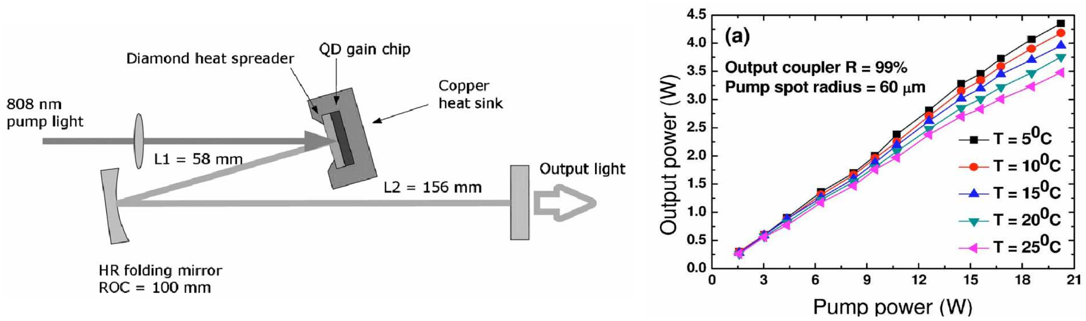
WP4 Highlights

Optically pumped VECSELs and efficient SHG

One of the key activities of the project was the development of optically pumped vertical-external-cavity surface-emitting lasers (OP-VECSELs) for multi-photon imaging, RGB generation and sub-picosecond pulses for continuum generation. Major achievements include:

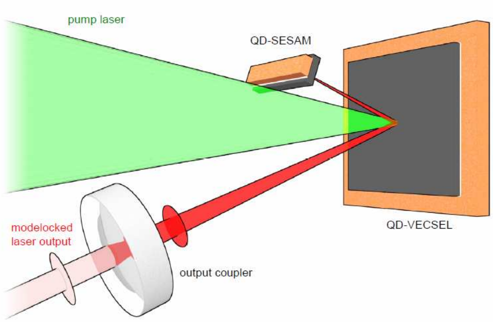
High-power quantum-dot-based semiconductor disk laser

The teams from Univ. Dundee, ORC Univ. Tampere, Innolume and ETHZ have demonstrated multi-watt cw output power from an optically-pumped quantum-dot VECSEL10. Continuous-wave output power of 4.35 W with 22% slope efficiency was demonstrated at a center wavelength of 1032 nm. This represents an increase in power of 15 times and an increase in slope efficiency of 10 times from the previously published results using Stranski–Krastanow grown quantum dots. An intra-cavity diamond heat spreader was used for thermal management. The maximum output power was limited by the available pump power, and no sign of thermal rollover was observed.



Schematic of the V-cavity laser configuration and (right) output power versus pump power characteristics of diamond heat spreader optically pumped VECSEL.

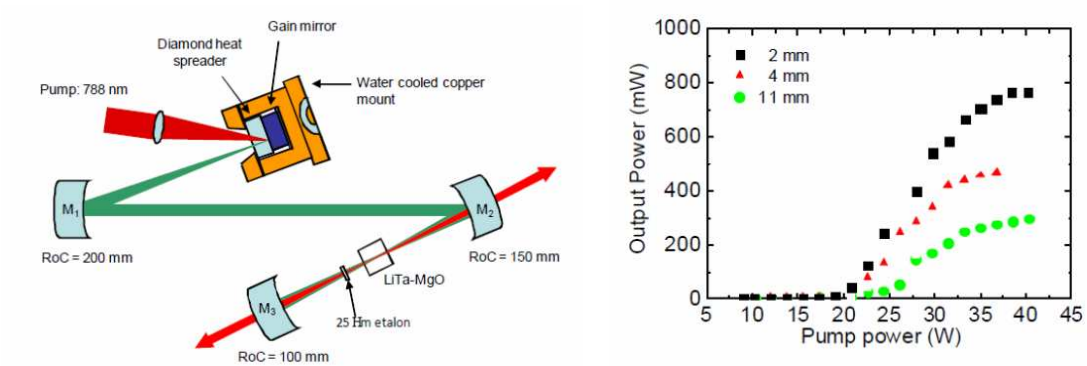
Femtosecond operation of a high power VECSEL



Partners ETHZ and INNOLUME reported on the first femtosecond vertical external cavity surface emitting laser (VECSEL) exceeding 1 W of average output power. The VECSEL is optically pumped, based on self-assembled InAs quantum dot (QD) gain layers, cooled efficiently using a thin disk geometry and passively modelocked with a fast quantum dot semiconductor saturable absorber mirror (SESAM). They have developed a novel gain structure with a flat group delay dispersion (GDD) of ±10 fs2 over a range of 30 nm around the designed operation wavelength of 960 nm. This amount of GDD is several orders of magnitude lower compared to standard designs. Furthermore, an optimized positioning scheme of 63 QD gain layers has been used to broaden and flatten the spectral gain. For stable and self-starting pulse formation, a QD-SESAM with a fast absorption recovery time of around 500 fs has been employed. An average output power of 1 W with 784-fs pulse duration at a repetition rate of 5.4 GHz hs been achieved. The QD-SESAM and the QD-VECSEL were operated with similar cavity mode areas, which is beneficial for higher repetition rates and the integration of both elements into a modelocked integrated external-cavity surface emitting laser (MIXSEL).

Efficient frequency conversion using a optically pumped VECSEL

Compact coherent laser sources emitting red light are required for several applications such as photodynamic therapy, laser projection displays, and biophotonics. An optically pumped semiconductor disk laser (OP-SDL or OP-VECSEL) can produce high power with nearly diffraction-limited beam and by using proper semiconductor compounds they can be designed to emit from 650 nm to midinfrared (midIR). However some wavelengths are hard to achieve; particularly, direct generation of visible light at nm from SDL is problematic due to the shortage of efficient semiconductor gain materials and the limited availability of short-wavelength high power pump sources. Alternatively, visible wavelengths can be generated from an infrared SDL by second-harmonic generation (SHG). FAST-DOT team of TUT (Finland) in collaboration with the team from UNIDUN (UK) have demonstrated an OP-SDL frequency doubled with periodically poled lithium tantalate crystal. The semiconductor disk laser exploited GaInNAs-based active region with GaAs–AlAs distributed Bragg mirror to produce emission at 1.2 µm. Crystals with various lengths were tested for intracavity frequency conversion and the achieved frequency doubled output power was 760 mW at 610 nm (red wavelength) with a 2-mm-long crystal.

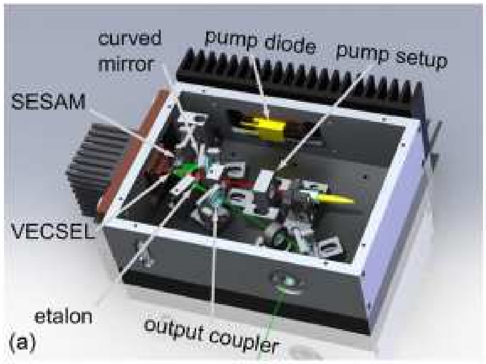


Left: Experimental setup for the frequency doubling with the OP-SDL. Right: Output power at red wavelength with different lengths of nonlinear crystal.

Low timing jitter of a free-running SESAM mode-locked VECSEL

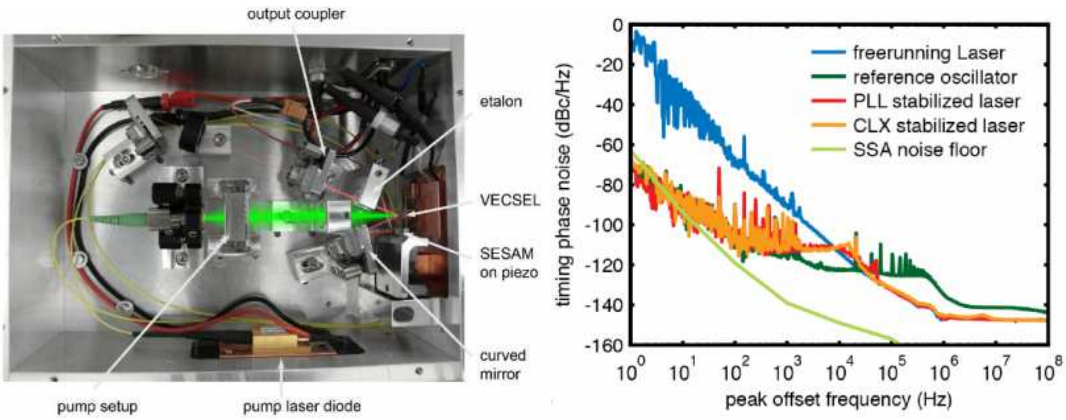
FAST-DOT partner ETHZ presented timing jitter measurements of an InGaAs quantum well vertical external cavity surface emitting laser (VECSEL) passively mode locked with a quantum dot semiconductor saturable absorber mirror (SESAM) at 2-GHz repetition rate.

The VECSEL generates 53-mW average output power in 4.6-ps pulses at 953 nm. The laser housing was optimized for high mechanical stability to reduce acoustic noise. A fiber-coupled multimode 808-nm pump diode which is mounted inside the laser housing is used. No active cavity length stabilization is employed. The phase noise of the free-running laser integrated over a bandwidth from 100 Hz to 1 MHz corresponds to an RMS timing jitter of ~212 fs, which is lower than previously obtained for mode-locked VECSELs. This clearly confirms the superior noise performance expected from a high-Q-cavity semiconductor laser. In contrast to edge-emitting semiconductor diode lasers, the cavity mode is perpendicular to the quantum well gain layers, which minimizes complex dispersion and nonlinear dynamics.



Record-low noise operation of an actively stabilized SESAM-modelocked VECSEL

The timing jitter of an actively stabilized SESAM modelocked VECSEL has been nvestigated. The repetition rate was phase-locked to a reference source using a piezo actuator and the timing phase noise power spectral density of the laser output was measured. The resulting rms timing jitter integrated over an offset frequency range from 1 Hz to 1 MHz gives a timing jitter of below 80 fs, several times lower than previous modelocked VECSELs and comparable to the noise performance of ion-doped solid-state-lasers.

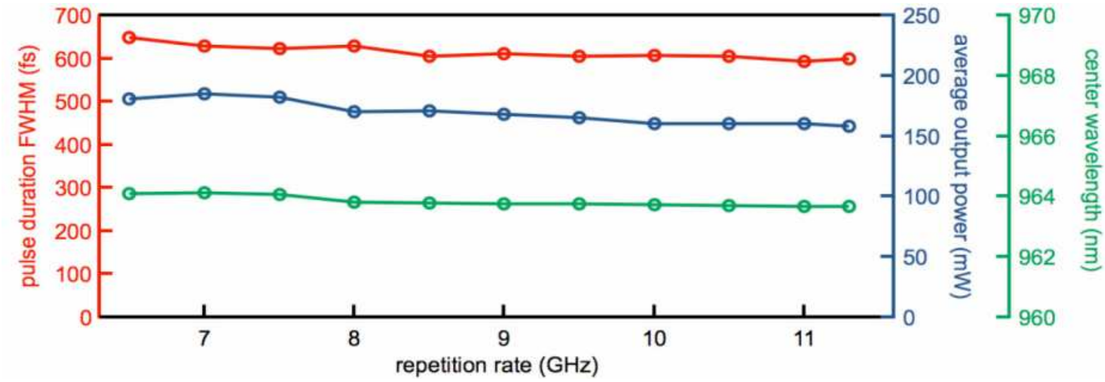


Left: Picture of the laser in the metallic housing including the Z-shaped cavity and the pump setup with a fiber-coupled pump diode. The pump beam is drawn in green and the laser beam in red. Right: two-sided timing phase noise of the laser and the reference oscillator.

Femtosecond VECSEL with Tunable Multi-Gigahertz Repetition Rate

We present a femtosecond vertical external cavity surface emitting laser (VECSEL) that is continuously tunable in repetition rate from 6.5 GHz up to 11.3 GHz. The use of a low-saturation fluence semiconductor saturable absorber mirror (SESAM) enables stable cw modelocking with a simple cavity design, for which the laser mode area on SESAM and

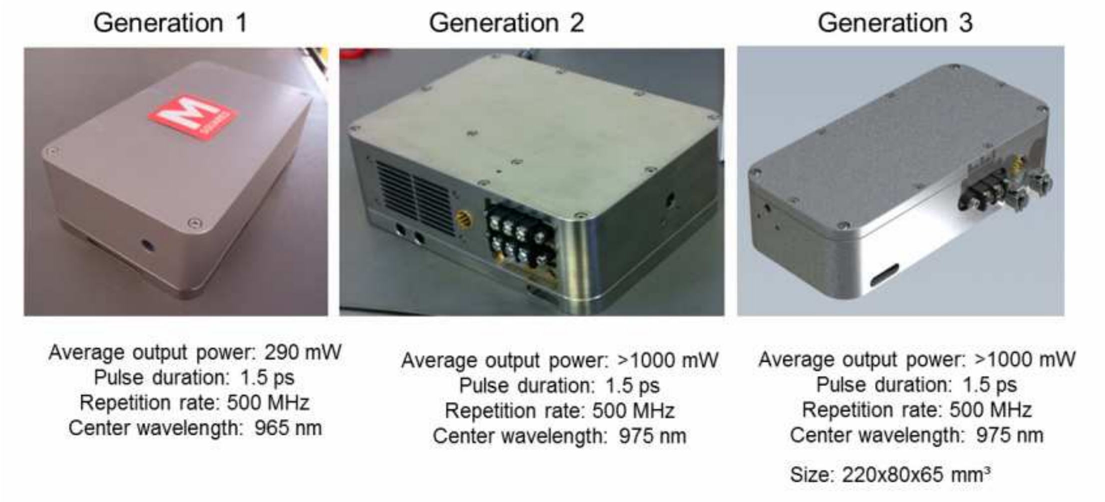
VECSEL are similar and do not significantly change for a variation in cavity length. Without any realignment of the cavity for the full tuning range, the pulse duration remained nearly constant around 625 fs with less than 3.5% standard deviation. The center wavelength only changed ±0.2 nm around 963.8 nm, while the output power was 169 mW with less than 6% standard deviation. Such a tunable repetition rate is interesting for various metrology applications such as for example optical sampling by laser cavity tuning (OSCAT).

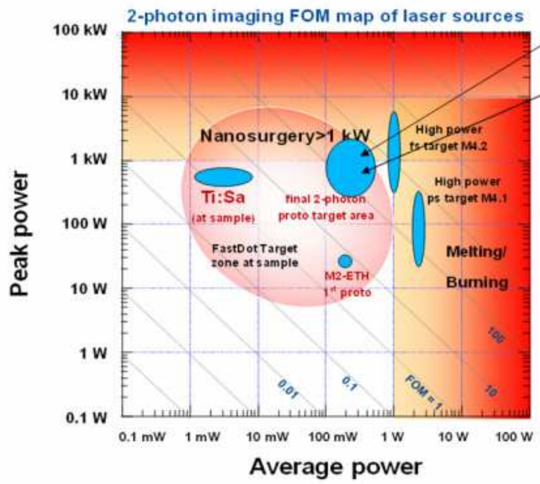


The repetition rate was tuned from 6.5 GHz up to 11.3 GHz. During the tuning we measured only small changes in output power (blue), with less than 6% standard deviation around 169 mW, while the pulse duration (red) was nearly constant around 625 fs with less than 3% standard deviation. The center wavelength (green) was extremely constant changing only about ±0.2 nm around 963.8 nm.

Multiphoton imaging with compact semiconductor disk lasers

M2 continued to investigate the performance of a compact, non expensive, easy to use ultrafast semiconductor disk laser (1W average power, 1.5 ps, 500MHz) for multiphoton imaging. The laser's operating wavelengths of 970 nm makes it ideal for nonlinear excitation of GFP as it has a two-photon action cross section peak at this wavelength. This property relaxes the required peak powers for TPEF imaging. We show the suitability of this laser for in-vivo imaging with GFP and other dyes; at different penetration depths; time-lapse studies and SHG imaging. The laser performance is evaluated in commercial microscopes and in comparison with Ti:sapphire lasers.





⇒ Achieved targeted performance, demonstrated MPI application