72-W vertical-external-cavity surface-emitting laser with 1180-nm emission for laser guide star adaptive optics

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We report a high-power optically-pumped vertical-external-cavity surface-emitting laser emitting at around 1180 nm. The free-running laser produced 72 W of output power at a heatsink temperature of 0°C and 53 W near room temperature (20°C). The GaAs-based gain mirror was bonded to a 2-mm-thick diamond attached to a TEC-cooled copper mount in order to enable efficient heat extraction for high-power operation. Moreover, the spectrum of the laser was narrowed down to 0.06 nm by employing a combination of a birefringent filter and an etalon inside the cavity which yielded a maximum of 19 W at a heatsink temperature of 20°C. The demonstration opens a new perspective for the realisation of sodium laser guide star adaptive optics employing frequency doubling of 1180 nm radiation.

Introduction: High-power vertical-external-cavity surface-emitting lasers (VECSELs) emitting in the 1160–1200 nm infrared range have attracted attention due to their ability to generate yellow-orange radiation through second harmonic generation (SHG) [1]. In general, VECSELs are recognised for their power scaling abilities and excellent beam quality, as well as for a broad wavelength coverage enabled by material engineering. The highest power measured from a VECSEL exceeds 100 W at an emission wavelength of 1028 nm [2], and the wavelength coverage extends from ultraviolet (via SHG) to 5 µm, though not without gaps due to material challenges [3]. The 1100–1200 nm range, for example, imposes challenges due to the strain arising from the large lattice mismatch between GaInAs quantum wells and GaAs. This strain can be alleviated by adding small amounts of nitrogen into the crystal, making the so-called diluted nitride structures [4]. Below 1200 nm, the strain can also be compensated by careful optimisation of the growth parameters, i.e. employing strain compensation layers [5]. Furthermore, the external cavity allows for an inclusion of wavelength selective intracavity components which enable narrow-linewidth emission (below MHz range) [6] and high-power frequency-doubling through nonlinear crystals [1, 7]. Single-frequency operation at >20 W of output power has already been demonstrated by Zhang *et al.* at a fundamental wavelength of 1013 nm [8]. These features make VECSELs well suited for applications requiring high-power and high beam quality at specific wavelengths not easily addressed with standard techniques.

Adaptive optics is often employed on earth-based telescopes to correct for the distortion of images caused by the variations in the index of refraction of air due to atmospheric turbulence. As part of the adaptive optics system, a reference object – a so-called guide star – is needed [9]. Unfortunately, there are not many naturally occurring guide stars in the sky, but one can be created artificially by exciting sodium atoms in the atmosphere with a laser. This process sets demanding specifications for the excitation laser. The wavelength needs to match the sodium D_2 line and emit high-power, which translates to >20 W of continuous wave radiation at the challenging yellow wavelength of 589 nm with a linewidth <250 MHz [10].

In this Letter, we demonstrate a VECSEL emitting 72 W of continuous wave emission at around 1180 nm at a heatsink temperature of 0°C, which is the highest power reported to date for this wavelength range. The laser operated at multi-transverse and -longitudinal modes with a full-width-at-half-maximum (FWHM) of 5.5 nm. With the laser guide star-target in mind, we modified the cavity for single transverse mode operation and narrowed the spectrum to 0.06 nm with the available birefringent filter (BRF) and etalon. In this configuration, a maximum output power of 19 W was demonstrated near room temperature (20°C). With appropriate shielding from mechanical and acoustical vibrations and thermal stabilisation of the intracavity elements, we believe that high-power single-frequency operation with similar output power is attainable. Furthermore, frequency conversion to the desired 589-nm yellow wavelength can be achieved either with internal [1, 7] or external cavity doubling [11].

Experimental setup: The VECSEL consisted of a semiconductor gain mirror and a partially transmissive dielectric mirror (i.e. output coupler). The top-emitting gain mirror was grown by molecular beam epitaxy and comprised a 26-pair AlAs/GaAs distributed Bragg reflector and an active region. The active region incorporated 10 GaInAs quantum wells located at the antinodes of the optical standing wave. The compressively strained quantum wells were embedded between GaAs barrier layers and GaAsP strain compensation layers. The active region was terminated with a GaInP window layer to prevent surface recombination, and the active region thickness was matched to make the gain mirror microcavity resonant at the signal wavelength.

Efficient heat extraction is vital for high-power VECSELs. To this end, the gain mirror was capillary bonded from the front surface to a 2-mm-thick diamond heat spreader, which was further bonded to a large temperature stabilised copper heatsink with indium. The copper heatsink arrangement employed four 200-W thermoelectric coolers to keep the heatsink temperature stable even at low temperatures. An antireflection coating was deposited on the diamond heat spreader to minimise losses for the signal and pump wavelengths.

An I-shaped laser cavity was formed between the gain mirror and the output coupler, shown in Fig. 1. For the free-running demonstration, we used a 109-mm-long cavity and a 3% transmissive output coupler with a radius of curvature of 150 mm. The gain mirror was pumped with a commercially available 808-nm diode laser. The pump light was delivered through a 200-µm core fibre and focused onto the surface through a lens arrangement at an angle of ∼30°. A relatively large top-hat spot size of 950 µm in diameter (4σ value) was used in this experiment to provide lateral power scaling.

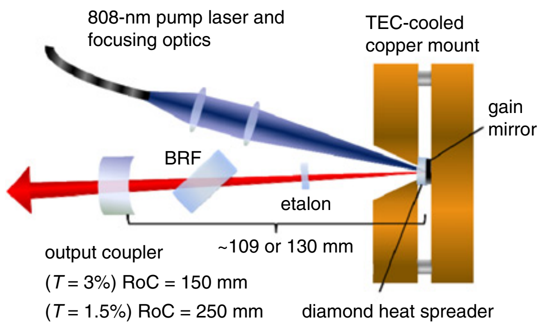

Fig. 1 *Cavity illustration of the 1180-nm VECSEL. The BRF and etalon were employed only in the longer cavity (l = 130 mm, RoC = 250 mm) for narrowing the spectrum*

In addition to the high-power free-running demonstration, we employed a second cavity to demonstrate the feasibility of the laser for narrow linewidth operation. In this setup, a 5-mm-thick quartz BRF and a 250-µm-thick YAG etalon were inserted into the cavity to narrow the spectrum. The length of the cavity was increased to 130 mm in order to make room for the BRF and the etalon. At the same time, the output-coupling mirror was changed to lower coupling (1.5%) to compensate for the losses produced by the new intracavity components, and the radius of the curvature increased to 250 mm to provide a larger mode size on the gain mirror. Moreover, the pump lens arrangement was adjusted to produce a smaller spot diameter (550 µm) for supporting fundamental transverse mode (TEM_{00}) operation.

Results: Fig. 2 shows the output power of the free-running VECSEL as a function of the incident pump power at heatsink temperatures of 0, 10 and 20°C. The incident pump power is defined as the total power incident on the diamond heat spreader and does not take into account the reflections from the diamond surfaces (estimated to be 5% with antireflection coating). The highest power of 72 W was measured at the heatsink temperature of 0°C. This corresponded to 257 W of incident pump power, 29% optical-to-optical conversion efficiency and 38% slope efficiency. To the best of our knowledge, this is the highest power reported at this wavelength range. During the 72-W operation, the spectrum of the laser was centred at 1185.5 nm and the FWHM was measured to be 5.5 nm, shown as an inset in Fig. 2. At heatsink temperatures of 10 and 20°C, the maximum output powers were 62 and 53 W, respectively.

For reference, we measured first the output power of the longer cavity with a 3% transmissive output coupler without any wavelength selective elements. A maximum of 25 W was measured at a heatsink temperature of 20°C. After the output coupler was changed to 1.5% coupling, we placed the BRF and the etalon inside the cavity and fixed the lasing wavelength to ~1178 nm. A maximum of 19 W of output power was measured at 20°C, and the FWHM linewidth of the uncovered table-top laser was 0.06 nm (Fig. 3). The resolution of the spectrum analyser was 0.01 nm. The beam profile was measured with a charge-coupled-device camera and showed single transverse mode operation (shown as an inset in Fig. 3).

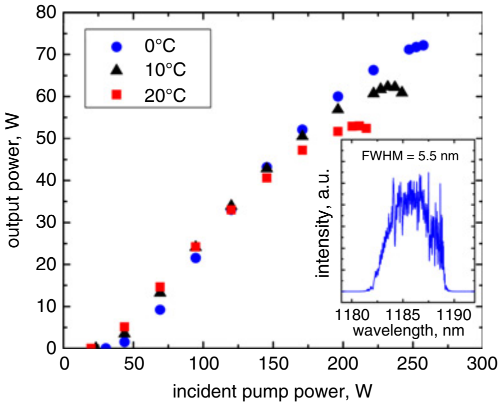

Fig. 2 *Output power curves for heatsink temperatures of 0, 10 and 20°C. Inset: Lasing spectrum recorded at 72 W of output power*

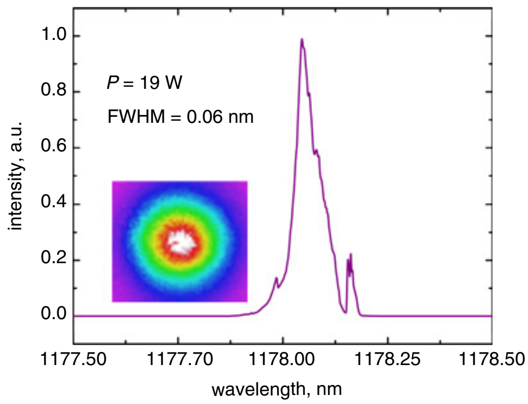

Fig. 3 *Normalised lasing spectrum at the maximum power (19 W) from the cavity including a 5-mm-thick BRF and 250-µm-thick YAG etalon. Inset: Beam profile measured at 19 W of output power*

The purpose of this wavelength narrowing was to demonstrate that high-power operation in single-frequency would be possible in the future with an appropriate mechanical design. In the future work, thicker BRF might be beneficial to further damp the unwanted cavity modes. In an earlier demonstration by Zhang *et al.*, a BRF with a thickness of 10 mm was employed to reach single-frequency operation [8], but in this letter, we were confined to the existing BRF stock in our lab.

Conclusions: We have demonstrated 72W of output power from a free-running VECSEL emitting at around 1180 nm at a heatsink temperature of 0°C. Near room temperature (20°C), the output power reached 53 W in the same configuration. Another cavity arrangement with additional intracavity elements (BRF and etalon) was employed to narrow the lasing spectrum down to 0.06 nm while emitting 19 W of output power near room temperature. The spectrum was narrowed to show that high-power operation is achievable even at more demanding spectral features. With further improvements of the cavity stabilisation, linewidth narrowing, and SHG, we target to demonstrate narrow-linewidth operation at 589 nm with spectral features fulfilling the needs of laser guide star adaptive optics.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Kantola, E., Leinonen, T., Ranta, S., *et al.*: 'High-efficiency 20 W yellow VECSEL', *Opt. Express*, 2014, **22**, (6), pp. 6372–6380, doi: 10.1364/OE.22.006372
2 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, doi: 10.1049/el.2012.0531
3 Guina, M., Rantamäki, A., and Härkönen, A.: 'Optically pumped VECSELs: review of technology and progress', *J. Phys. D: Appl. Phys.*, 2017, **50**, (38), pp. 1–37, doi: 10.1088/1361-6463/aa7bfd
4 Guina, M., Leinonen, T., Härkönen, A., *et al.*: 'High-power disk lasers based on dilute nitride heterostructures', *New J. Phys.*, 2009, **11**, 125019, doi: 10.1088/1367-2630/11/12/125019
5 Ranta, S., Tavast, M., Leinonen, T., *et al.*: '1180 nm VECSEL with output power beyond 20 W', *Electron. Lett.*, 2013, **49**, (1), pp. 59–60, doi: 10.1049/el.2012.3450
6 Burd, S.C., Allcock, D.T.C., Leinonen, T., *et al.*: 'VECSEL systems for the generation and manipulation of trapped magnesium ions', *Optica*, 2016, **3**, (12), pp. 1294–1299, doi: 10.1364/OPTICA.3.001294
7 Berger, J.D., Anthon, D.W., Caprara, A., *et al.*: '20 Watt CW TEM00 intracavity doubled optically pumped semiconductor laser at 532 nm', *Proc. SPIE*, 2012, **8242**, 824206, doi: 10.1117/12.907511
8 Zhang, F., Heinen, B., Wichmann, M., *et al.*: 'A 23-watt single-frequency vertical-external-cavity surface-emitting laser', *Opt. Express*, 2014, **22**, (11), pp. 12817–12822, doi: 10.1364/OE.22.012817
9 Max, C.E., Olivier, S.S., Friedman, H.W., *et al.*: 'Image improvement from a sodium-layer Laser guide star adaptive optics system', *Science*, 1997, **277**, (5332), pp. 1649–1652, doi: 10.1126/science.277.5332.1649
10 Enderlein, M., and Kaenders, W.G.: 'Sodium guide star (r)evolution', *Opt. Photon.*, 2016, **11**, (5), pp. 31–35, doi: 10.1002/opph.201600038
11 Wilson, A. C., Ospelkaus, C., VanDevender, A.P., *et al.*: 'A 750-mW, continuous-wave, solid-state laser source at 313 nm for cooling and manipulating trapped $^9Be^+$ ions', *Appl. Phys.*, 2011, **105**, (4), pp. 741–748, doi: 10.1007/s00340-011-4771-1