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Citation: *Appl. Phys. Lett.* **112**, 262105 (2018); doi: 10.1063/1.5033456

View online: <https://doi.org/10.1063/1.5033456>

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VECSEL design for high peak power ultrashort mode-locked operation

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(Received 5 April 2018; accepted 8 June 2018; published online 27 June 2018)

The generation of mode-locked pulses in vertical external-cavity surface-emitting lasers with a semiconductor saturable absorber mirror is studied by numerically solving the Maxwell semiconductor Bloch equations describing the propagating light field coupled to the electron-hole-pair excitations in the quantum wells. High peak-power sub-100 fs mode-locked pulses are realized through optimizing the gain chip design. The unequal spacing of up to four quantum wells in a given field antinode leads to a broad linear gain profile and reduced intracavity dispersion. The proposed designs are found to be robust with regard to uncontrollable growth uncertainties. *Published by AIP Publishing.*

<https://doi.org/10.1063/1.5033456>

Vertical external-cavity surface-emitting lasers (VECSELs) are compact, high brightness, wavelength flexible solid state lasers capable of producing high power single- or multi-wavelength outputs as well as high peak power mode-locked pulses with a duration approaching 100 fs.^{1–4} Specifically, their ultrashort high peak power mode-locked pulses can be used as high repetition rate sources for many applications including high resolution medical imaging, spectroscopy, materials processing and supercontinuum generation.^{5–10}

In order to realize ultrashort mode-locked pulses, one has to balance a variety of linear and nonlinear cavity design aspects such as the cavity dispersion;¹¹ the loss from the semiconductor saturable absorber mirror (SESAM) and output coupling;¹² the VECSEL cavity setup; and the gain chip design.

A stable ultra-short mode-locked pulse has a relatively wide spectrum that requires a wide spectral range with near-zero cavity round-trip dispersion. Whereas the small spatial dimensions of VECSELs are advantageous for pulse generation with high repetition rates in the GHz regime, this compactness and the relatively low round-trip gain severely restrict the ability to do *a posteriori* dispersion management. Hence, all dispersion compensating features must be engineered into the structure either directly at the growth level or through after-growth dielectric coatings. In practice, typically multi-layer dispersion compensating coatings have to be applied to the air interfaces of VECSEL's gain and SESAM chips.

In recent experiments, the shortest stable single mode-locked pulses have been limited to an intracavity temporal duration of 107 fs.^{13,14} As reported in Ref. 14, it was possible to externally compress the mode-locked pulse to 96 fs. However, despite the ongoing experimental efforts worldwide, not much further progress in pulse shortening has been reported.

In this letter, we propose designs of VECSEL gain structures that should allow for the generation of sub-100 fs pulses using only standard ingredients. In particular, we analyze a

family of gain chips that not only should have the capacity to produce ultrashort high-intensity mode-locked pulses, but also be minimally influenced by growth uncertainties and realizable in terms of strain and pump absorption. For our studies, we numerically solve the Maxwell-semiconductor Bloch equations (Maxwell-SBE) in a linear cavity with realistic refractive indices. A gain chip is placed at one end of an external cavity opposing a simple SESAM with a 1% output coupling loss. The pulse propagation is handled using Maxwell's equations and the macroscopic polarizations from the optically active quantum wells (QWs) are modeled using the SBE. Higher order correlation terms such as polarization dephasing and carrier scattering are approximated as effective rates. These rates are extracted from microscopic single pass simulations with approximations on the level of second Born-Markov. In our simulations, each QW is modeled separately by directly simulating the microscopic many-body dynamics. This model has been used in the past to study mode-locked pulses and analyze experimentally observed behavior.^{15–17}

The designs discussed in this letter are based on the multiple QW (MQW10) structure that we proposed for ultrashort pulse generation, theoretically allowing for sub-20 fs mode-locked pulses.¹⁶ In contrast to the conventional resonant periodic gain (RPG) structures, where all QWs are placed on consecutive antinodes of the standing wave, the MQW10 structure has ten QWs placed in a single antinode. Whereas the theoretically predicted features of this system are close to ideal, unfortunately, it is difficult to realize experimentally, mainly due to material strain considerations and low pump absorption. In order to remedy these shortcomings, we propose here the “ $3 \times 121 + 1$ ” structure shown in Fig. 1 and a family of similar configurations with the cluster of four QWs distributed over one, two, and four antinodes, as proposed in Ref. 18. We compare the performance of these QW arrangements to the antiresonant MQW10 and RPG10 systems discussed in Refs. 16 and 17.

Figure 1 shows a layout of the “ $3 \times 121 + 1$ ” structure, where three clusters of four QWs are placed on each

FIG. 1. A diagram showing the active region of the gain chip design for the “ $3 \times 121 + 1$ ” structure. The red vertical bars indicate the location of QWs and the blue curve is a standing wave at the peak gain frequency 1030 nm. The horizontal bars indicate the refractive index of individual material layers.

antinode and a single “booster” QW is located close to the distributed Bragg reflector (DBR). This gain chip contains 30 pairs of AlAs/AlGaAs DBR centered around the peak gain, an AlGaAs barrier region containing the QWs, and a two-layer $\text{Ta}_2\text{O}_5/\text{SiO}_2$ ($n = 2.078/1.450$) dispersion compensating/anti-reflection (AR) coating on top of an InGaP cap layer. The widths of the AR coating and the cap layer are numerically optimized to give a near zero group delay dispersion (GDD) at the peak gain wavelength. As can be seen in Fig. 1, each cluster contains four 8.35 nm wide InGaAs QWs separated by: 24 nm, 8 nm, and 24 nm of barrier material. This configuration of the four QWs has been optimized to produce short pulses and simultaneously reduce the growth related material strain of the structure.

There are a family of structures similar to the “ $3 \times 121 + 1$ ” structure shown in Fig. 1, where one has either one, two, or four clusters of QWs. These structures are also shown in the simulation results below and are intuitively named “ $1 \times 121 + 1$,” “ $2 \times 121 + 1$,” and “ $4 \times 121 + 1$.” The AR coating and the cap layer thickness are individually optimized for all simulated structures in order to reduce the respective dispersive effects.

The mode-locked pulse for each structure is determined using the following procedure for multiple QW background carrier densities: a simulation is initialized with a low energy 400 fs seed pulse plus spontaneous emission noise and simulated until a single stable mode-locked pulse has been established. The QW background carrier density is incrementally increased from a value close to the threshold, where no pulse can appear, until the density is so high that no single stable mode-locked pulse can be found. Figure 2 shows an overview of the single stable mode-locked pulse output peak intensities and the full width half maximum (FWHM) for all QW densities and structures.

The “ $N \times 121 + 1$ ” structures produce short duration pulses that can reach high peak powers, as seen in Fig. 2. In particular, the “ $1 \times 121 + 1$ ” structure yields the shortest pulse with the highest peak intensity that is almost three times higher than the pulses from the RPG10 structure. The

FIG. 2. An overview of stable mode-locked output pulses that result from different material structures as the gain chip QW background carrier density is varied. The markers indicate simulation results, while the lines are interpolations to guide the eye. The bold marks are simulations where the background carrier density results in the same linear peak gain. The shaded regions indicate the influence the small AR coating errors can have on the mode-locked pulses, located at the obtuse angle. The covered plot markers are examples for a thickness error of $\pm 2\%$ in their respective AR coatings.

“ $1 \times 121 + 1$ ” structure has only five QWs, thus it also requires a higher background carrier density compared to the other structures. This higher carrier density provides a broader gain and enables the structure with fewest QWs, to produce the mode-locked pulse with both the shortest duration and the highest peak intensity. The “ $2 \times 121 + 1$ ” structure has nine QWs spread out over two antinodes and produces similar mode-locked pulses to the MQW10. The QW background carrier densities of each structure are also similar, but the MQW10 has a slightly broader gain and allows for slightly shorter pulses. The “ $3 \times 121 + 1$ ” structure is observed to produce similarly short mode-locked pulses, but the background carrier density is slightly lower because there are four more QWs. Following this pattern, the “ $4 \times 121 + 1$ ” structure produces somewhat longer pulses at even lower peak intensities and many of these pulses are comparable to the RPG10 structure.

In experimental realizations of any VECSEL structure, the AR coating is grown on top of the gain chip and is susceptible to errors in layer thickness. Any deviation in individual layer thickness can drastically reduce the effectiveness of the whole AR coating and will naturally influence the resulting mode-locked pulse duration. Experimentally, it is possible to grow the different layers separately and mitigate the errors from each preceding run by correspondingly correcting the successive AR coating layer. In the end, this implies that the thickness of the final AR coating layer is the remaining important error source that is not easily controllable. Realistically, this error is estimated to be in the range of 2%–4%, but will depend on the operator, the machinery, and the material used.

Two examples are given in Fig. 2 that illustrate how the growth error in the final AR coating layer influences the resulting mode-locked pulses of the “ $1 \times 121 + 1$ ” and RPG10 structures. The grey regions contain two simulations for each configuration, where the final AR coating layer thickness has been given a $\pm 2\%$ error, which corresponds to an error of about 1.6 nm and 2.0 nm for each structure, respectively. For the “ $1 \times 121 + 1$ ” system, the initial mode-locked

pulse had a FWHM of 55.9 fs and a peak intensity of 1.229 MW/cm^2 and the +2% (−2%) error resulted in a 66.8 fs (68.7 fs) pulse duration with an intensity of 0.933 MW/cm^2 (0.927 MW/cm^2). This is in contrast to the RPG10 structure, where the initial pulse had a FWHM of 88.0 fs and an intensity of 0.361 MW/cm^2 and the +2% (−2%) deviation produced a pulse with a duration of 110.0 fs (158.0 fs) and an intensity of 0.267 MW/cm^2 (0.181 MW/cm^2).

In Fig. 3, we present an overview of the linear gain/absorption and GDD for different gain chips without a lasing cavity. Figure 3(a) shows that all structures produce the same peak gain at the appropriately chosen respective QW background densities. The resulting mode-locked pulses are indicated in Fig. 2 by a bold plot marker. As expected, when comparing the mode-locked pulse duration with the gain bandwidth, it is clear that the “ $N \times 121 + 1$ ” (for $N \leq 3$) and MQW10 structures have much broader gain and produce shorter pulses than the RPG10. However, the gain spectrum of the “ $4 \times 121 + 1$ ” structure is slightly narrower than the

gain from the RPG10 and thus, consistently, produces a slightly longer pulse at this background carrier density.

Figure 3(b) gives an overview of the GDD from each structure with the optically active QWs at the density used for Fig. 3(a). When designing the respective AR coatings, the goal was to flatten the passive dispersion (without QWs) over a wide bandwidth around the central frequency. As a consequence, the resulting structures all have near zero dispersion at the peak gain frequency. Prior theoretical and experimental studies found that it is beneficial to design structures to preemptively compensate for the QW dispersion by adding a small positive offset.^{14,19} Motivated by these findings, we applied an offset in the range 7–39 fs^2 such that the dispersion is zero at the peak gain frequency when the QWs are included in the calculations.

We clearly see in Figs. 3(b) and 3(c) that the RPG system exhibits significantly steeper GDD than the other configurations, which actually is an intrinsic feature of structures with long barrier regions. In Fig. 3(c), the GDD is calculated for the DBR and barrier material alone (i.e., no cap layer, no AR coating, no QWs). Here, one can see that the length of the passive barrier region provides substantial curvature to the GDD compared to the “ $1 \times 121 + 1$ ” structure and its family.

In order to produce even shorter mode-locked pulses, one can also attempt to compensate for the active dispersion, seen in Fig. 3(b); increase the amount of saturable absorption in the lasing cavity (e.g., by lowering the output coupling loss), as observed in Ref. 17; adjust the location of the SESAM bandgap compared to the gain peak; or conquer the DBR stopband limitation. The first three adjustments can result in a shorter pulse FWHM and perhaps a cleaner pulse spectrum, but the stopband width is a much bigger goal. It is possible to estimate that the current stopband width could support pulse durations around 20 fs, but these pulses are hard to realize because of the increased dispersion near the stopband edge. Eventually, the pulse durations come close to about 46 fs, which is a limitation of the DBR stopband, as observed in Ref. 16.

A shorter gain chip barrier region is advantageous in order to alleviate uncontrollable errors in the material growth and produce ultrashort pulses. The “ $N \times 121 + 1$ ” structures ($N \leq 3$) are much superior to RPG designs. Not only do they produce pulses with higher intensities and shorter durations, but they are also less sensitive to experimentally unavoidable uncertainties. The increased GDD curvature seen in Figs. 3(b) and 3(c) renders longer structures, such as the RPG10, very sensitive to the $\pm 2\%$ layer thickness error, and correspondingly makes the “ $N \times 121 + 1$ ” family less sensitive, as shown by the grey regions and simulations in Fig. 2.

In summary, our numerical studies show that the family of “ $N \times 121 + 1$ ” structures has a broad spectral amplification that is advantageous for ultrashort pulse generation. Too many QWs will create a high-peak and narrow gain bandwidth that becomes comparable to the gain from an RPG structure. Whereas the “ $1 \times 121 + 1$ ” structure produces the highest peak intensities and the shortest pulses, the short barrier region could result in problems with pump absorption. Hence, the “ $3 \times 121 + 1$ ” structure should be a reasonable compromise for experimentally realizable ultrashort mode-locked VECSEL systems.

FIG. 3. The linear gain, absorption, and GDD for multiple different gain chip designs. The bold plot markers in Fig. 2 indicate the resulting mode-locked pulses. (a) The SESAM absorption and output coupling loss (solid black) with the gain chip spectral amplification. (b) The GDD computed with the inverted QWs and dispersion compensating coating. (c) The GDD computed without the QWs, cap layer, or AR coating in the range 1.17–1.24 eV.

We thank Wolfgang Stolz (Philipps-Universität Marburg) and Alexandre Laurain (University of Arizona) for helpful discussions. This material is based upon work supported by the Air Force Office of Scientific Research under Award No. FA9550-17-1-0246.

- ¹U. Keller and A. C. Tropper, *Phys. Rep.* **429**, 67 (2006).
- ²A. C. Tropper, A. H. Quarterman, and K. G. Wilcox, *Adv. Semicond. Lasers* **86**, 269 (2012).
- ³B. W. Tilma, M. Mangold, C. A. Zaugg, S. M. Link, D. Waldburger, A. Klenner, A. S. Mayer, E. Gini, M. Golling, and U. Keller, *Light: Sci. Appl.* **4**, e310 (2015).
- ⁴A. Rahimi-Iman, *J. Opt.* **18**, 093003 (2016).
- ⁵X. Liu, D. Du, and G. Mourou, *IEEE J. Quantum Electron.* **33**, 1706 (1997).
- ⁶R. Aviles-Espinosa, G. Filippidis, C. Hamilton, G. Malcolm, K. J. Weingarten, T. Südmeyer, Y. Barbarin, U. Keller, S. I. Santos, D. Artigas *et al.*, *Biomed. Opt. Express* **2**, 739 (2011).
- ⁷Z. Mihoubi, K. G. Wilcox, S. Elsmere, A. Quarterman, R. Rungsawang, I. Farrer, H. E. Beere, D. A. Ritchie, A. Tropper, and V. Apostolopoulos, *Opt. Lett.* **33**, 2125 (2008).
- ⁸K. G. Wilcox, A. C. Tropper, H. E. Beere, D. A. Ritchie, B. Kunert, B. Heinen, and W. Stolz, *Opt. Express* **21**, 1599 (2013).
- ⁹C. R. Head, H.-Y. Chan, J. S. Feehan, D. P. Shepherd, S.-U Alam, A. C. Tropper, J. H. Price, and K. G. Wilcox, *IEEE Photonics Technol. Lett.* **25**, 464 (2013).
- ¹⁰A. H. Quarterman, L. E. Hooper, P. J. Mosley, and K. G. Wilcox, *Opt. Express* **22**, 12096 (2014).
- ¹¹O. D. Sieber, M. Hoffmann, V. J. Wittwer, M. Mangold, M. Golling, B. W. Tilma, T. Südmeyer, and U. Keller, *Appl. Phys. B* **113**, 133 (2013).
- ¹²P. Klopp, U. Griebner, M. Zorn, A. Klehr, A. Liero, M. Weyers, and G. Erbert, *Opt. Express* **17**, 10820 (2009).
- ¹³P. Klopp, U. Griebner, M. Zorn, and M. Weyers, *Appl. Phys. Lett.* **98**, 071103 (2011).
- ¹⁴D. Waldburger, S. M. Link, M. Mangold, C. G. E. Alfieri, E. Gini, M. Golling, B. W. Tilma, and U. Keller, *Optica* **3**, 844 (2016).
- ¹⁵I. Kilen, J. Hader, J. V. Moloney, and S. W. Koch, *Optica* **1**, 192 (2014).
- ¹⁶I. Kilen, S. W. Koch, J. Hader, and J. V. Moloney, *Optica* **4**, 412 (2017).
- ¹⁷I. Kilen, S. W. Koch, J. Hader, and J. V. Moloney, *J. Opt. Soc. Am. B* **33**, 75 (2016).
- ¹⁸J. V. Moloney, I. R. Kilen, and S. W. Koch, "Nonequilibrium pulsed femtosecond semiconductor disk laser with non-equidistant mqw structure," U.S. patent 9.853.417 B2 (2017).
- ¹⁹R. Paschotta, R. Häring, A. Garnache, S. Hoogland, A. Tropper, and U. Keller, *Appl. Phys. B* **75**, 445 (2002).