# HL 70: Semiconductor laser I: VECSEL and cascade lasers

Time: Wednesday 15:00–17:15 Location: POT 112

HL 70.1 Wed 15:00 POT 112

**Interband-Cascade-Lasers** — •Matthias Dallner, Robert Weih, Florian Hau, Sven Höfling, and Martin Kamp — Technische Physik and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Universität Würzburg, Am Hubland, 97074 Würzburg

Interband cascade lasers (ICLs) are promising candidates to meet the demand for efficient and relieable laser sources in the mid-infrared wavelength region coming from a variety of applications such as high sensitivity tunable laser absorption spectroscopy (TLAS) or medical diagnostics. Grown on GaSb-substrates ICLs are able to cover a wide spectral range from 3 $\mu m$ to 5.7 $\mu m$ in cw operation above room temperature. Long wavelength devices based on InAs substrates, utilizing highly doped InAs-layers instead of superlattice claddings in view of a higher thermal conductivity, have shown laser emission up to 10.4 $\mu m$. In this talk recent results on both, GaSb-based and InAs-based long wavelength ICLs are presented.

For ICLs grown on both substrates, GaSb and InAs, several design optimizations concerning the active region and the waveguide were examined. As a result GaSb based dry etched ridge waveguide lasers with more than 100 mW of cw output power at room temperature in the 3.5 $\mu m$ wavelength range could be fabricated. For the plasmon waveguide InAs-ICLs a maximum lasing temperature of -13 $°C$ in cw operation for a narrow ridge waveguide laser was achieved at 6 $\mu m$. In pulsed operation threshold current densities below 1 $kA/cm^2$ were measured.

HL 70.2 Wed 15:15 POT 112

**Monomode Interband Cascade Lasers in the MIR wavelength range** — •Julian Scheuermann[1], Michael von Edlinger[1], Robert Weih[2], Lars Nähle[1], Christian Zimmermann[1], Marc Fischer[1], Johannes Koeth[1], Sven Höfling[2], and Martin Kamp[2] — [1]nanoplus GmbH, Oberer Kirschberg 4, 97218 Gerbrunn, Germany — [2]Technische Physik University of Würzburg and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Am Hubland, 97074 Würzburg, Germany

Interband cascade lasers (ICLs) have evolved into important laser sources in the mid infrared (MIR) spectral range. Compared to quantum cascade lasers, they offer significant advantages with respect to threshold power density as well as overall power consumption. In contrast to conventional diode lasers, they are able to cover the entire wavelength region from 3 to 6 microns. This is extremely interesting for high accuracy gas sensing, since many gas species have their strongest absorption features in this range, including e.g. CH4, formaldehyde or NO. Novel monomode ICLs in the MIR wavelength range suited for applications in tunable laser absorption spectroscopy are presented in this talk. The focus is on the design and processing of distributed feedback ICLs and their temperature dependent characteristics. Vertical sidewall gratings defined by electron beam lithography and an optimized dry etch process are the key components to achieve application-grade device performance and monomode emission with high side mode suppression ratio. Continuous wave operation at temperatures up to 80°C with threshold currents below 80 mA was observed.

HL 70.3 Wed 15:30 POT 112

**In-phase supermode emission based on an evanescently coupled semiconductor laser array** — •Alexander Reinhold[1], Christian Zimmermann[1], Julian Scheuermann[1], Wolfgang Zeller[1], Johannes Koeth[1], and Martin Kamp[2] — [1]nanoplus Nanosystems and Technologies GmbH, Oberer Kirschberg 4, D-97218 Gerbrunn, Germany — [2]Technische Physik and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

Various fields of application demand compact, low cost, coherent light sources with high brilliance and emission of a single spectral mode. Suitable monolithic device concepts like semiconductor ridge waveguide arrays are extremely promising to achieve a narrow beam divergence with a high optical output power. Such arrays exhibit lateral mode coupling of adjacent ridge waveguides, leading to a distinct number of index guided supermodes with a large mode extension at the facet. For an array with a predefined number of ridge waveguides, coupled mode analysis postulates a distinct number of allowed supermodes with only the first order in-phase supermode exhibiting lateral single lobe emission. We have designed and fabricated arrays based on an AlGaAs/GaAs laser structure with an InGaAs double quantum well active region. In order to obtain devices with spectral single mode emission we have also realised arrays with wavelength selective elements. We achieved in-phase supermode emission with a lateral beam divergence of 5,6 ° at full width half maximum (FWHM) and optical output powers beyond 100 mW.

HL 70.4 Wed 15:45 POT 112

**Organic microlasers in vertical and lateral geometry** — •Tim Wagner, Markas Sudzius, Andreas Mischok, Robert Brückner, Hartmut Fröb, and Karl Leo — Institut für Angewandte Photophysik, Technische Universität Dresden, George-Bähr Str. 1, 01069 Dresden

Optical microcavities can trap light in a very compact volume by different mechanisms, for example, by total internal reflection or distributed Bragg reflection. As a result, properties such as confinement, positive optical feedback, wavelength selectivity and outcoupling mechanisms are realized in entirely different ways.

In this work, we compare lasing characteristics of two conceptually different structures — vertical-cavity surface-emitting lasers and distributed feedback lasers — which are based on the same set of materials and technology. The active material in all structures is a blend of the red laser dye DCM doped by 2 wt% into the host material $Alq_3$.

Although based on conceptually different microresonator structures, both devices show similar lasing thresholds $I_{th}$ and comparable optical confinement factors $\beta$. A systematic analysis of these characteristics allows us to identify dominating mechanisms, which are responsible for the lasing thresholds, and let us justify the balance between the positive optical feedback, which is defined by the optical resonator, against the different kinds of optical losses. Based on the results obtained, devices combining concepts of VCSEL and DFB will be discussed further.

HL 70.5 Wed 16:00 POT 112

**Single-frequency vertical-external-cavity surface-emitting laser with output power exceeding 10 W and sub-MHz linewidth** — •Fan Zhang[1], Bernd Heinen[1], Matthias Wichmann[1], Christoph Möller[1], Bernardette Kunert[2], Wolfgang Stolz[1], Arash Rahimi-Iman[1], and Martin Koch[1] — [1]Department of Physics, Philipps-Universität Marburg, Marburg D-35032, Germany — [2]NAsP III/V GmbH, Marburg D-35041, Germany

Vertical-external-cavity surface-emitting lasers (VECSELs) provide high power, highly coherent continuous-wave emission and a broad wavelength coverage (from UV to mid-IR) depending on the chip design. Moreover, the laser cavity can be extended by optical components, which allows for single-frequency operation. In recent years, single-frequency VECSELs have been intensively investigated. They have the potential to combine a high output power, a narrow linewidth and a large frequency tunability in one device. Such lasers are desirable tools for numerous applications, ranging from spectroscopy, metrology to optical free-space telecommunication. Here, we demonstrate a single-frequency VECSEL working at 1030 nm, and exceeding 10 W output power with sub-MHz linewidth at the same time. A maximum output power of 11 W is achieved at a net incident pump power of 42 W. Furthermore, an external Fabry-Perot cavity was used as frequency discriminator to measure the stability of the free-running laser. At a sampling time of 1 ms, we yield a considerably narrow linewidth, which is mainly limited by the mechanical vibrations and acoustical noise, of 750 kHz.

HL 70.6 Wed 16:15 POT 112

**SESAM mode-locked AlGaInP-VECSEL emitting femtosecond pulses** — •Roman Bek, Grizelda Kersteen, Hermann Kahle, Thomas Schwarzbäck, Michael Jetter, and Peter Michler — Institut für Halbleiteroptik und Funktionelle Grenzflächen and Research Center SCoPE, Universität Stuttgart, Allmandring 3, 70569 Stuttgart, Germany

Since 2000, semiconductor saturable absorber mirrors (SESAMs) have been used for passive mode locking of vertical external-cavity surface-emitting lasers (VECSELs) emitting in the infrared spectral range. These laser systems are able to produce femtosecond pulses with an average power of several watts. In contrast, the first passively mode-locked VECSEL emitting picosecond pulses in the visible spectrum could only be realized in 2013.

We present the first SESAM mode-locked VECSEL producing femtosecond pulses at a wavelength of 664 nm and a repetition rate of 836 MHz. We use an absorber containing two quantum wells close to the surface and an additional fused silica coating. Due to a plane diamond heatspreader bonded onto the gain chip, we observe side pulses with a time delay of 8.95 ps. The laser spectrum shows the superposition of a soliton-like part and a "continuum" which has already been observed for soliton-like mode-locked semiconductor disk lasers in the infrared spectral range.

HL 70.7 Wed 16:30 POT 112

**Frequency doubled AlGaInP-VECSELs for interference lithography** — •Hermann Kahle, Clarissa Wink, Jonas Weber, Ulrich Rengstl, Hendrik Niederbracht, Thomas Schwarzbäck, Michael Jetter, and Peter Michler — Institut für Halbleiteroptik und Funktionelle Grenzflächen and Research Center SCoPE, Universität Stuttgart, Allmandring 3, 70569 Stuttgart, Germany

The wide range of applications in biophotonics, television technologies, spectroscopy and lithography made the vertical external-cavity surface-emitting laser (VECSEL) an important category of power scalable lasers. We present an optically pumped, frequency doubled AlGaInP-VECSEL with a total of 20 compressively strained quantum wells (QWs). The QW packages are placed in a separate confinement heterostructure in a resonant periodic gain (RPG) design within strain-compensating quaternary AlGaInP barriers and cladding layers, respectively. The VECSEL operates in continuous-wave operation at fundamental wavelengths around 660 nm. Wavelength tuning measurements of the fundamental and frequency doubled output, realized by rotation of an intra-cavity birefringent filter will be shown. High power ultraviolet output can be used as light source for interference lithography. Details of the fabrication, characterization, laser setup as well as test structures of the application aiming on pre-structuring of semiconductor samples will be shown. A new power-scaling concept for semiconductor disk lasers towards high UV laser power for large area lithography is under investigation.

HL 70.8 Wed 16:45 POT 112

**Continuously tunable, self-seeded GaSb-based semiconductor disk laser emitting around 2.05$\mu$m** — •Peter Holl, Sebastian Kaspar, Steffen Adler, Marcel Rattunde, Andreas Bächle, Rolf Aidam, and Joachim Wagner — Fraunhofer-Institut für Angewandte Festkörperphysik, Tullastrasse 72, D-79108 Freiburg, Germany

Semiconductor disk lasers, also known as vertical-external-cavity surface-emitting laser (VECSEL), combine the wavelength versatility of semiconductor laser with the capability of a nearly diffraction-limited high-power output. Due to the broad gain spectrum of the semiconductor gain material, VECSELs are an attractive option to build a wavelength tunable laser source, which are needed for applications like high resolution spectroscopy.

In this presentation we will report on a tunable, self-seeded VECSEL emitting around 2.05 $\mu$m. An intra-cavity SiC heatspreader dissipates the heat of the active region to ensure high output power. At the same time we were able to overcome etalon effects that limit the selectable wavelengths to discrete values by using a wedged heatspreader, thus avoiding plane-parallel surfaces. The heatspreader inserts a tilted surface in the cavity acting as beam splitter, whose reflection is used to self-seed the laser. For this purpose the outcoupled beam is led onto a diffraction grating providing wavelength selective feedback into the cavity.

The achieved continuous tuning range around 2.05$\mu$m spans over 30nm, while the output power exceeds 400mW at room temperature.

HL 70.9 Wed 17:00 POT 112

**Emission intensity modulation of a VCSEL by ultrafast acoustics** — •Jan Tepper[1], Thomas Czerniuk[1], Christian Brüggemann[1], Sebastian Brodbeck[2], Christian Schneider[2], Martin Kamp[2], Sven Höfling[2], Boris Glavin[3], Dimitri Yakovlev[1,4], Andrey Akimov[4,5], and Manfred Bayer[1] — [1]Experimentelle Physik 2a, TU Dortmund, Dortmund, Germany — [2]Technische Physik, Universität Würzburg, Würzburg, Germany — [3]V. E. Lashkaryov Institute of Semiconductor Physics, Kiev, Ukraine — [4]A. F. Ioffe Physical-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia — [5]School of Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom

We report an ultrafast intensity modulation of a VCSEL's laser emission of up to 50% peak-to-peak by shifting the active medium's spectral profile using an acoustic strain pulse.

The sample under investigation is an AlAs/GaAs based microcavity, which inhabits quantum wells as the active medium. Its emission intensity strongly depends on how well the active medium's wavelength matches the cavity mode. By using high energy femtosecond laser pulses, we generate a strain pulse travelling through the sample. This strain pulse subsequently reaches the QWs and alters their band gap, which leads to an emission intensity modulation with an amplitude of 50% from peak to peak. Due to the small spatial separation of the QWs, the corresponding modulation frequencies lie in the THz regime. Qualitatively, the results can be described by rate equations in which the strain is treated as a perturbation of the laser's gain.