16 W DBR-free membrane semiconductor disk laser with dual-SiC heatspreader

Z. Yang✉, D. Follman, A.R. Albrecht, P. Heu, N. Giannini, G.D. Cole and M. Sheik-Bahae

A record output power of 16.1 W with a direct-bonded dual-SiC-heatspreader distributed Bragg reflector (DBR)-free active region at 10.5°C coolant temperature is reported. A comparison in laser performance confirms the dual-heatspreader DBR-free configuration dissipates heat more effectively than the single-heatspreader geometry.

Introduction: Semiconductor disk lasers (SDLs), also called vertical-external-cavity surface-emitting lasers (VECSELs), employ a thin-disk gain medium geometry and exhibit a number of advantages over typical semiconductor lasers including better beam quality and the potential for power scalability [1, 2]. For traditional SDLs, the gain chip is a periodic gain structure combined with an integrated semiconductor-based distributed Bragg reflector (DBR). This 'conventional' VECSEL structure is typically attached to intracavity or extracavity heatspreaders. Devices with this geometry have demonstrated more than 100 W of output power [3]. Further power scaling, however, is limited by the high thermal resistance of the DBR [4, 5], which hampers heat extraction from the active region. By eliminating the integrated Bragg mirror, our DBR-free geometry [6], also called membrane-external-cavity surface-emitting lasers [7], consists of only an active region and heatspreader(s), and can, in principle, dissipate heat more efficiently. This not only opens a promising route for high-power SDLs, but yields additional advantages including a simplified epitaxial structure, as well as access to additional operating wavelengths without the need for a lattice-matched DBR.

For these devices, two DBR-free geometries are currently being investigated: single and dual intracavity heatspreaders. According to previous thermal analyses based on finite-element modelling [6], under the same conditions, the dual-heatspreader geometry extracts heat more efficiently from the active region and exhibits a much lower temperature rise in the gain medium, thus enabling a higher output power. For lasing wavelengths near 1 µm, the single heatspreader geometry has demonstrated an output power of 6 W when directly bonded to diamond [8]. Recently, using a single SiC heatspreader, Mirkhanov *et al.* [9] reported 6 W of output power at a coolant temperature of 12°C, and 10.1 W at −10°C, while dual-diamond-heatspreader DBR-free SDLs have yielded 3.5 W, thus far limited solely by the available pump power [10]. In this paper, we directly compare the laser performance of DBR-free SDLs using these two geometries. With a SiC-sandwiched gain structure, we report 16.1 W output power at 1037 nm and a 10.5°C coolant temperature, which, to the best of our knowledge, is a new record for DBR-free SDLs. This is also the highest output power achieved for VECSELs with SiC heatspreaders.

Experiment setup: In this study, our active region epitaxial structure was grown by metal-organic chemical vapour deposition (CVD) at Sandia National Laboratories, consisting of 12 InGaAs quantum wells in a periodic gain structure with a separation of $\lambda/2$ ($\lambda = 1040$ nm) via GaAsP barriers, and capped by two InGaP window layers for carrier confinement. The material structure is the same as reported in [8].

High surface quality, low absorption, double-side polished single-crystal 4H-SiC wafers (0.37 mm in thickness and diced into $5 \times 5\ \text{mm}^2$ chips) are used as heatspreaders. Characterised with the two-colour Z-scan technique [11], our SiC wafer has a background absorption of $0.09\ \text{cm}^{-1}$ at 1020 nm, and $0.25\ \text{cm}^{-1}$ at 532 nm. At the wavelength of interest, SiC has comparable absorption with standard commercially-available single-crystal CVD diamond ($0.10\ \text{cm}^{-1}$), but is still higher than low absorption diamond ($0.01\ \text{cm}^{-1}$). SiC substrates, however, are more easily available and exhibit superior surface quality in terms of microroughness (RMS<0.2 nm for SiC) and surface figure. These properties are critical for achieving high-quality direct bonds in order to minimise the thermal resistance of the interface. Most importantly, commercially-available single-crystal SiC heatspreaders allow for wafer-scale substrate transfer of the gain medium. Such a batch fabrication process can be easily translated to a mass production process, yielding significant cost reduction for volume active medium fabrication.

In order to attach the heatspreader, the DBR-free epitaxial material is directly bonded onto SiC at room temperature. Here, the multi-quantum-well active region is removed from the initial GaAs growth wafer and transferred to a single uncoated SiC heatspreader without the use of an intermediary adhesive layer such as glue or solder. To create the dual-heatspreader structures, a second SiC chip (also uncoated) is then directly bonded to the top of the previously bonded semiconductor/SiC stack in a similar manner, resulting in a 'sandwiched' dual-heatspreader structure comprising SiC–semiconductor–SiC. The bonded active regions are $5 \times 5\ \text{mm}^2$, and inspection via Normaski microscopy confirms a low defect density at the bond interface. Photographs of single-heatspreader and dual-heatspreader gain elements are included in Fig. 1.

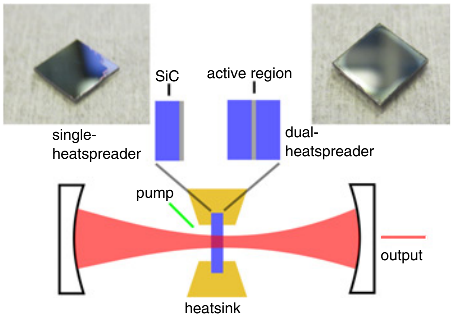

Fig. 1 *DBR-free SDL configuration including photographs of completed single-heatspreader and dual-heatspreader gain elements*

For thermal management in testing, the completed devices are clamped in a custom-machined copper mount, which is water cooled to 10.5°C. Indium foil is applied at the clamping interface between the copper mount and the gain structure, in order to reduce the thermal resistance. A 100 W, fibre-coupled laser diode at 808 nm is employed to pump the devices at a 20° angle of incidence. The laser cavity is formed with two concave partial reflectors of 10 and 15 cm radii of curvature, and the gain element is placed near the waist of the cavity mode, as shown in Fig. 1. Depending on the mirrors used, the total output coupling is 3 or 5%. Both cavity length and pump focus are optimised for matching the pump and cavity modes.

Results: Characterisation results for these lasers are shown in Fig. 2. Employing 3% output coupling, maximum output powers of 4.8 and 12.3 W are achieved with single- and dual-heatspreader geometries, respectively. Considering the absorbed pump power, the slope efficiencies are 26.3 and 30.0%, respectively. The slope efficiency is quite similar, which implies that the second SiC heatspreader introduces little optical losses. The discrepancy in efficiency is more likely due to the non-uniformity of the gain medium across the wafer surface.

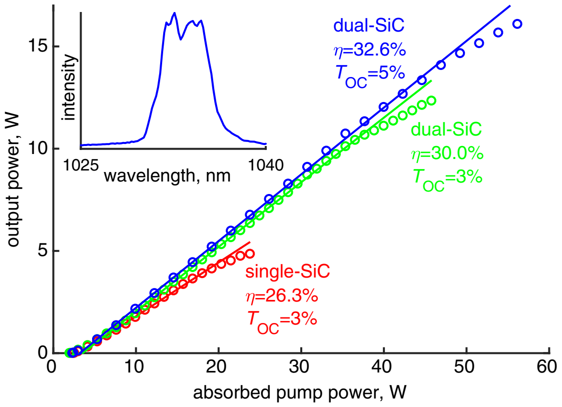

Fig. 2 *DBR-free laser performance with single- (red) and dual-heatspreader (green and blue) geometry. The circles represent experimental results, while the lines are linear fits. The inset is the laser spectrum for the dual-SiC geometry at 24 W of absorbed pump power*

In terms of the lasers spectral characteristics, the single-heatspreader geometry lases at 1026 nm at threshold, while the dual-heatspreader geometry at 1028 nm with <1 nm linewidth, limited by our spectrometer. At 24 W of absorbed pump power, the dual-heatspreader geometry has a linewidth of 5 nm. With higher pump powers, the centre wavelength redshifts to about 1037 nm.

At high pump powers, the output of both lasers deviates from their initial linear trend, which could be due to mode competition or the onset of thermal roll-over. Under the same pumping condition, the single-heatspreader geometry deviates from its initial linear slope efficiency at 22 W of absorbed pump power, while this occurs at 39 W for the dual-heatspreader geometry. Therefore, compared to directly cooling through the semiconductor surface, the second heatspreader significantly accelerates the thermal dissipation rate, which agrees with the previous thermal modelling results.

Initial measurements show no obvious sign of higher order mode operation. If the reduction in power is attributed to thermal roll-over, this could be mitigated by expanding the mode size or decreasing the coolant temperature further. Higher thermal conductivity heatspreaders, such as diamond, could also be used to increase the roll-over pump power [4].

With a total of 5% transmission, the dual-heatspreader geometry achieves 16.1 W of output power with 32.6% slope efficiency. To the best of our knowledge, this is a record output power from both a DBR-free SDL geometry and a VECSEL utilising SiC heatspreaders. The slope efficiency could be further improved by optimising output coupling efficiency and eliminating the parasitic cavity formed between the two SiC–air interfaces. Imperfect parallelism could lead to additional losses, which could be mitigated by antireflection coating or Brewster's angle geometry.

Conclusion: We have compared the laser performance of DBR-free SDLs with single- and dual-heatspreader(s) under the same pump conditions. It is evident that the second heatspreader significantly facilitates heat dissipation and, as a result, increases the thermal roll-over pump power, while barely affecting the laser slope efficiency. It is important to note that the same thermal management scheme can be applied to conventional VECSELs with integrated DBRs. Our 16.1 W of record output power also implies SiC heatspreaders, with their excellent surface quality and high thermal conductivity, could be a good alternative to diamond-based materials for a multitude of VECSEL applications.

Acknowledgments: The research was supported by Air Force Research Laboratory under contract FA9451-17-P-0513. A portion of this work was performed in the UCSB Nanofabrication Facility. The authors from UNM acknowledge the support by Air Force Office of Scientific Research under contract FA9550-16-1-0362 (MURI). This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Los Alamos National Laboratory (Contract DE-AC52-06NA25396) and Sandia National Laboratories (Contract DE-NA-0003525).

Submitted: *11 January 2018* E-first: *27 February 2018*
doi: 10.1049/el.2018.0101
One or more of the Figures in this Letter are available in colour online.

Z. Yang, A.R. Albrecht, N. Giannini and M. Sheik-Bahae (*Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd. NE, Albuquerque, NM 87131, USA*)

✉ E-mail: zyang01@unm.edu

D. Follman, P. Heu and G.D. Cole (*Crystalline Mirror Solutions LLC, 114 E Haley St., Suite G, Santa Barbara, CA 93101, USA*)

References

1 Okhotnikov, O.G.: 'Semiconductor disk lasers: physics and technology' (Wiley-VCH, Berlin, Germany, 2010)
2 Guina, M., Rantamäki, A., and Härkönen, A.: 'Optically pumped VECSELs: review of technology and progress', *J. Phys. D, Appl. Phys.*, 2017, **50**, (383001), pp. 1–37
3 Heinen, B., Wang, T.L., Sparenberg, M., *et al.*: '106 W continuous-wave output power from vertical external-cavity surface-emitting laser', *Electron. Lett.*, 2012, **48**, (9), pp. 516–517
4 Kemp, A.J., Valentine, G.J., Hopkins, J.-M., *et al.*: 'Thermal management in vertical-external-cavity surface-emitting lasers: finite-element analysis of a heatspreader approach', *J. Quantum Electron.*, 2015, **41**, (2), pp. 148–155
5 Piprek, J., Troger, T., Schroter, B., *et al.*: 'Thermal conductivity reduction in GaAs-AlAs distribution Bragg reflectors', *Photon. Technol. Lett.*, 1998, **10**, (1), pp. 81–83
6 Yang, Z., Albrecht, A.R., Cederberg, J.G., *et al.*: 'Optically pumped DBR-free semiconductor disk lasers', *Opt. Express*, 2015, **23**, (26), pp. 33164–33169
7 Kahle, H., Mateo, C.M.N., Brauch, U., *et al.*: 'Semiconductor membrane external-cavity surface-emitting laser (MECSEL)', *Optica*, 2016, **3**, (12), pp. 1506–1512
8 Yang, Z., Albrecht, A.R., Cederberg, J.G., *et al.*: '80 nm tunable DBR-free semiconductor disk lasers', *Appl. Phys. Lett.*, 2016, **109**, (022101), pp. 1–4
9 Mirkhanov, S., Quarterman, A.H., Kahle, H., *et al.*: 'DBR-free semiconductor disc laser on SiC heatspreader emitting 10.1 W at 1007 nm', *Electron. Lett.*, 2017, **53**, (23), pp. 1537–1539
10 Broda, A., Kuzmicz, A., Rychlik, G., *et al.*: 'Highly efficient heat extraction by double-diamond heat-spreaders applied to a vertical external cavity surface-emitting laser', *Opt. Quant. Electron.*, 2017, **49**, (287), pp. 1–7
11 Giannini, N., Yang, Z., Albrecht, A.R., *et al.*: 'Investigation into the origin of parasitic absorption in GaInP|GaAs double heterostructures', *SPIE Proc.*, 2017, **10121**, (10121F), pp. 1–7