High power ultrafast VECSELs and MIXSELs

B. W. Tilma, C. A. Zaugg, M. Mangold, S. M. Link, A. Klenner, M. Golling and U. Keller

Institute for Quantum Electronics, Department of Physics, ETH Zürich, Wolfgang-Pauli-Strasse 16, 8093 Zürich, Switzerland.

We present an overview of the latest results in high power ultrafast semiconductor laser sources based on vertical-external-cavity surface-emitting lasers (VECSELs) and modelocked integrated external-cavity surface-emitting lasers (MIXSELs). The on-going power scaling and reduction in pulse duration, in combination with the excellent noise performance makes these laser sources highly attractive for many applications in tele and data communications, optical clocking, and multi-photon imaging for example and in addition for new technological fields such as frequency comb metrology.

Introduction

The development of picosecond and femtosecond lasers has made a large impact in both fundamental science and industrial applications [1, 2]. Examples of successful implementation of these ultrafast lasers are the use in optical data transmission [3], photonic signal processing [4] and frequency combs [5, 6]. So far, these lasers mainly rely on modelocked diode-pumped solid-state lasers (DPSSL), which are often relative complex, bulky and expensive systems. Semiconductor lasers have already proven to be very reliable for continuous wave (cw) operation and are nowadays used in many applications ranging from the compact disc player up to complex integrated laser sources in optical networks [7]. Semiconductor based modelocked laser so far haven't had a large impact in industrial applications, mainly due to their complexity or lack in device performance.

Optically pumped vertical-external-cavity surface-emitting lasers (VECSELs [8]) modelocked with a semiconductor saturable absorber mirror (SESAM [9]) (a typical laser setup is shown in Fig. 1a) are very attractive ultrafast laser sources, which have the potential to replace modelocked DPSSL for a widespread field of applications. High output power levels, very good noise performance and excellent beam qualities clearly set them apart other semiconductor based modelocked lasers.

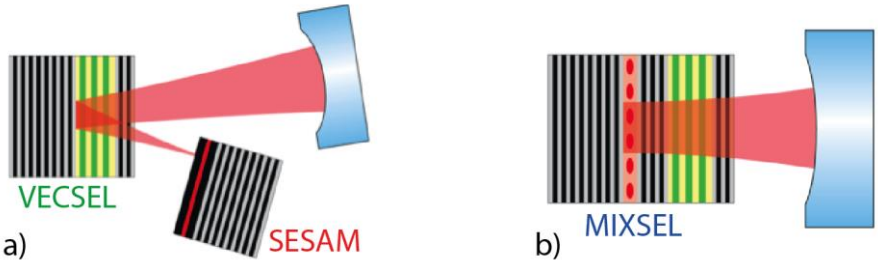

Fig. 1. Schematic diagram of: a) A conventional SESAM modelocked VECSEL consisting of a separate VECSEL gain chip and SESAM chip in a V-shaped cavity with an external output coupler. b) A MIXSEL where the saturable absorber is integrated in the gain chip, which forms a straight cavity with the output coupler.

After we demonstrated the first SESAM modelocked VECSEL in 2000 [10], we then demonstrated for the first time femtosecond pulses with >1 W of average output power

in 2011 [11]. This important milestone has been improved the last year to a record high average output power of 5.1 W in 682-fs-pulses [12] and 3.3 W in 400-fs-pulses [13]. To date, the shortest pulses achieved from a fundamentally SESAM modelocked VECSEL are 107-fs pulses with 3 mW of average output power [14]. Even shorter pulses of only 60 fs were achieved with bursts of pulses [15]. However, the combination of a sub-200-fs pulses with average output power levels above 1 W is still challenging. In order to improve our gain chips towards such high powers with short pulses, we recently developed a numerical model based on measurable macroscopic parameters. The calculations revealed, that 200-fs pulses and an average output power of 1 W should be feasible with a properly designed and fabricated VECSEL-SESAM combination [16].

The demonstration of the modelocked integrated external-cavity surface emitting laser (MIXSEL) [17], which combines the gain of the VECSEL with the saturable absorber of a SESAM in one single semiconductor layerstack (Fig. 1b), brought the technology to a higher integration level. Stable self-starting passive modelocking can be achieved in a simple straight cavity. A record high average output power of 6.4 W was achieved in 28-ps pulses at a repetition rate of 2.5 GHz [18]. Most recently we have been able to demonstrate the first femtosecond operation of a MIXSEL, generating 620-fs pulses at a repetition rate of 4.8 GHz and 101 mW of average output power [19]. In Fig. 2a an overview of the reported average output power levels versus pulse duration is given for both the SESAM modelocked VECSELs as well as for MIXSELs.

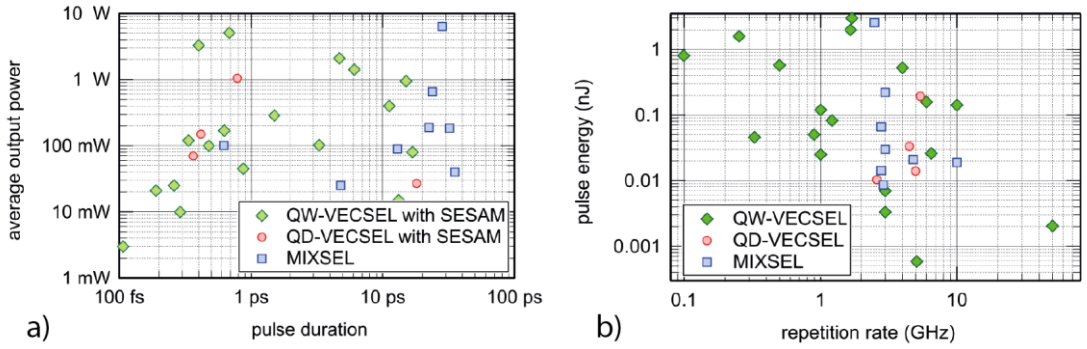

Fig. 2. Overview of published results achieved with QW-VECSELs (green), QD-VECSELs (red) and MIXSELs (blue): a) Recorded average output power versus pulse duration. b) Recorded pulse energy versus repetition rate.

Repetition rate scaling

Besides the optimization in terms of shorter pulses and higher output power, there is also a demand for stable pulse trains at certain repetition rates. Low repetition rates in the MHz-range in combination with high pulse energies are very attractive for numerous applications such as biomedical multi-photon imaging [20] where tissue heating has to be avoided by reducing the average output power, maintaining the high pulse energy. In other applications, such as optical sampling by laser cavity tuning (OSCAT) [21] and on-chip optical clocking [22], a very high repetition rate of 10 GHz or higher is required. Due to the very flexible cavity configuration, the VECSEL and MIXSEL technology can operate over this large operation range of almost three orders of magnitude (Fig. 2b). A 253 MHz fundamentally modelocked VECSEL was demonstrated producing 400 mW of average output power in 11.3-ps-pulses leading to

1.6 nJ pulse energy and 124 W peak power [23]. An even lower repetition rate of 100 MHz has been demonstrated with 30 mW of average output power in 20-ps-pulses and 0.3 nJ pulse energy [24]. The major challenge in low repetition rate fundamentally modelocked VECSELs and MIXSELs is the suppression of multiple pulses in the laser cavity, which decreases the pulse energy and destabilizes the repetition rate.

On the other side, ultrafast VECSELs with repetition rates as high as 50 GHz in the fundamentally modelocked regime [25] and up to 175 GHz in harmonically modelocked operation [26] were demonstrated. The repetition rate of fundamentally modelocked VECSELs is limited by the nature of the cavity design and the pulse duration. The MIXSEL approach on the other hand benefits from the simple straight cavity in which the output coupler can be moved closer to the semiconductor chip. Preliminary results show that in this way the repetition rate of a fundamentally modelocked MIXSEL can reach 100 GHz. Repetition rate tuning, required for example for OSCAT, has been demonstrated with a SESAM modelocked VECSEL from 6.5 GHz up to 11.3 GHz [27] with a nearly constant pulse duration of 625 fs and 169 mW average output power.

Noise performance and frequency stabilization

The high power levels achieved with the VECSEL and MIXSEL technology in combination with the short pulses in the fs-regime, makes them highly attractive sources for applications that rely on stable frequency combs [5]. So far these technologies benefit from the excellent low-noise performance of DPSSLs. For bringing the technology from scientific labs into industrial applications or even households, more compact, robust and cheaper sources are required. For a long time it was assumed that semiconductor lasers could not compete with the excellent noise figures of DPSSLs, mainly due to their low-Q cavities and the long gain sections which introduce complex dispersion, waveguiding effects and nonlinear dynamics. However, SESAM modelocked VECSELs and MIXSELs operate in high-Q cavities with low intracavity losses (including output coupling) in the range of 1%-5%. In addition, the interaction length with the quantum well or quantum dot based gain is very short due to the vertical propagation of the laser mode in the structure. One would expect low-noise performance from SESAM modelocked VECSELs and MIXSELs to compete with the excellent performance of modelocked DPSSL.

We therefore performed timing jitter measurements on a free-running [28] and a stabilized [29] SESAM modelocked VECSEL with a 2-GHz repetition rate at a center wavelength of 953 nm. The stabilized laser was actively stabilized to an electronic reference source with a cavity length control loop using a piezo-electric actuator. After detection of the output pulse train with a highly linear photodiode, the single-sideband timing phase noise power spectral density (PSD) was measured with a Signal Source Analyzer (SSA) (Fig. 3). Integration over an offset frequency range of 100 Hz – 100 MHz resulted in an rms timing jitter of 201 fs for the free-running laser and only 47 fs for the stabilized laser (34 ps and 58 fs in the range from 1 Hz – 100 MHz, respectively). These results are comparable to state-of-the-art timing jitter measurements on modelocked DPSSL [30] where values of 190 fs were measured in free-running operation (100 Hz – 1.56 MHz) and 26 fs for a stabilized cavity length (6 Hz - 1.56 MHz).

These results clearly demonstrate that SESAM modelocked VECSELs and MIXSELs can compete with modelocked DPSSLs in terms of low-noise performance and could therefore be used for applications such as frequency comb metrology in the near future.

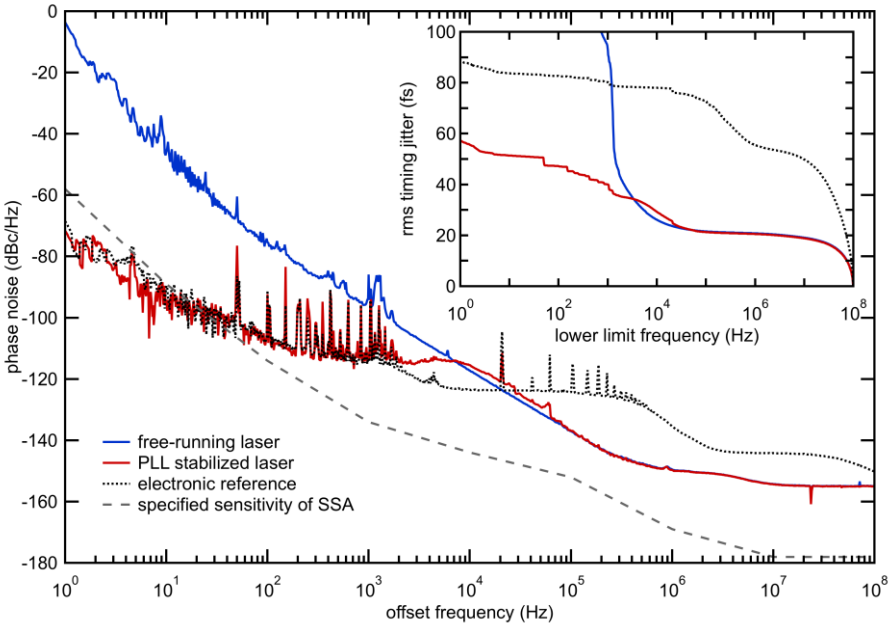

Fig. 3. Measured timing phase noise PSD (SSB) of the free-running laser (blue), the PLL stabilized laser (red) and the reference source (dotted black). The specified sensitivity level of the SSA is given as well (dashed gray). Inset: RMS timing jitter integrated from the lower limit frequency to 100 MHz.

Electrically pumped VECSELs

Another obvious step in the continuous improvement of the technology is to go from optically pumped VECSELs to electrically pumped VECSELs (EP-VECSELs) [31, 32]. Discarding the external pump diode reduces setup complexity and makes these lasers highly attractive for system integration. So far, there were only a few successful attempts of modelocked EP-VECSELs [33-35] since the step from optical pumping to electrical pumping is challenging. The main difference to optical pumping is the fundamental trade-off between optical and electrical losses due to required doping in the semiconductor layerstack to conduct the electrical current. The additional optical losses can be compensated with an intracavity DBR mirror to enhance the electrical field in the active region for more gain. Unfortunately, this step limits the available gain bandwidth and large values of group delay dispersion inhibit femtosecond pulse durations [35]. Besides that, mode-size power scaling is limited by non-uniform current injection in the active region at larger devices [32]. Despite these major challenges we recently demonstrated 6.3 ps pulses in 6.2 mW of average output power [36]. To our knowledge these are the shortest pulses from a modelocked EP-VECSEL producing several milliwatts of average output power.

Conclusion and outlook

SESAM modelocked VECSELs and MIXSELs are attractive semiconductor laser sources that deliver ultrashort laser pulses with picosecond and femtosecond pulse durations in combination with watt-level average output power levels in the gigahertz

repetition rate range. The excellent beam quality and low-noise performance makes them highly attractive for several applications where they can replace conventional complex ion-doped DPSSLs. With the ongoing development we expect the first fully stabilized frequency comb from a modelocked VECSEL or MIXSEL within the near future.

Acknowledgments

This work was supported by ETH Zurich with the FIRST cleanroom facility and was financed by the Swiss Confederation Program Nano-Tera.ch, which was scientifically evaluated by the Swiss National Science Foundation (SNSF).

References

[1] U. Keller, "Recent developments in compact ultrafast lasers," *Nature,* vol. 424, pp. 831-838, 14.08. 2003.

[2] U. Keller, "Ultrafast solid-state laser oscillators: a success story for the last 20 years with no end in sight," *Appl. Phys. B,* vol. 100, pp. 15-28, 2010.

[3] D. Hillerkuss, R. Schmogrow, T. Schellinger, M. Jordan, M. Winter, G. Huber, T. Vallaitis, R. Bonk, P. Kleinow, F. Frey, M. Roeger, S. Koenig, A. Ludwig, A. Marculescu, J. Li, M. Hoh, M. Dreschmann, J. Meyer, S. Ben Ezra, N. Narkiss, B. Nebendahl, F. Parmigiani, P. Petropoulos, B. Resan, A. Oehler, K. Weingarten, T. Ellermeyer, J. Lutz, M. Moeller, M. Huebner, J. Becker, C. Koos, W. Freude, and J. Leuthold, "26 Tbit s^{-1} line-rate super-channel transmission utilizing all-optical fast Fourier transform processing," *Nat. Photon.,* vol. 5, pp. 364-371, 2011.

[4] P. J. Delfyett, S. Gee, C. Myoung-Taek, H. Izadpanah, L. Wangkuen, S. Ozharar, F. Quinlan, and T. Yilmaz, "Optical frequency combs from semiconductor lasers and applications in ultrawideband signal processing and communications," *Lightwave Technology, Journal of,* vol. 24, pp. 2701-2719, 2006.

[5] I. Coddington, W. C. Swann, and N. R. Newbury, "Coherent Multiheterodyne Spectroscopy Using Stabilized Optical Frequency Combs," *Physical Review Letters,* vol. 100, p. 013902, 2008.

[6] H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller, "Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation," *Appl. Phys. B,* vol. 69, pp. 327-332, 1999.

[7] R. Nagarajan, M. Kato, J. Pleumeekers, P. Evans, D. Lambert, A. Chen, V. Dominic, A. Mathur, P. Chavarkar, M. Missey, A. Dentai, S. Hurtt, J. Bäck, R. Muthiah, S. Murthy, R. Salvatore, C. Joyner, J. Rossi, R. Schneider, M. Ziari, H.-S. Tsai, J. Bostak, M. Kauffman, S. Pennypacker, T. Butrie, M. Reffle, D. Mehuys, M. Mitchell, A. Nilsson, S. Grubb, F. Kish, and D. Welch, "Large-scale photonic integrated circuits for long-haul transmission and switching," *Journal of Optical Networking,* vol. 6, pp. 102-111, 2007/02/01 2007.

[8] M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, "High-power (>0.5-W CW) diode-pumped vertical-external-cavity surface-emitting semiconductor lasers with circular TEM00 beams," *IEEE Photon. Technol. Lett.,* vol. 9, pp. 1063-65, 1997.

[9] U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE J. Sel. Top. Quantum Electron.,* vol. 2, pp. 435-453, 1996.

[10] S. Hoogland, S. Dhanjal, A. C. Tropper, S. J. Roberts, R. Häring, R. Paschotta, and U. Keller, "Passively mode-locked diode-pumped surface-emitting semiconductor laser," *IEEE Photon. Technol. Lett.,* vol. 12, pp. 1135-1138, 2000.

[11] M. Hoffmann, O. D. Sieber, V. J. Wittwer, I. L. Krestnikov, D. A. Livshits, Y. Barbarin, T. Südmeyer, and U. Keller, "Femtosecond high-power quantum dot vertical external cavity surface emitting laser," *Optics Express,* vol. 19, pp. 8108-8116, 2011.

[12] M. Scheller, T. L. Wang, B. Kunert, W. Stolz, S. W. Koch, and J. V. Moloney, "Passively modelocked VECSEL emitting 682 fs pulses with 5.1W of average output power," *Electronics Letters,* vol. 48, pp. 588-589, 2012.

[13] K. G. Wilcox, A. C. Tropper, H. E. Beere, D. A. Ritchie, B. Kunert, B. Heinen, and W. Stolz, "4.35 kW peak power femtosecond pulse mode-locked VECSEL for supercontinuum generation," *Opt. Express,* vol. 21, pp. 1599-1605, 2013.

[14] P. Klopp, U. Griebner, M. Zorn, and M. Weyers, "Pulse repetition rate up to 92 GHz or pulse duration shorter than 110 fs from a mode-locked semiconductor disk laser," *Applied Physics Letters,* vol. 98, pp. 071103-3, 2011.

[15] A. H. Quarterman, K. G. Wilcox, V. Apostolopoulos, Z. Mihoubi, S. P. Elsmere, I. Farrer, D. A. Ritchie, and A. Tropper, "A passively mode-locked external-cavity semiconductor laser emitting 60-fs pulses," *Nat. Photonics,* vol. 3, pp. 729-731, Dec 2009.

[16] O. Sieber, M. Hoffmann, V. Wittwer, M. Mangold, M. Golling, B. Tilma, T. Sudmeyer, and U. Keller, "Experimentally verified pulse formation model for high-power femtosecond VECSELs," *Applied Physics B,* 2013/04/27 2013.

[17] D. J. H. C. Maas, A.-R. Bellancourt, B. Rudin, M. Golling, H. J. Unold, T. Südmeyer, and U. Keller, "Vertical integration of ultrafast semiconductor lasers," *Appl. Phys. B,* vol. 88, pp. 493-497, 2007.

[18] B. Rudin, V. J. Wittwer, D. J. H. C. Maas, M. Hoffmann, O. D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, and U. Keller, "High-power MIXSEL: an integrated ultrafast semiconductor laser with 6.4 W average power," *Opt. Express,* vol. 18, pp. 27582-27588, 2010.

[19] M. Mangold, V. J. Wittwer, C. A. Zaugg, S. M. Link, M. Golling, B. W. Tilma, and U. Keller, "Femtosecond pulses from a modelocked integrated external-cavity surface emitting laser (MIXSEL)," *accepted for publication in Opt. Exp.,* 2013.

[20] R. Aviles-Espinosa, G. Filippidis, C. Hamilton, G. Malcolm, K. J. Weingarten, T. Südmeyer, Y. Barbarin, U. Keller, S. I. C. O. Santos, D. Artigas, and P. Loza-Alvarez, "Compact ultrafast semiconductor disk laser: targeting GFP based nonlinear applications in living organisms," *Biomed. Opt. Express,* vol. 2, pp. 739-747, 2011.

[21] T. Hochrein, R. Wilk, M. Mei, R. Holzwarth, N. Krumbholz, and M. Koch, "Optical sampling by laser cavity tuning," *Optics Express,* vol. 18, pp. 1613-1617, 2010/01/18 2010.

[22] A. Bhatnagar, C. Debaes, R. Chen, N. C. Helman, G. A. Keeler, D. Agarwal, H. Thienpont, and D. A. B. Miller, "Receiver-less clocking of a CMOS digital circuit using short optical pulses," in *2002 IEEE/LEOS Annual Meeting; Conference Proceedings, 15th Annual Meeting of the IEEE Lasers & Electro-Optics Society*, Glasgow, Scotland, 2002, pp. 127-8.

[23] C. A. Zaugg, M. Hoffmann, W. P. Pallmann, V. J. Wittwer, O. D. Sieber, M. Mangold, M. Golling, K. J. Weingarten, B. W. Tilma, T. S¸dmeyer, and U. Keller, "Low repetition rate SESAM modelocked VECSEL using an extendable active multipass-cavity approach," *Opt. Express,* vol. 20, pp. 27915-27921, 2012.

[24] C. A. Zaugg, A. Klenner, O. D. Sieber, M. Golling, B. W. Tilma, and U. Keller, "Sub-100 MHz Passively Modelocked VECSEL," in *CLEO: 2013*, San Jose, California, 2013, p. CW1G.6.

[25] D. Lorenser, D. J. H. C. Maas, H. J. Unold, A.-R. Bellancourt, B. Rudin, E. Gini, D. Ebling, and U. Keller, "50-GHz passively mode-locked surface-emitting semiconductor laser with 100 mW average output power," *IEEE J. Quantum Electron.,* vol. 42, pp. 838-847, Aug. 2006.

[26] K. G. Wilcox, A. H. Quarterman, V. Apostolopoulos, H. E. Beere, I. Farrer, D. A. Ritchie, and A. C. Tropper, "175 GHz, 400-fs-pulse harmonically mode-locked surface emitting semiconductor laser," *Opt. Express,* vol. 20, pp. 7040-7045, 2012.

[27] O. D. Sieber, V. J. Wittwer, M. Mangold, M. Hoffmann, M. Golling, T. S¸dmeyer, and U. Keller, "Femtosecond VECSEL with tunable multi-gigahertz repetition rate," *Opt. Express,* vol. 19, pp. 23538-23543, 2011.

[28] V. J. Wittwer, C. A. Zaugg, W. P. Pallmann, A. E. H. Oehler, B. Rudin, M. Hoffmann, M. Golling, Y. Barbarin, T. Sudmeyer, and U. Keller, "Timing Jitter Characterization of a Free-Running SESAM Mode-locked VECSEL," *Photonics Journal, IEEE,* vol. 3, pp. 658-664, 2011.

[29] V. J. Wittwer, R. van der Linden, B. W. Tilma, B. Resan, K. J. Weingarten, T. Sudmeyer, and U. Keller, "Sub-60-fs Timing Jitter of a SESAM Modelocked VECSEL," *IEEE Photonics Journal,* vol. 5, pp. 1400107-1400107, 2013.

[30] A. Schlatter, B. Rudin, S. C. Zeller, R. Paschotta, G. J. Spühler, L. Krainer, N. Haverkamp, H. R. Telle, and U. Keller, "Nearly quantum-noise-limited timing jitter from miniature Er:Yb:glass lasers," *Opt. Lett.,* vol. 30, pp. 1536-1538, June 15, 2005.

[31] P. Kreuter, B. Witzigmann, D. J. H. C. Maas, Y. Barbarin, T. Südmeyer, and U. Keller, "On the Design of Electrically-Pumped Vertical-External-Cavity Surface-Emitting Lasers," *Appl. Phys. B,* vol. 91, pp. 257-264, 2008.

[32] Y. Barbarin, M. Hoffmann, W. P. Pallmann, I. Dahhan, P. Kreuter, M. Miller, J. Baier, H. Moench, M. Golling, T. Südmeyer, B. Witzigmann, and U. Keller, "Electrically pumped vertical external cavity surface emitting lasers suitable for passive modelocking," *IEEE J. Selected Topics in Quantum Electronics*, vol. 17, pp. 1779-1786, 2011.

[33] K. Jasim, Q. Zhang, A. V. Nurmikko, A. Mooradian, G. Carey, W. Ha, and E. Ippen, "Passively modelocked vertical extended cavity surface emitting diode laser," *Electron. Lett.*, vol. 39, pp. 373-375, 2003.

[34] K. Jasim, Q. Zhang, A. V. Nurmikko, E. Ippen, A. Mooradian, G. Carey, and W. Ha, "Picosecond pulse generation from passively modelocked vertical cavity diode laser at up to 15 GHz pulse repetition rate," *Electron. Lett.*, vol. 40, pp. 34-35, 2004.

[35] W. P. Pallmann, C. A. Zaugg, M. Mangold, V. J. Wittwer, H. Moench, S. Gronenborn, M. Miller, B. W. Tilma, T. Südmeyer, and U. Keller, "Gain characterization and passive modelocking of electrically pumped VECSELs," *Opt. Express*, vol. 20, pp. 24791-24802, 2012.

[36] W. P. Pallmann, C. A. Zaugg, M. Mangold, I. Dahhan, M. Golling, B. W. Tilma, B. Witzigmann, and U. Keller, "Ultrafast Electrically Pumped VECSELs," *Photonics Journal, IEEE*, vol. 5, pp. 1501207-1501207, 2013.