Princeton Optronics

is now

Member of the ams Group

The technical content of this Princeton Optronics document is still valid.

Contact information:

Headquarters:
ams AG
Tobelbader Strasse 30
8141 Premstaetten, Austria
Tel: +43 (0) 3136 500 0
e-Mail: ams_sales@ams.com

Please visit our website at www.ams.com

Compact 4.7 W, 18.3% wall-plug efficiency green laser based on an electrically pumped VECSEL using intracavity frequency doubling

Pu Zhao, Bing Xu, Robert van Leeuwen, Tong Chen, Laurence Watkins, Delai Zhou, Peng Gao, Guoyang Xu, Qing Wang, and Chuni Ghosh*

Princeton Optronics, Inc., 1 Electronics Drive, Mercerville, New Jersey 08619, USA
**Corresponding author: cghosh@princetonoptronics.com*

Received May 2, 2014; revised July 11, 2014; accepted July 11, 2014;
posted July 14, 2014 (Doc. ID 211399); published August 7, 2014

We have demonstrated a compact, 4.7 W green laser based on an electrically pumped vertical external-cavity surface emitting laser through intracavity frequency doubling. The overall wall-plug efficiency (electrical to green) was 18.3%. The power fluctuations were measured to be ±1.4% over a 2 h time period.

OCIS codes: (140.7260) Vertical cavity surface emitting lasers; (140.3515) Lasers, frequency doubled; (190.2620) Harmonic generation and mixing.
http://dx.doi.org/10.1364/OL.39.004766

Nowadays, there is increasing demand for laser displays in television, mobile phone, and movie theater projector applications. The light source for a full-color laser display is realized by mixing three separate lasers with red, blue, and green wavelengths. Currently, the green laser remains a bottleneck in achieving efficient high power laser displays. Direct green laser diode technology has made great progress in recent years, but this technology is still far away from being mature and green output powers are restricted to only 1 W with a wall-plug efficiency of 14% [1]. Most green sources are, therefore, still provided by intracavity frequency doubled solid-state lasers. These lasers tend to be bulky and expensive, the exception being the green microchip laser, but its output is also at most 1 W [2].

Recently, vertical external-cavity surface emitting lasers (VECSELs), also referred to as semiconductor disk lasers, have become an attractive alternative to high power high-efficiency solid-state lasers in the wavelength region around 1 μm [3–5]. They operate with high performance in the wavelength region between 0.65 and 1.15 μm. It has also been demonstrated that the VECSEL could efficiently generate laser radiation in the visible region based on intracavity frequency doubling [6–9]. A VECSEL is composed of a gain medium with a structure similar to a vertical cavity surface emitting laser (VCSEL) and an external cavity, which may include lenses, mirrors, and other optical components. The VECSEL has similar advantages as both the VCSEL and the solid-state laser, such as compact size, round beam, wide working temperature range, better beam quality, flexible mode manipulation etc. In addition, the VECSEL has the advantage of good thermal management due to its extremely efficient capability of heat spreading, which is a very important factor for power scaling.

VECSELs can be optically pumped or electrically pumped. The electrical pumping method is more attractive since it is a less complex pumping scheme. Moreover, the electrically pumped VECSEL (EP-VECSEL) can easily be designed as a 2D array with multiple lasing elements, dramatically scaling up the output power [10]. As a consequence, the EP-VECSEL is more suitable for mass production, which greatly reduces its manufacturing costs. To achieve higher output power from a single device, a larger active area is required so that more electrical power can be injected. However, because it is difficult to inject current uniformly into a larger active region, the output power generated by intracavity second harmonic generation (SHG) from single devices has so far been limited to around 100 mW [11–13].

In this Letter, we report an EP-VECSEL with a large active area and demonstrate its capability for high efficiency SHG with green output power at the multi-Watt level. In the experiment, we achieved continuous-wave (CW) green output power of 4.7 W at 531 nm with a wall-plug efficiency of 18.3% (electrical to green efficiency). To the best of our knowledge, these results are the highest values that have been reported to date from an intracavity frequency doubled EP-VECSEL. In addition, the output power was very stable, with a variation of ±1.4% over a 2 hour time period.

The epitaxy materials of the EP-VECSEL gain device used in this experiment were grown on an n-type GaAs substrate using MOCVD. The substrate doping concentration is low, $<2\times10^{17}\ \mathrm{cm}^{-3}$, in order to minimize free carrier absorptions. The gain section consists of strained InGaAs/GaAs multiple quantum wells (MQW). The MQW is sandwiched between n-type spacers/distributed Bragg reflector (DBR) and p-type spacers/DBR layers, both of which are made of highly doped GaAs/AlGaAs layers for electrical conduction. The p-type DBR has a high reflectivity (>99%) and, therefore, functions as the end-mirror of the laser cavity. On the other side of the MQW, the n-type DBR has a lower reflectivity and forms an internal cavity with p-type DBR. To fabricate such devices, on the epitaxial side, Ti/Pt/Au disks with a targeted diameter are evaporated to form the p-type contacts, which at the same time act as the self-aligned mask for subsequent dry-etching (RIE) of mesas, deep enough to expose the aluminum-rich layer. The samples are then exposed to high humidity in a furnace (350°C–420°C) for the selective oxidation process for electrical confinement. The

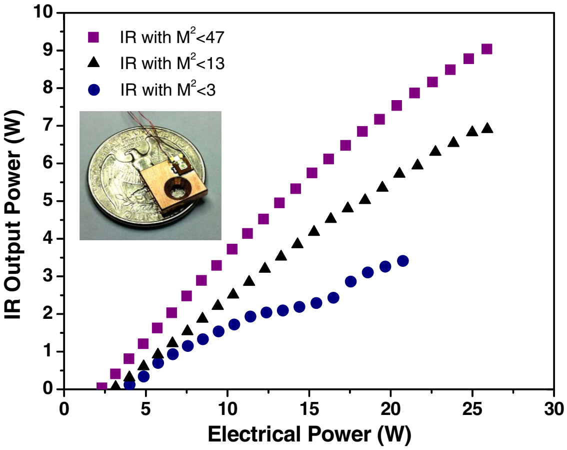

Fig. 1. Continuous-wave IR output power as a function of pumped electrical power. Inset: the gain device of EP-VECSEL packaged onto a C-mount.

emission area of the device is also controlled by oxide apertures. In this research, the emission diameter of the circular emission area was designed to be 390 μm, which is large for an EP-VECSEL. On the substrate side, the substrate is thinned to a less than 150 micron thickness, to minimize absorption losses, and then polished to an optical finish. A quarter wave Si_3N_4 anti-reflection (AR) coating is deposited using PECVD, followed by patterning, etching of the field nitride and, finally, Ge/Au/Ni/Au N-metals evaporation. This gain device with such a large area is capable of providing sufficient IR power for efficient frequency doubling.

The IR performance of the device was tested and the results are shown in Fig. 1. The measurement was based on a simple bare cavity configuration consisting of only the gain device and a flat output coupler (OC) with a reflectivity of 81%. A stable cavity was formed due to the thermal lens in the gain device. By changing the distance between the gain device and OC, the transverse mode structure of the output beam could be varied. As the OC was moved toward the gain device, the fundamental mode size became much smaller than the active region of the device so that output beam became multimode. With 25.9 W injected electrical power, 9.04 W multimode output power was achieved, corresponding to a wall-plug efficiency of 34.9%. The beam quality M^2 was measured to be around 47. The peak wall-plug efficiency was measured to be 37.9% at 15.18 W electrical input. Then, as the distance between gain device and OC was increased, the laser was forced to operate at lower order transverse modes thus improving the beam quality. With 20.75 W electrical pumping power, we achieved 3.41 W output power with a wall-plug efficiency of 16.4%. The M^2 beam quality parameter was measured to be less than 3.

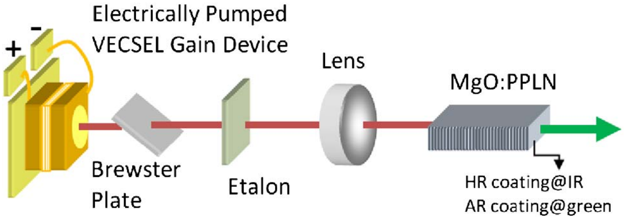

Fig. 2. Experimental setup for the electrically pumped vertical external cavity surface emitting green laser.

A schematic of the setup for intracavity SHG is presented in Fig. 2. The EP-VECSEL gain device is mounted on a C-mount package, which is attached to a metal heat sink cooled by a thermoelectric cooler (TEC). During the measurements, the temperature of heat sink was kept constantly at 20°C. By not using liquid cooling, the laser design could be kept compact which is a great benefit for laser packaging. Due to the thermal lens effect in the gain device, it is possible to use the flat surface of the nonlinear optical crystal as the OC of the laser. The output surface of the crystal is high-reflection (HR) coated for IR and AR coated for green, while the input surface is AR coated for IR and HR coated for green. In this approach all the green power is coupled in the forward direction.

In this experiment, we chose a MgO: PPLN crystal as the optical frequency converter. The crystal is 1 mm thick, 7 mm long, with a periodically poling period of 6.94 μm. To improve the IR to green conversion efficiency, a plano-convex lens with a 15 mm focal length was introduced into the cavity to decrease the beam size and, thus, increase the intracavity IR power density at the MgO:PPLN crystal. A Brewster plate was used to stabilize the polarization and ensure that the polarization direction of the IR beam was parallel to the electric poling direction of MgO:PPLN crystal. In addition, a wavelength selective etalon was inserted into the cavity, reducing the IR bandwidth to around 0.2 nm, which is narrower than the acceptance bandwidth of the 7 mm MgO:PPLN crystal. The total cavity length is around 70 mm.

The measured CW green output power is shown as a function of electrical power in Fig. 3. At 25.97 W electrical input power, we achieved 4.74 W green power at 531 nm, corresponding to a wall-plug efficiency of 18.3%. When considering the 2.2% loss at 531 nm from the filter (not shown in Fig. 2), which blocks the residual IR power of the beam, the real green power is 4.85 W, corresponding to a wall-plug efficiency of 18.7%. To the best of our knowledge, the CW green power and efficiency are the highest values achieved to date using an intracavity frequency doubled EP-VECSEL. The M^2 beam quality parameter was measured to be around 13. To

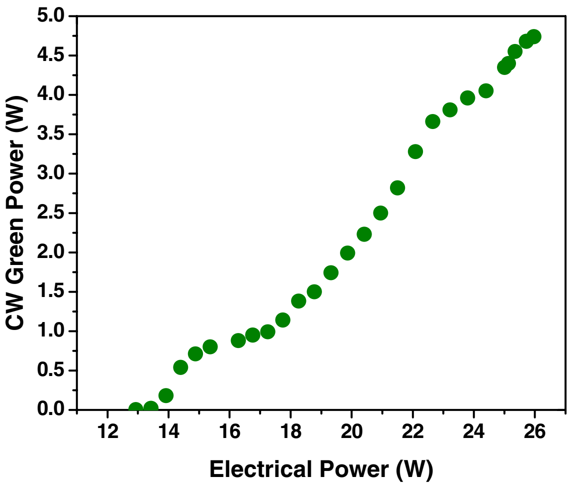

Fig. 3. Continuous-wave green output power was measured as a function of pumped electrical power.

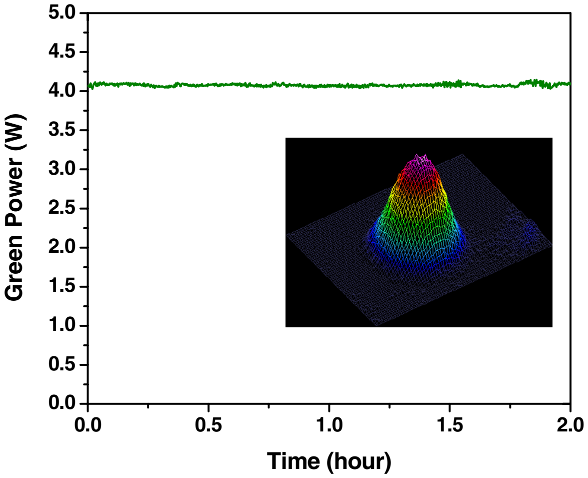

Fig. 4. Stability measurement of the green output power. Inset: green beam profile measured by a CCD camera.

estimate the optical conversion efficiency, we replaced the MgO:PPLN crystal with OCs with various reflectivities and measured the IR output power. At 25.97 W electrical input power, 6, 5.43, and 3.98 W IR output power were measured when using OCs with 19%, 15%, and 9% transmission, respectively. By comparing the IR power to the green power generated at the same electrical input power, it was estimated that the SHG efficiency achieved was equivalent to the output coupling efficiency of an OC with transmission between the 9% and 15% range.

We investigated the output power stability by measuring the power as a function of time. With the output power set at 4.09 W, the power fluctuations were recorded in a time period of 2 h. As shown in Fig. 4, the variation is within ±1.4% of the total output power. The far field beam intensity profile was measured using a CCD camera and it is shown in the inset of Fig. 4.

In summary, we have demonstrated a high power, high efficiency CW green output from an intracavity frequency doubled EP-VECSEL. To the best of our knowledge, the 4.7 W green output power and 18.3% electrical to green wall-plug efficiency are the highest power and efficiency that have been reported to date from an EP-VECSEL. The laser is compact, TEC cooled, electrically pumped, and has a simple cavity structure. All of these properties will greatly benefit packaging for a product suitable for mass production. Furthermore, due to the fact that VECSELs can deliver high performance all across the 0.65–1.15 μm wavelength region, this technology could be extended to achieve powerful and portable lasers at other visible wavelengths, or even in the UV region.

References

1. S. Masui, T. Miyoshi, T. Yanamoto, and S. I. Nagahama, in *Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)* (IEEE, 2013), paper 6600212.
2. Y. Lu, Q. Xu, Y. Gan, and C. Xu, IEEE Photon. Technol. Lett. **22**, 990 (2010).
3. B. Rudin, A. Rutz, M. Hoffmann, D. J. H. C. Maas, A.-R. Bellancourt, E. Gini, T. Südmeyer, and U. Keller, Opt. Lett. **33**, 2719 (2008).
4. K. S. Kim, J. R. Yoo, S. H. Cho, S. M. Lee, S. J. Lim, J. Y. Kim, J. H. Lee, T. Kim, and Y. J. Park, Appl. Phys. Lett. **88**, 91107 (2006).
5. A. Garnache, S. Hoogland, A. C. Tropper, I. Sagnes, G. Saint-Girons, and J. S. Roberts, Appl. Phys. Lett. **80**, 3892 (2002).
6. T. D. Raymond, W. J. Alford, M. H. Crawford, and A. A. Allerman, Opt. Lett. **24**, 1127 (1999).
7. E. U. Rafailov, W. Sibbett, A. Mooradian, J. G. McInerney, H. Karlsson, S. Wang, and F. Laurell, Opt. Lett. **28**, 2091 (2003).
8. A. Harkonen, J. Rautiainen, M. Guina, J. Konttinen, P. Tuomisto, L. Orsila, M. Pessa, and O. G. Okhotnikov, Opt. Express **15**, 3224 (2007).
9. A. Hein, S. Menzel, and P. Unger, Appl. Phys. Lett. **101**, 111109 (2012).
10. J. F. Seurin, C. L. Ghosh, V. Khalfin, A. Miglo, G. Xu, J. D. Wynn, P. Pradhan, and L. A. D'Asaro, Proc. SPIE **6908**, 690808 (2008).
11. R. V. Leeuwen, J. F. Seurin, G. Xu, and C. Ghosh, Proc. SPIE **7193**, 71931D (2009).
12. J. G. McInerney and A. Mooradian, Proc. SPIE **7919**, 79190L (2011).
13. H. Lindberg, S. Illek, I. Pietzonka, M. Furitsch, A. Plößl, S. Haupt, M. Kühnelt, R. Schulz, U. Steegmüller, T. Höfer, and U. Strauß, Proc. SPIE **7919**, 79190D (2011).