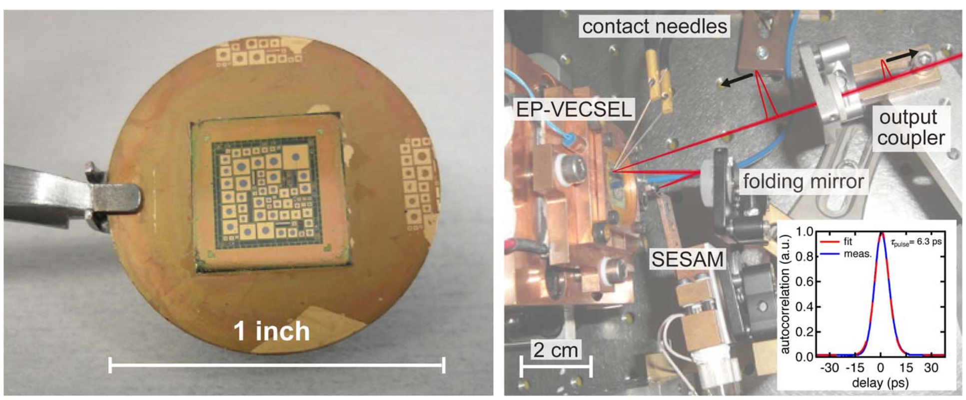
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Ultrafast Electrically Pumped VECSELs

Volume 5, Number 4, August 2013

W. P. Pallmann
C. A. Zaugg
M. Mangold
I. Dahhan
M. Golling
B. W. Tilma
B. Witzigmann
U. Keller



DOI: 10.1109/JPHOT.2013.2274773
1943-0655 ©2013 IEEE

Ultrafast Electrically Pumped VECSELs

W. P. Pallmann,[1] C. A. Zaugg,[1] M. Mangold,[1] I. Dahhan,[2] M. Golling,[1] B. W. Tilma,[1] B. Witzigmann,[2] and U. Keller[1]

[1]Department of Physics, Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland
[2]Department of Electrical Engineering and Computer Science, Computational Electronics and Photonics Group, University of Kassel, 34121 Kassel, Germany

DOI: 10.1109/JPHOT.2013.2274773

Manuscript received July 4, 2013; accepted July 19, 2013. Date of publication July 25, 2013; date of current version August 1, 2013. This work was supported by the Swiss Confederation Program Nano-Tera.ch, which was scientifically evaluated by the Swiss National Science Foundation. Corresponding author: W. P. Pallmann (e-mail: pallmann@phys.ethz.ch).

Abstract: We present an improved design for electrically pumped vertical external-cavity surface-emitting lasers (EP-VECSELs) optimized for passive modelocking with a semiconductor saturable absorber mirror (SESAM). In continuous-wave (cw) multimode operation, up to 170 mW of output power are demonstrated at a wavelength of 967 nm. Overcoming our prior limitation, we demonstrate fundamental transverse mode operation with 26 mW of average output power. Passively modelocking one of the fabricated EP-VECSELs with a quantum-well SESAM, we have achieved 6.3-ps pulses with an average output power of 6.2 mW at 1.46-GHz repetition rate, the shortest pulse duration from this type of laser to date. With slightly longer pulses of 7.3 ps, an average output power of 13 mW is obtained. Tradeoffs for further output power scaling and reduced pulse duration are discussed.

Index Terms: Infrared lasers, semiconductor lasers, diode lasers, modelocked lasers, ultrafast lasers.

1. Introduction

Optically pumped vertical external cavity surface emitting lasers (OP-VECSELs [1]) have shown impressive performance with high average power for both continuous-wave (cw) and modelocked operation [2]. Up to 20 W cw in fundamental TEM_{00}-mode operation [3] and 106 W cw in multi-mode operation [4] have been demonstrated. Passively modelocked with a semiconductor saturable absorber mirror (SESAM [5]), 682-fs pulses with 5.1 W of average output power [6] and pulse durations down to 60 fs in bursts of pulses [7] have been reported. Integrating the saturable absorber into the VECSEL gain chip has led to a more compact device, the MIXSEL (modelocked integrated external-cavity surface emitting laser), generating the highest average output power of any modelocked semiconductor laser of 6.4 W in 28-ps pulses [8].

In order to allow access to low-cost applications such as optical clocking, chip-to-chip interconnects or optical communication, it is vital to further reduce the complexity and size of modelocked VECSELs. To achieve this, electrical pumping is the first important step towards more compact and cost-efficient ultrafast VECSELs. However, the design of an electrically pumped VECSEL (EP-VECSEL) requires a carefully balanced trade-off between optical and electrical properties. Nevertheless, an impressive 500 mW cw in fundamental mode operation have been demonstrated from an EP-VECSEL by the *Novalux Corporation* [9]. However, modelocking results using these chips have been limited to 40 mW with 57-ps pulses [10] and tens of milliwatts with 15-ps pulses [11].

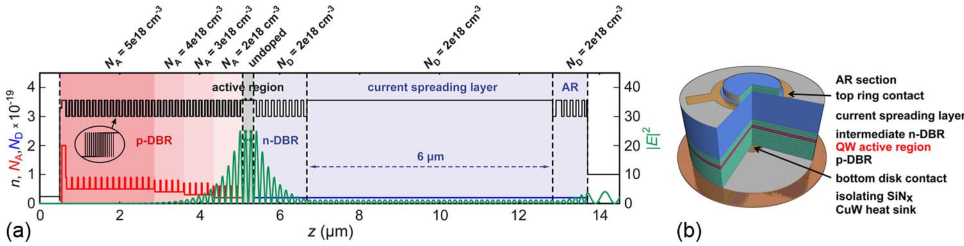


Fig. 1. (a) Design of the EP-VECSEL gain chip: the black lines represent the refractive index profile, the green lines the squared electric field, the red and blue lines the p- and n-doping, respectively. The absolute bulk doping values are also given on top. The inset shows a detailed view of the digital alloy grading in the p-DBR. (b) Schematic of the EP-VECSEL gain chip on a CuW heat sink. The antireflection (AR) section can be etched away below the top contact to reduce electrical resistance.

In 2008, we published guidelines based on numerical simulations for the design of EP-VECSELs optimized for modelocked operation [12]. With our first realization of EP-VECSELs we obtained up to 120 mW in cw multi-mode operation and verified our design guidelines [13]. Single-mode performance was very limited at that time due to the high reflectivity of the intermediate n-doped distributed Bragg reflector (n-DBR). In 2012, we presented a detailed gain characterization of EP-VECSELs in collaboration with *Philips Technologie GmbH* [14]. There we also demonstrated that an EP-VECSEL with an optimized n-DBR reflectivity is suitable for passive modelocking. 9.5-ps pulses with 7.6 mW of average output power were generated.

Here we present our own SESAM modelocked EP-VECSEL successfully fabricated at ETH Zurich with improved design, overcoming previous limitations. Up to 170 mW in cw multi-mode operation (200-μm diameter device at -20 °C heat sink temperature) and 26 mW in fundamental TEM_{00}-mode operation (70-μm diameter device at 2 °C heat sink temperature) are obtained. Passively modelocking the 70-μm device with a quantum well based SESAM, we measured 7.3-ps pulses with 13.1 mW average output power at a repetition rate of 1.46 GHz. With lower output power of 6.2 mW, 6.3-ps pulses are obtained. This is the shortest pulse duration from a passively modelocked EP-VECSEL to date. Limitations and different approaches for increasing the output power and reducing the pulse duration are discussed towards the end of this paper.

2. Improved Design

All details of the realization of our initial EP-VECSEL design and the fabrication scheme have been published in [13]. In this section, the general design will be briefly reviewed and we then focus on the design improvements.

Fig. 1(a) shows the design of the EP-VECSEL gain chip, Fig. 1(b) contains a schematic of the device including the top and bottom contacts. Current is injected into the device through a bottom disc contact underneath the p-doped DBR and a top ring electrode. The holes in the p-doped region exhibit a lower mobility than the electrons in the n-doped region [12]. Consequently, the holes stay in the volume above the bottom disc contact whereas the electrons move through the current spreading layer to the center of the device, where they can recombine with the holes in the quantum well active region. This in combination with a small bottom disc contact creates a confined current injection profile that supports fundamental transversal mode operation.

The structure is grown by molecular beam epitaxy (MBE). The bottom p-DBR acts as end mirror of the laser cavity. It consists of 30 quarter-wave layer pairs of $Al_{0.9}Ga_{0.1}As$/GaAs. The $Al_{0.9}Ga_{0.1}As$/GaAs material system should have a lower electrical resistance than the previously used AlAs/GaAs material system due to the smaller band offset at the hetero-interfaces between the materials [12]. To further reduce the energy-band discontinuities at the material interfaces, we employ a digital alloy grading [15], as shown in the inset in Fig. 1(a). Furthermore, we apply an optimized bulk doping profile for low optical and electrical losses by increasing doping levels in the structure where the electric field (shown in green in Fig. 1(a)) is low. Near the active region, where

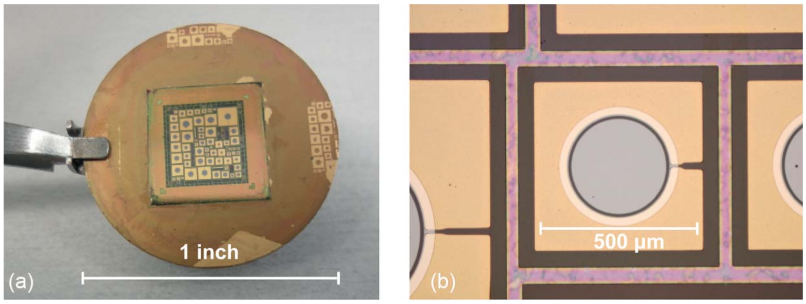


Fig. 2. Realization of the EP-VECSEL gain chip. (a) One-inch CuW-wafer with 63 differently sized lasers and (b) magnified image of a device with a bottom contact diameter of 90 μm and a top contact opening of 324 μm.

the electric field is the highest, the lowest doping levels are used. At the material interfaces in the p-DBR where the electric field has a node, we additionally increase the doping level by 4e18 cm^{-3}. The undoped active region consists of 2×3 InGaAs quantum wells (QWs) embedded in GaAs, positioned in two adjacent antinodes of the standing wave pattern. The peak photoluminescence (PL) at room temperature is detuned by 20 nm from the design wavelength of 960 nm to ensure maximum gain at high current injection and thus high temperature [16]. The intermediate n-doped DBR increases the field in the QW active region and thus the small-signal gain. This is essential to overcome additional losses from free carrier absorption associated with the doping of the device. Previously, we have shown that choosing the number of quarter-wave layer pairs in the n-DBR too high leads to a deterioration in beam quality [13]. Therefore, we reduced the number of pairs to 9 (previously: 11), resulting in a field enhancement of around 25 (60) in the active region. The calculated reflectivity of the n-DBR is 81% (93%). The current spreading layer (CSL) consists of a 6-μm-thick GaAs layer. The structure is completed by a 12-layer semiconductor antireflection (AR) coating to reduce sub-cavity effects from the CSL. A key factor in the performance of EP-VECSELs is the heat management. Excessive heat from high ohmic losses or a high thermal resistance of the device lead to a thermal rollover already at low currents limiting the maximum output power. Consequently, we have increased the heat transfer area of our EP-VECSELs by making the overall device size larger while maintaining the size of the bottom and top contacts. Fig. 2 shows the realization of the EP-VECSEL gain chip. In Fig. 2(a), the one-inch CuW-wafer with 63 differently sized lasers is shown. The devices exhibit different bottom contact diameters (BCD) and top contact openings. Fig. 2(b) is a magnified image of a device with a 90 μm BCD and a top contact opening of 324 μm.

3. Continuous Wave (CW) Characterization

To compare the performance of the differently sized devices on the fabricated chip, we first measured the cw multi-mode output power of all lasers. Fig. 3(a) shows the cw multi-mode output power as function of the bottom contact diameter. All lasers were measured in a straight cavity with a curved output coupler (OC) with a radius of curvature (ROC) of 25 mm and a transmission of 5.5%. The heat sink temperature was kept constant at 3 °C. The variation in output power for devices of the same size is most likely related to non-uniform defect density and processing of the chip. Fig. 3(b) shows the light-current-voltage (LIV) curve of the largest device with a bottom contact diameter of 200 μm. The same cavity was used as before, except the heat sink temperature was reduced to -20 °C. Nearly 170 mW of output power are obtained at an injected current of 984 mA.

To enable stable passively modelocked operation, it is necessary to operate the devices in a single transversal mode. In [13] we have already shown the electroluminescence profiles of our EP-VECSELs and demonstrated that confined and homogeneous current injection is achieved even for large devices. With the significantly lower intermediate n-DBR reflectivity of our new design transversal single-mode operation should be possible. Table 1 shows beam quality measurements

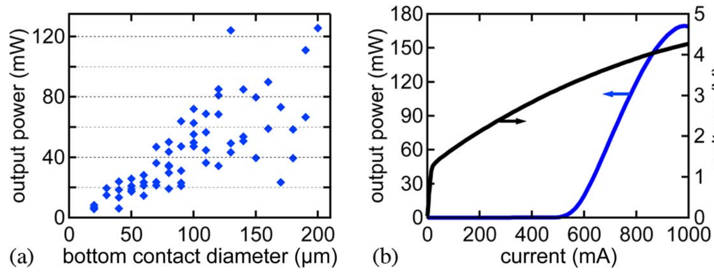


Fig. 3. Continuous-wave (cw) multi-mode output power of the EP-VECSELs. (a) cw multi-mode output power of devices with different bottom contact diameter, measured in a straight cavity at 3 °C heat sink temperature and an output coupler transmission of 5.5% and (b) LIV-curve of a device with a bottom contact diameter of 200 μm, measured in a straight cavity at -20 °C heat sink temperature and an output coupler transmission of 5.5%.

TABLE 1

Beam quality measurements of EP-VECSEL devices with different bottom contact diameter, measured in a Z-shaped cavity at a heat sink temperature of 2 °C with an output coupler (OC) transmission of 1.1%. For comparison the multi-mode output power in a straight cavity at 3 °C and an OC transmission of 5.5% is also given.

bottom contact diameter (µm)	output power (mW)	beam quality (M^2 value)	multi-mode output power (mW)
70	26	1.0	47
90	33	1.6	64
100	31 / 47	1.6 / 2.5	63
120	26	1.5	85

of differently sized devices. The measurements were carried out in a Z-shaped cavity similar to the one later used for the modelocking experiments. Instead of a SESAM a DBR was used. The OC had a ROC of 40 mm and an optimized transmission of 1.1% in this configuration. The heat sink was kept constant at 2 °C. For each device, the cavity was optimized for maximum output power with the lowest achievable M^2 value. As a reference, the cw multi-mode output power from Fig. 3(a) is also given.

For a 70-μm-diameter device, up to 26 mW with excellent beam quality $(M^2 = 1.0)$ were achieved. For larger devices the output power still increases slightly, but the beam quality is already reduced. At the same time, the output power ratio compared to the cw multi-mode measurements drops for larger devices. Consequently, the device with a 70-μm BCD was chosen for the modelocking experiments.

4. Passive Modelocking Experiments

Fig. 4 shows the experimental setup for the passive modelocking experiments. A Z-shaped cavity was used to match the resonator mode with the pumped area of the 70-μm BCD-device and to focus onto the SESAM. This is necessary to ensure that the losses saturate before the gain, enabling stable modelocked operation [17], [18]. The ROC of the OC was 60 mm; the folding mirror had a ROC of 20 mm. This resulted in a mode size radius of around 35 μm on the EP-VECSEL and 20 μm on the SESAM. Both the SESAM and the EP-VECSEL gain chip were mounted on a Peltier-cooled copper heat sink for temperature stabilization and tuning.

The SESAM is based on a single AlAs-embedded InGaAs quantum well and a 4-pair semiconductor AR coating with a layer of fused silica (FS) on top. The measured saturation fluence

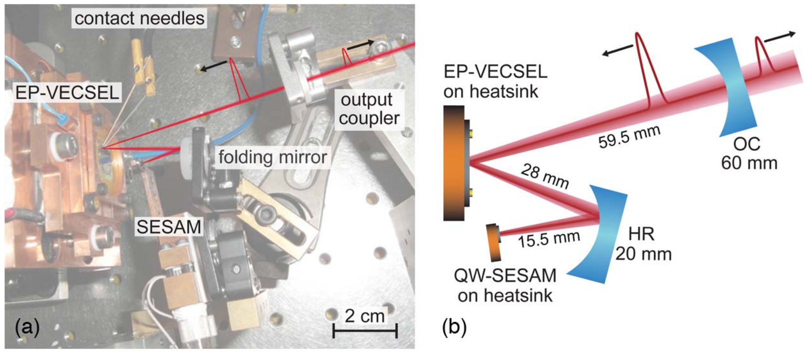


Fig. 4. Experimental setup for the modelocking experiments. (a) Picture of the Z-shaped laser cavity with the SESAM, folding mirror, EP-VECSEL gain chip and the curved output coupler. The chip is contacted with two prober needles. (b) Schematic containing details of the cavity.

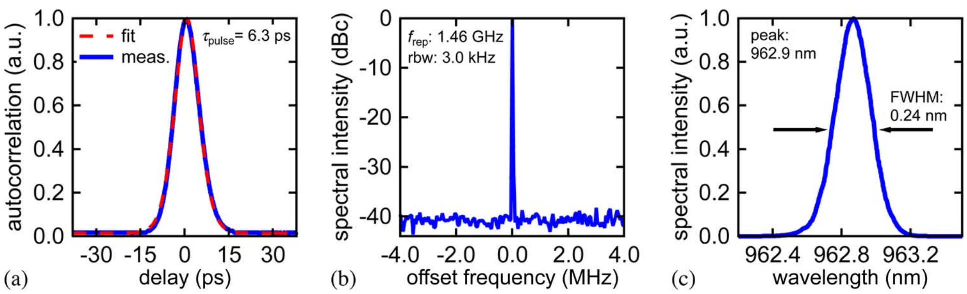


Fig. 5. Modelocking results. (a) Second harmonic generation intensity autocorrelation, (b) microwave spectrum, and (c) optical spectrum of the 6.3-ps pulses at 1.46 GHz pulse repetition rate and 6.2 mW average output power. rbw: resolution bandwidth, f_{rep}: repetition frequency.

[19] of the SESAM was 16.5 μJ/cm^2 and the modulation depth 0.84% for a wavelength of 963.1 nm and a heat sink temperature of 35.5°C, as later used in the experiment. For a second experiment, a similar SESAM was used with a SiN_x-layer on top. This resulted in a measured saturation fluence of 16.2 μJ/cm^2 and a modulation depth of 0.69% for a wavelength of 963.1 nm and a heat sink temperature of 26 °C.

5. Passive Modelocking Results

Using the SESAM with the SiN_x top-coating, stable modelocked operation was achieved at a pump current of 259 mA and a heat sink temperature of -21 °C. The OC transmission was 0.5%. The SESAM was temperature-stabilized at 26 °C to shift the absorption to a longer wavelength. The average output power was 6.2 mW. Fig. 5(a) shows the measured second harmonic generation intensity autocorrelation and the sech^2-fit of a 6.3-ps pulse. The microwave spectrum in Fig. 5(b) is measured with a resolution bandwidth of 3.0 kHz and shows a span of 8 MHz around the fundamental repetition rate of 1.46 GHz. The optical spectrum in Fig. 5(c) is centered at a wavelength of 962.9 nm and has a spectral width of 0.24 nm full width at half maximum (FWHM). The resulting time-bandwidth-product (TBP) is $\Delta\nu\Delta\tau = 0.5$, corresponding to about 1.56 times a transform-limited sech^2-pulse.

In a similar cavity configuration with the FS-coated SESAM, we obtained 13.1 mW of average output power with slightly longer pulse duration of 7.3 ps at the same repetition rate of 1.46 GHz. The optical spectrum shows a FWHM of 0.24 nm at 962.9 nm, resulting in a TBP of 0.56, roughly 1.7 times the transform limit. The injected current was 266 mA, and the EP-VECSEL and SESAM temperature were -20.7 °C and 35.5 °C, respectively. The OC transmission had a value of 0.85%.

Obtaining even shorter pulse durations from an EP-VECSEL is challenging. On the one hand, the gain bandwidth of these resonant structures is large enough to support significantly shorter pulses [14]. On the other hand, the structural resonance leads to strongly wavelength dependent group delay dispersion values in the order of several 10 000 fs^2 around the resonance, setting a lower limit for the theoretically possible pulse duration [18]. A possibility would be to reduce the number of intermediate n-DBR pairs further, but this would decrease the gain and consequently lead to a reduction in average output power.

To scale the average output power, a simple approach would be to scale the pumped area. However, Table 1 shows that for larger devices the single-mode output power does not necessarily scale with the pumped area. Therefore, the optimization must focus on the increase of the single-mode output power from small devices. This can be achieved by reducing optical losses in the structure by decreasing average doping levels and the resistance of the device at the same time. We expect that the design of the p-DBR and the active region should allow for this optimization. One could also consider partly etching the p-DBR to improve the current confinement, as it was proposed and simulated in [20]. Furthermore, the thermal resistance of the device needs to be improved. The influence of a better thermal resistance on the performance of EP-VECSELs has already been simulated in [21]. Our current CuW heat sinks have a thermal conductivity of around 200 $W \cdot K^{-1} \cdot m^{-1}$. Composite copper-diamond heat sinks offer values of around 550 $W \cdot K^{-1} \cdot m^{-1}$ [22] while maintaining a coefficient of thermal expansion (CTE) matched to GaAs and are consequently a highly interesting alternative.

6. Conclusion

We presented an improved design of EP-VECSELs optimized for passive modelocking. Up to 170 mW in cw multi-mode operation are generated. Overcoming previous limitations, fundamental transversal mode operation is demonstrated, yielding 26 mW with an M^2-value of 1.0 from a 70-μm-diameter device. Passively modelocking this device with a SESAM led to 6.3-ps pulses with an average output power of 6.2 mW at a repetition rate of 1.46 GHz. This is to the best of our knowledge the shortest pulse duration from a passively modelocked EP-VECSEL reported to date. Using a different top-coating on the SESAM, 7.3-ps-pulses with 13.1 mW of average output power were generated.

A further increase of the average output power is expected by reducing optical losses in the devices and using a heat sink with a higher thermal conductivity. Composite diamond materials like copper-diamond offer a two to three times higher thermal conductivity than CuW and should lead to a significant increase in output power.

References

[1] 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, no. 8, pp. 1063–1065, Aug. 1997.

[2] U. Keller and A. C. Tropper, “Passively modelocked surface-emitting semiconductor lasers,” *Phys. Rep.*, vol. 429, no. 2, pp. 67–120, Jun. 2006.

[3] B. Rudin, A. Rutz, M. Hoffmann, D. J. H. C. Maas, A.-R. Bellancourt, T. Gini, E. Südmeyer, and U. Keller, “Highly efficient optically pumped vertical emitting semiconductor laser with more than 20-W average output power in a fundamental transverse mode,” *Opt. Lett.*, vol. 33, no. 22, pp. 2719–2721, Nov. 2008.

[4] B. Heinen, T. L. Wang, M. Sparenberg, A. Weber, B. Kunert, J. Hader, S. W. Koch, J. V. Moloney, M. Koch, and W. Stolz, “106 W continuous-wave output power from vertical-external-cavity surface-emitting laser,” *Electron. Lett.*, vol. 48, no. 9, pp. 516–517, Apr. 2012.

[5] 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. Topics Quantum Electron.*, vol. 2, no. 3, pp. 435–453, Sep. 1996.

[6] 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.*, vol. 48, no. 10, pp. 588–589, May 2012.

[7] 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,” *Nature Photon.*, vol. 3, no. 12, pp. 729–731, Dec. 2009.

[8] 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. Exp.*, vol. 18, no. 26, pp. 27 582–27 588, Dec. 2010.
[9] J. G. McInerney, A. Mooradian, A. Lewis, A. V. Shchegrov, E. M. Strzelecka, D. Lee, J. P. Watson, M. Liebman, G. P. Carey, B. D. Cantos, W. R. Hitchens, and D. Heald, "High-power surface emitting semiconductor laser with extended vertical compound cavity," *Electron. Lett.*, vol. 39, no. 6, pp. 523–525, Mar. 2003.
[10] 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, no. 1, pp. 34–35, Jan. 2004.
[11] 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, no. 4, pp. 373–375, Feb. 2003.
[12] 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, no. 2, pp. 257–264, May 2008.
[13] 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. Sel. Topics Quantum Electronics*, vol. 17, no. 6, pp. 1779–1786, Nov./Dec. 2011.
[14] 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. Exp.*, vol. 20, no. 22, pp. 24 791–24 802, Oct. 2012.
[15] M. G. Peters, B. J. Thibeault, D. B. Young, J. W. Scott, F. H. Peter, A. C. Gossard, and L. A. Coldren, "Band-gap engineered digital alloy interfaces for lower resistance vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 63, no. 25, pp. 3411–3413, Dec. 1993.
[16] J. G. McInerney, A. Mooradian, A. Lewis, A. V. Shchegrov, E. M. Strzelecka, D. Lee, J. P. Watson, M. K. Liebman, G. P. Carey, A. Umbrasas, C. A. Amsden, B. D. Cantos, W. R. Hitchens, D. L. Heald, V. V. Doan, and J. L. Cannon, "Novel 980-nm and 490-nm light sources using vertical cavity lasers with extended coupled cavities," in *Proc. SPIE*, Brugge, Belgium, 2003, pp. 21–31.
[17] R. Paschotta, R. Häring, U. Keller, A. Garnache, S. Hoogland, and A. C. Tropper, "Soliton-like pulse-shaping mechanism in passively mode-locked surface-emitting semiconductor lasers," *Appl. Phys. B.*, vol. 75, no. 4/5, pp. 445–451, Oct. 2002.
[18] M. Hoffmann, O. D. Sieber, D. J. H. C. Maas, V. J. Wittwer, M. Golling, T. Südmeyer, and U. Keller, "Experimental verification of soliton-like pulse-shaping mechanisms in passively mode-locked VECSELs," *Opt. Exp.*, vol. 18, no. 10, pp. 10 143–10 153, May 2010.
[19] D. J. H. C. Maas, B. Rudin, A.-R. Bellancourt, D. Iwaniuk, S. V. Marchese, T. Südmeyer, and U. Keller, "High precision optical characterization of semiconductor saturable absorber mirrors," *Opt. Exp.*, vol. 16, no. 10, pp. 7571–7579, May 2008.
[20] I. Dahhan, Y. Barbarin, M. Hoffmann, W. P. Pallmann, C. A. Zaugg, M. Golling, T. Südmeyer, U. Keller, and B. Witzigmann, "Current confinement in EP-VECSELs for high power single-mode operation suitable for passive mode-locking," in *Proc. SPIE Photon. Europe*, Brussels, Belgium, 2012, p. 84330C.
[21] B. Witzigmann, I. Dahhan, P. Kreuter, Y. Barbarin, M. Hofmann, W. Pallmann, M. Golling, T. Südmeyer, and U. Keller, "Design and simulation of electrically pumped mode-locked VECSELs," in *Proc. SPIE*, 2011, vol. 7919, pp. 79190O-1–79190O-7.
[22] K. Yoshida and H. Morigami, "Thermal properties of diamond/copper composite material," *Microelectron. Reliab.*, vol. 44, no. 2, pp. 303–308, Feb. 2004.