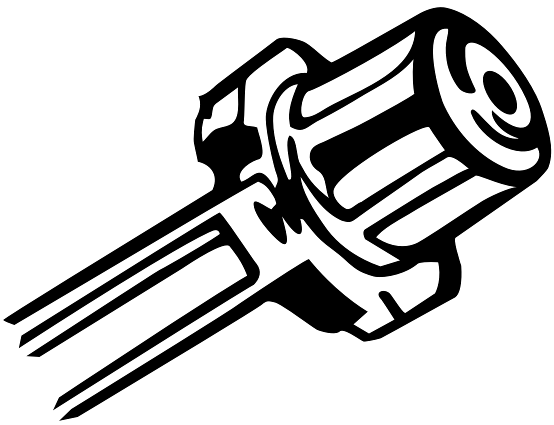
V Workshop
on Physics and Technology of Semiconductor Lasers

Kraków, 17-20 XI 2013

Welcome

The fifth Workshop on Physics and Technology of Semiconductors Lasers (WPTSL V) is held this year in Kraków, Poland. This meeting traditionally gathers Polish and international community working in the field of semiconductor laser diodes. The scope of the workshop covers: edge emitting devices including nitride laser diodes, VCSELs and VECSELs as well as quantum cascade lasers based on various material systems. This workshop has an ambition to mix the state of the art presentation given by renowned scientist with the selected presentations given by young scientist covering the recent developments in the field. Workshop is organized jointly by the Institute of High Pressure Physics of Polish Academy of Sciences (Unipress) and the Centre of Nanophotonics of Institute of Electron Technology.

We wish you fruitful and pleasant time in Kraków,
Piotr Perlin, Maciej Bugajski



November 17th 2013 (Sunday)

19:00	*Welcome glass of wine: Hotel Qubus*

November 18th 2013 (Monday)

Hour	*No*	*Type*	*Title*	*Author*
8:30-8:40			***Conference opening***	
8:40-9:10	Mo1	I1	Emission Characteristics of InGaN-Based Regularly Arranged Nanocolumn Arrays	Katsumi Kishino Sophia University, Japan
9:10-9:40	Mo2	I2	Progress in nonpolar and semipolar GaN-based laser diodes	Dan Cohen, UCSB, USA
9:40-9:55	Mo3	C1	Cyan AlGaN-cladding free nitride laser diodes grown by PAMBE	Henryk Turski Unipress, Poland
9:55-10:10	Mo4	C2	Effect of index-antiguiding on the lasing threshold of narrow RW (In,Al) GaN laser diodes investigated by self-consistent simulations	Luca Radaelli Ferdinand Braun Institute, Berlin
10:10:10:25	Mo5	C3	InGaN GRINSCH laser diodes	Szymon Stańczyk Unipress, Poland
10:25-11:00			***Coffee break 1***	
11:00-11:30	Mo6	I3	Long wavelength VCSELs and VECSELs made by wafer fusion	Elyahou Kapon EPFL, Switzerland
11:30-12:00	M07	I4	High power femtosecond pulse vertical-external-cavity surface-emitting lasers	Keith Wilcox University of Southampton, UK
12:00-12:15	Mo8	C4	Switchable, two wavelength emitting VECSEL	Artur Broda ITE, Poland

12:15-12:30	Mo9	C5	GaAs/AlOx high contrast gratings for 980 nm VCSELs	Marcin Gębski Lodz Technical University, Poland
13:00-14:30			***Lunch***	
14:30-15:00	Mo10	I5	MBE growth and optimization of THz quantum cascade lasers	Zbig Wasilewski University of Waterloo, Canada
15:00-15:30	Mo11	I6	II-VI/III-N Micro-Chip Laser Diode Converters	Sergey Ivanov Ioffe Institute, Russia
15:30-15:45	Mo12	C6	Doping versus threshold current in mid-IR QCL – a NEGF model	Andrzej Kolek Rzeszów University of Technology, Poland
15:45-16:00	Mo13	C7	Application of pressure-tuned laser diodes in spectroscopy	Witold Trzeciakowski Unipress, Poland
16:00-18:00			***Poster session – beer***	

November 19th 2013 (Tuesday)

9:00-9:30	Tue1	I7	Progress toward optimizing 850 nm and 980 nm vertical cavity surface emitting lasers (VCSELs) for optical interconnects	James Lott TU Berlin, Germany
9:30-10:00	Tue2	I8	Subwavelength high contrast grating mirrors for applications in vertical-cavity surface-emitting lasers	Maciej Dems Lodz University of Technology, Poland
10:00-10:15	Tue3	C8	Numerical simulation of optical properties of long-wavelength wafer-fused VCSELs with intra-cavity patterning	Tomasz Czyszanowski Lodz University of Technology, Poland
10:15-10:30	Tue4	C9	Semiconductor double-chirped mirrors for dispersion compensation in femtosecond Yb:KYW lasers	Łukasz Zinkiewicz Physics Department Warsaw University, Poland

10:30-11:00	***Coffee break 2***			
11:00-11:30	Tue5	I9	Future Light Sources for Pico Projection	Jelena Ristic Osram OS, Germany
11:30-12:00	Tue6	I10	UV Lasers – Status and Prospects	Michael Kneissl TU Berlin, Germany
12:00-12:15	Tue7	C10	High power InGaN superluminescent diodes	Anna Kafar Unipress, Poland
12:15-12:30	Tue8	C11	GaN-based ridge waveguide laser diodes: optimizing the optical mode profile	Katarzyna Holc Fraunhofer IAF, Germany
12:30-12:45	Tue9	C12	Thermal stability of InGaN laser diodes	Agata Bojarska Unipress, Poland
13:00-14:30	***Lunch***			
14:30-15:00	Tue10	I11	High performance AlInGaAs transmission lasers for FTTX applications	Wyn Meredith CST Global, Scotland
15:00-15:30	Tue11	I12	Excitation of 2D plasma waves in semiconductor quantum well and its effect on lasing in InGaN diodes	Igor Smetanin Lebedev Institute, Russia
15:30-15:45	Tue12	C13	Improved upper heat stream removal in high-power laser diodes using graphene oxide layers	Andrzej Maląg ITME, Poland
15:45-16:00	Tue13	C14	High-power laser diodes with multi-stripe-gain distribution	Grzegorz Sobczak ITME, Poland
16:00-16:15	Tue14	C15	Strain compensated 4.7 μm AlInAs/InGaAs/InP QCLs – Non-equilibrium Green's function modeling of electro-optical characteristics	Maciej Bugajski ITE, Poland
19:00-24:00	***Conference Diner***			

November 20th 2013 (Wednesday)

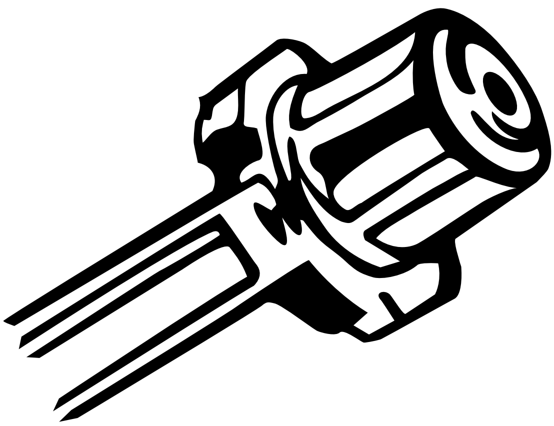
9:00-9:30	Wed1	I13	Combining MOVPE & low-temperature MBE for efficient green laser diodes	Lise Lahourcade EPFL, Switzerland
9:30-10:00	Wed2	I14	Picosecond pulse generation in GaN-baser laser diodes	Ulrich Schwarz University of Freiburg, Germany
10:00-10:15	Wed3	C16	Optical simulations of InGaN/GaN edge emitting lasers with reduced AlGaN cladding thickness	Tomasz Czyszanowski Lodz University of Technology, Poland
10:15-10:30	Wed4	C17	Far field pattern of AlGaN cladding free blue laser diodes grown by PAMBE	Grzegorz Muzioł Unipress, Poland
10:30-11:00			***Coffee break 3***	
11:00-11:30	Wed5	I15	Type II quantum well structures for mid-infrared emitting interband cascade lasers: challenges, limitations and prospects	Grzegorz Sęk Wroclaw University of Technology, Poland
11:30-12:00	Wed6	I16	(AlGaIn)N-based laser diodes: future applications and present problems	Michał Leszczyński TopGaN Ltd., Poland
12:00-12:15	Wed7	C18	GaN laser diodes for systems applications	Steve Najda TopGaN Ltd., Poland
12:15-12:30	Wed8	C19	Power limits of III-N-based single and multi emitter laser diodes	Maciej Kuc Lodz University of Technology, Poland
12:30-12:45	Wed9	C20	Hydrostatic pressure tuning of emission wavelength and optical gain in GaInNAs/GaAs quantum wells	Marta Gładysiewicz - Kudrawiec Wroclaw University of Technology, Poland
12:45-13:00	Wed10	C21	Pressure studies of leakage in laser diodes	Artem Bercha Unipress, Warsaw, Poland
13:00-13:10			***Closing remarks***	

Poster presentations November 18th 4-6 PM

Po1	Numerical analysis of mid-ir quantum cascade laser optical properties	Piotr Karbownik ITE, Poland
Po2	Dedicated quantum cascade laser driver	Artur Trajnerowicz ITE, Poland
Po3	MBE growth of VECSEL heterostructures: the challenge of control of the layer thickness and the strain relaxation	Jan Muszalski ITE, Poland
Po4	Full-physical simulation of the novel on-axis pumped VECSEL with High Contrast Grating	Jarosław Walczak Lodz University of Technology, Poland
Po5	Numerical modeling of optical properties of vertical-external-cavity surface-emitting lasers	Adam Sokół Lodz University of Technology, Poland
Po6	Fabrication of THz quantum cascade lasers	Anna Szerling ITE, Poland
Po7	Epitaxy of AlGaAs/GaAs structures for THz quantum-cascade lasers	Kamil Kosiel ITE, Poland
Po8	Computer simulation of operation of GaN/AlGaN quantum well ultraviolet diode laser	Łukasz Piskorski Lodz University of Technology, Poland
Po9	Spin orbit splitting in InGaxAsSby/InAs layers for heterojunction lasers	Mateusz Dyksik Wroclaw University of Technology, Poland
Po10	Optical characterization of of InAs-substrate-based type II quantum wells for long-wavelength mid-infrared interband cascade laser with plasmon waveguiding enhancement	Filip Janiak Wroclaw University of Technology, Poland
Po11	Coupling of multiple laser diodes into a fiber	Yurii Ivonyak Unipress, Poland
Po12	Optical properties of AlGaAsGaAs superlattices for quantum cascade lasers for mid infrared and terahertz range	Marcin Motyka Wroclaw University of Technology, Poland

Po13	Investigating up-conversion phenomena in active glasses using pressure-tuned laser diodes	Ryszard Piramidowicz Warsaw University of Technology, Poland
Po14	Photonic integrated circuits for application in multi-wavelength communication systems	Stanisław Stopiński Warsaw University of Technology, Poland
Po15	Tuning of InGaN/GaN laser diodes band structure by hydrostatic pressure	Jakub Goss Unipress, Poland
Po16	Thermal characteristics and power roll-over of GaAs/AlGaAs quantum cascade lasers	Kamil Pierściński ITE, Poland
Po17	Wafer fused VECSELs emitting in 1.3 μm and 1.5 μm range	Kamil Pierściński ITE, Poland

Abstracts



Emission Characteristics of InGaN-Based Regularly Arranged Nanocolumn Arrays

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Hiroaki Hayashi 1)
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GaN nanocolumns, which were first self-assembled by molecular-beam epitaxy (rf-MBE) [1], were employed to fabricate visible to ultraviolet nanocolumn LEDs [2-4]. But self-assembling process tended to introduce emissions in multi-color spots [3]; it is, therefore necessary to fabricate regularly arranged GaN nanocolumns for uniform color emission. We developed Ti-mask selective area growth (SAG) of the GaN nanocolumns [5, 6], based on which emission color control of InGaN-based nanocolumn array has been demonstrated [7], realizing monolithic integration of nanocolumn LEDs with different emission colors [8]. Then the periodic arrangement in InGaN-based nanocolumn arrays provides a 2D distributed feedback (DFB) scheme for light confinement, providing a stimulated emission as 471 nm [9]. Recently, optically pumped green light stimulated emissions of InGaN/GaN nanocolumn arrays have been demonstrated [10].

In this talk, we describe emission characteristics of InGaN-based regularly arranged triangular-lattice GaN nanocolumn arrays.

InGaN/GaN MQW nanocolumn arrays were highly excited under a 355 nm Nd:YAG laser light with a pulse width of 5 ns at 20 Hz. Lasing emissions based on 2D-DFB scheme were successfully observed in the green wavelength range from 530 to 566 nm on the same substrate, as shown in Fig.1. The emission wavelength was controlled by structural parameters, such as column period, and diameter.

Employing the emission-color control technology with nanocolumn diameter, the monolithic integration of nanocolumn LEDs emitting in the different colors of green (541 nm) and orange (597 nm) has been demonstrated [8]. In this talk, the successful operation of integrated nanocolumn LEDs (L=300 nm) with four different emission colors of blue (465 nm), sky-blue (489 nm), green (510 nm) and yellow (570 nm), respectively is described as shown in Fig.2.

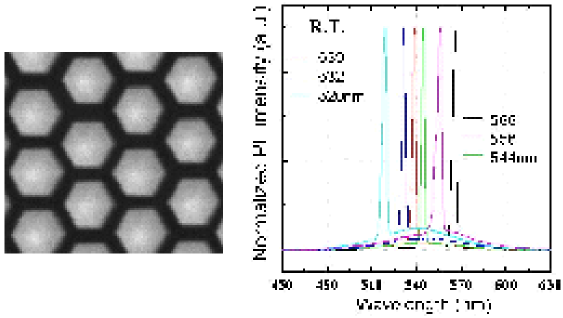

Fig.1 Green stimulated emission of nanocolumn arrays from 520 to 566 nm in wavelength

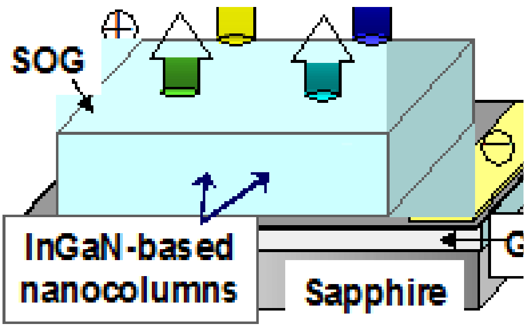

Fig. 2 Monolithic integration of four colors nanocolumn LEDs (blue, sky-blue, green, yellow)

This study was partly supported by a Grant-in-Aid for Scientific Research on Specially Promoted Research #24000013 from JSPS.

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Progress in Nonpolar and Semipolar GaN-based Laser Diodes

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Devices grown on c-plane GaN suffer from large internal electric fields due to discontinuities in spontaneous and piezoelectric polarization effects which cause charge separation between holes and electrons in quantum wells and limits the radiative recombination efficiency. Nonpolar GaN devices, such as in the m-plane (1100), are free from polarization related electric fields since the polar c-axis is parallel to any heterointerfaces. Semipolar GaN-based devices have reduced electric fields and in some cases, such as (2021), show a high propensity for Indium update for InGaN quantum wells. In this talk, we present highlights in recent UCSB work on nonpolar and semipolar GaN-based laser diodes.

Unlike their c-plane counterparts, strained III-N layers grown on semipolar substrates have easy dislocation glide on the inclined c-plane [1] and also show slide on inclined prismatic planes [2,3,4]. Strained layers grown on m-plane substrates show prismatic slip on inclined m-planes [4]. In this talk we emphasize recent results on the realization of long wavelength (1122) laser diodes on pseudomorphic buffer layers [5] and (2021) laser diodes on buffers with limited relaxation via limited area epitaxy [6]. Additionally, we present progress in lasers on (2021) and m-plane substrates.

References:

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[2] Feng Wu, E.C. Young, I. Koslow, M.T. Hardy, P. S. Hsu, A.E. Romanov, S. Nakamuara, S.P. DenBaars and J. S. Speck, Appl. Phys. Lett. 99, 251909 (2011).

[3] Matthew T. Hardy, Po Shan Hsu, Feng Wu, Ingrid L. Koslow, Erin C. Young, Shuji Nakamura, Alexey E. Romanov, Steven P. DenBaars and James

S. Speck, Appl. Phys. Lett. 100, 202103 (2012).
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[5] Po Shan Hsu, Matthew T. Hardy, Feng Wu, Ingrid Koslow, Erin C. Young, Alexey E. Romanov, Kenji Fujito, Daniel F. Feezell, Steven P. DenBaars, James S. Speck and Shuji Nakamura, Appl. Phys. Lett. 100, 021104 (2012).
[6] Matthew T. Hardy, Feng Wu, Po Shan Hsu, Daniel A. Haeger, Anisa Mysaferi, Shuji Nakamura, James S. Speck, and Steven P. DenBaars – manuscript submitted for publication.

Cyan AlGaN-cladding free nitride laser diodes grown by PAMBE

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Green LDs operating at 500 – 530 nm have been demonstrated in nitride-based structures grown by Metal Organic Vapour Phase Epitaxy either on polar, semipolar and nonpolar substrate orientations. On the other hand, the progress in understanding the growth mechanism for nitrides in Plasma Assisted Molecular Beam Epitaxy (PAMBE) has led to the demonstration of true-blue AlGaN-cladding free LDs [1] which in turn has renewed interest in this technology.

The key difficulty for InGaN growth is high nitrogen overpressure required at optimum growth temperature. Therefore we propose to grow InGaN layers with extremely high N flux, maintaining the non-interacting beams conditions in PAMBE. We had already shown that by increasing the nitrogen flux in PAMBE up to 0.7 μm/h we were able to achieve optically pumped lasing from single quantum well laser structures in the range of 470 – 501 nm [2].

In this work we demonstrate the first AlGaN-cladding free LDs grown by PAMBE on commercial HVPE GaN substrates, which operate at 482 nm at the optical powers up to 250 mW in continuous wave mode. The quantum wells were grown for high N flux of 2 μm/h. We used a simplified separate confinement heterostructure design with GaN claddings. The optical mode was confined by the 120 nm thick $In_{0.08}Ga_{0.92}N$ waveguide.

We will discuss the InGaN growth mechanisms in PAMBE, in particular, the role of nitrogen in suppression of In segregation in

QWs. The influence of LD design on the LDs parameters, like threshold current and optical beam quality will be presented.

References:

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Acknowledgements:

This work was supported partially work was supported partially by the National Centre for Research and Development Grant INNO-TECH 157829, the National Science Centre Grant No. 02938, and the EU Innovative Economy Grant (POIG.01.01.02-00-008/08).umn diameter, the monolithic integration of nanocolumn LEDs emitting in the different colors of green (541 nm) and orange (597 nm)

Effect of index-antiguiding on the lasing threshold of narrow RW (In,Al)GaN laser diodes investigated by self-consistent simulations

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In (In,Al)GaN laser diodes, narrow ridge-waveguides are essential, in order to achieve lateral-single-mode operation. An unusually strong dependence of the threshold current on the ridge-waveguide etch depth has been observed, when the width of the ridge is in the range of a few micrometers [1] [2].

Strong index-antiguiding is proposed as an explanation, and a very large value of the antiguiding factor R is experimentally determined. The mode behavior is investigated by self-consistent simulation: according to the results, antiguiding can quantitatively explain the difference in threshold and is consistent with peculiarities observed in the lateral far-field patterns [3]. Deep ridge etching well into the p-waveguiding layer can limit the threshold, albeit higher modes may oscillate. Based on these investigations, narrow ridge-waveguide laser diodes emitting at 415 nm under CW operation with threshold currents below 55 mA and maximum output power of more than 30 mW were realized.

References :

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Acknowledgements:

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InGaN GRINSCH laser diodes

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Graded-index separate confinement heterostructure (GRIN SCH) in GaAs laser diodes is the subject of intense investigation since the early eighties until the present day. The results show that applying optimized GRIN SCH can improve greatly optoelectronic parameters of laser diodes. According to our knowledge, until present day there are hardly any reports on applying GRIN SCH in laser diodes based on GaN system.

In this work we present our first attempt at InGaN laser diodes with graded-index separate confinement heterostructure (GRIN SCH). Investigated structure was grown by metalorganic vapor phase epitaxy (MOVPE) on GaN substrate obtained by ammonothermal method. The devices were fabricated as p-up, ridge-waveguide diodes with 700 µm long resonator and 3 µm wide ridge. The content of Al in 330 nm thick bottom guiding layer is changing linearly from 7%, which is corresponding to Al content in cladding layer, to 0%. For p-side, 320 nm thick guiding layer, Al content is changing linearly form 0% to 4%.

The devices are characterized by low threshold current density (approximately 3.5 kA/cm^2), high differential gain (approximately 0.8 $cm^{-1}mA^{-1}$) and high optical power. The emitted wavelength was 420 nm. All results were obtained under DC operation. For better understanding of influence of this type of structure on optoelectronic parameters and in order to optimize the structure we performed theoretical calculation of optical field distribution in the structure.

Long wavelength VCSELs and VECSELs made by wafer fusion

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The realization of vertical cavity surface emitting lasers (VCSELs) operating in the 1200-2000nm spectral range has presented significant technological challenges in terms of materials preparation and device fabrication. Unlike their shorter-wavelength counterparts, it is difficult to epitaxially grow these VCSELs in a single run, and the best materials suitable for their different components do not belong necessarily to the same system.

We review recent progress in this area, achieved with the application of wafer fusion of GaAs-based distributed Bragg reflectors (DBRs) with InP-based quantum well (QW) active regions in which carrier injection is implemented with regrown tunnel junction mesas [1]. Low power consumption, adequate single mode output power (1-2mW typically in the 20-90°C range), precise (~1nm) emission wavelength setting, 10Gb/s direct modulation capability, low noise operation, wide range (several nm) continuous wavelength tunability, compatibility with industrial manufacturing and testing, and long term reliability [2] in accordance with Telcordia specifications have been achieved with this technology. These qualities make these VCSELs suitable for applications in low power consumption high bandwidth communication links, integration with silicon photonic circuits, and optical spectroscopy for chemical sensing.

In addition, a similar wafer fusion technique allows the fabrication of vertical external cavity surface emitting lasers (VECSELs) emitting in the same spectral range [3]. Output powers of several Watts near 1300nm and 1500nm wavelengths, as well as single wavelength operation, picosecond pulse generation and frequency doubling using intra-cavity elements, were demonstrated with such optically pumped VECSELs. Potential progress with similar electrical cavity VECSEL devices [4] will also be discussed. These high power, compact laser devices may find applications in laser projectors, infrared illuminators and fiber laser pumping.

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High power femtosecond pulse vertical-external-cavity surface-emitting lasers

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Optically pumped semiconductor lasers have developed into a mature technology for a broad range of continuous wave applications. Over 100 W CW output power was recently reported [1] and Coherent inc. now have a range of products based on intra-cavity frequency conversion in optically pumped semiconductor lasers, with powers up to 20 W at 532 nm commercially available.

The same advantages of wavelength engineering and the external cavity combined with the surface emission geometry and thin active region enable near-transform-limited femtosecond pulse generation in mode-locked VECSELs at GHz repetition rates [2, 3]. Recently, the exploitation of thermal management techniques in the gain region developed in CW VECSELs, has allowed the average power, and hence peak power of mode-locked VECSELs to be scaled by more than an order of magnitude [4, 5].

I will discuss the key structure design and growth considerations for femtosecond pulse generation as well as the mode-locking techniques which are exploited. I will discuss how these components can be brought together to create a flexible repetition rate, multi-Watt femtosecond pulse laser, and the potential applications including frequency comb generation that these lasers should enable.

References:

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[5] M. Scheller, T.-L. Wang, B. Kunert, W. Stolz, S. W. Koch, and J. V. Moloney, "Passively modelocked VECSEL emitting 682 fs pulses with 5.1 W of average output power," Electron. Lett. 48 (10), 588–589 (2012)

Switchable, two wavelength emitting VECSEL

A. Broda,
J. Muszalski
P. Gutowski
I. Sankowska
J. Kubacka-Traczyk
A. Jasik
A. Wójcik-Jedlińska
A. Trajnerowicz
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In recent years Vertical-External-Cavity Surface-Emitting Lasers (VECSEL) are of great interest as the attractive sources of coherent light. The external cavity and flexibility of the semiconductor epitaxy allows to design and fabricate VECSEL source for almost any wavelength directly or by intracavity frequency conversion (e.g. second harmonic generation process (SHG)). Moreover, the flexibility for accurate wavelength control by means of bandgap engineering has enabled to develop VECSEL capable of two wavelength emission [1,2]. In previous work we have demonstrated a simultaneous dual-wavelength emission by enclosing the two different types of active regions inside a single microcavity [3].

In this paper we report the realization of switchable two wavelength VECSEL. The laser emitting at 967nm or 1017nm can operate at each wavelengths up to 1W, each in the single TEM_{00} mode. The emission wavelengths are switched by simply changing laser operation conditions: the pump power or the temperature of heatsink. This has been achieved by a special design of the heterostructure. The heterostructure consists of a single active region enclosed in a two mode microcavity. Both the increase of the pump power or the heat sink temperature results in a spectral red-shift of the gain maximum, what, in turn, switches the laser emission from short to long wavelength mode. At the same time the drop of the gain value due to the temperature increasing is compensated by the larger value of longitudinal confinement factor for the longer wavelength mode.

We believe that coaxial two wavelength laser emission can be an attractive source in a number of application, especially where a high reliability of beam guiding is required or the space is limited. The application of the SHG process in a cavity of the switchable two wavelength VECSEL can transfer it to a two color source, as for instant, blue and green what can be of great use in the low volume projectors.

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GaAs/AlOx high contrast gratings for 980 nm VCSELs

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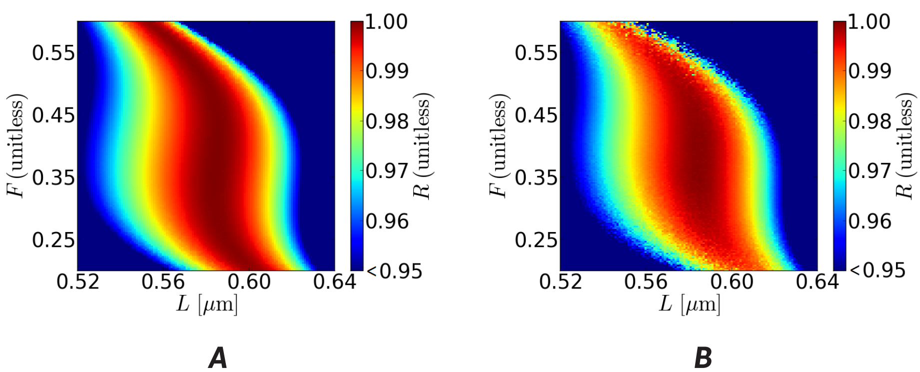
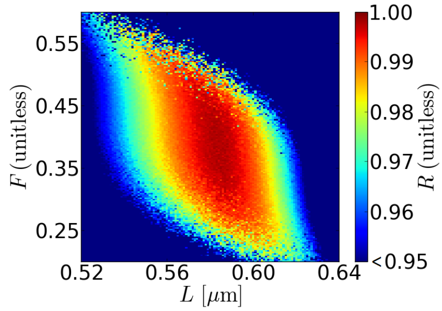
A three dimensional, fully vectorial optical numerical model is used to design GaAs/AlOx high contrast grating (HCG) for use as the top mirror of a 980 nm arsenide-based vertical-cavity surface-emitting laser (VCSEL). The results demonstrate that such configuration if carefully designed by advanced numerical models can offer better performance in comparison to conventional distributed Bragg reflectors. Manufacturing process of a HCG might involve undesirable imperfections leading to deterioration of its optical properties (Fig. 1). Hence we perform error analysis assuming random nonperiodicity of the HCG and consider broad range of absorption, which mimic the realistic structure. We show that HCG reveals tolerance to both parameters.





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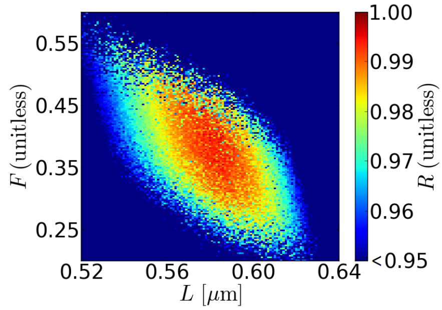

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Fig. 1 Averaged reflectance (R) of the HCG mirror in the domain of fill factor (F) and HCG period (L) for varied standard deviations A) 5 nm, B) 15 nm, C) 25 nm, D) 35 nm.

Acknowledgements:

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MBE growth and optimization of THz quantum cascade lasers

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Since their initial demonstration in 2002 [1], THz QCLs have achieved a remarkable progress and can now operate in 1.2 - 4.5THz spectral range with maximum operating temperatures for the best devices of ~200K. [2] Increasing their operating temperatures to commercially available thermoelectric coolers range (~240K) will make THz QCLs very attractive to a broad range of potential applications in areas such as biological sensing, pharmaceutical sciences, THz wave imaging, security screening and ICT, to mention just a few. In 2007 [3] we have proposed3 the simplest at the time resonant phonon depopulation (RP)–type THz QCL design based on a three quantum well $GaAs/Al_{0.15}Ga_{0.85}As$ active module, which proved to be particularly effective in increasing the population inversion and hence the gain at higher temperatures. Indeed, in 2008 Capasso's Harvard group [4] demonstrated with this design a record high lasing temperature of 178K, using low-loss copper metal-metal waveguides, while in 2009 a temperature of 186K was reported by Hu's MIT group [5] using the diagonal variation for this THz QCL with decreased leakage channels. The relative simplicity of the three well design permitted us to conduct a series of experimental studies, using a unique to molecular beam epitaxy (MBE) capability [6] of well controlled variation of only one structure parameter across the substrate, while retaining excellent spatial uniformity for the remaining parameters [7,8]. The same simplicity has also helped to develop an analytical model [9] explaining the observed trends, giving us a valuable tool to further optimize the laser performance. This effort resulted in a new world record T_{max} of 199.5K [2], while the insight gained on the way spurred vigorous activities which led to new promising laser designs [10,11]. Even though the achieved operating temperatures have already surpassed early expectations, there are no obvious fundamental limits which would prevent GaAs/AlGaAs THz QCLs from operating right up to room temperature [12]. Perhaps the most controversial and the least understood at present is the role of interfacial roughness on scattering of the tunneling electrons, which can be an important gain limiting factor in GaAs/AlGaAs material system as well as other material systems presently considered for THz QCL devices. Thus further optimization of MBE growth may well be the key to promote progress in this area.

In this talk we give an overview of the state of the art in the field of THz QCL devices and present a condensed account of the quest for the high operating temperature with emphasis on the molecular beam epitaxial process and related challenges.

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II-VI/III-N Micro-Chip Laser Diode Converters for Green-Yellow Spectral Range

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The lack of "true" green compact semiconductor lasers on the market stimulates studies of direct-emitting III-N green laser diodes (LDs) as well as search for alternative ways of obtaining efficient compact green laser emitters. Recent fabrication of cw InGaN LDs on semi-polar (11-22) GaN substrates, emitting at a wavelength up to 536 nm [1] and exhibiting the 5000 h lifetime for the range λ=525-530 nm [2], has been a real breakthrough in this racing. Nevertheless, the "true" green (530-550 nm) and yellow-green (555-570 nm) ranges of the visible spectrum are still unreachable for III-N LDs at this stage, and one can expect strong limitation of their output power for this ranges in the future. So, the restart of II-VI green-yellow LDs development [3] as well as elaboration of the violet-green laser converter composed of a high-efficiency Cd(Zn)Se/ZnMgSSe laser heterostructure optically pumped by the emission of a blue-violet InGaN LD [4] are still of a great importance. Both the optimization of low-dimensional II-VI laser heterostructures (by using of graded-index superlattice waveguide, precise strain compensation, choice of a proper QD active region design) [5] and appearance on the market of high-power blue-violet LDs have resulted in demonstration of the II-VI/III-V LD converter emitting in green (λ=543 nm) with the maximum pulse output power of 154 mW and quantum conversion efficiency of η=25.4% [6]. Pulse InGaN/GaN LD emitting at 416 nm with P_{exc}~1 W (TopGaN) was used for pumping.

The paper will report on recent progress in developing the optically-pumped yellow-green II-VI QD laser structures grown by MBE on GaAs(001) with the threshold power density below 1 kW/cm^2 (300K). In particular, employing of the n-type modulation doping of cladding and waveguide layers, further reduction of point and extended defect density, as well as extending lasing wavelength to the yellow range will be considered. As a result, the optimized II-VI structures are employed for fabrication of pulse green micro-chip LD converters (based on blue-U440 pumping InGaN LDs, cylindrical micro-lens, and a TO-18 package), which exhibit the output power above 1 W (at τ_{pulse}=4ns, η~14 %) and 160 mW (at τ_{pulse}=200ns). The yellow-green micro-chip LD converters emitting in the 558-566 nm range, as dependent on the II-VI laser cavity length, have been fabricated as well. They demonstrate the maximum pulse output power ~ 90 mW (at τ_{pulse}=200ns).

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Influence of doping on threshold current in mid-IR QCL– a NEGF model

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Although not exclusively, most experiments on mid-IR quantum cascade lasers (QCLs) show monotonic increase of the threshold current with the doping of the active layers. Such dependence was observed e.g. for InGaAs/AlInAs devices lasing at ~9 mm and was attributed to the "increased free carrier absorption in the core region" [1]. This statement mirrors the current state of art of understanding this phenomenon. Numerical simulations of the device like this in Ref. [1] performed with our nonequilibrium Greens function (NEGF) solver [2] [3] reveal, however, that in the core region there is no absorption at the lasing frequency. Instead, we have observed that threshold current increases due to the thermal backfilling of lower laser subband what destroys the gain. We have been able to quantitatively describe this dependence with the scaling relation binding threshold current density J_{th} and threshold voltage U_{th}.

Namely,

$J_{th}\,\tau_4 = a + b\,\exp(-CU_{th}/kT)$

(1)

where a, b, C are numerical coefficients, τ_4 is the upper state lifetime and n_s is the sheet doping density of the active wells. This relation has been tested with our simulation data: threshold I-V values for different doping and temperatures after appropriate scaling collapse onto a single straight line. Such test has been passed also by other m-IR QCL designs. We conclude that Eq. (1) could become a general test that QCLs should pass in the case when thermal backfilling of lower laser state is the major deteriorating process.

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Application of pressure-tuned laser diodes in spectroscopy

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We have recently developed laser-diode tuning methods using pressure, temperature and external grating [1-4]. By tuning several commercially available laser diodes we can reach any emission wavelength in the range 570nm - 2400nm. It is possible to apply these tunable laser diodes to modulation measurements such as photoreflectance, electro-reflectance and photo-current where they would replace light from the lamp and monochromator. The application of the probe beam from a tunable laser diode will enhance the spatial and spectral resolution of modulation techniques. It also opens up the possibility of using fiber probes in these measurements, mapping the strain distribution in microstructures, studying individual quantum dots etc.

The second category of methods where tunable laser diodes can replace conventional tunable lasers (like Titanium-Sapphire or dye lasers) includes photoluminescence excitation (PLE) and resonant Raman scattering (RRS). In this case the application of laser diodes increases the available spectral range. This seems useful for semiconductor structures grown on InP and GaSb operating in the 1-3 micron range.

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Progress Toward Optimizing 850-nm and 980-nm Vertical Cavity Surface Emitting Lasers (VCSELs) for Optical Interconnects

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We highlight our work on high bit rate and energy efficient directly modulated 850-nm and 980-nm vertical cavity surface emitting lasers (VCSELs) for applications in optical interconnects (OIs) [1], [2], [3], [4]. Ubiquitous VCSEL-based OIs are now, or are envisioned to be employed in a plethora of systems vital to the continued growth of all imaginable current and future Internet, Cloud services, and electronic gadget technologies including data centers, super and personal computers, industrial and consumer free-space OIs, integrated intra- and inter-chip OIs, and very short reach board-to-board OIs. We review our innovative VCSEL epitaxial designs, processing schemes, and characterization methods. We explain our record experimental results including VCSELs that transmit error free data (with bit error ratios < 1e-12) across 50-m, 500-m, and 1000-m of standard multimode optical fiber (MMF) at up to 40-Gbit/s, 30-Gbit/s, and 25-Gbit/s, respectively, each with dissipated heat energies of only about 100-fJ/bit [1], [2], [3]. Finally we reveal our most recent experimental and numerical optical modeling results, including studies of cavity photon lifetime [5] and selected nanometer-scale material enhancements to our VCSEL designs.

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Subwavelength high contrast grating mirrors for applications in vertical-cavity surface-emitting lasers

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Optical gratings have been studied for a long time. Their physical principles are well known and they found their applications in numerous optical devices. However, in last few yeast, there have been-rapid increase in scientific interest in a particular class of gratings, which consist of materials with high refractive index contrast and have lattice period smaller than the free-space wavelength of the incident light. Under some circumstances such gratings can act as perfect broad bandwidth mirrors and, hence, can be used as a replacement or distributed Bragg reflectors in vertical-cavity surface-emitting lasers (VCSELs). Such substitution can offer numerous advantages over classical approach like e. g. full stability of polarization of the emitted light, reduced mass and thickness of the mirrors, or possibility of easy introduction of spatial variation of the reflectivity that can be used to focus the light beam or to achieve single-mode operation of the laser.

In the talk we discuss the physical basis of operation of such mirrors and the methods of numerical modeling of their properties. Furthermore, we present simulation results of various subwavelength hight-contrast grating (HCG) structures based on Si and GaAs high index materials combined with SiO2 and AlOx cladding low index material layers respectively. Reflectivity simulations at 980 nm wavelength show that reflectivity exceeding 99.8% can be obtained in a broad range of grating parameters. Additionally the same parameters assure very strong discrimination between two polarization directions. Finally we present a numerical analysis of properties of VCSELs incorporating such gratings in their design.

We would like to acknowledge Polish-Singapore grant no. 1/3/POL-SIN/2012 “A Novel Photonic Crystal Surface Emitting Lasers Incorporating a High-Index-Contrast Grating” and the support of Polish National Centre for Research and Development within project LIDER.

Numerical simulation of optical properties of long-wavelength wafer-fused VCSELs with intra-cavity patterning

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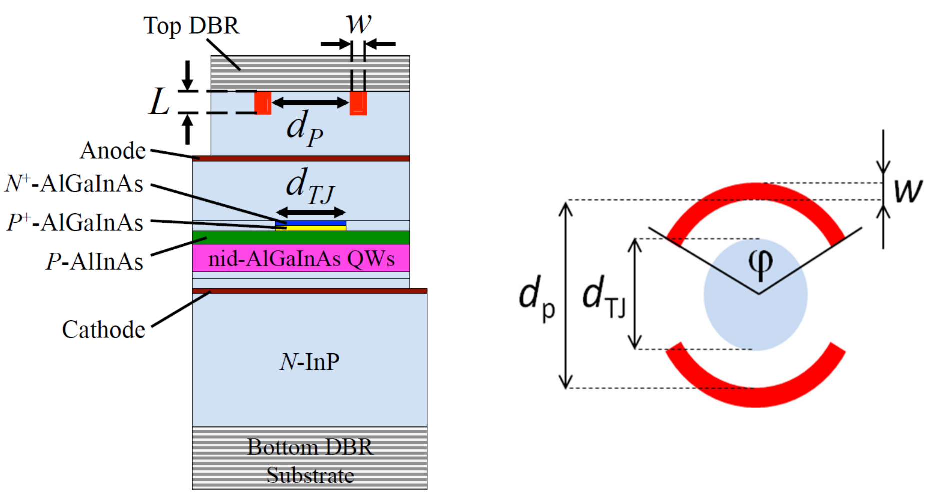
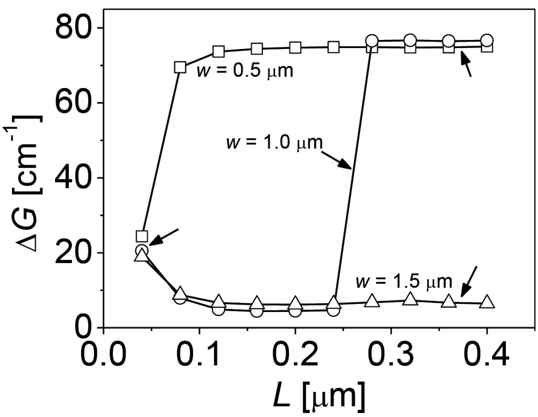
We demonstrate the results of numerical simulations of 1.3 μm InAlGaAs/InP VCSEL with ring pattern etched at the interface between the cavity and top DBR (Fig. 1a,b). The design reveals the unique attribute of selective confinement of the fundamental mode and strong discrimination of higher order modes. Three different behaviours driven by different lateral parameters of the etchings can be induced (Fig. 1c). The increase of the etching depth confines the fundamental mode and either: 1) confines first order mode (Fig. 1c, w = 1.5 μm); or, 2) pushes first order mode out of the aperture (Fig. 1c, w = 0.5 μm); or, 3) confines first order mode for shallow etching and pushes it out of the aperture for deeper etching (Fig. 1c, w = 1.0 μm).



[a] **[b]**



[c]

Fig. 1 a) Schematic cross-section of the patterned VCSEL with definitions of the geometrical parameters of the etched ring, b) top view of the ring (d_p – aperture of the ring) and tunnel junction (d_{TJ} –aperture of the tunnel junction), c) the modal gain difference between HE_{11} and HE_{21} as the function of the etching depth of the ring for d_p = 7 μm, d_{TJ} = 6 μm, φ= 180^o and for three different widths (w).

We performed extensive optimisation of the required etching parameters. The optimal structure allows higher order modes discrimination in broad range of injected currents, which facilitates improvement of the maximal emitted power and increase of the wavelength tuning range in the single mode regime.

Acknowledgements:
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Semiconductor double-chirped mirrors for dispersion compensation in femtosecond Yb:KYW lasers

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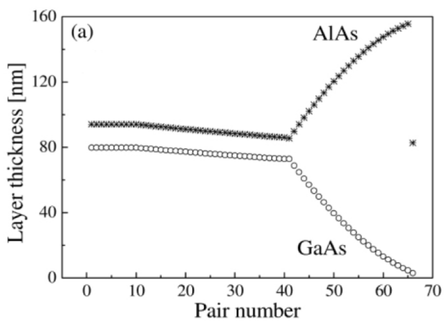
Dispersion compensation is one of the main factors influencing stable and optimized mode-locked operation in femtosecond lasers [1]. We present a semiconductor double-chirped mirror (SDCM) with high negative group delay dispersion (GDD) of about -2500 fs^2 and the reflection exceeding 98.9% over the spectral range spanning ±4 nm around 1030 nm [2].

The mirror was fabricated using molecular beam epitaxy (MBE) and consists of 65 pairs of GaAs/AlAs layers and an antireflective SiNx layer, summing up to the total thickness of 10.8 μm (see Fig. 1). When used to compensate the cavity dispersion in a diode-pumped femtosecond Yb:KY(WO4)2 oscillator [3], at 490 mW of the absorbed pump power, the laser delivered 110 mW in pulses of 240 fs duration.



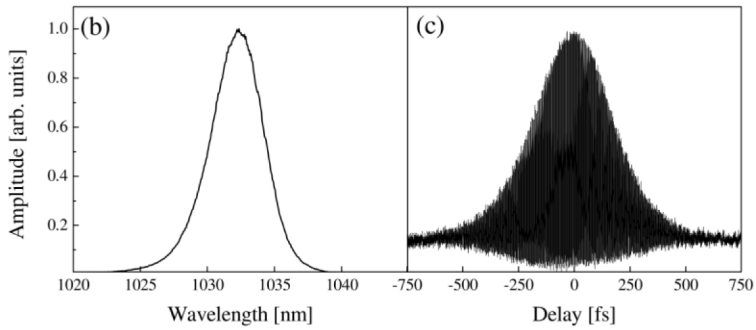


Figure 1. The design of the high dispersion AlAs/GaAs double-chirped mirror structure (a). The antireflective layer is not shown. Measured spectrum (b) and interferometric autocorrelation (c) of the Yb:KYW oscillator pulse train. The spectral FWHM is 4.5 nm and the pulse duration FWHM is 240 fs (assuming sech envelope).

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Future Light Sources for Pico Projection

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At present the emission of InGaN based laser diodes (LDs) covers the spectral range from UV, through blue and all the way into true green. InGaN based LDs can nowadays be found in a wide variety of appliances. According to recent market research reports, one of the highest market potential for the InGaN based LDs in the nearest future may be mobile projection. This market would directly benefit from replacement of the robust frequency-doubled green lasers by miniature InGaN-based direct green laser, resulting in compact projectors that would be integrated into the next-generation mobile phones. However, this type of application requires the LDs that can provide at least 20 lm. When compared to LEDs, LDs are more expensive but would enable sharp pico projection on any desired surface and at larger distances.

InGaN based blue laser is already fit for mobile projection applications. Even though the blue laser is nowadays already in the Watt category and as such used in commercial 2000lm business projectors, However for mobile projection purposes even the powers of the order of 100mW would suffice. On the other hand, semiconductor lasers also present a number of technical inconveniences, such as speckles or stray light emission.

In this paper we will address the progress in visible InGaN-based LDs, both blue as green. We will show that the main limiting factor for green LDs operation at higher currents of is the LDs' self-heating which directly hinders generation of higher output powers. Improved design single-mode R&D samples are designed for current levels that result in output powers of 100 mW with a roll-over above 200 mW under cw-operation.

We will also discuss some technical issues that concern generation of stray-light-free LDs emission. As potential light sources for pico projection, an alternative to the blue LDs application, we will also address blue super luminescent diodes, both blue (P>100mW) and green, with broad emission spectrum and thus nearly speckle-free.

UV Lasers – Status and Prospects

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Ultraviolet (UV) semiconductor laser diodes are of great interest for applications in the area of medical diagnostics, high throughput drug screening, fluorescence spectroscopy, and sensing. Group III-nitride heterostructures are hereby ideally suited since they are able to cover large portions of the UV spectral range. However, the emission of (In)AlGaN-based current-injection laser diodes has so far been limited to the UV-A band with the shortest wavelength laser reported to emit at 336 nm. In this paper we will review progress in the development of UV-C laser diodes and discuss epitaxial growth challenges as well as quantum well active region and waveguide designs for AlGaN-based lasers emitting in the deep UV spectral range. One of the major impediments for UV-C lasers is the lack of a suitable substrate. Bulk AlN substrates would be ideal, but are currently available only in small sizes and limited quantities. AlGaN alloys can be grown on sapphire substrates; however, the defect density in these templates is typically in the 10^{10} cm^{-2} range. We will present novel approaches to reduce the defect densities in Al(Ga)N layers on sapphire using epitaxial lateral overgrowth (ELO), which yield defect densities in the mid 10^{8} cm^{-2} range. Lasing between 272 nm and 292 nm was observed for optically pumped AlGaN multiple quantum well (MQW) heterostructures grown pseudomorphically on ELO AlN/sap-

phire and bulk AlN substrates. The lowest threshold energy densities were near 50 mJ/cm^2 for UV-C lasers grown on low defect density bulk AlN substrates and just slightly higher for lasers on ELO AlN/sapphire. We will also discuss the effects alloy composition and strain in the AlGaN quantum wells and barriers on the band-structure and optical gain of AlGaN MQW lasers. At shorter wavelengths the split-off hole band moves closer to the conduction band relative to the heavy and light hole bands and as a consequence a transition from TE mode to TM mode lasing can be expected. Nevertheless in all cases of this study the lasers exhibited TE mode lasing even at wavelength as short as 272 nm. Finally, in order to realize low-voltage UV-C laser diodes low resistance AlGaN cladding layers are required for lateral current-injection. For AlGaN cladding layers with high aluminum mole fractions (x > 70%) even n-type doping of AlGaN becomes challenging. We will show that low resistance Si-doped n-$Al_{0.81}Ga_{0.19}N$ layers can be realized on low defect density ELO AlN/sapphire with free electron concentration of 1.5 x 10^{19} cm^{-3} and mobilities of 26 cm^{2}V^{-1}s. Even at very high aluminum mole fractions of x = 96% $Al_xGa_{1-x}N$:Si layers with a resistivity as low as 3.35 Ωcm could be realized. Although additional challenges, e.g. the p-doping of AlGaN and efficient hole injection into the active region, have to be resolved, these examples demonstrate that AlGaN-based laser diodes can in principle reach the UV-C wavelength range.

High power InGaN superluminescent diodes

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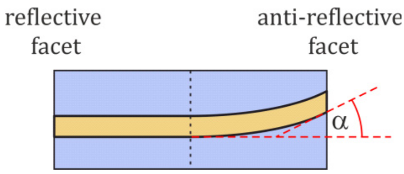
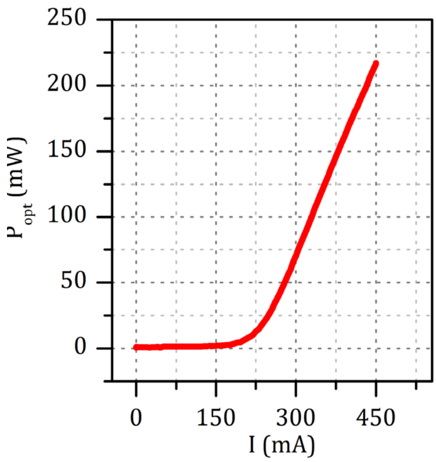
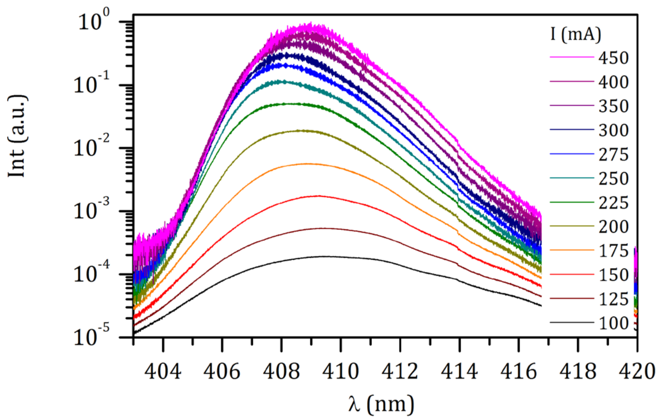
Superluminescent diodes (SLDs) are semiconductor devices which emit a narrow light beam of very low time coherence. The epitaxial structure of such devices is identical to that of a laser diode. However, a specific shape of waveguide can be defined, which prevents light from oscillation in the structure.



Within our current work, we fabricated InGaN SLDs with a bent waveguide in a shape of letter "j" (see Fig. 1). This geometry provides light reflection from the rear facet (straight end) and low reflection from the bended end. We fabricated devices of three chip lengths: 750 μm, 1000 μm and 1500 μm. The studied bend angles are in a range of 4.75° to 8°.

Devices were tested under DC bias and at room temperature. We achieved output optical powers exceeding 200 mW under CW operation (spectra and optical power vs. current dependence are shown in Fig. 2 and Fig. 3). At low current densities the spectra are smooth and wider than 7 nm. With increasing current density the width of the spectrum decreases and modulations appear. A thorough investigation of the influence of bend angle value on modulation depth in emitted spectrum was conducted. We compare the experimental results with calculation of reflectivity of a tilted waveguide facet. We also closely analysed changes of diode parameters (spectrum width, emitted optical power, optical power vs. current characteristic shape) with respect to chip length. J-shape geometry looks extremely promising for superluminescent diodes, as it assures high output power accompanied with low spectral modulations.





GaN-based ridge waveguide laser diodes: optimizing the optical mode profile

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Long lifetime reliability and good operating parameters determine the quality standard of a laser diode. Among many other aspects, the optical mode profile reflects the outcome of both structure design and full fabrication process which determine the final device performance. Using different characterization methods, like atomic force microscopy (AFM), white light interferometry (WLI), far-field measurements and Hakki-Paoli gain spectroscopy, we investigate the influence of the surface roughness on the vertical mode profile and discuss how the process of ridge formation by reactive ion etching (RIE) contributes to the optical mode guiding and internal losses.

Emission Wavelength Dependence of Characteristic Temperature of InGaN Laser Diodes

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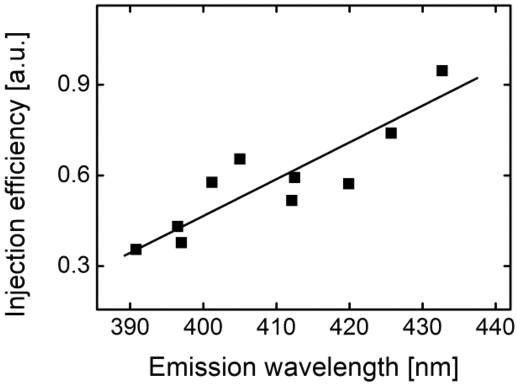
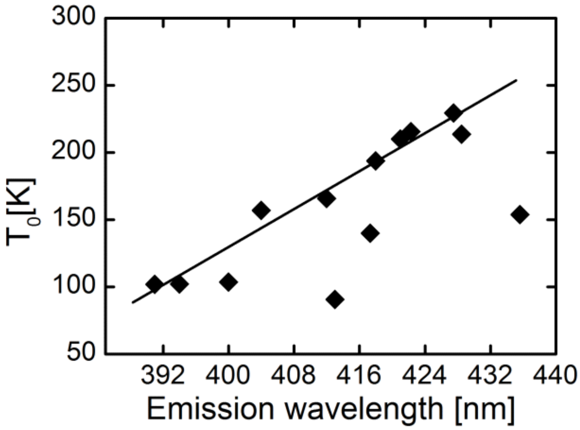
We have determined the characteristic temperature T0 of various InGaN laser diodes emitting in the spectral range of 390-436 nm. All the structures were grown by MOCVD (metalorganic chemical vapor deposition). The characteristic temperature T0 of these devices increases steeply with the increasing emission wavelength from T_0=100 K at λ=391 nm to the value of 230 K for λ=427 nm (FIG.1).

In order to explain the observed evolution of T_0, we measured the light – current characteristics at low current densities and at different temperatures. Analysis of obtained results revealed that the injection efficiency is lower and much more sensitive to the temperature change at shorter wavelength [FIG. 2]. The analysis of activation energies of electroluminescence, which appeared to be almost equal to the effective QW depths, proves that observed behavior is predominantly related to the thermal escape of carriers from quantum wells.

This work was partially supported by the European Union within European Regional Development Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08) and Polish Ministry of Science and Higher Education, grant NN202131339. This work was also supported by EIT+ research task „Nanomaterials for Optoelectronic and Sensory Applications" in the research program „Application of Nanotechnology in Advanced Materials" (project number: POIG 01.01.02-02-002/08), EU-funded under the Innovative Economy Operational Program.


Injection efficiency [a.u.]
0.3
0.6
0.9
390
400
410
420
430
440
Emission wavelength [nm]


T_0[K]
50
100
150
200
250
300
392
400
408
416
424
432
440
Emission wavelength [nm]

High performance AlInGaAs transmission lasers for FTTX applications

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The inexorable growth in broadband communications is creating an enormous market for low cost, single-mode, InP based semiconductor lasers emitting around 1.3-1.55um. Current Fibre To The Home, (FTTH) technologies deployed (Passive Optical Networking achitectures such as GPON, EPON) operate at line rates of 1.25-2.5 Gb/s. However, satisfying future bandwidth demand will require implementation of new PON standards such as 10GPON, and extended reach (LR) PON, and high capacity WDM PON (ranging from course to ultra high density (UDWDM) mutiplexing using coherent detection schemes). The future semiconductor laser source requirements for all such standards can be condensed into several drivers:

- Improving performance to 10Gb/s transmission rates and beyond
- Increasing output power for longer reach in uncooled packaging schemes
- High quality spectral output: narrow optical linewith and wavelength tunability
- Offering all the above at consumer grade pricing

This is a huge challenge to an industry that is used to producing lower volume, ultra-high specification diode sources at premium pricing. Current commercial grade sources used for high specification operation include directly modulated Distributed Feedback lasers (DFBs), Buried Heterostructure Electroabsorption-modulated lasers (EMLs) and Chirp-managed lasers (CMLs). All have inherent complexities which create yield issues or expensive packaging, thus making consumer grade pricing extremely challenging.

We report research results from project ALOHA (AlInGaAs Lasers for Optical Home Access), which aims to develop the device and manufacturing technology to enable a step change in the price-performance curve for InP based laser components for Next Generation PON standards.

ALOHA was supported by the UK Technology Strategy Board via the ERANET PIANO+ programme.

Excitation of 2D plasma waves in semiconductor quantum well and its effect on lasing in InGaN diodes

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It is well known that in semiconductor quantum wells the 2D electron – hole plasma oscillations can be effectively excited in ballistic field-effect transistors and analogous electronic devices. This problem has been intensively studied in conventional solid-state electronics, in which 2D plasma oscillations were considered for a decades as a prospective way to build THz radiation source.

In this report, resonant excitation of 2D electron-hole plasma oscillation by beating of counter-propagating optical waves in flat (GaAs) and tilted (InGaN) quantum wells is discussed in the frame of self-consistent hydrodynamic approach. Such plasma oscillations can explain the observed mode clustering effect in InGaN laser diodes, consisting in the modulation of the diode spectrum with period enhanced by an order of magnitude with respect to the individual mode spacing. Excited plasma oscillations can provide self-consistent DFB-like feedback coupling in InGaN diode.

Improved upper heat stream removal in high-power laser diodes using graphene oxide layers

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Heat removal from the active region of high-power laser diodes (LDs) still remains an issue to be optimized. In the typical p-side-down mounting the most of the generated heat flux is received by the heatsink due to its proximity to the LD's active region (the lowest thermal resistance). Removal of considerable part of the heat flux directed toward the n-contact is less efficient, however, being dependent only on convection and wiring. The 'vice-type' mounting, such as 'golden bullet package' or 'bar-in-groove assembly' [1, 2] often used in the case of laser arrays is a good solution to this problem, but it is hardly applicable to cooling individual LDs. A solution can be finding a medium effectively removing the heat flux from the n-contact directly to the heatsink. Such medium of high thermal conductivity has to be simultaneously electrically isolating to prevent short-circuiting. The medium meeting these requirements proves to be grapheme oxide (GO), which additionally, in the form of aqueous suspension has low viscosity facilitating its application.

Effect of using GO was tested by comparing a thermal shift of LD's spectral characteristics connected with drive current increase. Various schemes of GO application (to side walls, to n-contact) were compared. In some of them serious reduction of thermal resistance has been recorded.

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Acknowledgements:
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High-power laser diodes with multi-stripe-gain distribution

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To obtain high-power laser diode (HP LD) usually the construction including broad active (BA) stripe is used. Such solution leads to reduce the quality of the beam because of multi mode character of the waveguide. One of the symptoms is the widening of the far-field in the lateral direction (slow axis) with increasing drive current [1].

It is connected with appearance

of higher order lateral modes. To limit this effect the multi-stripe-gain distribution laser diode (MSG-LD) design is proposed.

The idea is to form the laterally-periodic gain distribution in the active region of LD. Numerical simulations shows that in this construction the higher order lateral mode has the highest modal gain so its threshold current is low. The maximal width of the emitted beam is reached near threshold current of the MSG-LD.

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Acknowledgements:

The work is supported by the research funds of the Polish National Center of Science under the grant number UMO-2011/01/B/ST7/03333.

Strain compensated 4.7 μm AlInAs/InGaAs/InP QCLs – Non-equilibrium Green's function modeling of electro-optical characteristics

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In this paper we present the results of electro-optical characterization of strain compensated AlInAs/InGaAs/InP quantum cascade lasers emitting at 4.7 μm. The active region of the lasers was of 4-well 2-phonon resonance design [1]. The devices were MO CVD grown ridge waveguide (RWG), epi-side up mounted with uncoated facets. The lasers with 10 μm cavity width and the length of 3 mm, 4 mm and 5 mm were investigated. The current-voltage and light-current characteristics have been analysed and discussed with the aim of non-equilibrium Green's function (NEGF) model [2,3]. In this approach all quantities are computed within one-band model which takes into account nonparabolicity through energy dependent effective mass. Scattering mechanisms included in the simulations are LO and LA phonons, alloy disorder, and interface roughness. The e-e scattering is included through Hartree term. In spite that the only adjustable parameter is the height of interface roughness we were able to find good agreement between experimental and modeled characteristic (I-V, P-I and lasing frequency). The measured electro-optic characteristics of the laser with 10 μm x 3 mm cavity dimensions are shown in Fig.1. The comparison of NEGF calculated and experimental current-voltage ((I-V) characteristics is shown in Fig.2.

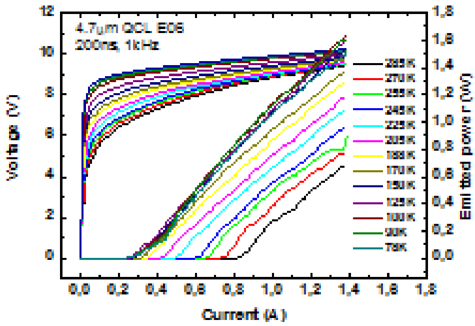

Fig. 1 Current-voltage ((I-V) and light-current (P-I) characteristics of 10 μm x 3 mm RWG AlI tures.

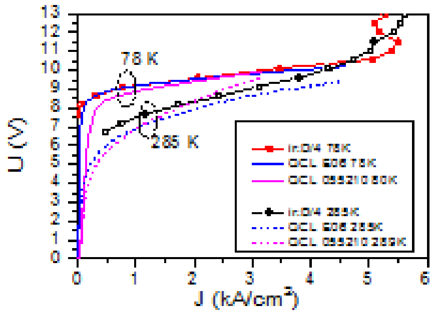

Fig. 2 NEGF calculated and experimental current-voltage (I-V) characteristics of 10 μm x 3 mm RWG AlInAs/InGaAs laser at liquid nitrogen and room temperature.

2-D waveguide analysis has been done by using fully vectorial waveguide solver based on the film mode matching method [4]. Waveguide losses and differential gain have been determined experimentally. They were used as the input parameter of the model to calculate above threshold characteristics of the lasers.

In our model electronic transport is fully resolved in k-space. Exemplary k-resolved density of states N(E, k, z) and electrons n(E, k, z) are shown in Fig. 1. Calculations reveal that electronic distribution in lower laser subband is non-thermal and have local maximum at the value of in-plane energy equal to the lasing energy. In the upper subband the carrier distribution is thermal-like. Lasing occurs without global population inversion because the gain which arises from the population inversion in low-k states of upper and lower laser subbands is not suppressed by high-k absorption due to nonparabolicity which shifts absorption peak to lower frequencies.

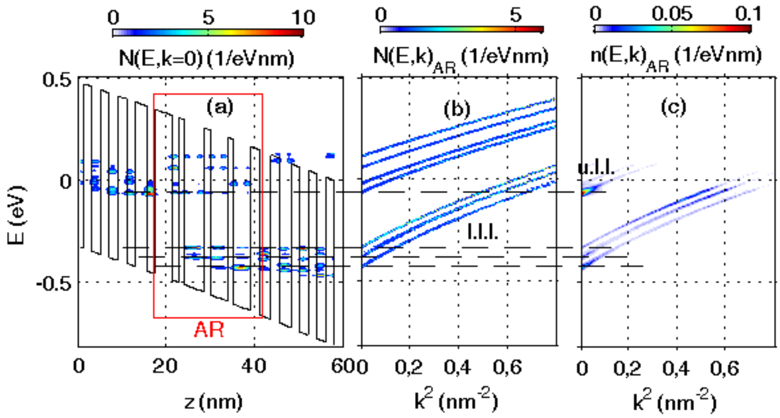

Fig. 3: (a) Spatially resolved density of states N(E, k) for vanishing transverse momentum k = 0. (b, c) Momentum resolved density of states (b) and density of electrons n(E, k) (c), both averaged over the active region (red box) of QCL period. Calculations were done for T = 77 K and bias U = 0.424V/period. Upper (u.l.l.) and lower (l.l.l) laser levels are marked with dashed lines.

In conclusion, we show that reliable simulation methods which can deal with the complicated physical phenomena involved in the quantum cascade lasers operation are necessary to predict the behaviour of quantum cascade lasers and to optimize their performance. Calculations reveal that electronic distribution in lower laser subband is non-thermal and lasing occurs without global population inversion.

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Combining MOVPE & low-temperature MBE for efficient green laser diodes

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III-nitrides have already proven to be excellent candidates for application in optoelectronic devices operating within ultraviolet to green spectral range. Nevertheless, the quantum wells (QWs) designed to increase the wavelength towards green emission ([In] > 25 %) still suffer from rather low internal quantum efficiency and thermal instability. One of the issues when fabricating such QWs is the large difference in the growth temperature of InGaN and GaN/AlGaN layers. This is especially significant for laser diodes (LDs) grown by metal-organic vapour phase epitaxy (MOVPE) where the growth of p-doped layers induces a large thermal budget onto the InGaN QWs. After the growth of the active region, the substrate temperature has to be increased (> 200°C) to keep good crystalline quality and electronic properties. This potentially leads to thermal degradation of the QWs. In this paper, we will present a way of circumventing this degradation, by the combined use of MOVPE and molecular beam epitaxy (MBE) techniques, MBE presenting the advantage of enabling lower growth temperatures than MOVPE.

We will first investigate the thermal degradation of indium-rich InGaN QWs grown by MOVPE. For this study, InGaN multiple-QWs with [In] > 15 % were independently annealed under conditions chosen to mimic the growth of the p-doped region of a LD. Structural analysis reveals the change in both QW shape and composition upon annealing, ultimately leading to loss of interfaces and metallic indium cluster formation. Degradation of the luminescence of the samples is observed as well, characterized by the appearance of dark areas in fluorescence mappings. With an in-depth study of these dark regions, we will show that the degradation is correlated to a blue line emission at around 2.75 eV whose origin will be discussed. From this study, we found the upper temperature limit for growing the p-type layers to be around 850°C.

In the second part, we will focus on low-temperature Mg-doping by ammonia-MBE (NH_3-MBE). We demonstrate GaN and AlGaN layers with a doping efficiency N_A-$N_{D/}$[Mg] | $_{Max}$ higher than for MOVPE layers. Thus, we combine both techniques to fabricate a LD: Half of the structure including the p-type waveguide is grown by MOVPE while the p-cladding and contact layers are grown by NH_3-MBE. We finally analyze the optoelectronic characteristics of fully processed devices.

Picosecond pulse generation in GaN-baser laser diodes

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GaN-based laser diodes with monolithically integrated saturable absorbers are compact short-pulse, high peak power light sources in the violet and blue spectral range. We demonstrate multi-segment, edge-emitting laser diodes with an absorber section in the center or at the edge of the cavity. With a bow-tie waveguide geometry a peak power of 10 W and pulse length shorter than 10 ps are achieved in self-Q-switching mode. We investigate the impact of band-structure and absorber dynamics on self-Q-switching in multi-section GaN based laser diodes at high reverse bias. Envisioned applications for these multi-section laser diodes are high-density optical storage systems, high-resolution bioimaging, and nanoprocessing.

GaN-based laser diodes with monolithically integrated saturable absorbers are compact short-pulse, high peak power light sources in the violet and blue spectral range. We demonstrate multi-segment, edge-emitting laser diodes with an absorber section in the center or at the edge of the cavity. With a bow-tie waveguide geometry a peak power of 10 W and pulse length shorter than 10 ps are achieved in self-Q-switching mode. We investigate the impact of band-structure and absorber dynamics on self-Q-switching in multi-section GaN based laser diodes at high reverse bias. Envisioned applications for these multi-section laser diodes are high-density optical storage systems, high-resolution bioimaging, and nanoprocessing.

Optical simulations of InGaN/GaN edge emitting lasers with reduced AlGaN cladding thickness

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We present the numerical optimization of the epitaxial design of InGaN/GaN edge emitting lasers. The analysis has been carried out with one-dimensional Transfer Admittance Method and has been verified by the demonstration of the InGaN/GaN edge emitting laser with substantially reduced cladding thickness [1]. In the simulation we show that very high doping level of the substrate, assuring the electron concentration on the level of 6 10^{19} cm^{-3} allows to reduce the thickness of the n-cladding layer to 100 nm and its Al content to 5% (Fig. 1). The reduction of the thickness and the Al content in the n-cladding is expected to improve thermal and electrical performance of the laser. We also show the exhaustive analysis of parameters of other layers affecting optical properties of the devices.

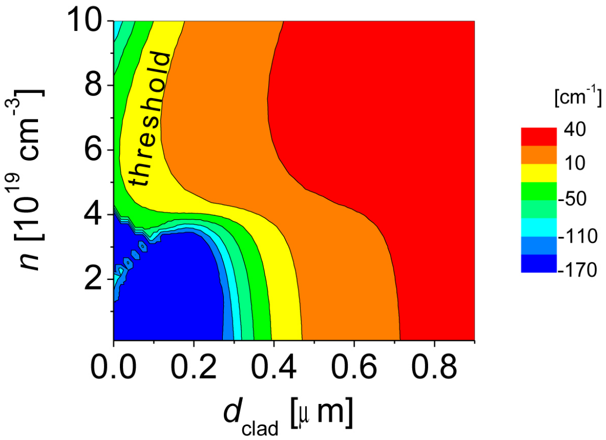

Fig. 1 Modal gain as the function of the electron concentration (n) in GaN substrate and thickness of n-AlGaN cladding layer (d_{clad})

References:

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Far field pattern of AlGaN cladding free blue laser diodes grown by PAMBE

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Application of laser diodes (LDs) to data storage technology and laser projectors demand very high beam quality. Nitride based LDs suffer from leakage of optical modes to GaN substrate which is pronounced as ripples in the far field pattern [1] which significantly worsens the beam quality. The amount of light leaking to the substrate increases for LDs emitting at longer wavelengths. Leakage of optical modes to GaN substrate is often reduced by increasing the n-type AlGaN cladding thickness. Strauss et.al. [1] had shown that for LDs emitting at λ=440 nm a cladding as thick as 3 μm is needed to fully suppress ripples in far field pattern and obtain a Gaussian shaped beam. Growth of such thick AlGaN claddings without cracks in the structure is demanding for epitaxy.

In this paper we present another way to obtain Gaussian shaped far field pattern for blue LDs. We have grown AlGaN cladding free LDs by Plasma Assisted Molecular Beam Epitaxy (PAMBE), where the optical mode is confined by thick, high In content InGaN waveguide [3]. Growth of thick high quality InGaN layers needed for waveguides is crucial to obtain good LD characteristics. Recent advantages in understanding of growth mode of InGaN layers by PAMBE [5] allowed us to obtain high quality InGaN waveguide. Due to the fact that effective refractive index of the light propagating in InGaN waveguide is higher than refractive index of GaN there is no leakage of optical modes to

GaN substrate. We show Gaussian shaped far field patterns with no ripples. AlGaN cladding free blue and green LDs can prove to be the choice for new generation laser projectors.

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Type II quantum well structures for mid-infrared emitting interband cascade lasers: challenges, limitations and prospects

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Applications related to the sensing of hazardous and environmentally relevant gases drive the growing demands with respect to all the sensor components, requiring especially cheap, compact and fast laser sources. However, in many cases the respective devices that need to be able to emit in the ranges of the maximal absorption, which for many gasses falls into the mid infrared range, are not commercially available. The target range, which is usually about 3-5 μm (and beyond, up to 8 μm even), can potentially be achieved by several approaches having however their limitations. The common type I quantum-well-based laser diodes have not exceeded the 4 μm emission yet at room temperature [1], whereas quantum cascade lasers (QCLs) have been demonstrated down to 3 μm already [2]. Another solution is the so called interband cascade laser (ICL) proven to be operational between 3 and 5 μm and which can additionally offer significantly lower power consumption than the QCLs [3]. However, his needs still further improvements regarding especially the performances in the longer wavelengths range due to increasing carrier losses and simultaneous natural decrease of the type II transition oscillator strength.

We have investigated, both experimentally and theoretically, the active part of the ICL's based on InAs/(Ga,In)(As,Sb) materials combination forming a broken gap system, i.e. confining electrons and holes in spatially separate layers (in InAs and GaInAsSb, respectively). The lasers are grown either on GaSb or InAs substrates. The presentation will be focused on possibilities and challenges regarding the extension of the emission range into the longer wavelengths, and the active region optimizations aimed at maximizing the optical transition oscillator strength via tailoring the electronic structure and the combined strain and wave function engineering. In case of the latter, we have demonstrated recently that addition of arsenic into the commonly used ternary layer of GaInSb for the holes confinement can significantly enhance the transition oscillator strength, while keeping still the type II design [4].

This communication will also cover such issues as the band offsets importance, its sensitivity to the composition of the layers, the active transition intensity versus various structure parameters and external factors as temperature or electric field, and finally the predominant carrier loss mechanisms. With respect to the latter, the effect of arsenic addition into the valence band well layer on the interface quality and the related formation of carrier traps and on photoluminescence thermal quenching will be reported. For all those a combination of several spectroscopic techniques has been used, both emission-like (photoluminescence) and absorption-like (modulated reflectivity spectroscopy) supported by the energy level calculations employing a multiband k.p model. Eventually, the potential for further structure optimization and prospects for the improved performance of laser devices in the long wavelength range will be given.*

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(AlGaIn)N-based laser diodes: future applications and present problems

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In the first part of the presentation, I will show a number of market attractive future applications of nitride laser diodes and their arrays. These applications are targeted by TopGaN in collaboration with a number of European partners in projects of the VIIth Framework and include the following devices:

1. 380-390 nm for printing and chemical reaction stimulation,
2. 440-450 and 520-530 nm for RGB modules used in mobile phone projectors, television sets, billboards (also 3D), cinema projectors,
3. 480-490 nm for "Last mile" and underwater communication.

In the second part of my talk, I will show the present status of TopGaN/Unipress technology with respect to each wavelength range. In some of the areas, we are gaining big successes, as in the manufacturing of the high-power (above 4 W cw) laser arrays. In some areas, as in the green LDs, we still have to overcome a number of material and processing issues.

These issues will be shown in the third part of my talk and will include the following topics:

1. GaN substrate quality and size,
2. Polar and semi-polar orientation of the GaN substrates,
3. Off-orientation of the GaN substrates realized by polishing or by lateral patterning,
4. Cracking of AlGaN cladding layers and its elimination by lateral patterning ,

5. Crystallographic and InGaN quantum well with a high In content,
6. Influence of hydrogen on the the InGaN quantum wells,
7. Stability of InGaN upon being overgrown at high temperature.

The issues listed above will be discussed in more details by other speakers from Unipress/TopGaN.

GaN laser diode technology for system applications

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AlGaInN laser diode technology is reviewed for a wide range of system applications. The AlGaInN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v., i.e, 380nm, to the visible, i.e., 530nm, by tuning the indium content of the laser GaInN quantum well. Ridge waveguide GaN LD's are fabricated to achieve single mode operation suitable for telecom and display applications. Visible light communications at high frequency (up to 2.5 Gbit/s) using a directly modulated 422nm Gallium-nitride (GaN) blue laser diode is reported. High power operation of AlGaInN laser diodes is also described. We demonstrate the operation of a single chip, high power AlGaInN laser diode 'mini-array' consisting of a 3 stripe common p-contact configuration at powers up to 2.5W cw in the 408-412 nm wavelength range. Low defectivity and highly uniform GaN substrates allow arrays and bars of nitride lasers to be fabricated. Laser bars of up to 5mm with 20 emitters have shown optical powers up to 4W cw at ~410nm with a common contact configuration. Alternatively, the laser bar can have each emitter individually addressable allowing photonic integration of complex free-space and/or fibre optic systems within a very small form-factor package.

Power limits of III-N-based single and multi emitter laser diodes

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High power III-N-based laser diodes (LDs) find numerous applications including optical storage systems, high speed printing, high brightness laser display systems, photolithography, biomedical, laser annealing, marker systems, and solid-state lighting. The performance of these devices under room-temperature (RT) continuous-wave (CW) operation is the crucial point for most applications. In CW RT operation of III-N LDs the output power is affected by parasitic ohmic heating and limited by both thermal roll-over and effect of catastrophic optical mirror damage (COD). The thermal roll-over can be pushed to higher power by reducing the thermal resistance of the chip and its package. The thermal resistance depends on various factors, e.g. heat sink materials, mounting configuration, chip dimensions, substrate thickness, quality of epitaxial layers etc. A widely used solution to increase output power is using multiple emitters monolithically integrated into one chip [1]. However, an additional issue of multi emitter design is thermal crosstalk between emitters. To suppress this effect, thermally optimized layout design of the III-N-based multi emitter LDs is required.

In this paper we investigate numerically the power limits and thermal resistance of the III-N-based single and multi emitter LDs in the p-up configuration. In the single emitter LDs we change the chip width, the substrate thickness, the thickness of p-type gold electrode and both the thickness and thermal conductivity of top-mounted diamond-based heat spreader. For multi emitter LDs we change the number of emitters and the distance between them. For the optimized single emitter LDs we estimated the increase of maximal output power over 350% the nominal power (160 mW). In the multi emitter LDs we optimized the number and distribution of the emitters.

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Hydrostatic pressure tuning of emission wavelength and optical gain in GaInNAs/GaAs quantum wells

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The tuning of emission wavelength from semiconductor lasers by hydrostatic pressure seems to be very useful for various applications. So far this method was successfully applied to lasers based on InGaAs/GaAs, GaInAsP/InP, and (Al)InGaSb/GaSb quantum wells (QWs) [1-4]. In general, it was observed that emission wavelength shifts linearly with the hydrostatic pressure while the output power is almost insensitive to the external hydrostatic pressure. Such a behavior means that the band structure of given QWs scales very proportionally and hence the optical gain is insensitive to the external hydrostatic pressure. Significantly different changes in the band structure and optical gain are expected for GaInNAs/GaAs QWs. In this material system the conduction band is strongly non-parabolic and sensitive to the external hydrostatic pressure. This non-parabolicity can be quite well reproduced within the band anticrossing model (BAC) [5, 6], which assumes that nitrogen creates a resonant level located in the conduction band of GaInAs host. This level interacts with the conduction band of GaInAs host. Due to this interaction two non-parabolic bands appear instead of the nitrogen resonant level and the conduction band of GaInAs host. The sensitivity of the resonant nitrogen level to hydrostatic pressure is much weaker than the sensitivity of conduction band of GaInAs host and hence non-linear dependence of energy gap with the hydrostatic pressure is observed for GaInNAs alloys. In order to model the hydrostatic pressure dependence of the band structure and the optical gain in GaInNAs/GaAs QWs the standard 8-band kp model has to be extended by the resonant nitrogen level. In this work the band structure and optical gain have been calculated for GaInNAs/GaAs QWs with various indium and nitrogen concentrations within the 10-band kp model including the nitrogen resonant level [7]. Obtained results are compared with calculations for N-free QW (GaInAs/GaAs QW), which are performed within 8-band kp model. It is clearly shown that with the increase in hydrostatic pressure the emission wavelength changes non-linearly for N-containing QWs and linearly for N-free QWs. The optical gain in N-containing and N-free QWs is sensitive and in-sensitive to the external hydrostatic pressure, respectively. The observed differences between the two QW systems are attributed to the BAC interaction between the nitrogen resonant level and the conduction band of GaInAs host.

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Pressure studies of leakage in laser diodes

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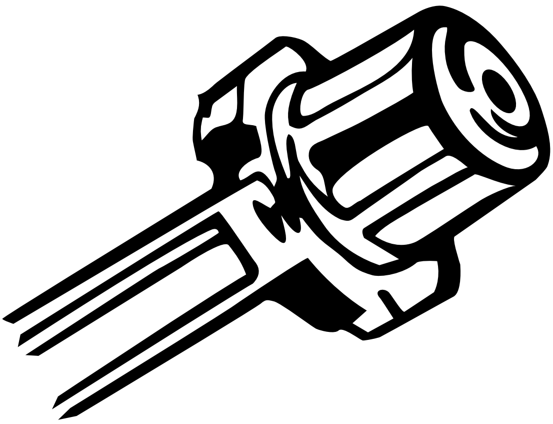
Reduction of leakage currents is important for improving laser diode characteristics. Leakage increases temperature sensitivity of threshold current. For AlGaInP laser diodes leakage is the main obstacle for extending their operation into the orange and yellow spectral range. Since the AlGaAs barriers and claddings may be indirect (with L or X minima coming into play) high pressure may be used to distinguish between Γ, L, and X barriers since they have very different pressure coefficients.

Threshold current in 808 nm GaAsP/AlGaAs laser diode has been measured as a function of pressure (up to 1.8 GPa) and temperature (from 80K to 300K). The results have been analyzed in order to separate leakage current from radiative current and to determine the effective barrier for leakage and its pressure dependence. Our data indicates that both X and L minima in the barriers and in the claddings contribute to leakage.

Acknowledgements:

This work was supported by the Polish National Center for Research and Development (NCBiR) through grant INNOTECH-K1/IN1/32/156848/NCBR/12.



Numerical analysis of mid-IR quantum cascade laser optical properties

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Quantum cascade lasers (QCLs), due to their compact size, are very promising mid-IR sources for application in detection system. For such systems the sensitivity is one of the key parameters. To obtain the best parameters of such systems the stable, reliable single mode operating sources are needed [1]. One of the solutions for obtaining single mode emission is distributed feedback (DFB) QCL. In this work we present numerical analysis of QCL's optical properties based on effective index method [2] for determining intensity of radiation end effective index in cavity. Coupled mode theory [2] is used for determining mode selection of periodical structure formed on the top of mesa.

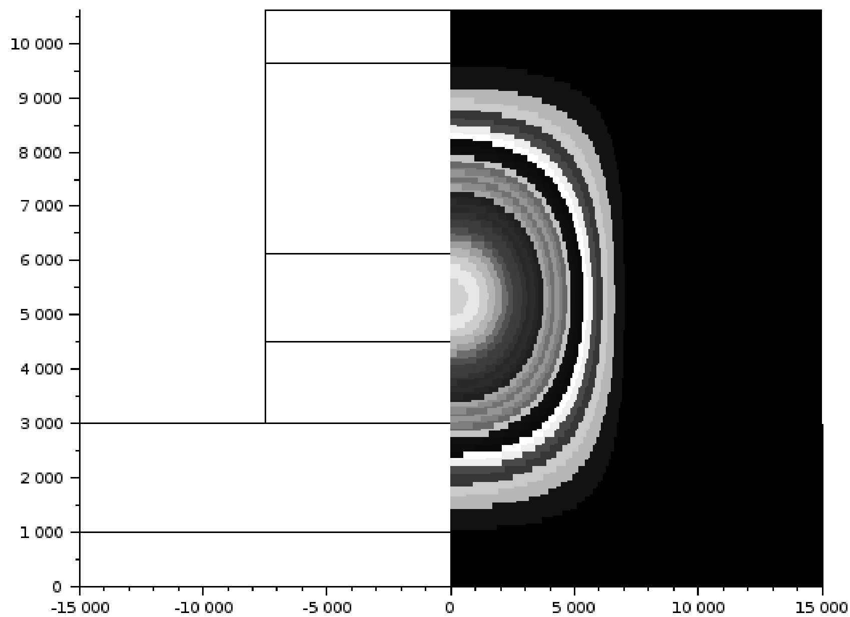

Fig.1. 2D mode intensity in ridge waveguide QCL

In the Fig. 1. there is an example of two dimensional calculation of mode distribution in QCL's structure described in [3].

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Dedicated quantum cascade laser driver

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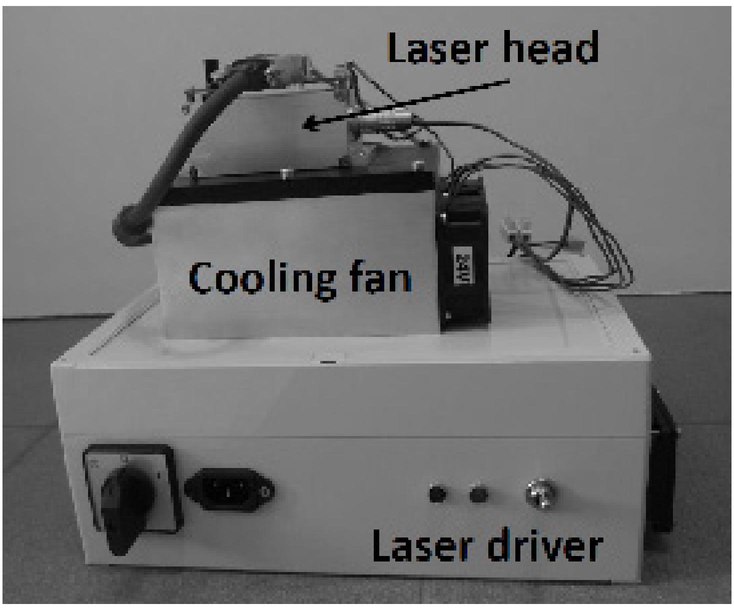
Quantum cascade lasers are compact mid-infrared coherent light sources that are very attractive for a variety of applications. For a proper operation they need a good and precise thermal and electrical excitation control. In this work we present a laser driver designed to drive quantum cascade lasers based on both GaAs and InP.

The laser driver consists of a laser head with a power stage, a two stage thermoelectric cooler (TEC) and a heat sink with a cooling fan as well as a main unit with power supplies for laser head, TEC and fan and driving electronics (microcontroller and FPGA unit). The system is presented on Fig. 1 (left panel).



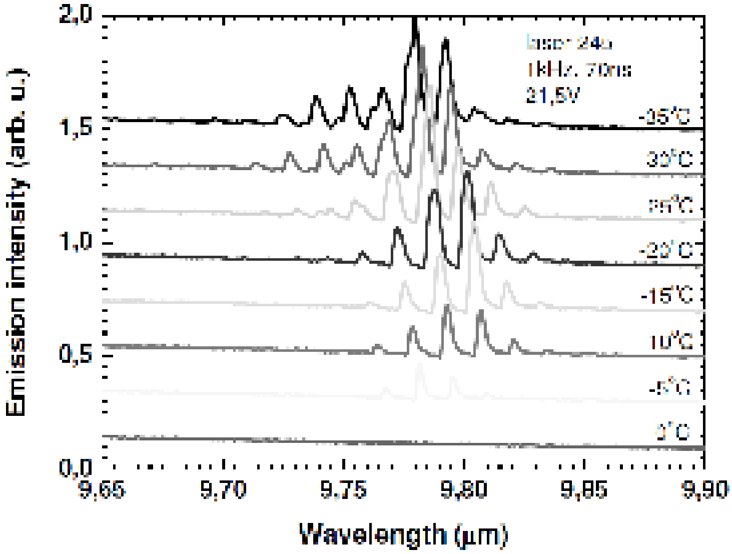


Fig. . Quantum cascade laser driver (left panel) and obtained laser spectra for various working temperatures (right panel).

The driver enables laser operation in pulse mode with voltages up to 15 V and currents up to 10 A with repetition frequency up to 10 kHz and filling factor not exceeding 1%. Working temperature can be controlled with a precision of 50 mK in a range from -35°C to ambient. The need of high voltage and current pulses resulted in assembling the power gain circuit as a part of the laser head and connected to the laser with flat wires decreasing an inductance to approximately 30 nH. As a consequence, steep pulse slopes were obtained (less than 10 ns rising and falling times). Thanks to use of a pre-polarizing pulse (a pulse with an amplitude below the laser threshold) it was possible to excite the laser with 8 ns pulses.

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MBE growth of VECSEL heterostructures: the challenge of control of the layer thickness and the strain relaxation

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During the Molecular Beam Epitaxy (MBE) growth of the Vertical-External-Cavity Surface-Emitting Laser (VECSEL) heterostructures one has to address two main challenges: the control of growth rate and of the strain arising from the lattice mismatch between the layers of both the distributed Bragg reflectors (DBR) and most of all the active regions.

The active region layers together with a window layer, which prevents the carrier diffusion towards the surface form a microcavity. The total length of a microcavity defines the laser emission wavelength. In order to provide high gain and efficient use of the pump power the large number of the quantum wells (QW), usually 10-12 is employed. They positions follow the resonant periodic gain scheme. This approach results in large microcavity $11/2\lambda$- $13/2\lambda$. For larger microcavity, larger emission wavelength shift is observed for any deviation from the designed layer thickness. In consequence the growth rate precision below 1% is desired. Such high precision of the layer thickness can be achieved when the subsequent heterostructures are grown in possibly short period of time. This requires an efficient characterization scheme.

In this presentation we report on the characterization of the MBE grown wafers of the VECSEL heterostructures and their device suitability. The most effective characterization technique is High Resolution X-Ray Diffraction. This technique provides the precise information on the layer thickness. However because of the high complexity of the VECSEL heterostructure we have found that for proper revealing of all layers parameters a complementary data obtained from optical characterization is of great use. The reflectivity and photoluminescence provide the data on the DBR and microcavity layers thicknesses and the QW emission wavelength. The HRXRD is time consuming especially when the reciprocal space maps are measured in order to establish the strain relaxation degree. Because of that a complementary technique was applied. The spatially resolved photoluminescence has shown that the strain relaxation manifest by the black lines, which are easily observable. The full wafer PL mapping has shown that the highest concentration dislocation is along the margin of the epitaxial area edge. Moreover, the acquired data have shown that the black lines tend to form bundle. The final evaluation of the strain relaxation was performed by the measurements of the polarization of the stimulation emission which tends to be along the [0-11] direction.

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Full-physical simulation of the novel on-axis pumped VECSEL with High Contrast Grating

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We present the numerical analysis of optically pumped vertical external cavity surface emitting laser (VECSEL) with bottom DBR substituted for HCG deposited on the second diamond heat spreader (Type2; fig. 1) allowing simple and efficient integration with the optical fiber. The proposed design of the silicon HCG can serve as a bottom mirror which is transparent for pumping laser since it assures nearly 100% reflectivity for the emitted wavelength (1560 nm) and less than 4% for pumping beam (980 nm).

We show that the new VECSEL structure assures more efficient transport of the heat to the copper heat sink with respect to the typical VECSEL with one top diamond heat spreader (Type1; fig. 1). Simulations show that the Type2 assures the reduction of the thermal impedance by 25% and increase of the emitted power by 80% (Fig. 2). As a result of the spectrally narrow peak of the high reflectivity and the polarization discrimination of the HCG, Type2 brings also: stable wavelength of the emission and single polarization of the output beam.

Acknowledgements:

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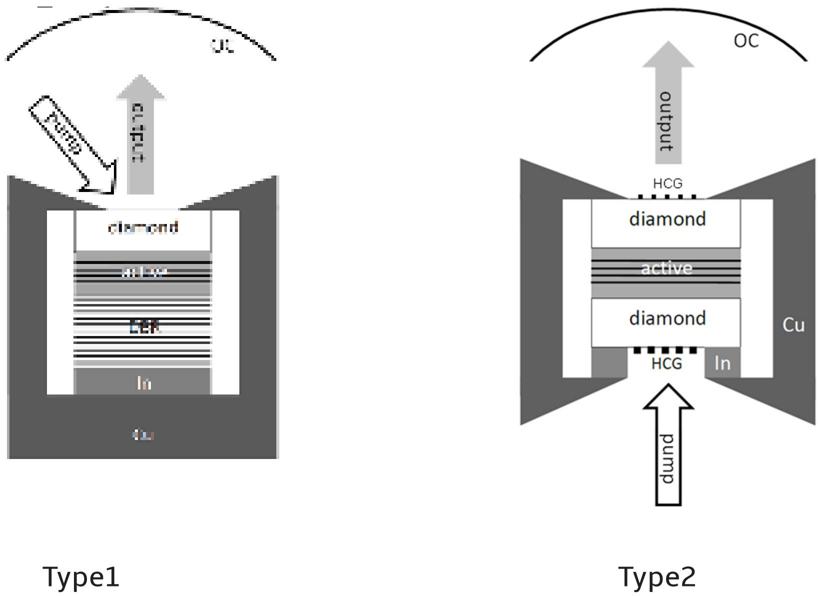

Fig. 1. Two simulated VECSEL structures.

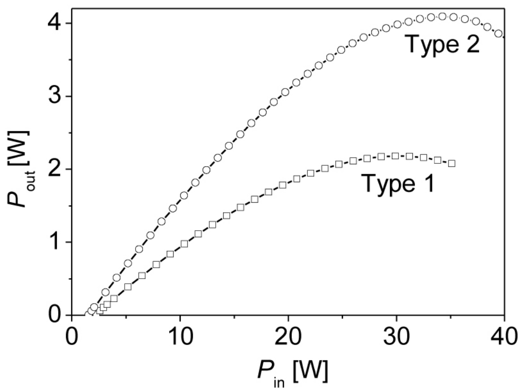

Fig. 2. Simulated output power of both VECSEL designs.

Numerical modeling of optical properties of vertical-external-cavity surface-emitting lasers

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Optically pumped vertical-external-cavity surface-emitting lasers (VECSELs), also known as semiconductor disk lasers (SDLs), are modern semiconductor devices, which give a possibility to generate high-power radiation with excellent beam quality. They combine advantages of vertical-cavity surface-emitting lasers (VCSELs), edge-emitting lasers (EELs) as well as solid-state lasers [1]. Because of that VECSELs can find broad applications, for example in medical, telecom and multimedia markets.

In a typical VECSEL, the semiconductor structure (which is the active mirror) acts as the additional internal cavity, which extends from the DBR mirror to the semiconductor-air interface. If the semiconductor ethalon is resonant, the intensity of laser radiation in the active region is high, which lowers the laser threshold. However, the spectrum of the confinement factor is narrow, so resonant structures are very temperature-sensitive. If the ethalon is antiresonant the light intensity in quantum wells is lower, but the spectrum of the confinement factor is wider which results in higher laser tunability. In addition, antiresonant structures are much less temperature-sensitive then resonant ones.

In the paper we simulate and compare optical properties of the resonant, antiresonant and intermediate designs of optically pumped VECSELs. Calculations were performed using the numerical model developed in Photonics Group, Institute of Physics, Lodz University of Technology.

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Fabrication of terahertz quantum cascade laser

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The paper presents main problems of technology of device fabrication of terahertz-range quantum-cascade lasers (THz QCLs). The used laser heterostructure is of a three-quantum-well design, which operation is based on radiative intersubband transitions taking place in a double-well region and on a resonant-phonon depopulation of the laser's lower state [1]. The lasers operate above cryogenic temperatures, with current density below 1,5kA/cm^2.

The THz-QCL fabrication comprises several technological steps. An obtainment of appropriate electrical and optical properties of junctions that are formed by the semiconductor structure and metallic layers (the laser's metal-metal waveguide claddings) was found to be the crucial problem of the device fabrication technology. The further main problem of fabrication is an appropriate method of integration of the laser structure and a receptor substrate, in terms of electrical parameters and mechanical stability of this connection.

The paper discusses selected technological problems, like for example an obtainment of low-series-resistance and time-stable and thermal-stable electrical metal-semiconductor contacts that must be characterized by a very good lateral uniformity and shallow diffusion depths. Basic properties of the fabricated THz QCLs, e.g., their temperature-dependent L-I-V characteristics, will be shown.

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Epitaxy of AlGaAs/GaAs structures for THz quantum-cascade lasers

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The paper presents main problems of technology of AlGaAs/GaAs epitaxial structures intended for terahertz-range quantum-cascade lasers (THz QCLs). The studied heterostructure is of a three-quantum well design [1], which operation is based on radiative intersubband transitions taking place in a double-well region and on resonant-phonon depopulation of the laser's lower state.

Epitaxy of the presented structures creates specific problems, in part because of a relatively big total thickness of the multilayered structure, and hence a very long-lasting (typically over 10-hour long) deposition process; hence a risk from loss of stability of an epitaxial system arises. The other difficulties come when relatively low AlGaAs barriers are to be grown within the structure - like for example the barriers made of ~ 15%-aluminum-containing layers, which is, indeed, a composition used for our THz QCL structure. In this case serious problems with strict determination (by X-ray diffractometry for example) of compositions and thicknesses of the individual layers arise. There is also a significant problem with adjustment of an appropriate doping dose that is to be delivered to a set of active modules of the laser. This is because THz QCL active regions are only relatively slightly doped; n-type doping concentrations for selected fragments of the modules fall typically in the range of 10^{15}-10^{16} cm^{-3}, that is typical for electrically active impurities (i.e., unintentionally introduced foreign atoms), as well. The further difficulties of low-level-doping calibration are caused by a presence of a near-surface depletion layer, which thickness increases with decreasing doping concentration. For the above-mentioned low doping range even a relatively small doping mistake may be detrimental - too low doping of the active modules may be a reason of too short dynamic range of the laser, while too big dopant concentration may cause too high free-carrier absorption losses.

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Computer simulation of operation of GaN/AlGaN quantum well ultraviolet diode laser

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In this work a self-consistent optical-electrical-thermal-recombination model of the ultraviolet GaN/AlGaN diode lasers is presented. This model provides a deeper understanding not only the physical phenomena occurring in the edge-emitting lasers (EEL) but also mutual interactions between these phenomena. Moreover, it may be used to verify an usefulness of the selected structure modifications and their influence on the laser output characteristics.

The modelled laser structure is very similar to the 369-nm single quantum well GaN/$Al_{0.15}Ga_{0.85}N$ EEL grown on the epitaxially laterally overgrown GaN (ELOG) substrate [1] proposed by Nagahana et al. [2]. After achieving the room temperature continuous-wave threshold characteristics for the basic structure we have optimised its design by changing the etch depth and width of the ridge and thickness of the bottom cladding in order to achieve the lowest values of maximal active-region temperature and threshold current.

References:

[1] S. Nagahama et al., Japanese Journal of Applied Physics, 40, 3075-3081 (2001). [2] S. Nagahama et al., Japanese Journal of Applied Physics, 40, L785-L787 (2001).

Acknowledgements:

This work was supported by the European Union within European Regional Development Fund, through Innovative Economy grant POIG.01.03.01-00-159/08 InTechFun.

Spin orbit splitting in InGaxAsSby/InAs layers for heterojunction lasers

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A very important parameter, which must be taken into account in designing the laser structures, is the spin-orbit splitting in the valence band.The resonance between the split-off valence bands and the energy of the emitted photons results in a significant increase of the Auger recombination rate and enhanced intervalence band absorption, which deteriorates the luminescent characteristics of the IR-emitters like e.g. the hetrojunction lasers [1]

In this work, we investigate thick layers of narrow-gap InGaAsSb material with high In content grown on InAs substrates by liquid phase epitaxy, beeing potentially able to cover spectrally the range of the waves longer than 3 μm.

We present temperature dependence of photoluminescence (PL) and photoreflectance (PR) spectra connected to the energy gap and the spin-orbit split off transition in $InGa_xAsSb_y$/ $Ga_{0.84}In_{0.16}As_{0.22}Sb_{0.78}$/InAs layers measured by the FTIR spectrometer in the mid infrared range [2]. In case of $Ga_{0.84}In_{0.16}As_{0.22}Sb_{0.78}/In_{0.83}Ga_{0.14}As_{0.82}Sb_{0.17}$/InAs heterostructure, the energy gap thermal coefficient has been found to be α= -0.43 meV/K and the spin orbit splitting has been determined as Δso = 0.460eV [3]. Finally, the spin-orbit splitting compositional dependence has been detected as being nonlinear with the negative bowing parameter $C(\Delta_0)$ = -0.25 eV. There are two compositions of the quaternary alloy ($InGa_{0.03}AsSb_{0.06}$ and $InGa_{0.93}AsSb_{0.87}$) for which a resonance condition ($E_0 = \Delta_0$) can be realized at 77 K. Owing to the bandgap spin-orbit splitting resonance, the InGaAsSb might have the unique feature of very low excess noise factor in avalanche photodiodes operating in mid infrared spectral range.

References:

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[2] M. Motyka, G. Sęk, J. Misiewicz, A. Bauer, M. Dallner, S. Höfling, and A. Forchel, Appl. Phys. Exp. 2 (12) 126505 (2009)

[3]M. Motyka, F. Janiak, G. Sęk, J. Misiewicz, K.D. Moiseev, Appl. Phys. Lett.100, 211906 (2012)

Acknowledgements:

This work was performed in framework of the programs of General Physics Division of RAS and Presidium of RAS and was in part supported by Russian Basic Researches Foundation (grant #11-02-00234). In addition, M.M. would like to also acknowledge the Ministry of Science and Higher Education for financial support from the Iuventus Plus program.

Optical characterization of of InAs-substrate-based type II quantum wells for long-wavelength mid-infrared interband cascade laser with plasmon waveguiding enhancement

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Mid-infrared semiconductor lasers are continuously increasing their application range during the last years including for instance gas sensing for detection and control of the presence or concentration of harmful gases like CO_2, SO_x, NH_3, and many others. Type II InAs-based quantum well system is potentially able to cover spectrally the range of 2 to 8 µm, and beyond, and is possible to be easily integrated into a photonic sensor unit for gas detection.

Hereby, we present optical studies of a set of such InAs-substrate-based structures predicted for interband cascade lasers with type II quantum well active region. First of all, photoluminescence and modulated reflectivity spectra have been measured in the range of the interband transitions and then confronted with the energy level calculations to verify the electronic structure. Structures emitting in a broad range from 3 to above 9 m have been investigated.

In order to precisely control and optimize the doping of the cladding layers to minimize the threshold gain of these lasers, it is very helpful to have a nondestructive method for measuring the cladding layer carrier concentration. Reflectance measurements of highly doped samples involve identifying a minimum in the reflectance spectrum near the plasma frequency that occurs when the reflectance drops sharply as the frequency of the incident light increases [1]. This is the so-called plasma-edge effect that occurs when the incident light frequency is varied across the region where the real part of the dielectric function changes sign. The minimum in the reflectance spectral curve is located approximately at the frequency where the real part of the dielectric function equals unity, i.e. plasmonic frequency in this case.

Reflectance measurements on an FTIR spectrometer based setup have been performed on a set of samples: Si doped InAs layers and full interband cascade laser structures on InAs. The obtained results allowed verifying the assumed growth conditions and layer structure details as compositions, and thicknesses, including the carrier concentrations in the cladding layers.

Reference:

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Acknowledgements:

The work was supported by the EC within Project WideLase No. 318798 of the 7th Framework Program and by the COPERNICUS Award of the Foundation for Polish Science and Deutsche Forschungs Gemeinschaft.

Coupling of multiple laser diodes into a fiber

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Many applications require high power laser light in a thin fiber. Sophisticated microoptics has been developed to couple laser bars or laser-bar stacks into multi-mode fibers [1-4]. Very high powers (up to kW) can be achieved in such devices, but all lasers in a bar or stack emit at a given wavelength. On the other hand, individual emitters with powers in the 300-1500 mW range are available in small packages at certain typical wavelengths and with good beam quality. This includes 405 nm BlueRay diodes, 445 nm blue lasers for displays, 532 nm green frequency doubled YAG lasers, 635 nm and 660 nm red lasers, 780 nm CD lasers etc. We describe a simple method for coupling many such lasers into a single multi-mode fiber. The method cannot compete with bars or stacks (in terms of power in the fiber) but it allows to use laser diodes (LD) with different emission wavelengths e.g. combining red, blue and green light. We optimized the optical elements using the Zemax ray-tracing software and we built three demonstrators based on violet, blue and red lasers.

In our device diode lasers are coupled to a multi-mode fiber (with 50-200 micron core) using a reflector in the form of a regular pyramid or rods with oblique truncations. The demonstrator using 8 violet (405 nm) diodes achieves 3.5W in the fiber, 5.5W using 8 blue (445 nm) diodes and 3.5W using 638 nm diodes. Our method is superior to using fiber combiners (a bundle of fibers welded to a single fiber with larger diameter) since we achieve higher brightness.

References

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Acknowledgements:

This work was supported by the Polish National Center for Research and Development (NCBiR) through grant INNOTECH-K1/IN1/32/156848/NCBR/12.

Optical properties of AlGaAs/GaAs superlattices for quantum cascade lasers for mid infrared and terahertz range

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AlGaAs/GaAs superlattices with layer composition and thicknesses imitating the active region of quantum cascade lasers (after H. Page [1]) emitting at about 9 μm were investigated. Using optical spectroscopy techniques (photoreflectance, and photoluminescence) together with numerical calculations performed within the effective mass approximation, we studied the band structure of the formed conduction minibands including the modification of the wave functions and probability distribution under the external electric field [2]. The used growth rates of the GaAs/AlGaAs superlattices have been verified by investigating the Stokes shift between the emission and absorption spectra. The magnitude of this shift has been connected with interface quality in the periodic structure.

In the second part, optical studies of the AlGaAs/GaAs active regions of QCLs predicted for terahertz radiation emission will be reported. The optical spectroscopy was performed employing Fourier transformed spectrometer based setup [3]. Transmission spectra were collected by using a glowbar as a source of the probing light and a bolometer for far infrared detection. The obtained spectra have shown a number of optical features connected to both, phonon related absorption in GaAs (AlGaAs) and intersubbnad absorption in the AlGaAs/GaAs superlattices. The fundamental transition energy has been found to be approx. 13meV (~3.2THz).

Eventually, it has been shown that testing the active-region-like structures of the QCLs can be performed by using photoluminescence/ photo transmittance measurements realized within the Fourier Transformed based concept providing detailed information on the energy level structure. This allows determining or predicting the final emission wavelength in the operational devices.

References:

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[2] M. Motyka, F. Janiak, J. Misiewicz, M. Wasiak, K. Kosiel, M. Bugajski , Opto-Electronics Review 19 151 (2011)
[3] M. Motyka, G. Sęk, J. Misiewicz, A. Bauer, M. Dallner, S. Höfling, and A. Forchel, Appl. Phys. Exp. 2 (12) 126505 (2009)

Acknowledgements:
This work is partially supported by two grants of National Science Centre:
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Investigating up-conversion phenomena in active glasses using pressure-tuned laser diodes

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The up-conversion phenomena in dielectric media doped with RE^{3+} ions are a subject of intensive research since 1967. Due to a specific, multi-photon nature of the majority of up-conversion processes one of the most important aspect of investigating such a phenomena is a proper choice of the excitation wavelength. This leads directly to a second problem which is the availability of appropriate light source, which, in optimal case should offer high intensity of radiation combined with narrow-band spectrum and tunability over broad spectral range. Access to the unique technology of hydrostatic pressure-tuned laser diode modules, mastered at Institute of High Pressure Physics of Polish Academy of Sciences, enables realization of all above mentioned postulates and valuable support in investigation of up-conversion phenomena in dielectric optical materials doped with rare-earth ions.

In this work we present the results of our recent investigations of up-conversion phenomena in erbium and thulium doped low phonon glasses for applications in fiber lasers and fiber amplifiers operating in untypical spectral ranges. In every investigated case the pressure-tuned multimode semiconductor lasers (with a nominal lasing wavelengths of 1120 nm, 1535 nm and 1850 nm) were used as an excitation sources, enabling experimental determination of optimal pumping wavelengths for erbium and thulium ions in a new glass media and careful analysis of mechanisms responsible for observed luminescence behavior as well. The obtained results will be presented not only in the context of their scientific value but also as a proof of usability of this new tool in optical spectroscopy and its potential application in active devices.

Acknowledgements:
This work has been supported by the National Science Centre, Poland, decision number: DEC-2011/03/B/ST7/01917.
Anna Jusza and Krzysztof Anders have been supported by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Programme.

Photonic integrated circuits for application in multi-wavelength communication systems

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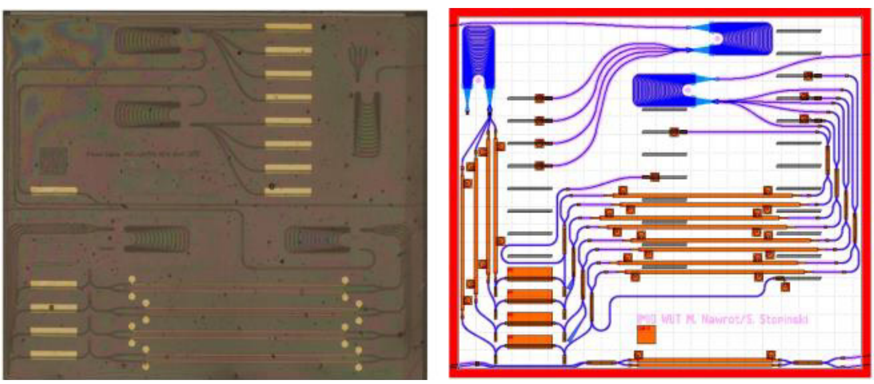
Recent advances in the development of the generic InP-based photonic integration technology allowed realizing advanced devices with improved functionality [1]. One of the most important advantages of photonic integrated circuits (PICs) is the suitability of multi-channel operation, what is very important for application in wavelength division multiplexed (WDM) networks [2].

In this work we demonstrate selected ASPICs dedicated to application in multi-channel optical communication systems. These devices comprise multiple lasers and/or modulators on a single chip and utilize an arrayed waveguide grating to multiplex the signals to a single output. Fig. 1 presents microscope photographs of these devices, designed and characterized in the Eastern Europe Design Hub (in cooperation with COBRA Research Institute), operating within the PARADIGM consortium and localized at Warsaw University of Technology.



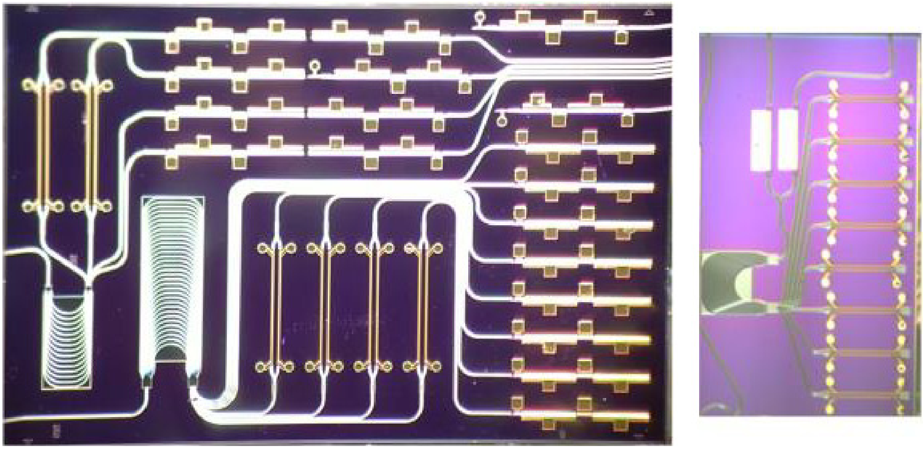


Fig. 1. From the left side: multi-wavelength transmitters based on filtered-feedback lasers (the first two chips), a multi-wavelength transmitter based on DBR lasers, a multi-wavelength modulator.

References:

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Acknowledgements:

This work was supported by the EU FP7 project PARADIGM (grant no. ICT 257210) and the Dean's grant realized at the Faculty of Electronics and Information Technology.

Tuning of InGaN/GaN laser diodes band structure by hydrostatic pressure

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Built-in electric field is a common issue in the nitride emitters based on InGaN/GaN quantum wells (QWs) grown along polar c-axis of wurtzite hexagonal structure. It has been demonstrated that applying hydrostatic pressure to nitride laser diodes represents a very useful tool for studying the presence of built-in electric field. The examined sample was a laser diode with 13% In content in the triple InGaN QWs with a gradient index waveguide (GRINSCH) and quantum barrier doped by Si donors. We studied lasing spectra as well as electroluminescence and gain as functions of hydrostatic pressure and applied current (i.e., concentration of injected carriers). A characteristic blue shift of EL at low density of injected carriers was clearly observed. With increasing applied pressure the lasing energy rises with a rate of 34 meV/GPa what reflects the conditions of fully screened electric field. Interestingly in the optical gain spectra two peaks are present. With increasing current and pressure the high-energy peak exhibits a blue-shift similar to the EL behavior (about 30 meV/GPa), whereas the low-energy peak shows a red-shift with current increase and much smaller blue-shift with pressure. We suggest that differences in the QWs In-content and/or width are responsible for this additional maximum.

Thermal characteristics and power roll-over of GaAs/AlGaAs quantum cascade lasers

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The GaAs/AlGaAs quantum cascade lasers (QCLs) are important infrared light sources with various applications in defense and civilian fields for environmental monitoring, medical diagnostics and other gas sensing applications. Their application is however limited by degradation of performance characteristics induced by the strong heating of their active regions. The large electrical power density required for operation, and the low thermal conductivity of complex multilayer heterostructures contribute to high temperature gradients in the devices. Elevated temperatures cause the leakage of electrons from the upper laser level into delocalized continuum states and backfilling of the lower laser level; both effects decreasing the population inversion. These are the main limiting factors of the high temperature operation of the devices. To expand the potential applications of QCLs, high power levels, high wall plug efficiency and duty cycle are required. Therefore the in depth experimental analysis of laser characteristics combined with numerical modeling is essential to understand the thermal processes and power rollover mechanisms in QCLs. The number of experimental techniques has been used for the thermal characterization of QCLs: thermoreflectance spectroscopy, temperature dependent Light - Current-Voltage (L-I-V) characteristics and spectral characteristics. The experimental results are compared with thermal modeling of QC lasers performed by finite element analysis (FEA). Fig.1 presents L-I-V characteristics, typical for investigated QC lasers.

The rollover observed in (L-I) curves (see Fig.1), can be explained in terms of two effects, the thermal rollover (the positive feedback loop between increasing laser core temperature and threshold current density) and Stark shift of the laser levels causing their misalignment with increasing current (Stark rollover). For low temperatures of heat sink (77 K-140 K) a voltage step in the current-voltage curve, corresponding to a rapid drop in optical power, is observed. It occurs at supply current 3.4 A (current density 15kA/cm^2) and voltage ~ 13V. The current at which a maximum available power is attained doesn't change which is characteristic for Stark rollover. While increasing temperature (190K-270K), the transition from Stark rollover to thermal rollover is observed. The characteristic feature of thermal rollover is that the drop of peak power occurs at progressively increasing current and is less abrupt than in the previous case. To verify postulated mechanisms of (L-I) characteristic rollover the emission spectra at different supply currents and heat sink temperatures (see Fig.2) have been measured. We observe different spectral behavior as a function of current at low temperatures (80K ,130 K), when Stark type rollover is postulated as a mechanism responsible for power drop, and at the higher temperatures (190 K) when it is believed that thermal rollover mechanism dominates. In the first case the spectra for the current exceeding the peak power shift with current towards lower energies due the field induced shift of the laser levels, whereas at the second case the power drop can be entirely attributed to the temperature increase. In that regime the current increase results in much smaller voltage (electric field) change over the laser core as evidenced by high temperature (I-V) characteristics. The development of the two mode combs at currents below the one referring to the peak power is due to the Rabi splitting. The lasers with a narrow ridge tend to develop a splitting in the spectrum, approximately equal to twice the Rabi frequency. Electro-optical analysis of power rollover mechanisms in QCLs has been supplemented by thermoreflectance measurements providing information about temperature increase at QCLs mirror. Fig.3 presents high resolution temperature distribution maps and vertical line scans through the active core of the laser for two different supply currents. As, contrary to interband lasers, emitted radiation is not absorbed at the mirror surface, that temperatures represent true temperature inside the device.

By combining the different experimental and numerical results, an insight into the thermal behavior of AlGaAs/GaAs QCLs is gained. The thermal optimization of the devices focuses on the optimization of heat dissipation, which is essential to increase the maximal operation temperature and further progress the applications of the QCLs.

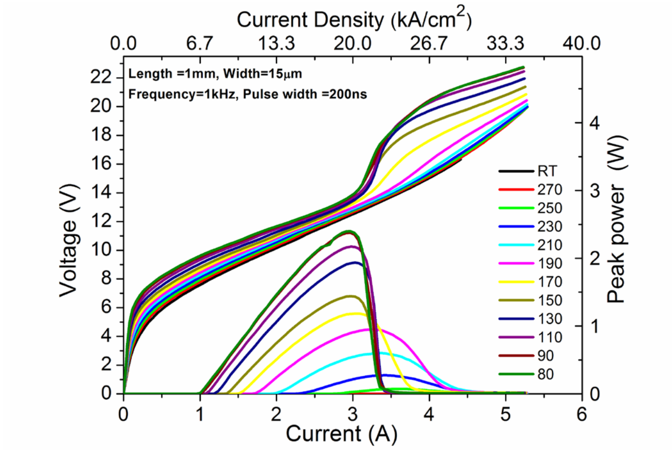
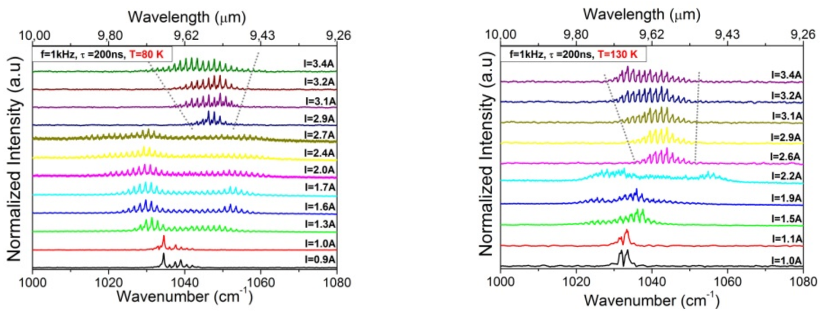


Fig.1. Light-current-voltage characteristics for temperatures ranging from 77K to RT for QCL with mesa dimensions 15μm x 1 mm.



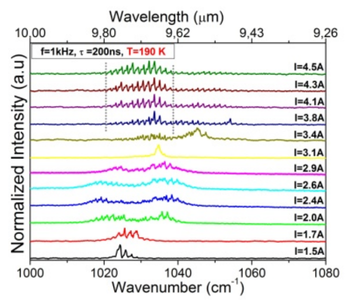
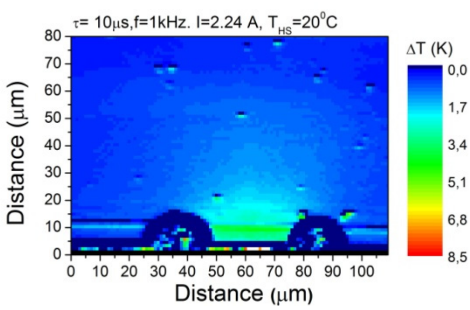


Fig.2. Normalized emission spectra at different supply current for heat sink temperature T=80K (a), T=130K (b), T=190K (c), for QCL with mesa dimensions 15μm x 1 mm.



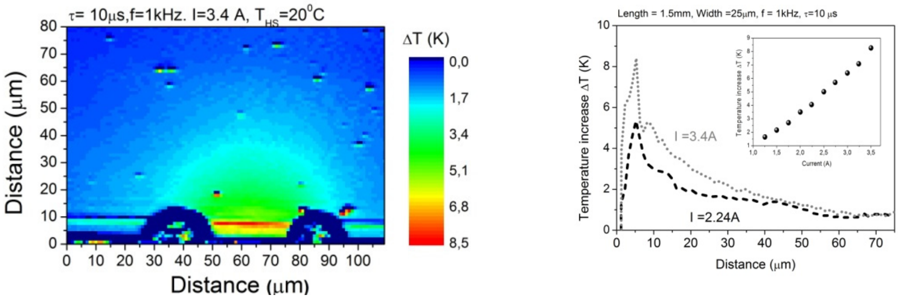


Fig.3. Temperature distribution maps (scanned area 80 μm x 115 μm) measured for supply current I = 2.24 A (a) and I = 3.4A (b); pulse width τ=10 μs and frequency f =1 kHz. Temperature line scans for different supply currents. Inset: maximal temperature increase versus supply current (c).

Wafer fused VECSELs emitting in 1.3 μm and 1.5 μm range

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A. Mereuta 3)
V. Yakovlev 2)
G. Suruceanu 3)
E. Kapon 2) 3)

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VECSELs combine many properties of traditional solid- state disk lasers and semiconductor gain material. They are particularly well suited for intracavity frequency conversion (high intracavity conversion efficiency >25% pump to SHG). Both optical and electrical pumping schemes are possible. Potential for broad gain bandwith, multi-Watt output and power scaling.

In this work we report on design, fabrication and characterization of long wavelength wafer fused vertical external cavity surface emitting lasers (VECSELs). Both electrically and optically pumped devices were fabricated and tested.

Electrically pumped VECSELs were designed to emit at 1470nm. The devices consisted of a half vertical cavity surface emitting laser (1/2-VCSEL) structure assembled with a concave dielectric external mirror. The 1/2-VCSEL structure was fabricated based on wafer fusion technique, and composed of QWs grown on InP substrate, a tunnel junction for electrical injection and AlGaAs/GaAs semiconductor Bragg mirror. Using wafer fusion technique, we demonstrate Room-Temperature (RT) continuous-wave (CW) laser operation from 35-μm diameter EP-VECSEL device. More than 6 mW of CW output power and 25 mW in pulse operation demonstrated in this study represents the highest power reported to date from a semiconductor disk laser at this wavelength and indicates a substantial improvement by a factor of more than 10 over all-InP based structures.

Optically pumped VECSEL was fabricated in "flip-chip" configuration, using wafer fusion. The sophisticated processing used, includes The device emitted more than 1W CW at 1320 nm with 3% output coupler transmission. Device was pumped with 980nm high power laser head. Results show the need for improved heat sinking.

Further improvement of wafer fused VECSELs' performance is expected by improving the heat management in case of both pumping schemes. Additional steps in design of electrically pumped devices should be taken to improve the current injection uniformity.

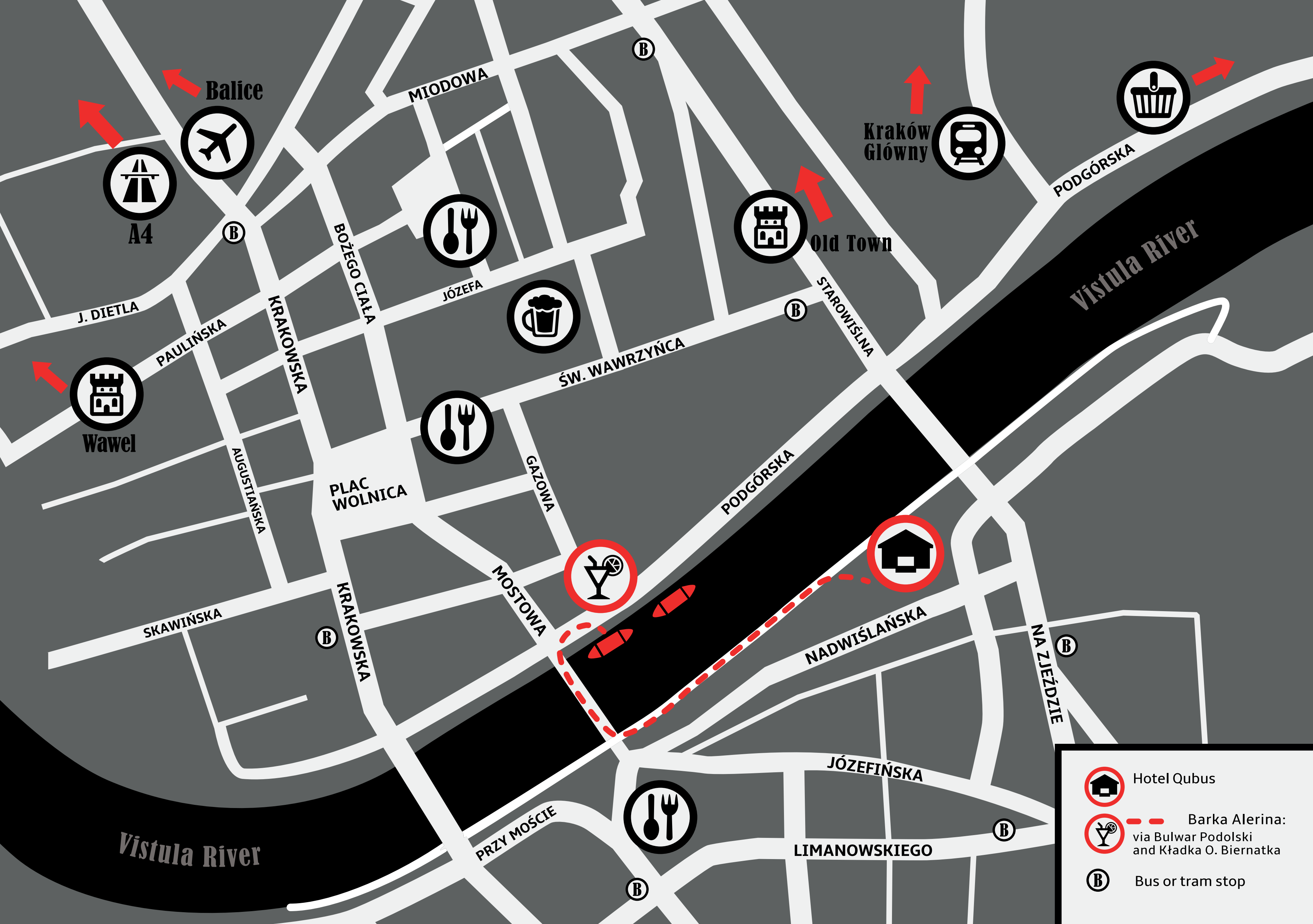
Notes

November 17th 2013 (Sunday)
19:00 Opening glass of wine at Qubus Hotel

November 18th 2013 (Monday)	
8:30-8:40	***Conference opening***
8:40-9:10	Katsumi Kishino
9:10-9:40	Dan Cohen
9:40-9:55	Henryk Turski
9:55-10:10	Luca Radaelli
10:10-10:25	Szymon Stańczyk
10:25-11:00	***Coffee break 1***
11:00-11:30	Elyahou Kapon
11:30-12:00	Keith Wilcox
12:00-12:15	Artur Broda
12:15-12:30	Marcin Gębski
13:00-14:30	***Lunch***
14:30-15:00	Zbig Wasilewski
15:00-15:30	Sergey Ivanov
15:30-15:45	Andrzej Kolek
15:45-16:00	Witold Trzeciakowski
16:00-18:00	***Poster session – beer***

November 19th 2013 (Tuesday)	
9:00-9:30	James Lott
9:30-10:00	Maciej Dems
10:00-10:15	Tomasz Czyszanowski
10:15-10:30	Łukasz Zinkiewicz
10:30-11:00	***Coffee break 2***
11:00-11:30	Jelena Ristic
11:30-12:00	Michael Kneissl
12:00-12:15	Anna Kafar
12:15-12:30	Katarzyna Holc
13:00-14:30	***Lunch***
14:30-15:00	Wyn Meredith
15:00-15:30	Igor Smetanin
15:30-15:45	Andrzej Maląg
15:45-16:00	Grzegorz Sobczak
16:00-16:15	Maciej Bugajski
19:00-24:00	***Conference Diner***

November 20th 2013 (Wednesday)	
9:00-9:30	Lise Lahourcade
9:30-10:00	Ulrich Schwarz
10:00-10:15	Tomasz Czyszanowski
10:15-10:30	Grzegorz Muzioł
10:30-11:00	***Coffee break 3***
11:00-11:30	Grzegorz Sęk
11:30-12:00	Michał Leszczyński
12:00-12:15	Steve Najda
12:15-12:30	Maciej Kuc
12:30-12:45	Marta Gładysiewicz
12:45-13:00	Artem Bercha
13:00-13:10	***Closing remarks***



Balice
A4
Wawel
Old Town
Kraków
Główny
Vistula River
Vistula River
MIODOWA
BOŻEGO CIAŁA
J. DIETLA
PAULIŃSKA
KRAKOWSKA
KRAKOWSKA
JÓZEFA
ŚW. WAWRZYŃCA
STAROWIŚLNA
PODGÓRSKA
PODGÓRSKA
AUGUSTIAŃSKA
PLAC
WOLNICA
GAZOWA
MOSTOWA
SKAWIŃSKA
NADWIŚLAŃSKA
NA ZJEŹDZIE
JÓZEFIŃSKA
LIMANOWSKIEGO
PRZY MOŚCIE
B
Hotel Qubus
Barka Alerina:
via Bulwar Podolski
and Kładka O. Biernatka
Bus or tram stop