Novel semiconductor lasers attractive for UV-visible applications

Mahmoud Fallahi, Chris Hessenius, Yushi Kaneda, Jörg Hader, Jerome Moloney, Bernardette Kunert, Wolfgang Stolz, and Stephan Koch

Frequency doubling of an optically pumped vertical-external-cavity surface-emitting laser enables a new multiwatt tunable yellow-orange light source.

Compact, tunable, high-power semiconductor lasers, particularly those covering the UV and visible regions of the spectrum, are needed for many military and commercial applications. Yellow-orange sources are particularly desirable for sodium guide-star lasers, quantum computing, and medical applications. Semiconductor lasers in the visible region typically use one of two approaches: growth of a direct-band material with the proper energy gap, or frequency conversion of a near-IR source. Optically pumped vertical-external-cavity surface-emitting lasers (VECSELs) are strong, low-cost candidates to meet these critical features. In addition, easy access to the laser intracavity allows for new features, such as frequency doubling (also known as second-harmonic generation, SHG), linewidth narrowing, or quality switching (‘Q switching’), the production of a pulsed output beam. Compared to electrically pumped semiconductor lasers, optically pumped VECSELs have several advantages. For example, optical pumping is an easy way to achieve uniform pumping over a large area. In addition, using a barrier-pumping scheme eliminates the sensitivity to the pump wavelength and allows the use of cheap, readily available pump sources. Since no doping is required, cavity loss can be minimized.

The VECSEL gain structure can be accurately designed using a many-body microscopic quantum-design tool to maximize pump absorption and improve both modal gain and high-power operation. Combined with 3D optical/thermal optimization and gain-subcavity detuning, this allows for development of multiwatt sources emitting at various wavelengths.

Appropriate choices for the external mirror and cavity length allow VECSELs to operate in the fundamental transverse mode (TEM00) with high efficiency. By inserting a nonlinear crystal into the laser cavity, where the circulating power is 100 times stronger than the output power, efficient SHG can be achieved. Our team has successfully developed a wide range of high-power VECSELs with many desirable features, including large-range wavelength tuning, narrow linewidth, and high beam quality at various near-IR and visible wavelengths.

To create a yellow-orange VECSEL, we grew a structure consisting of ten repeats of highly compressive strained indium-gallium arsenide (InGaAs) quantum wells. Each quantum well is surrounded by gallium-arsenide-phosphide strain-compensation layers and GaAs barriers. The thickness and composition of each layer is optimized such that the quantum wells are positioned at the antinodes of the cavity standing wave to provide resonant periodic gain (RPG) in the active region. A high-reflectivity distributed-Bragg reflector (DBR)-stack made of 21 pairs of aluminum-gallium arsenide/aluminum arsenide is

Figure 1. Schematic of a V-shaped vertical-external-cavity surface-emitting laser (VECSEL) for yellow-orange generation. QW’s: Quantum wells. LBO: Lithium-triborate crystal. DBR: Distributed-Bragg reflector. BF: Birefringent filter.

Continued on next page
grown on top of the active region. The wafer is then cleaved and mounted onto a chemical-vapor-deposition (CVD) diamond heat sink for efficient heat dissipation. A V-shaped cavity, shown in Figure 1, is used to produce the yellow-orange laser. An intracavity birefringent filter inserted at Brewster’s angle is incorporated to improve the spectral purity. Wavelength tuning is achieved by rotating the birefringent filter about its normal direction.

To characterize the fundamental operation of the laser, we focused a fiber-coupled 808nm pump source on a 500µm-diameter spot on the chip. A folding concave mirror that is highly reflective at the fundamental (∼1175nm) wavelength is used along with an external flat mirror that is 4% transmissive. The external flat mirror serves as the output coupler. More than 8.5W output power is achieved at ∼1175nm. The $M^2$ factor, which indicates beam quality, is about 1.5 at more than 8W output power (see Figure 2), indicating a near-TEM$_{00}$ transverse mode at high-power operation.

After the fundamental characterization, we replaced the flat output coupler with a highly reflective flat mirror to create the high-Q cavity needed for efficient SHG. A lithium-triborate crystal is inserted close to the flat mirror for frequency doubling. For a 500µm-diameter pump spot, the laser generates more than 5W of yellow-orange light at ∼587nm. The overall pump optical-power-to-yellow-light optical-conversion efficiency exceeds 14%, which is the result of high-performance fundamental generation and efficient intracavity frequency doubling. Figure 3 presents the wavelength tuning of the yellow-orange laser. In Figure 4 we show the yellow-laser output created by intracavity frequency doubling of a highly strained InGaAs/GaAs tunable VECSEL.

In summary, semiconductor VECSELs can be used to create high-power UV (240nm) to near-IR (∼2µm) lasers. It is likely

Continued on next page
that in the near future VECSELs will be a viable alternative for many of the tasks for which diode-pumped solid-state lasers are currently used. VECSELs also offer the potential to scale average output power to very high levels by incorporating multichips in the same cavity. Multichip VECSELs, combined with high-quality quantum-well growth and improved processing techniques, may lead to kilowatt-level tunable lasers.\(^6\)

**Author Information**

**Mahmoud Fallahi, Chris Hessenius, and Yushi Kaneda**  
College of Optical Sciences  
University of Arizona  
Tucson, AZ

**Jorg Hader and Jerome Moloney**  
Nonlinear Control Strategies Inc. and  
University of Arizona  
Tucson, AZ

**Bernadette Kunert, Wolfgang Stolz, and Stephan Koch**  
University of Marburg  
Marburg, Germany

**References**