Quantum dot membrane external-cavity surface-emitting laser at 1.5 μm

Cite as: Appl. Phys. Lett. 118, 231101 (2021); https://doi.org/10.1063/5.0053961
Submitted: 13 April 2021. Accepted: 25 May 2021. Published Online: 07 June 2021

H.-M. Phung, P. Tatar-Mathes, C. Paranthoën, C. Levallois, N. Chevalier, M. Perrin, A. Kerchaoui, H. Kahle, M. Alouini, and M. Guina

ARTICLES YOU MAY BE INTERESTED IN

InP-based single-photon sources operating at telecom C-band with increased extraction efficiency
Applied Physics Letters 118, 221101 (2021); https://doi.org/10.1063/5.0045997

Perspective on the future of silicon photonics and electronics
Applied Physics Letters 118, 220501 (2021); https://doi.org/10.1063/5.0050117

Low-threshold strain-compensated InGaAs/(In,Al)GaAs multi-quantum well nanowire lasers emitting near 1.3 μm at room temperature
Applied Physics Letters 118, 221103 (2021); https://doi.org/10.1063/5.0048807
Quantum dot membrane external-cavity surface-emitting laser at 1.5 μm

Cite as: Appl. Phys. Lett. 118, 231101 (2021); doi: 10.1063/5.0053961
Submitted: 13 April 2021; Accepted: 25 May 2021;
Published Online: 7 June 2021

H.-M. Phung,1,a) P. Tatar-Mathes,1 C. Paranthoen,2 C. Levallois,2 N. Chevalier,2 M. Perrin,2 A. Kerchaoui,2 H. Kahle,1 M. Alouini,2 and M. Guina1

AFFILIATIONS
1Optoelectronics Research Centre (ORC), Physics Unit/Photonics, Faculty of Engineering and Natural Science, Tampere University, Korkeakoulunkatu 3, 33720 Tampere, Finland
2Institut FOTON, UMR-CNRS 6082, Institut National des Sciences Appliquées de Rennes, University of Rennes, 35700 Rennes, France

a)Author to whom correspondence should be addressed: hoy-my.phung@tuni.fi

ABSTRACT
A membrane external-cavity surface-emitting laser (MECSEL) with an InAs/InP quantum dot (QD) based gain region is demonstrated. The pumping scheme employs a 90° off-axis parabolic mirror to focus the diode laser pump beam to a nearly circular pump spot. With this pump arrangement, the QD MECSEL with SiC heat spreaders produced 320 mW output power at room temperature with direct emission in the near-infrared at 1.5 μm. We report a record value of 86 nm for the tuning range at this wavelength region, owing to a broad QD gain bandwidth and wide tunability in MECSELS.

Vertical-external-cavity surface-emitting lasers (VECSELS) have emerged as a versatile platform for high-power coherent light sources with high beam quality. In terms of operation principles and cavity architecture, VECSELS integrate the major benefits of thin-disk solid-state lasers as well as semiconductor lasers. The high-quality beam is rendered possible by the external cavity, while the semiconductor bandgap engineering enables wavelength versatility in a broad range. The key element of a VECSEL is the semiconductor gain mirror, which typically consists of a multi-quantum well (QW) or multi-quantum dot (QD) gain structure and a monolithically integrated distributed Bragg reflector (DBR). To achieve gain and enable lasing, such a gain mirror, which is incorporated in the external cavity configuration, is typically pumped optically. Although semiconductor gain media ensure a much broader wavelength coverage compared to solid-state lasing materials, the power capability and wavelength coverage of VECSELS are neither equally distributed nor available at all possible wavelengths covered by typical III–V compound semiconductors. There are various reasons behind this state of fact, ranging from the maturity of technology at certain wavelengths to more profound ones related to intrinsic features of the material systems used.

For example, owing to the mature development stage of the InGaAs/AlGaAs material system, ensuring a high reflectivity, high carrier confinement, and relatively good thermal conductivity, the highest power VECSELS have been demonstrated at around 1 μm. However, if one moves away from this wavelength range requiring different material systems, either the DBR, the carrier confinement, thermal conductivity, or a combination of these features will become increasingly difficult to manage. Simplifying this analysis, we can point out the limitation arising from the DBR, which requires specific layers with a reasonable high refractive index contrast and also being compatible in terms of lattice constant with the QW or QD gain heterostructure. These features are readily available for the 1 μm region but become an issue when targeting lasing in the 1.3–1.5 μm region, where the QWs are InP-based rendering impossible the use of GaAs/AlGaAs DBRs. To overcome the spectral limitations of the DBR and to some extent also improve the operation of the gain heterostructure by better thermal management, an alternative laser concept has emerged, the membrane external-cavity surface-emitting laser (MECSEL). In MECSELS, the gain medium is comprised only of the thin QW or QD heterostructure (without a DBR), which is then used in an external cavity architecture. Moreover, in MECSELS, the thermal management is more efficient as the active structure can be bonded between two intra cavity heat spreaders, i.e., it is cooled from both sides with heat spreaders in the close proximity of the gain region. In turn, this...
enables us to use heat-spreading materials with lower conductivity but more cost-effective as silicon carbide (SiC). Owing to these advantages, recent efforts have led to the demonstration of MECSELs emitting in the red and near-infrared.23–25

In this paper, we focus our attention on the important 1.5 μm telecom region, where the DBR technology is particularly difficult due to the low refractive index contrast of InP-based materials. For the sake of generality, we point out that although 1.5 μm monolithic InP-based VECSELs have been demonstrated,16–19 the highest output power reported at room temperature operation is only 140 mW, which is a small fraction of what would be available at 1 μm. We note here that the thermal resistance of this VECSEL, measured under laser operation, is as high as 470 K/W.26–27 To have a better thermal resistance of 34 K/W, a hybrid metal-metamorphic AlAs/GaAs DBR has been implemented.28–30 Alternative demonstrations, involving GaInAsN/GaAs QWs and AlAs/GaAs DBR pairs grown on GaAs, have also resulted in rather low output power in the 80 mW range.31 An alternative solution to the monolithic approach is to grow the InP-based active structure and the AlAs/GaAs DBR separately on two different types of substrates, and afterwards combining them via wafer-fusion.32–33 This involves a higher level of complexity. Nevertheless, this technique has enabled to fabricate high-power VECSELs exceeding 3.65 W at 1.55 μm. In particular, we demonstrate wavelength tuning over a large bandwidth. The laser implemented an optical pumping scheme34 to favor an almost circular pumping.

The QD MECSEL structure was grown by gas source molecular beam epitaxy (GSMBE) on a 300 μm thick InP substrate with a (311)B crystal orientation. First, a 100 nm thick InGaAs etch stop layer was fabricated. The gain structure consisted of 20 InAs QD layers separated by 15 nm thick GaInAsP barrier layers and distributed over groups of five QD layers with InP cladding layers as schematically illustrated in Fig. 1.

The structure has been designed with a fixed number of QD layers per groups. To optimize the structure in terms of charge carrier distribution, an increase in the thickness of the GaInAsP barrier absorbing layers compensated for the exponential decrease in the input pump absorption. As a consequence, the total thicknesses of the absorbing layers from the back up to the front side are as follows: 240, 160, 120, and 90 nm. The whole structure appears, thus, as asymmetric, but is still resonant with a 2.5 μm design because of the InP/SiC interface. Here, the InP cladding layer between the first and second QD layers is more than twice thicker than the other InP cladding layers in the gain structure. The antinode between these two QD layers is practically left out, such that each QDs group is carefully positioned at stationary field antinodes. Details of the QD fabrication by the Stransk–Krastanov growth mode, the gain structure and its laser performance as a VECSEL at 14 °C employing intra cavity diamond heat spreaders have been described elsewhere.35

After the growth was completed, the substrate was mechanically thinned before being removed wet-chemically with an HCl solution. An H₂PO₄·H₂O·H₂O solution was applied to eliminate the InGaAs process layer. After the etching process, the membrane was bonded between two uncoated 4H SiC heat spreader pieces and mounted into a copper heat sink. During all operation conditions, the membrane heat spreader sandwich was cooled in a heat sink mount via water/glycol cooling at a temperature of 19 °C. A schematic illustration of the V-cavity for the output power and wavelength tuning experiments performed is shown in Fig. 1. The V-cavity consisted of a plane output-coupling mirror M3, and two curved high-reflecting mirrors M1 and M2, which both had the same reflectivity of R_M1, M2 > 99.8 % and the same radius of curvature of r_M1, M2 = 200 mm. The mirror distances of M1 and M2 to the gain membrane sandwich were adjusted to L₁ = 195 mm and L₂ = 199 mm. M3 was positioned under an opening angle of 11° between L₂ and L₃. The distance between M2 and M3 was L₃ = 199 mm. The calculated cavity mode diameter on the gain membrane was about 200 μm using the ray transfer method for a Gaussian beam. A 980 nm LIMO diode laser coupled into a multimode fiber with a 200 μm core diameter and a numerical aperture of 0.22 was used as a pump source. The fiber output was collimated by a 100 mm plano-convex lens and focused onto a spot size of about 360 μm in diameter by a 90° off-axis parabolic mirror (MPD249H-M01 from Thorlabs) with a protected gold coating, the pump beam is focused down to a nearly circular pump spot onto the laser-active membrane as illustrated. This also favors an almost round beam profile of the MECSEL as captured by a scanning slit beam profiler.

![Image](https://example.com/image.png)
Following the Fresnel equations, approximately 20% of incident pump power was reflected at the SiC heat spreader front surface for incident angles between 0° and 15°. Pump transmission measurements revealed an absorption by the gain membrane of about 65% of the incident pump power.

The QD MECSEL output characteristics are shown as a function of the absorbed pump power in Fig. 2 and include the transmission from M1, M2, and M3 with an outcoupler reflectivity of $R_{M3} = 99\%$.

Lasing was achieved with a threshold pump power of $P_{pump,th} = 4.7$ W. By increasing the pump power further to a value of 22.6 W of absorbed power, a maximum output power of 320 mW was obtained with a differential efficiency of 2%. As can be seen in Fig. 2, the output power was limited by thermal rollover, which was setting in at about 22 W absorbed pump power. The QD MECSEL produced a near-diffraction-limited fundamental transverse mode profile, in both sagittal and tangential planes with an M² value of less than 1.05, measured with a dual scanning-slit BP209-IR/M beam profiler and a Thorlabs M² M2MS measurement system. As can be seen in Fig. 1, the MECSEL beam profile reproduced from the scanning-slit measurement was nearly circular, which is most likely favored by the circular pump approach.

A set of spectra was simultaneously recorded with an Ando AQ6317C optical spectrum analyzer with a resolution of 0.02 nm during the output power measurements. In addition to the spectral red shift, the emission spectrum widened with pump power. This was probably due to the state-filling effect in QDs, as the threshold of higher emission energy modes could be reached at high excitation power and contribute to lasing. The inset in Fig. 2 shows an emission spectrum at 21 W absorbed pump power. It contained typical Fabry–Pérot resonances, related to the spectral filtering induced by the 350 μm thick intra cavity SiC heat spreaders.

Furthermore, the spectral red shift by heating up the gain membrane by the pump source was determined as 0.07 nm/K with the heat sink temperature. Correspondingly, the thermal resistance is obtained.

Temperature tuning experiments have been conducted by inserting a birefringent filter within the cavity (see Fig. 1) using different output coupler reflectivities. This 1.5 mm thick filter enables to cover a large free spectral range of 180 nm. With a $R_{M3} = 99\%$ outcoupler, the emission wavelength was tunable from 1474 nm to 1519 nm as illustrated in Fig. 3. The broader tuning range of 86 nm was achievable with a high-reflecting $R_{M3} > 99.8\%$ outcoupling mirror. Compared to earlier 1.5 μm VECSELs, the highest tuning range has been achieved at the 1.5 μm wavelength band, here, in this work.

The polarization behavior of the QD MECSEL was analyzed without any intra cavity elements inside a linear cavity to avoid any preferred polarization that would be given by a V-cavity. The mirrors M1 and M2 with the mirror distances of about $L_1 = L_2 = 197$ mm were used. An ultra broad band wire grid polarizer from Thorlabs (WP25M-UB) with an extinction ratio of 1000:1 was set behind M2. With the transmission axis fixed at 0° (p-polarization) axis and 90° (s-polarization) axis, the measured output power curve was linearly increasing with pump power as shown in Fig. 4 without power drop. Also, the spectra taken at both polarization axes at an absorbed pump power of 16.4 W in the inset of Fig. 4 revealed that there was no wavelength hopping.

To determine the degree of linear polarization (DOP), the polarizer was rotated over a full cycle. The DOP was calculated with the maximum and minimum output power $P_{max}$ and $P_{min}$ from M2 transmitted through the polarizer by

$$DOP = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}.$$ 

As can be seen in Fig. 5, the DOP was calculated to be larger than 99%, meaning that the MECSEL was almost fully s-polarized. In VECSELs, similar values have been obtained. The preferential polarization state was fixed at lasing. No switching over the wafer and the whole output power characteristic was observed. This originates most likely from the QD anisotropy, similarly to the recently reported VCSELs integrating the same 1.5 μm InAs QDs.
In conclusion, we demonstrated a QD MECSEL operating at 1.5 µm. With the combination of the broad gain of InAs QDs and the absence of the DBR, the MECSEL has made a record tuning range of over 320 mW of output power was achieved at room temperature with relatively low cost SiC heat spreaders available in wafer quality. To optically pump the gain membrane under small pump incident angles below 15° with an almost circular pump spot, a 90° off-axis parabolic mirror was integrated in the pump optics. In the future, this pump approach could be extended by a second set of pump optics, positioned on the opposite side of the MECSEL for double-side pumping or pump recycling by reflecting the transmitted pump beam back to the MECSEL structure to increase the pump efficiency. Additionally, a high DOP larger than 99% was obtained where the s-polarized modes were far more prominent than the p-polarized ones, which was reproducible across the sample. From the application point of view, QD MECSELs with a near diffraction limited beam with an M² value of less than 1.05 and a broad gain bandwidth could be applied in coherent Doppler LIDAR in the future for wind velocity sensing, wind turbulence measurements, or wake vortices detection created by aircrafts in flight formations.

The authors acknowledge the Academy of Finland (No. 326455), the PREIN Flagship Programme, the Magnus Ehrnrooth Foundation, the Finnish Foundation for Technology Promotion, and the French National Agency of Research (ANR IDYLIC Project, Grant No. ANR-15-CE24-0034-01) for the funding. The authors would like to acknowledge RENATECH+ (the French national network of facilities for micromanufacturing) with NanoRennes platform for the sample growth.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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 Photonics Technol. Lett. 9, 1063–1065 (1997).
2. E. Kantola, J.-P. Penttinen, S. Ranta, and M. Guina, “72-W vertical-external-cavity surface-emitting laser with 1180-nm emission for laser guide star adaptive optics,” Electron. Lett. 54, 1135–1137 (2018).
3. R. 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. 48, 516–517 (2012).
4. M. Guina, A. Härkönen, V.-M. Korpijärvi, T. Leinonen, and S. Suomalainen, “Semiconductor disk lasers: Recent advances in generation of yellow-orange and mid-IR radiation,” Adv. Opt. Technol. 1, 2012.
5. H. Kahle, C. M. N. Mateos, U. Brauch, P. Tatar-Mathes, R. Bek, M. Jetter, T. Graf, and P. Michler, “Semiconductor membrane external-cavity surface-emitting laser (MECSEL),” Optica 3, 1506–1512 (2016).
6. V. Jakólewicz, J. Walczak, M. Gebski, A. K. Sokol, M. Wasiak, P. Gallo, A. Sirbu, R. P. Sarzala, M. Dems, T. Czyżewski, and E. Kapon, “Double-diamond high-contrast gratings vertical external cavity surface emitting laser,” J. Phys. D: Appl. Phys. 47, 065104 (2014).
7. Z. Yang, A. R. Albrecht, J. G. Cederberg, and M. Sheik-Bahae, “Optically pumped DBR-free semiconductor disk lasers,” Opt. Express 23, 33164–33169 (2015).
8. Z. Yang, D. Fellman, A. R. Albrecht, P. Heu, N. Giannini, G. D. Cole, and M. Sheik-Bahae, “16 W DBR-free membrane semiconductor disk laser with dual-SiC heatspreader,” Electron. Lett. 54, 430–432 (2018).
9. A. Broda, A. Kuźmiński, G. Rychlik, K. Chmielewski, A. Wójcik-Jedlińska, I. Sankowska, K. Gołębska-Malec, K. Michalak, and J. Muszalski, “Highly efficient heat extraction by double diamond heat-spreaders applied to a vertical external cavity surface-emitting laser,” Opt. Quantum Electron. 49, 287 (2017).
10. S. Mirkhanov, A. H. Quarterman, H. Kahle, R. Bek, R. Pecoroni, C. J. C. Smyth, S. Vollmer, S. Swift, P. Michler, M. Jetter, and K. G. Wilcox, “DBR-free semiconductor disc laser on SiC heatspreader emitting 10.1 W at 1007 nm,” Electron. Lett. 53, 1537–1539 (2017).
11. H. Kahle, J.-P. Penttinen, H.-M. Phung, P. Rajala, A. Tukiainen, S. Ranta, and M. Guina, “Comparison of single-side and double-side pumping of membrane external-cavity surface-emitting lasers,” Opt. Lett. 44, 1146–1149 (2019).
12. H.-M. Phung, H. Kahle, J.-P. Penttinen, P. Rajala, S. Ranta, and M. Guina, “Power scaling and thermal lensing in 825-nm emitting membrane external-cavity surface-emitting lasers,” Opt. Lett. 45, 547–550 (2020).
13. B. Jeżewski, A. Broda, I. Sankowska, A. Kuźmiński, K. Gołębska-Malec, K. Czuba, and J. Muszalski, “Membrane external-cavity surface-emitting laser emitting at 1640 nm,” Opt. Lett. 45, 539–542 (2020).
M. Strassner, "Room temperature CW lasing operation of monolithically grown monolayer InAlAsSb/GaAs VECSEL operating at 1550 nm," IEEE J. Sel. Top. Quantum Electron. 25, 1–1 (2019).

M. Herper, A. van der Lee, J. Kolb, S. Gronenborn, H. Moench, and P. Loosen, "VCSEL pumped VECSEL concept with compact design," Electron. Lett. 55, 705–707 (2019).

A. Laurain, J. Hader, and J. V. Moloney, "Modeling and optimization of transverse modes in vertical-external-cavity surface-emitting lasers," J. Opt. Soc. Am. B 36, 847–854 (2019).

A. R. Albrecht, T. J. Rotter, C. P. Hains, A. Stinta, J. V. Moloney, K. J. Malloy, and G. Ralakrishnan, "Multi-watt 1.25 μm quantum dot VCSELs," Electron. Lett. 46, 856–857 (2010).

B. Heinen, F. Zhang, M. Sparenberg, B. Kunert, M. Koch, and W. Stolz, "On the measurement of the thermal resistance of vertical-external-cavity surface-emitting lasers (VECSELs)," IEEE J. Quantum Electron. 48, 934–940 (2012).

A. Laurain, M. Myara, G. Beaudoin, I. Sagnes, and A. Garnache, "High power single-frequency continuously-tunable compact extended-cavity semiconductor laser," Opt. Express 17, 9503–9508 (2009).

C. Paranthoen, C. Levallois, G. Brévalle, M. Perrin, A. Le Corre, N. Chevalier, P. Turban, C. Cornet, H. Folliot, and M. Alouini, "Low threshold 1550 nm emitting QD optically pumped VCSEL," IEEE Photonics Technol. Lett. 23, 69–72 (2011).

Z. Yang, A. R. Albrecht, J. G. Cederberg, and M. Sheik-Bahae, "80 nm tunable DBR-free semiconductor disk laser," Appl. Phys. Lett. 109, 022110 (2016).

C. M. N. Mateo, U. Brauch, H. Kahle, T. Schwarzbäck, M. Jetter, M. Abdou Ahmed, P. Michler, and T. Graf, "2.5 W continuous wave output at 665 nm from a multipass and quantum-well-pumped AlGaInP vertical-external-cavity surface-emitting laser," Opt. Lett. 41, 1245–1248 (2016).

P. J. Rodrigo and C. Pedersen, "Comparative study of the performance of semiconductor laser based coherent doppler lidars," Proc. SPIE 8241, 292–298 (2012).

Q. Hu, P. J. Rodrigo, and C. Pedersen, "Remote wind sensing with a CW diode laser lidar beyond the coherence regime," Opt. Lett. 39, 4875–4878 (2014).

S. Wu, B. Liu, J. Liu, X. Zhai, C. Feng, G. Wang, H. Zhang, J. Yin, X. Wang, R. Li, and D. Gallagher, "Wind turbine wake visualization and characteristics analysis by Doppler lidar," Opt. Express 24, A762–A780 (2016).