

Highly efficient optically pumped vertical-emitting semiconductor laser with more than 20 W average output power in a fundamental transverse mode

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We have demonstrated an optically pumped vertical-external-cavity surface-emitting laser (OP-VECSEL) generating more than 20 W of cw output power in a fundamental transverse mode ($M^2 \approx 1.1$) at 960 nm. The laser is highly efficient with a slope efficiency of 49%, a pump threshold of 4.4 W, and an overall optical-to-optical efficiency of 43%. © 2008 Optical Society of America

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High-power and efficient optically pumped semiconductor lasers with good beam quality are highly desirable for a wide variety of applications. They benefit from the advantages of the semiconductor gain material, such as the high quantum efficiency, high-gain cross section, and bandgap engineering. Bandgap engineering enables operation over a broad wavelength range from the UV to the mid-IR, accessing spectral regions, which are not covered by other lasers. However, the achievable brightness of semiconductor lasers is substantially lower than it is for other laser types. Applications that require several watts in a fundamental transverse mode have typically relied on diode-pumped, ion-doped, solid-state bulk or fiber lasers. Edge-emitting semiconductor lasers are currently restricted to a few watts of output power owing to end facet damage and thermal issues, which both arise from the limited mode area. Mode area limitations also prevent electrically pumped vertical-cavity surface-emitting lasers (VCSELs) from exceeding power levels above a few milliwatts in a fundamental transverse mode, because current injection becomes more challenging at larger beam areas. The combination of a VCSEL gain structure with an external cavity, referred to as the vertical-external-cavity surface-emitting laser (VECSEL), substantially increased the TEM₀₀ output power to currently ≈ 0.5 W [1]. The concept of optically pumped VECSELs (OP-VECSELs) [2,3] further reduces the limitation in mode area and enables multi-watt operation in a diffraction-limited beam. In an analogy of optically pumped solid-state thin-disk lasers [4], OP-VECSELs offer the possibility to scale the optical output power with pump spot area while maintaining high beam quality.

So far OP-VECSELs with a fundamental transverse mode beam have been restricted in average output power to ≈ 4 W ($M^2 < 1.15$) [5] and ≈ 4.4 W ($M^2 < 1.13$) [6] with overall optical-to-optical conversion efficiencies of 20% and 25%, respectively. Higher

output powers and higher efficiencies were achieved only at the expense of reduced transverse beam quality; for example, 8 W with an M^2 of 1.8 [7], 12 W with an M^2 of 2 [8], and 30 W with an M^2 of 3 [9]. Here we have demonstrated an OP-VECSEL operating in a fundamental transverse mode ($M^2 < 1.1$) at an output power of 20.2 W with a simple straight cavity. In contrast to other results [10,11], we did not use an intracavity diamond heat spreader bonded directly on the semiconductor gain chip, but instead we grew the semiconductor layer structure in reverse order, soldered it directly onto a diamond heat spreader, and removed the substrate [12]. This approach does not suffer from the optical properties of the diamond heat spreader etalon, which typically introduces a modulated spectrum corresponding to the etalon modes. In addition, this approach allows for simple passive mode locking with a semiconductor saturable-absorber mirror inside the laser cavity [6].

Our gain structure was grown by metal-organic vapor-phase epitaxy on a GaAs substrate and consists of three parts: the bottom mirror, the active region, and an antireflective (AR) structure. Figure 1 shows the refractive index profile of the semiconductor gain structure and the on-axis standing-wave intensity pattern of the incoming laser beam normalized to the incoming peak intensity. The design is optimized for the laser wavelength around 960 nm (0° angle of incidence) and the pump wavelength of 808 nm (45° angle of incidence). The Al_{0.2}Ga_{0.8}As/AlAs bottom mirror is a 36-pair Bragg reflector optimized for high reflectivity at the laser wavelength (99.95%) but also for high reflectivity at the pump wavelength (97%). This results in a double pass through the active region, which leads to an 85% absorption of the pump light. The active region contains seven In_{0.13}Ga_{0.87}As quantum wells (QWs) placed in the maxima of the standing wave pattern of the laser field. They are separated by spacer layers made of pump-absorbing GaAs and GaAs_{0.94}P_{0.06} lay-

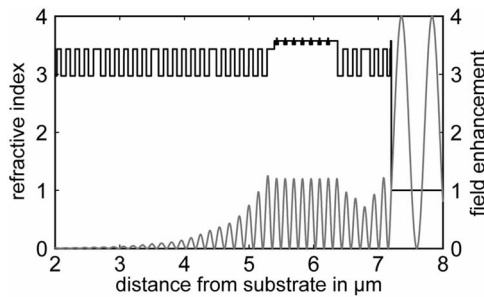


Fig. 1. VECSEL gain structure with vertical refractive index profile and normalized intensity pattern. The structure consists of a double-periodic bottom mirror, a gain section, and an AR section.

ers. The tensile-strained $\text{GaAs}_{0.94}\text{P}_{0.06}$ layers serve as strain-compensating layers and are positioned on both sides of the QWs. The $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{AlAs}$ AR section is placed on top toward the external cavity and is also optimized for both the laser and the pump wavelength: It reflects less than 1% of the laser power and less than 3% of the pump power.

The structure was grown in reverse order, meaning that first the etch stop layers and the AR section were grown, followed by the gain section and the bottom mirror. Smaller pieces were then cleaved from the wafer, metallized with Ti-Pt-Au, and finally soldered to heat spreaders with In in a fluxless soldering process under vacuum. As heat spreaders we used commercial chemical-vapor-deposition diamonds with a thickness of $530\ \mu\text{m}$ and a thermal conductivity $>1800\ \text{W/Km}$. Afterward the GaAs substrate was removed in a wet-chemical etching procedure. The design and processing of our gain structure has been described in detail in [12]. The reduced thickness of the semiconductor material ($\approx 7\ \mu\text{m}$) leads to low thermal impedance and to a nearly one-dimensional heat flow into the heat sink, which makes the device power scalable: The output power can be doubled by applying twice the pump power to twice the mode area without raising the temperature in the gain structure. However, at one point the power scalability breaks down, when the major part of the thermal impedance results from the heat sink (where the heat flow is not one dimensional) and no longer from the semiconductor structure. In our case the thermal conductivity of copper ($400\ \text{W/Km}$) was not sufficient, and we therefore chose diamond as heat-sink material with a thermal conductivity of $>1800\ \text{W/Km}$.

Figure 2 shows the laser setup used in this experiment. The laser is formed by a simple straight standing-wave cavity with the semiconductor gain structure as one end mirror and the output coupler as the second end mirror. The gain structure was pumped by a fiber-coupled diode array, emitting at 808 nm with up to 55 W of optical power on a circular spot with a radius of approximately $240\ \mu\text{m}$. The laser mode inside the semiconductor structure is defined by the external cavity (i.e., cavity length and the curvature of the output coupler) and has a radius of $\approx 215\ \mu\text{m}$, slightly smaller than the pump spot. The output coupler had a transmission of 0.7% and a

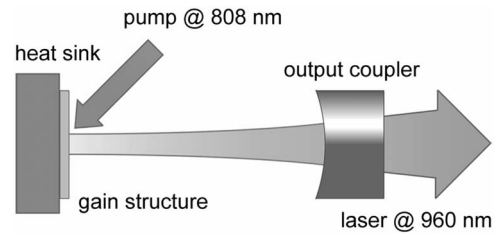


Fig. 2. VECSEL cavity setup.

radius of curvature of 500 mm, and the cavity length was 50 mm. The thermal lens was measured to be negligible. The heat sink was temperature stabilized by a water-cooled high-power peltier element and was held at $-20\ ^\circ\text{C}$.

Figure 3 shows the cw output power of the VECSEL versus the incident pump power. The slope efficiency is 49.1%, the pump threshold is 4.4 W, and the maximum optical-to-optical conversion efficiency is 43.2%. At output powers $>18\ \text{W}$ we start to observe a rollover owing to the temperature rise in the gain structure; the maximum achieved output power was 20.2 W. The output power was continuously adjustable from threshold up to 20.2 W without any discontinuities or signs of instabilities. This also indicates that the thermal lens was rather weak and had no influence on the laser performance. The VECSEL operated at the maximum output power for several hours without any signs of degradation. Only when the laser was pumped beyond the thermal rollover, irreversible damage occurred. We believe that this happens when the temperature in the gain structure reaches the In melting temperature, which destroys the solder junction and thus raises the thermal impedance.

Figure 4 shows the beam-quality measurement, which was done at the maximum output power. The M^2 was measured to be 1.0 ± 0.1 in sagittal and 1.1 ± 0.1 in tangential direction, indicating fundamental mode operation. Figure 5 shows the optical spectrum located at approximately 960 nm, also taken at the maximum output power.

In conclusion, we have presented an optically pumped cw VECSEL generating 20.2 W in a fundamental TM beam ($M^2 < 1.1$). To our knowledge this is

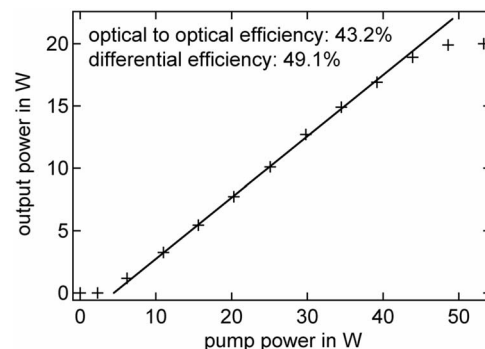


Fig. 3. Output power versus pump power: The maximum optical-to-optical conversion efficiency is 43.2% and the slope efficiency is 49.1%.

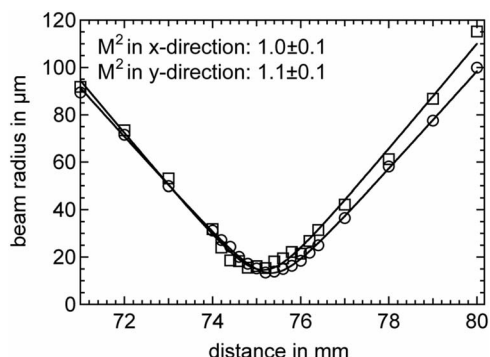


Fig. 4. Beam-quality measurement is $M^2 < 1.1$ in both directions.

the highest output power achieved by a VECSEL with such high beam quality. We have demonstrated a slope efficiency as high as 49.1% and a maximum optical-to-optical conversion efficiency of 43.2%. With such performance, OP-VECSELs become an attractive alternative to ion-doped solid-state, and fiber lasers, which are widely used in applications requiring tens of watts power in a fundamental transverse mode beam. OP-VECSELs appear suitable for further power scaling by increasing proportionally pump power and mode area. We expect that these semiconductor lasers, which can operate at wavelengths not

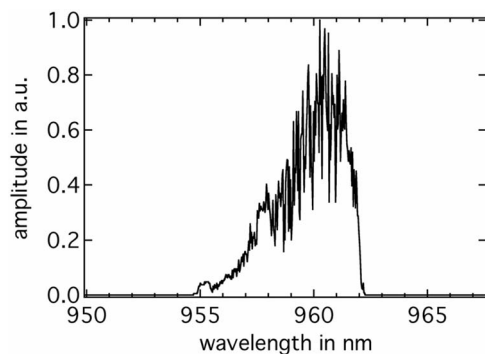


Fig. 5. Optical spectrum centered at 960 nm.

easily accessible by other laser types, will achieve output powers in the 100 W range in a fundamental transverse mode.

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