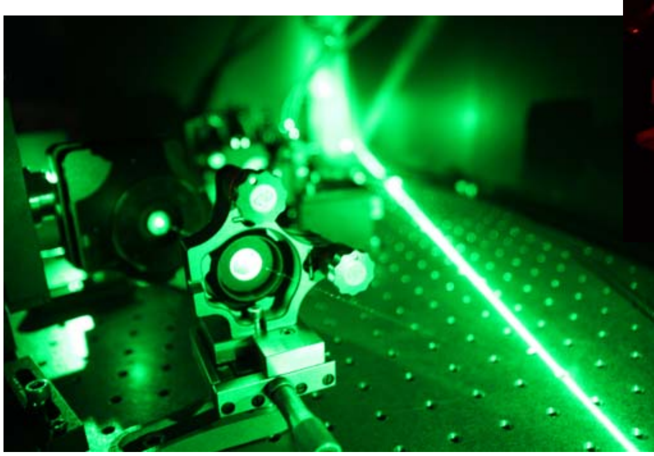
NATAL

Nano-Photonics Materials and Technologies for Multicolor High-Power Sources
IST-NMP 016769

Publishable Final Activity Report





1 Introduction

NATAL project had as its primary targets the development of new semiconductor materials and laser technologies for generating high-brightness visible and ultraviolet radiation. The key technologies deployed in the project concentrated on optically-pumped semiconductor-disk laser (OP-SDL) architecture, often also referred to as the VECSEL (Vertical-External-Cavity Surface Emitting Laser). Basic research and development, but also field trials and demonstrations, have been developed over a period of three years, starting in July 2005. This work has been supported by the European Commission with 2.7 million € in funding under the 6th R&D Framework Program (FP6). Total investment in the project, including contributions from companies, was 4.1 million €.

The project was coordinated by the Optoelectronics Research Centre (ORC), Tampere University of Technology Finland, and was carried out as a collaboration between some of the leading European academic institutions and industrial partners. This research collaboration was driven by novel semiconductor gain material grown by the ORC and the Technical University of Berlin (Germany). Generation of record-high power visible light at the Institute of Photonics, University of Strathclyde (UK), was amongst the highlights of NATAL. For the first time ever, blue laser diodes were used for direct optical pumping of red SDL material highlighting new avenues for the development of compact and powerful lasers with emission in the visible and the UV. Chalmers University of Technology has developed and advanced 3-D simulation tool that takes into account electro-optical and thermal properties of the gain chip but also the effect of external optical elements. These advances represent a major breakthrough in terms of theoretical work on VECSEL design and simulation. Using support provided by OptoCap Ltd., Livingston (UK) and EpiCrystals Ltd. (Finland), the partners achieved the current world record in optical power at 1220 nm. These SDLs could be frequency converted to generate more than 4.5 W of high-brightness radiation at 610 nm. In the project, TOPTICA AG of Munich (Germany) developed early stage demonstrators allowing single frequency operation, tunability, frequency conversion and system integration. As the most eminent commercial result, project partner OSRAM Opto Semiconductors in Regensburg (Germany) has already started to develop VECSEL-based technology for low power RGB projection, while EpiCrystals has entered the commercial field with its proprietary DeCIBEL® technology.

The NATAL consortium has surely propelled this very exciting field of laser research into new spectral regions, and new power levels in the NIR spectral range, but has also opened up a variety of technologically interesting lines in the visible spectrum, with output powers of up to a few watts demonstrated/achieved through use of compact frequency-doubling set-ups. For more details please visit the NATAL website http://www.orc.tut.fi/natal.html

2 Project execution

2.1 Project objectives

Visible and ultraviolet lasers are required for a number of applications, such as laser projection (RGB generation), spectroscopy, laser lithography, process control and monitoring, and photodynamic therapy and other medical applications. Large parts of the visible and ultraviolet spectrum can not be accessed directly using semiconductor laser diodes, due to a lack of suitable semiconductor materials. Consequently, in many cases more complex and expensive gas, ion, and solid-state lasers have been deployed instead. An alternative approach is to use the so-called frequency-doubling technique to convert infrared laser radiation into visible radiation. Optically-pumped VECSEL technology enables the use of infrared and visible semiconductor gain materials, with the possibilities for power scaling and efficient intracavity frequency-doubling. This laser technology could provide a compact and low cost alternative for today's visible lasers. Moreover, frequency-doubled microchip VECSELs could fill the "green gap" that currently impedes the volume production of laser TVs and laser projection systems.

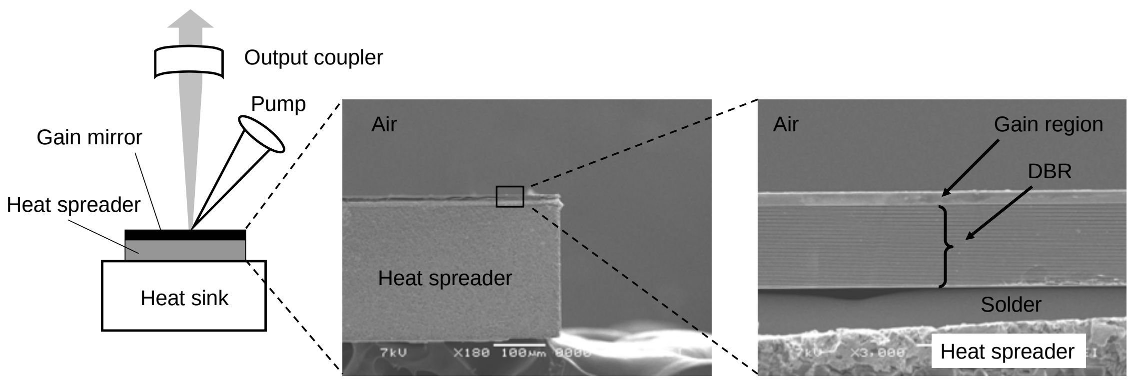


Figure 1: *Schematic presentation of VECSEL cavity and micrographs of the semiconductor gain mirror, soldered onto a heat spreader. DBR=Distributed Bragg Reflector.*

The NATAL partners combined their expertise to develop various novel formats of optically-pumped semiconductor vertical external cavity surface-emitting laser (OPS-VECSEL) for commercial exploitation. The project targeted development of proprietary device designs, epitaxy of semiconductor materials, novel micro-fabrication and packaging methods and nonlinear frequency-conversion. The main objectives of the projects were:

- **Objective 1:** Development of nano-materials, advanced micro-optical elements and novel processing techniques for high-power OP-VECSELs operating in the spectral ranges 630 – 670 nm, 940 nm, 1040 nm and 1180–1220 nm.

- **Objective 2:** Development of frequency-doubled VECSELs emitting at 335 nm, 470 nm, 520 nm, and 590–610 nm.

- **Objective 3:** Application development and establishment of new routes for commercialization.

The specific technical targets of the project in respect to the power levels at different operation wavelengths are listed below in Table 1.

***Table 1**: Specific technical targets of the project. (SHG=Second-Harmonic Generation i.e. frequency-doubling, M^2 is the beam quality factor, cw = continuous wave)*

Wavelength domain	**Direct generation/ SHG**	**Power in TEM_{00} mode ($M^2 < 1.5$)**	
		NATAL target	**State-of-the-art at the start of the project**
940 nm	Direct generation	> 5 W cw	0.5W cw
1040 nm, 1180–1220 nm	Direct generation	> 5 W cw > 5 W cw	3W cw [1] 60 mW [2]
630–690 nm	Direct generation	> 1 W cw	0.4 W cw [3]
470 nm, 520 nm, 610 nm	SHG	> 0.5 W cw	50 mW (456 nm) CW 30 mW cw [4]
315–345 nm	SHG	10 mW cw	Not available at the start of the project

2.2 Project partners

The project was a partnership of leading European researchers and organizations with expertise related to VECSELs, including device design, epitaxy of nano-materials, novel micro-fabrication and packaging methods, and laser science and technology. Among the partners were major contributors to the development of world-wide VECSEL technology to date (ORC Tampere, Chalmers University of Technology, University of Strathclyde, Toptica Photonics AG, OSRAM Opto-Semiconductors), together with one of the world‘s leading teams in quantum dot lasers, the Technical University of Berlin. In addition OptoCap Ltd. provided expertise in packaging applicable to VECSEL devices, with the target of delivering robust and industrially-scalable devices.

***Figure 2:** NATAL partners*

[1] S. Lutgen et al., "3W cw output from a optically pumped semiconductor disk laser at 1050nm", CLEO2004, CTuC4
[2] E. Gerster et al., "Orange-emitting frequency-doubled GaAsSb/GaAs semiconductor disk laser", J. of Appl. Phys., 92, 7397 (2003).
[3] J.E. Hastie et al., "High Power, Continuous Wave Operation of a Vertical External Cavity Surface Emitting Laser at 674 nm", Advanced Solid-State Lasers Conference, (2005).
[4] A.C. Tropper et al., "Vertical-external-cavity semiconductor lasers", Topical Review, J. of Phys. D: Appl. Phys., 37, R75 (2004).

The industrial partners provided application-focus for the project. Besides contributing to achievement of the technical objectives, they identified major routes to exploit VECSEL-based light sources by developing applications and establishing connections to the end-users. Immediate niche applications exist in particular for high power red, green and blue VECSELs. Red VECSELs are the highest priority for multiple high-value applications, such as holography, absolute distance interferometry, confocal Raman spectroscopy, high-speed data storage, and the more scientifically but nevertheless attractive laser atom cooling and manipulation. The blue and green devices provide the complementary primary colors for RGB displays, including rear and front projection, mobile displays or 3D displays.

2.3 Work performed

The backbone of the project was the ability to fabricate GaAs-based semiconductor nanostructures used as the gain media in VECSELs. Multiple quantum well gain structures were grown by ORC Tampere using the so called molecular beam epitaxy (MBE) technique. One of the MBE reactors was equipped with a radio frequency plasma system that allowed incorporation of nitrogen into the quantum wells, enabling the infrared emission wavelength to shift to longer wavelength (1150–1350 nm). The quantum dot gain materials were grown by the Technical University of Berlin using the metal organic chemical vapor deposition (MOCVD) method.

The performance of a VECSEL not only depends on the growth process, but also on its layer design, thermal management and external cavity elements. During the course of the project CTH developed a complete 3-D VECSEL simulation software that takes into account the gain medium, thermal effects and external cavity elements.

The Institute of Photonics (IoP) of the University of Strathclyde in Glasgow carried out the major task of VECSEL design, characterization and development of novel laser concepts, as well as processing compact VECSEL chips with micro-lenses etched on a diamond element in the laser cavity. An important part of the work carried out at the IoP included characterization and frequency-doubling of red VECSELs.

The work of the industrial partners OSRAM, TOPTICA and EpiCrystals concentrated on the applications and development/demonstration of prototype lasers. OptoCap carried out the tests and development of industrially suitable packaging solutions.

The NATAL research program was organized around six closely interconnected Work Packages (WPs) as listed below:

- WP 1 was dedicated to overall consortium management
- WP 2 focused on “*Design, Simulation & Device Concepts*”.
- WP 3 focused on *“Materials development and fabrication”*.
- WP 4 concerned the *“Physical management of the laser cavity and VECSEL demonstration”*.
- WP 5 dealt with *“Assembly, testing and conversion”*.
- WP 6 aimed at exploitation and dissemination of the results.

2.4 Project results and outcome

The most important scientific results of the project relate to development of new semiconductor gain materials and laser concepts. This section highlights the project results and puts them into context with the state of the art achievements outside the NATAL framework.

2.4.1 Project highlights

Development of a comprehensive VECSEL simulator (WP2)

CTH created an advanced 3-D simulation tool that takes into account electro-optical and thermal properties of the gain chip but also the effect of external optical elements. The simulator contains a number of sub-models that are combined into a single simulation tool. These advances represent a major breakthrough in terms of theoretical work on VECSEL design and simulation, and it is the most comprehensive VECSEL model available.

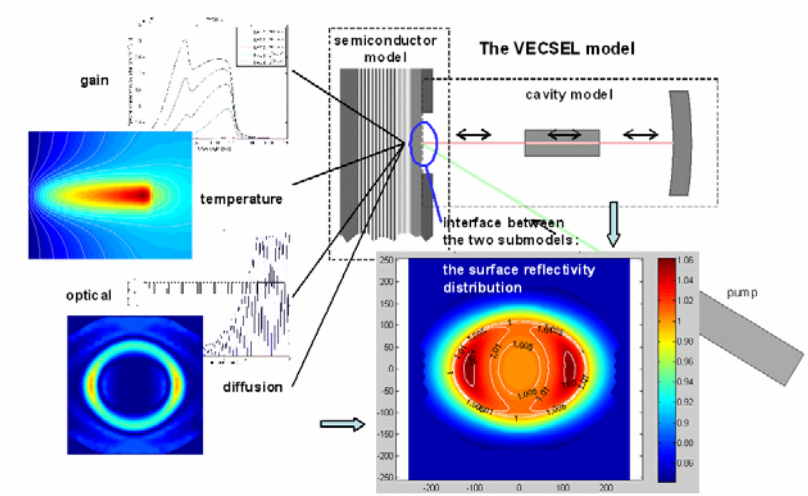


Figure 3: *The two sub-models and their interaction through the spatially varying reflectivity of the semiconductor surface*

Development of high power 1220 nm GaInNAs VECSELs for frequency-doubling (WP3, WP4, WP5)

An essential part of the material development was to realize GaAs-based VECSEL structures for multiwatt operation near 1220 nm wavelength. One way to achieve lasing from GaAs at such a long wavelength is to introduce a small amount of nitrogen into the InGaAs quantum wells. The GaInNAs structures were grown at the ORC and they were successfully used in frequency-doubling experiments, generating 4.5 W of output power near 610 nm.

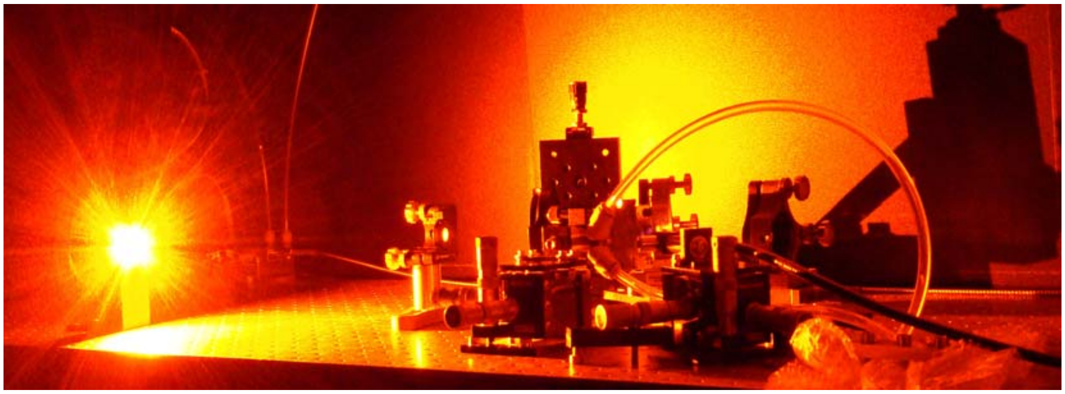


Figure 4: *Orange-red output from a frequency-doubled GaInNAs VECSEL.*

Development of the first quantum dot VECSELs (WP3, WP4)

The very first VECSEL based on a quantum dot gain structure/mirror was fabricated by the Technical University of Berlin. Successful structures were grown for the wavelengths 940 nm, 1040 nm and 1220 nm, with maximum power exceeding 1 W at 1040 nm. Both Stranski-Krastanow and sub-monolayer quantum dots were deployed. In comparison to a traditional quantum well gain medium, the quantum dots offered spectral properties that were highly independent of the operation temperature and operating power.

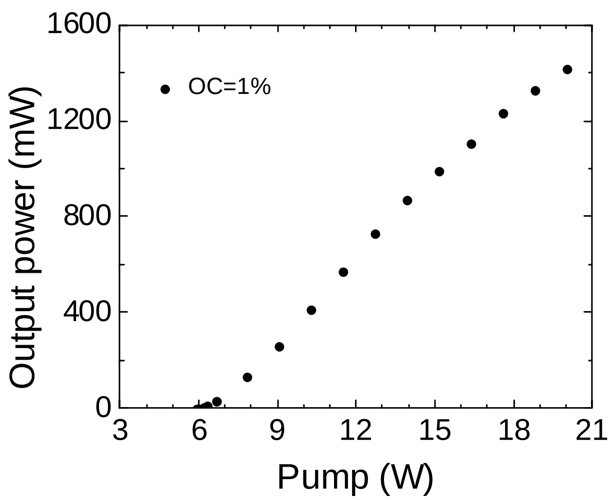


Figure 5: *Light output curve of the 1040 nm quantum dot VECSEL given as a function of incident pump power. OC=Output Coupler transmission.*

High power 674 nm VECSEL (WP3, WP4)

The high power red-emitting VECSEL, demonstrated by the University of Strathclyde, was based on AlInGaP semiconductor alloys. The semiconductor active mirror was bonded to a diamond platelet for heat dissipation purposes, aligned within a three mirror cavity and pumped using a green diode-pumped solid-state laser. Laser action was achieved with up to 1.1 W of output power at 674 nm and tunable operation demonstrated from 669 to 685 nm upon insertion and rotation of an intracavity birefringent filter

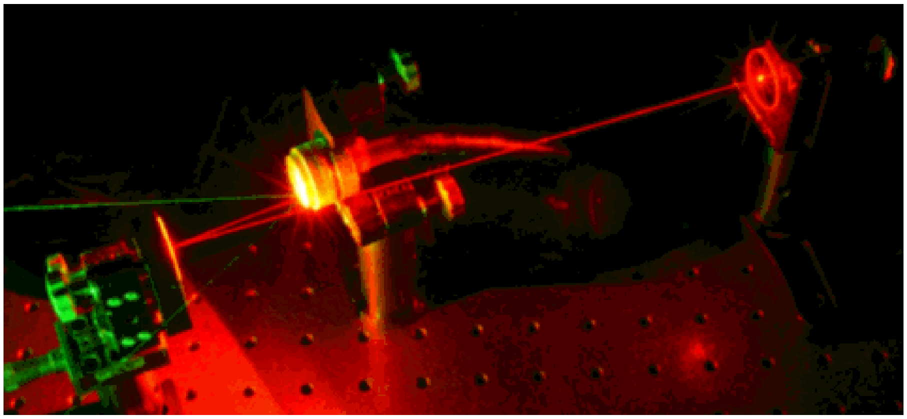


Figure 6: *Picture of green laser pumped red-emitting VECSEL.*

Ultraviolet emission from the 674 nm VECSEL (WP5)

Ultraviolet light generation is the key to a wide range of applications including lithography, biomedicine, high density optical storage and spectroscopy. Within NATAL, UV emission was obtained by exploiting a direct-red emitting VECSEL and the frequency-doubling nonlinear conversion effect. The introduction of a nonlinear crystal of beta-barium borate (BBO) inside the red VECSEL cavity enabled ultraviolet light to be produced with a maximum power of 120 mW at 338 nm. The output wavelength was tuned over a range of ~5 nm with a birefringent filter.

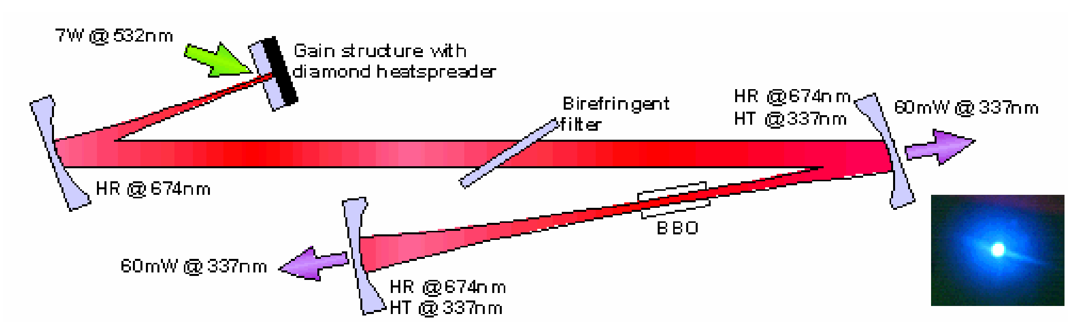


Figure 7. *Schematic diagram of the frequency-doubled VECSEL cavity. BBO is the beta-barium borate (ß-BaB_2O_4) crystal, HR is high reflection, HT is high transmission.*

Blue diode pumped red VECSEL (WP4)

The first demonstration of direct red emitting VECSELs by the IoP was made using a 532 nm frequency-doubled solid state laser. Direct diode-pumping using high power (>500mW) GaN blue diodes is a more attractive solution commercially as it reduces the cost and complexity of the system. A setup using two 500 mW polarization-coupled 445 nm GaN laser diodes was assembled which permitted the demonstration of continuous wave VECSEL operation with 340 mW threshold, up to 17 mW of output power, and 16 nm tuning capabilities around 668 nm.

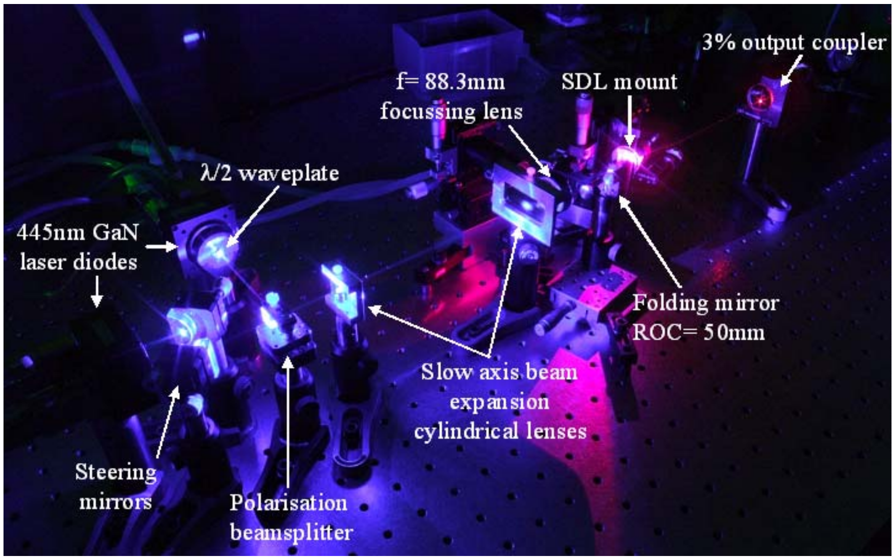


Figure 8: *Picture of the first GaN-diode-pumped red-emitting VECSEL.*

Micro-chip VECSELs (WP2, WP4)

IoP directed significant efforts toward development of micro-chip VECSELs. These components were produced by contacting a thin diamond platelet onto the VECSEL gain mirror surface, and coating the diamond surface with a high reflectance dielectric coating. Therefore, the laser cavity is formed between the gain mirror and the coating on the diamond. Such a design is highly compact and allows fabrication of etched micro-lenses on the diamond for enhanced laser mode control.

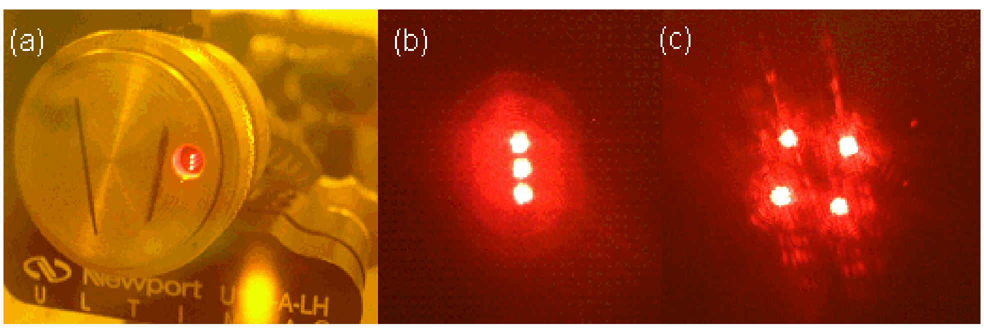


Figure 9: *Red micro-chip VECSEL with 3 separate laser operating on a single chip.*

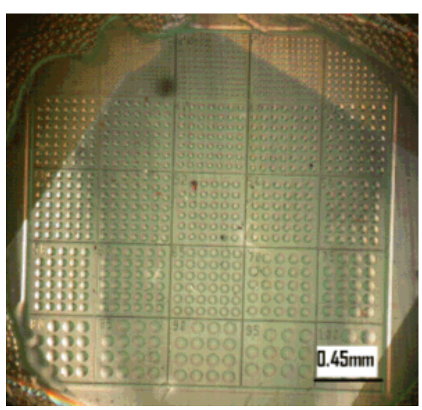


Figure 10: *Processed micro-lenses on diamond surface.*

Development of commercial products (WP4, WP5, WP6)

The purpose of the project was not only to produce new scientific results, but also to generate knowledge and technologies that could be exploited commercially by the industrial partners of the project. The academic partners had the capability to perform theoretical simulations, wafer fabrication and processing, whereas of the industrial partners OptoCap was specialized in packaging solutions, EpiCrystals in wafer production and processing of advanced RGB lasers, TOPTICA in laser systems for the scientific market, and OSRAM in volume production of VECSEL systems for high volume end-user applications. In other words, the project partners formed a consortium capable of developing new laser components from the laboratory to volume fabrication. The development work of the industrial partners was focused on bringing the VECSEL technology from science into laser systems and commercial mass production.

NATAL has enabled OSRAM to make use of the expertise of university groups for capillary bonding of VECSELs, which represents the cutting edge research technology of choice in improved power scalability of VECSELs. The collaborations within NATAL have allowed OSRAM to evaluate capillary bonded heat spreader VECSELs as an alternative to conventional flip-chip components. Such VECSELs have shown significantly improved thermal performance and are thus a candidate for second-generation green laser products. Strategies for high-volume manufacturing have been developed up to the realization of first demonstrator prototypes.

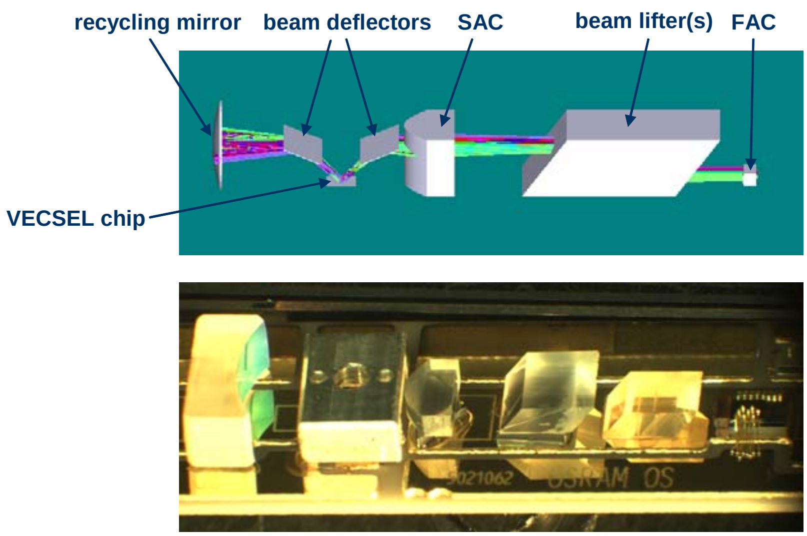


Figure 11: *New pumping concept developed by OSRAM for compact VECSELs.*

TOPTICA has an existing business in the commercialisation of spectroscopic laser sources with customized spectral coverage, tunability, and unique power features. One aim of the project and the main task for TOPTICA Photonics AG was to develop a small, portable, yet versatile platform to demonstrate and evaluate the VECSEL technology for scientific markets. This development was driven by the opportunity offered in NATAL to achieve the spectral regions from 1150nm to 1250nm and frequency-doubling thereof. To achieve the targets, in particular the flexibility, we decided to exclude any external cavity setup from integration. The demonstrator unit can be mounted onto a breadboard where any external cavity with standard optical components can be added. Within an outer size of only 12 cm x 11 cm x 40 cm the demonstrator unit contains:

- *Sample holder for the VECSEL chips*
- *Pump optics with separate fast and slow axis collimation*
- *Pump laser diode (e.g. 4.0 Watts at 808 nm)*
- *Thermoelectric coolers for both VECSEL chip and pump diode*
- *Complete electronics with microprocessor control*

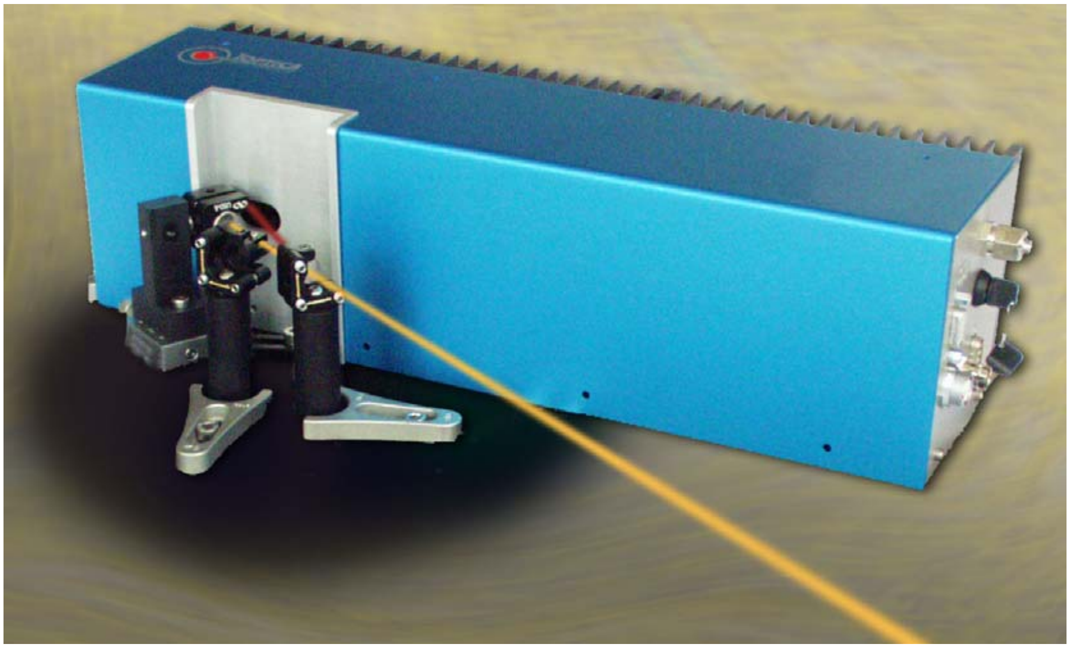


Figure 12: *Photograph of TOPTICA's VECSEL demonstrator for generation of orange-red radiation.*

2.4.2 Project result in respect to the state-of-the-art

The initial targets of project were met with good success. While the industrial competitors have showed great progress at the 900–1100 nm wavelengths, it can be said that the main achievements of NATAL have been made at the 335 nm, 670 nm and 1220 nm wavelengths and in development of quantum dot VECSELs. Prior to the start of the project, 335 nm ultraviolet VECSEL sources and quantum dot VECSELs had not been demonstrated. Both of these achievements present current state of the art. The results obtained from directly emitting 670 nm and 1220 nm quantum well VECSELs also present the current state of the art at the end of the project.

Table 2: *Optical power demonstrated by NATAL VECSELs versus state-of-the-art. All demonstrations are for nearly single-mode operation.*

Wavelength	Gain medium	Achievements	State-of-the-art
670 nm	InGaP QW	1.1W	NATAL
930 nm	InGaAs QW	3.9W	12W [1]
1040 nm	InGaAs QW	5.5W	10W [2]
1220	InGaAsN QW	5.2W	NATAL

[1]: K.S. Kim et al., *IEEE Photonics Technology Letters*, **19**, 20, pp1655–1657, (2007).
[2]: J. Chilla, et al. "High power optically pumped semiconductor lasers", 2004 Photonics West San Jose, CA (2004)

3 Dissemination and use of knowledge

Table below summarizes the key technologies developed within the project and their exploitation status.

Table 3: Exploitable technologies

Exploitable Knowledge	Exploitable products or measures	Sectors of application	Owner & partners involved
High power GaInNAs VECSELs (1180–1260 nm)	*Proprietary technology on epitaxial growth of GaInNAs wafers and VECSEL assembly. The knowledge is available mainly at the university partners.*	*1. Scientific 2. Display and laser projection 3. Medical*	***ORC**, IoP, EpiCrystals TOPTICA*
Quantum dot VECSELs	*Proprietary technology on epitaxial growth*	*1. Scientific*	***TUB, IoP, ORC***
Micro-chip VECSELs	*Compact VECSEL sources / VECSEL arrays*	*1. Scientific*	*IoP Strathclyde*
Red VECSELs and UV VECSEL	*Compact UV sources. Demonstrator available at university partners.*	*1. Spectroscopy 2. Lithography 3. Process control 4. Medical*	*IoP Strathclyde*
3D VECSEL simulator	*Software for advanced VECSEL design*	*1.Component design: Industry and universities*	*CTH*
Micro-optical VECSEL assembly	*Medium power RGB sources. Product development.*	*1. Displays 2. Projections*	*OSRAM*
Universal VECSELs system	*Demonstrator. Product available at TOPTICA.*	*1. Spectroscopy 3. Medical*	*TOPTICA*
DeCIBEL laser platform	*Low power RGB sources. Product development stage.*	*1. Displays 2. Projection*	*EpiCrystals*

The project had a tremendous success in publishing new scientific results. NATAL partners have pioneered new research areas related to VECSELs and are routinely present on the list of invited speakers at major optoelectronics conferences. Results have been published in scientific journals and conferences, as well as in professional magazines. The academic activities showed very strong results in terms of education; several Ph.D. and M.Sc. theses have been published during the course of the project.

***Table 4:** An overview of dissemination activities of NATAL.*

Type	Amount
Press release(press/radio/TV)	*12*
Conference publications	*44*
Journal publications	*23*
Project web-site **http://www.orc.tut.fi/natal.html**	*1*
Summer school	*1*
Work shop	*2*
Conference booth	*1*
Ph.D. theses	*4*

The complete list of scientific publications and links to articles can be found at: http://www.orc.tut.fi/natal_publ.html

Ph.D. theses based on NATAL results

Antti Härkönen: "*Optically-Pumped Semiconductor Disk Lasers for Generating Visible and Infrared Radiation*", March 2008, Tampere University of Technology.
Lynne G. Morton: "*Visible and ultraviolet vertical external cavity surface emitting semiconductor lasers*", University of Strathclyde.
Stephanie Giet: "*Grating-controlled infrared vertical external cavity surface emitting lasers*", University of Strathclyde, July 2008.
Hans Lindberg: "*High Power, Long Wavelength Semiconductor Disk Lasers for Continuous and Mode-Locked Operation*", March 2006, Chalmers University of Technology.

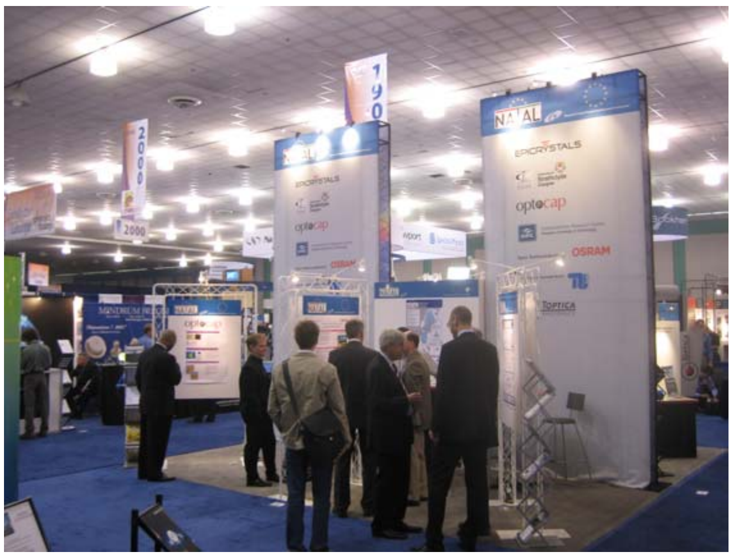


Figure 13: *Photograph from NATAL booth at CLEO 2008 exhibition.*

4 Conclusion

NATAL project has helped to generate a significant amount of knowledge and new technologies in Europe in the field of optically-pumped vertical-external-cavity surface-emitting lasers. The industrial partners of NATAL have showed significant effort towards realizing compact volume production lasers based on the technologies developed with in the project. In the project TOPTICA developed early stage demonstrators allowing single-frequency operation, tunability, and frequency conversion in a compact system. The most important impact on commercialization of VECSEL technologies is expected to be made by OSRAM, which has engaged in the development of VECSEL-based technology for low power RGB projection. EpiCrystals has also entered the commercial field with its proprietary DeCIBEL technology, a complementary but yet related platform to a VECSEL. At the scientific level NATAL enabled breakthrough results in fabrication of novel compound semiconductor materials application, new laser architectures, and new operation wavelength. First in the world demonstrations of QDs VECSELs, as well as compact red and UV VECSELs have open new research areas. In particular the QD VECSEL approach is currently pursued within the Fast-Dot IP project.