Demonstration of a 20-W membrane-external-cavity surface-emitting laser for sodium guide star applications

D. Priante,[1] M. Zhang,[1] A.R. Albrecht,[1] R. Bek,[2] M. Zimmer,[2] C. Nguyen,[3] D. Follman,[3] G.D. Cole,[3] and M. Sheik-Bahae[1,✉]

[1]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*

[2]*Twenty-One Semiconductors GmbH, Neckartenzlingen, Germany*

[3]*Thorlabs Crystalline Solutions, Santa Barbara, California, USA*

✉Email: msb@unm.edu

We present a record 20-W continuous-wave output power membrane-external-cavity surface-emitting laser (MECSEL) double-bonded to silicon carbide (SiC) heat spreaders emitting around 1178 nm. We achieved a maximum slope efficiency of 27.7% and an optical-to-optical efficiency of 26.7%. By utilising an intracavity birefringent filtre, the wavelength was tuned over 75 nm and maximum output power of 12.7 W was recorded at 1178 nm. This study shows the potential of MECSELs to achieve high-performance and cost-effective optically pumped semiconductor disk lasers targeting applications in sodium guide stars.

Introduction: Sodium guide star lasers (SGLs) integrated in modern astronomical telescopes have quickly transformed the quality and resolution of all-sky coverage imaging for applications in astronomy and space surveillance. Current SGL implementations are dominated by dye lasers, sum-frequency generation using solid-state lasers, or master-oscillator followed by a Raman fibre amplifier [1]. Nevertheless, due to the large size (>100 kg), optical complexity, and cost involved (>$1 M), recent efforts have led to the development of devices at the frontier between solid-state and semiconductor laser technologies. Semiconductor vertical-external-cavity surface-emitting lasers (VECSELs) fulfil the requirements owing to their low cost, high efficiency and compactness. Moreover, these devices offer many advantages over standard semiconductor lasers such as high brightness, good beam quality, ultra-short pulse generation, single-frequency operation, the use of intracavity elements, wavelength tunability, and low noise operation [2]. The highest VECSEL output power reported to date is 106 W at 1028 nm [3]. For SGL applications, however, the 1.1–1.2 μm wavelength range faces material growth challenges due to the large lattice mismatch between the gallium arsenide (GaAs) base substrate and indium gallium arsenide (InGaAs) quantum wells, resulting in strain accumulation and leading to low crystal quality. Despite this, devices operating at $\sim$1178 nm have shown high output power [4] and, with intracavity frequency doubling, 10 and 20 W at 589 nm have been reported [5, 6]. Notwithstanding the advantages, challenges such as long growth time and complexity of the distributed Bragg reflector (DBR), as well as its high thermal resistance, have spurred the search for alternative technologies. Recently, DBR-free semiconductor disk lasers or membrane-external-cavity surface-emitting lasers (MECSELs) have emerged as potential solutions to these limitations, providing advantages such as a simplified epitaxial structure (consisting solely of an active region with confining layers) as well as access to new wavelengths without the need for a lattice-matched DBR [7–12].

Herein, we report a record output power of 20.2 W in continuous-wave operation under 75 W of absorbed power in a dual-SiC-bonded MECSEL operating around 1178 nm. A linewidth of 0.5 nm was measured employing a 2-mm-thick birefringent filtre (BRF) and output power of 12.7 W at the wavelength of interest. Slope efficiencies of 25.4% and 27.7% were achieved with and without the BRF, respectively. Moreover, the laser wavelength was tuned from 1119 to 1194 nm using the same BRF and cavity configuration.

Gain structure and experiment setup: The multi-quantum-well (MQW) gain structure was grown using metal-organic chemical vapour deposition in a 3 × 2″ showerhead reactor. The active region consists of 11 InGaAs quantum wells arranged in a resonant periodic gain structure [13], embedded in GaAs barriers, which include GaAsP layers for strain compensation. The membrane is enclosed by 20-nm thick gallium indium phosphide (GaInP) cladding layers on both sides to prevent surface recombination, yielding a total device thickness of 2 μm. A 250-nm Al$_{0.92}$Ga$_{0.08}$As layer between the membrane and the (100) GaAs substrate serves as an etch stop layer for the substrate removal process. The heat spreaders comprise two 0.5-mm-thick double-side polished single crystal 10 × 10 mm^2 4H-silicon carbide (4H-SiC) chips with high surface quality and low absorption. Despite the higher absorption and lower thermal conductivity of SiC compared to optical grade single-crystalline chemical vapour deposition (CVD) diamond, the superior surface quality of SiC is a key factor to attain high-quality bonding and intimate thermal contact. Single-crystal SiC wafers are also available in larger sizes (currently up to 15-cm diameter) and at lower costs, enabling wafer-scale gain chip manufacturing.

To construct the MECSEL gain chips, the epi material was directly bonded to a single heat spreader using a low-temperature plasma-assisted bonding process and the GaAs growth substrate and etch stop layers were subsequently selectively etched to transfer the MQW structure to a first SiC heat spreader. Next, the SiC/epi stack was bonded to a second SiC substrate to create a dual-heat spreader structure similar to the devices described in [7]. Finally, the external SiC faces were anti-reflection coated with an SiO$_2$ film deposited via plasma-enhanced CVD (refractive index of $\sim$1.45), with no metallisation.

The completed gain chip was clamped between two water-cooled copper mounts. Indium foil is used to improve thermal contact with the copper heatsink. The chip is optically pumped using a fibre-coupled 808-nm diode laser (maximum output power of 100 W) through a 200-μm core fibre and focused onto the sample at an angle of 25 degrees. The linear MECSEL cavity is 26-cm-long and consists of output couplers with a radius of curvature of 15 and 25 cm with a total transmissivity of 2%. The laser mode radius at the gain chip was calculated to be 190 μm, while the pump beam radius was set at 200 μm and adjusted to provide optimal output power.

Results: Figure 1 depicts the temperature-dependent device output power as a function of the absorbed pump power. All the curves were measured up to the roll-over point. We obtained a maximum power of 20.2 W with an optical-to-optical conversion efficiency of 26.7% and slope efficiency of 27.7% at −10°C. To the best of our knowledge, this represents a record for both MECSEL devices emitting around 1178 nm and MECSEL devices in general. Previous work reported optical powers of 16.1 [7] and 10.1 W [10] at a wavelength of 1037 and 1007 nm, respectively. It is noted that the slope efficiency does not change drastically with temperature and the output power is only limited by the thermal roll-over.

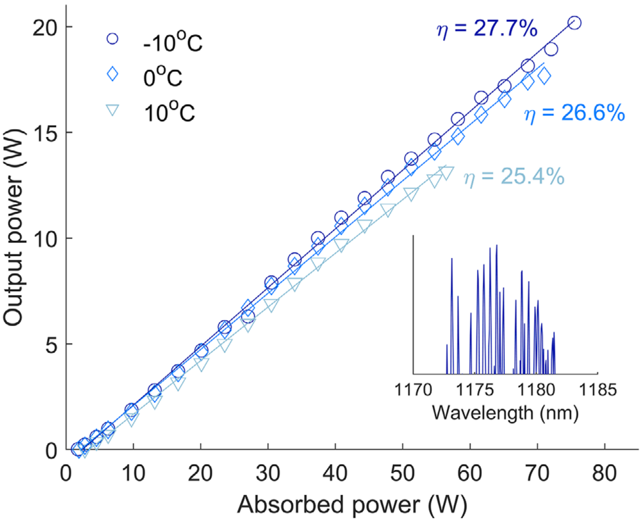

Fig 1 *Temperature-dependent output power curves as a function of absorbed pump power. The inset shows the multimode lasing spectrum recorded under 40 W of absorbed pump power at −10°C*

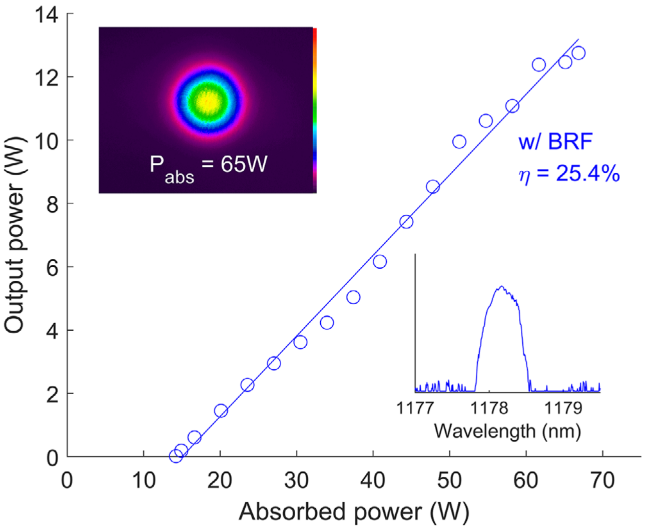

Fig 2 *Device performance measured with an intracavity birefringent filtre (BRF) at a temperature of −10°C. The top-left inset shows the beam profile at 65 W of absorbed power with the BRF. The bottom-right inset shows the spectrum using the BRF under 65 W of absorbed power*

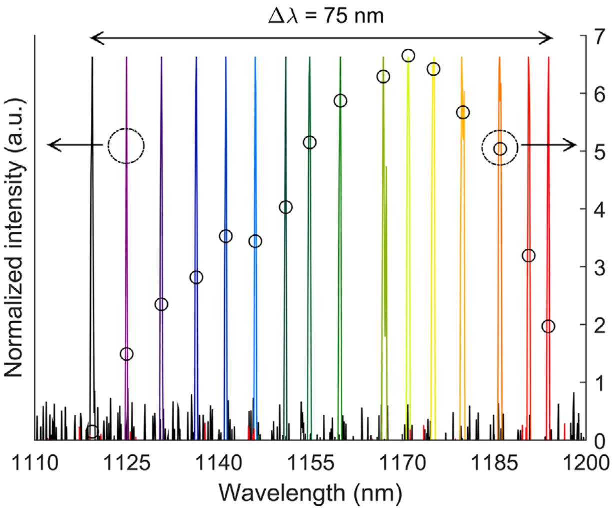

Fig 3 *Normalised emission spectra using a 2-mm-thick BRF. The output power was recorded under 46 W of absorbed pump power at a heatsink temperature of 5°C*

At high-power operation, the spectrum of the device was centred near 1178 nm and the full-width-at-half-maximum (FWHM) was measured to be 8 nm as shown in the inset of Figure 1.

Figure 2 shows the device performance with the BRF set to a wavelength of 1178.2 nm. The maximum output power was recorded at 12.7 W with a slope efficiency of 25.4%. The bottom-right inset shows the spectrum measured at 65 W of absorbed power having an FWHM of 0.5 nm with a spectrometer resolution of 0.06 nm. The beam profile of the 1178 nm laser using the BRF is depicted in the top-left inset and shows a good quality Gaussian beam at high-power operation.

The laser wavelength was tuned by placing an intracavity 2-mm-thick quartz BRF at Brewster's angle. The maximum spectral tuning range achieved by rotating the BRF was 75 nm, from 1119 to 1194 nm, using 2% total output coupling as shown in Figure 2. The output power was recorded under 46 W of absorbed power at 5°C. Previously, we reported a maximum tuning range of 78 nm centred at 1160 nm using high-reflecting mirrors [8]. It is noted that in typical VCSEL and VECSEL devices employing periodic gain structures, the gain region is adjacent to at least one of the global cavity nodes imposed by the DBR, and the periodic gain structure acts as a spectral filtre depending on the intracavity position, thus enhancing the mode selectivity. In contrast, the gain structure in MECSELs can be placed anywhere inside the cavity. We previously reported the analysis on the MECSEL integrated gain factor where the FWHM bandwidth of the sinc function is twice that of the standard VECSEL [14], enabling enhanced wavelength tunability.

Conclusion: We have reported on the characterisation of a MECSEL emitting at 1178 nm targeting applications in SGLs. The comparison of the device with and without a BRF resulted in maximum output powers of 20.2 and 12.7 W and slope efficiencies of 27.7% and 25.4%, respectively. This constitutes a record in terms of output power for both MECSELs emitting at 1178 nm and MECSELs in general. Additionally, using the same BRF, the laser wavelength was capable of tuning over a range of 75 nm, from 1119 to 1194 nm using 2% output coupling.

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