High-Performance Mode-Locking with up to 50 GHz Repetition Rate from Integrable VECSELs

B. Rudin, D. J. H. C. Maas, D. Lorenser, A.-R. Bellancourt, H. J. Unold, and U. Keller
Department of Physics, Insitute of Quantum Electronics, Ultrafast Laser Physics Group, ETH Zurich, 8093 Zurich, Switzerland.
rudin@phys.ethz.ch

E. Gini and D. Ebling
FIRST Center for Micro- and Nanoscience, ETH Zurich, 8093 Zurich, Switzerland

Abstract: We present passively mode-locked vertical-external-cavity surface-emitting semiconductor lasers in a 1:1 mode ratio configuration, achieving record repetition rates of 30-50 GHz, average output powers up to 177 mW, and pulse widths as short as 2.1 ps.

OCIS codes: (140.4050) Mode-locked lasers; (250.7260) Vertical cavity surface emitting lasers

1. Introduction and Motivation

In the past few years, a novel type of laser has bridged the gap between semiconductor lasers and solid-state lasers. The vertical-external-cavity surface-emitting laser (VECSEL) combines the best of both worlds: the semiconductor gain medium allows for flexible choice of emission wavelength via bandgap engineering and offers a wealth of possibilities from the semiconductor processing world. In combination with the mature optical pumping technology and heat removal of solid-state thin-disk lasers, the performance of VECSELs surpasses anything possible to date with conventional semiconductor lasers. Continuous-wave output powers of up to 30 W with an M^2 of 3 have been reported from such optically pumped VECSELs [1], and electrically pumped devices have reached 0.5 W single-mode output power [2].

Concerning high-performance passive mode locking, a domain where solid-state lasers have been dominant for years, VECSELs possess the advantage of a large gain cross-section, which suppresses Q-switching instabilities. Thus, VECSELs are ideally suited for high-repetition-rate mode locking in combination with high average output powers. After the first demonstration of a passively mode-locked VECSEL in 2000 [3], pulse width and output power have improved continuously to 486-fs pulses at 10 GHz with 30 mW [4] and 4.7-ps pulses at 4 GHz with 2.1 W average output power [5].

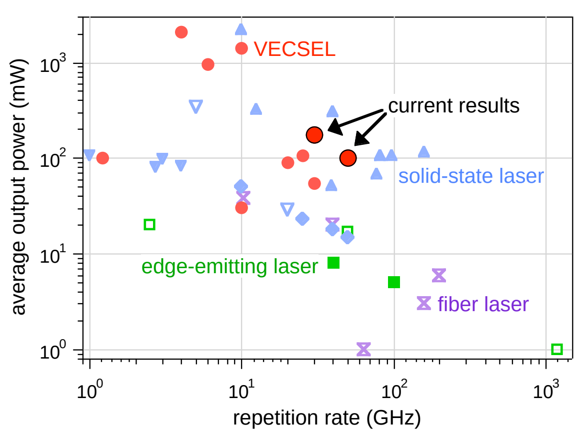

Fig. 1. Overview of high-repetition-rate laser sources. Open symbols denote active mode locking, filled symbols passive mode locking.

The comparison of various high-repetition-rate sources in Fig. 1 shows that VECSELs have already pulled even with solid-state lasers in the regime between 1 and 10 GHz. Above 10 GHz, however, VECSEL mode locking becomes rather difficult due to cavity geometry limitations. We have been able to circumvent these limitations by developing novel quantum-dot-based SESAMs (semiconductor saturable absorber mirror), which allow mode locking in a simple, low-divergence cavity with identical mode areas on VECSEL gain and SESAM. This allows to construct extremely compact cavities, with which we have now achieved new mode locking milestones including up to 50 GHz repetition rate with 102 mW in 3.1-ps pulses, up to 177 mW average power at 30 GHz in 6.1-ps pulses, and 2.1-ps pulses at 30 GHz with 65 mW average power in free-running operation without an etalon.

The ultimate advantage of these novel 1:1 mode-locked VECSELs, however, is the possibility to monolithically integrate the SESAM device into the VECSEL gain structure [6]. As opposed to conventional edge-emitting semiconductor lasers, where such integrated devices exist already, integrated VECSELs could deliver output powers and beam quality which rival those of high-repetition-rate solid-state lasers. Such a device would be a revolution in the market segment of high-repetition-rate solid-state lasers and enable novel, inexpensive, rugged, and maintenance-free miniature devices (e.g. for hand-held projection systems or outer space applications).

2. Experimental Results

The cavity setup used for the mode-locking experiments has a V-shaped geometry and consists of the semiconductor gain structure which serves as a folding mirror, the SESAM, and a curved output coupler with a radius of curvature that determines the resonator mode. The folding half-angle of the V-cavity is 15°. An etalon is used for tuning the wavelength of operation into a region where the intracavity group delay dispersion (GDD) is favorable for obtaining stable mode locking and short pulses. The gain structure is pumped at an angle of 45°, perpendicular to the plane of the laser cavity. The SESAM used in these experiments consists of a highly reflecting AlAs/GaAs Bragg mirror and an absorber layer embedded in a resonant GaAs cavity, grown by molecular beam epitaxy (MBE). In order to achieve a low saturation fluence, the absorber layer consists of self-assembled InAs quantum dots (QD). For high-repetition-rate mode locking, the recovery time of the QDs is reduced by employing low-temperature growth. A description of the VECSEL structure can be found elsewhere [6]. Figure 2 shows the pulse characterization of a 30-GHz cavity using a flat output coupler, which results in a dynamically stable cavity controlled by the thermal lens that builds up in the VECSEL chip above a certain pump power. The resulting 6.1-ps pulses are only 1.3x above transform limit, the average output power is 177 mW. Using our current approach, the repetition rate is limited at 50 GHz due to cavity geometry.

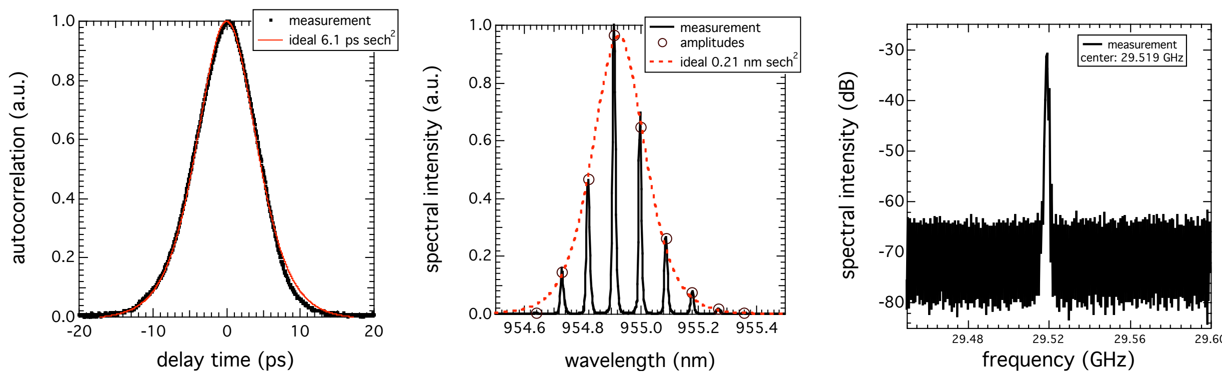

Fig. 2. Pulse characterization of the 30-GHz result with 177 mW average output power. Left: autocorrelation with $sech^2$-fit, center: optical spectrum with $sech^2$-fit through mode amplitudes, right: RF spectrum on a 100-MHz span with 1-MHz resolution bandwidth.

3. Conclusions and Outlook

We have demonstrated record performance from passively mode-locked VECSELs, including repetition rates up to 50 GHz, output powers up to 177 mW at 30 GHz, and pulse widths as short as 2.1 ps. The key to achieving these results was the development of a low-saturation-fluence quantum-dot SESAM, which allows mode locking with identical mode areas on the VECSEL gain chip and the SESAM. While this result already rivals those of conventional solid-state lasers, even better performance in combination with enhanced compactness and ruggedness can be expected from integrated VECSELs: thanks to the identical mode areas, it is now feasible to combine the two devices into a single one, streamlining fabrication, facilitating cavity alignment, and maximizing the attainable repetition rates.

References

[1] J. Chilla et al, "High Power Optically Pumped Semiconductor Lasers," presented at Photonics West 2004, Solid State Lasers XIII: Technology and Devices, in Proc. SPIE 5332, 2004.

[2] J. G. McInerney et al, "High-power surface emitting semiconductor laser with extended vertical compound cavity," *Electron. Lett.*, vol. 39, pp. 523-525, 2003.

[3] S. Hoogland et al., "Passively mode-locked diode-pumped surface-emitting semiconductor laser," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1135-1138, 2000.

[4] S. Hoogland et al., "10-GHz Train of Sub-500-fs Optical Soliton-Like Pulses From a Surface-Emitting Semiconductor Laser," *IEEE Phot. Tech. Lett.*, vol. 17, pp. 267-269, 2005.

[5] A. Aschwanden et al., "2.1-W picosecond passively mode-locked external-cavity semiconductor laser," *Opt. Lett.*, vol. 30, pp. 272-274, 2005.

[6] D. Lorenser et al., "Towards Wafer-Scale Integration of High Repetition Rate Passively Mode-Locked Surface-Emitting Semiconductor Lasers," *Appl. Phys. B*, vol. 79, pp. 927-932, 2004.