21.2% Wall-plug efficiency green laser based on an electrically pumped VECSEL through intracavity second harmonic generation

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ABSTRACT

We have achieved a 21.2% wall-plug efficiency green laser at 532 nm based on an electrically pumped vertical external-cavity surface emitting laser (VECSEL) through intracavity second harmonic generation. The continuous-wave green output power was 3.34 W. The VECSEL gain device is cooled by using a thermoelectric cooler, which can greatly benefit packaging. Both power and efficiency can be further scaled up by optimizing external-cavity design and improving the performance of VECSEL gain device.

Keywords: green laser, vertical external-cavity surface emitting laser, electrical pumping, intracavity second harmonic generation.

1. INTRODUCTION

Recently, vertical external-cavity surface emitting lasers (VECSELs) have become an attractive alternative to high power high-efficiency solid-state laser in the wavelength region around 1μm [1-3]. It has also been demonstrated that VECSELs could efficiently provide visible laser output based on intracavity frequency doubling [4-7]. Such lasers provide the advantage of efficient thermal management due to its unique capability of spreading heat, which is a very important property for power scaling. Besides, the intracavity frequency doubling technique has become very mature, especially due to the advanced development of quasi-phase-matched nonlinear optical crystals [8-10].

There are basically two approaches for pumping a VECSEL, namely optical pumping and electrical pumping. The electrical pumping method is more attractive since it is a less complex pumping scheme. Moreover, the electrically pumped VECSEL can easily be designed as an array that is composed of multiple lasing elements. Consequently, the output power can be dramatically scaled up [11-12]. As a result, the electrically pumped VECSEL is believed to be more suitable for mass production so that the manufacturing cost could be greatly reduced.

In order to improve the output power from a VECSEL with an array as the gain device, it is beneficial to achieve higher output power or higher efficiency from each gain element first. The most immediate approach is to increase the emitting area of the gain device. As the active area is increased, more IR output power will be available. However, as the active area and current are both increased, it is difficult to inject current uniformly into a larger active region. Due to this reason, the SHG output power in the visible region, until recently, been limited far below the Watt level [13-15].

In our recent work, we reported an electrically pumped VECSEL with a large emitting area and demonstrated its capability for high efficiency intracavity second harmonic generation (SHG) with output powers at the multi-Watt level [16]. In that experiment, we achieved a continuous-wave green output power of 4.7W at 531nm with a wall-plug efficiency of 18.3% (electrical to green efficiency).

In this paper, we reported our most recent experimental result of an electrically pumped green VECSEL which has a wall-plug efficiency as high as 21.2%. It was achieved by using a VECSEL gain device with an even larger emitting area than in Ref. [16]. We achieved higher IR power, while still controlling the 1.06μm IR beam to a similar beam size at the intra-cavity doubling crystal, thus improving the beam intensity. As the SHG efficiency is proportional to this parameter, we can therefore improve the overall green wall-plug efficiency.

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2. EXPERIMENTAL SETUP

The schematic of setup for the electrically pumped green VECSEL is similar to that in Ref [16]. The electrically pumped VECSEL gain device is mounted on C-mount package, which is attached to a metal heat sink cooled by a thermoelectric cooler (TEC). By not using liquid cooling, this design can make the laser rather compact providing a great benefit for laser packaging and mass production. The two end mirrors of this laser cavity are the distributed Bragg reflector (DBR) in the gain device and the output surface of nonlinear optical crystal, respectively. They both have high reflectivity for IR at 1.06 μm. While these two end-mirrors have flat surfaces, we placed a plano-convex lens (focal length equals 15 mm) between these two elements. The laser mode has beam waists both on the DBR mirror of VECSEL gain device and output surface of crystal. The beam size on the gain device is restricted by the size of active region. By changing the position of lens between two end-mirrors of laser cavity, we can vary the beam size ratio of the two beam waists. Correspondingly, we can actively control the actual beam size on the nonlinear optical crystal. Therefore, the IR power density could be controlled accordingly.

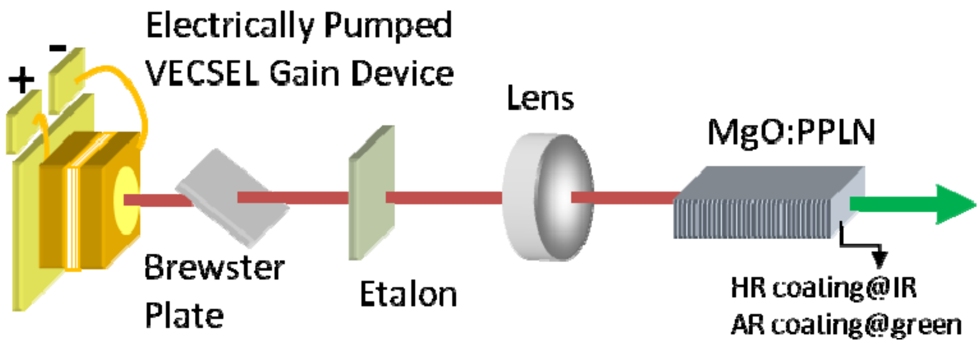

Figure 1. Experimental setup for the electrically pumped vertical external cavity surface emitting green laser.

The VECSEL gain device has an InGaAs/GaAs multiple quantum wells (MQW) structure to provide the gain at 1064 nm. The MQW structure is sandwiched between n-type DBR and p-type DBR. 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 structure, the n-type DBR has a lower reflectivity and forms an internal cavity with p-type DBR. The n-type DBR was grown on the GaAs substrate, which functions as the interface between the VECSEL gain device and the external cavity. The output surface of GaAs substrate is anti-reflection (AR) coated to minimize the optical loss. The emission size of the device was controlled by oxide apertures. In this experiment, the emission diameter after oxidation was increased to 440 μm which is 50 μm larger than the gain device used in Ref. [16]. The increased active area is capable of providing more IR power which could be used to increase the IR beam density. Such improvement is a critical factor for improving the efficiency of the frequency doubling process.

In this experiment, we chose MgO: PPLN crystal as the optical frequency converter. The crystal is 1mm thick, 7 mm long with a periodically poling period of 6.94 μm. The output surface of the crystal is high-reflection (HR) coated for IR and AR coated for green, while the other surface is AR coated for IR and HR coated for green. In this approach, all the green power is coupled out in the forward direction.

A Brewster plate is used to stabilize the polarization of VECSEL, and to ensure that the polarization direction of the IR beam is parallel to electric poling direction of MgO: PPLN crystal. In addition, a wavelength selective etalon is inserted into the cavity such that the IR bandwidth is reduced to around 0.2 nm, which is narrower than the acceptance bandwidth of the 7 mm MgO: PPLN crystal.

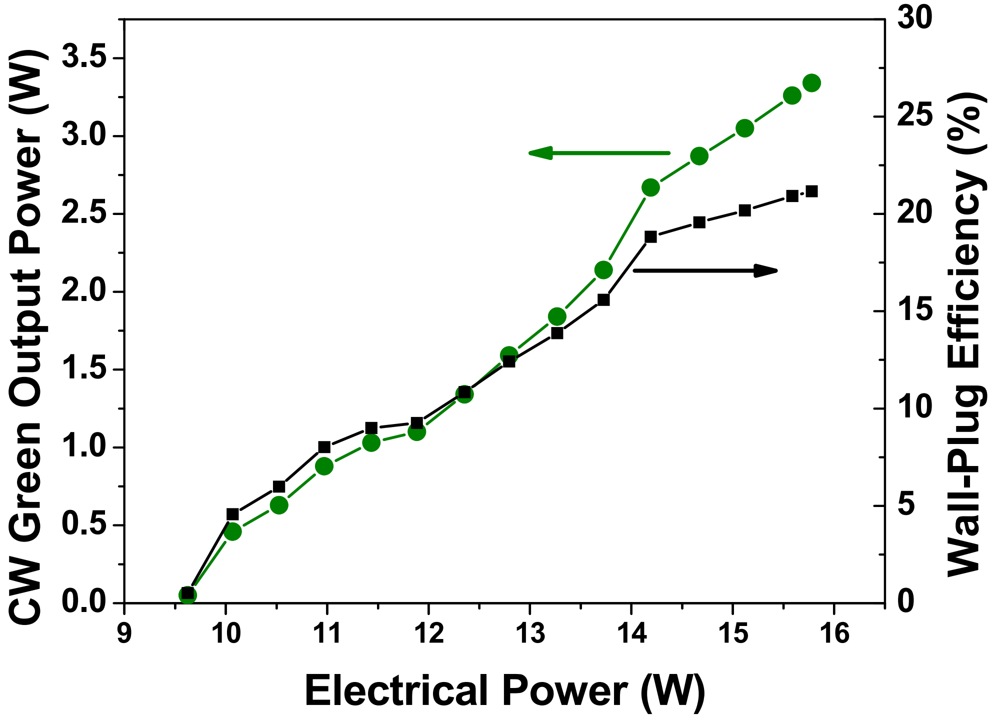

Figure 2 Continuous-wave green output power and corresponding wall-plug efficiency as a function of electrical power.

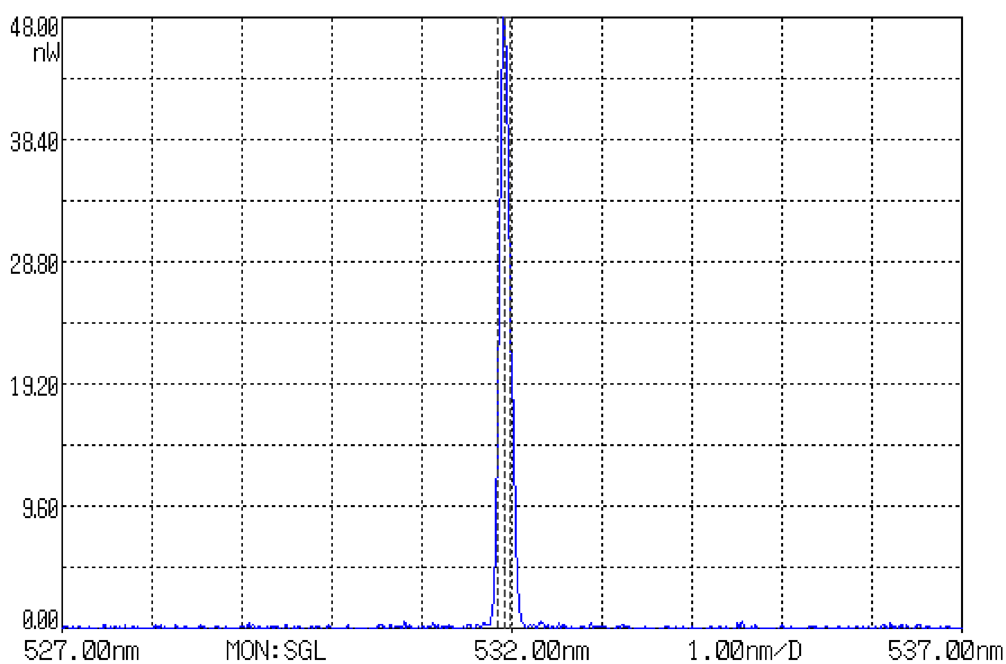

Figure 3 Spectrum of the output at 532nm.

3. CW GREEN RESULTS

The measured CW green output power is shown as a function of electrical power in Fig. 2. At the pumping electrical power of 15.78 W, we have achieved 3.34 W CW green output power, corresponding to a wall-plug efficiency of 21.2%. To the best of our knowledge, this wall-plug efficiency is the highest value achieved to date by using an electrically pumped VECSEL. The center wavelength of the spectrum is at 532 nm, which is shown in Fig. 3. The beam quality M^2 is measured to be around 13. We have also measured far field beam intensity profile using a CCD camera, shown in Fig. 4.

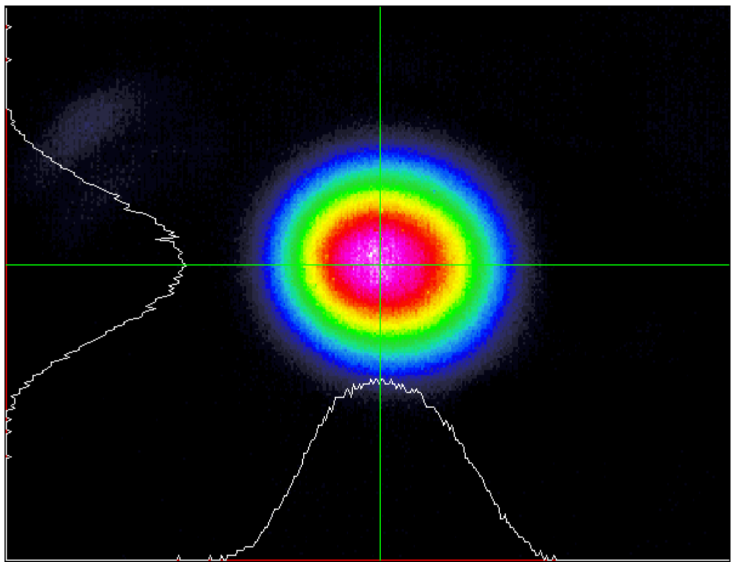

Figure 4 Green beam profile measured by a CCD camera.

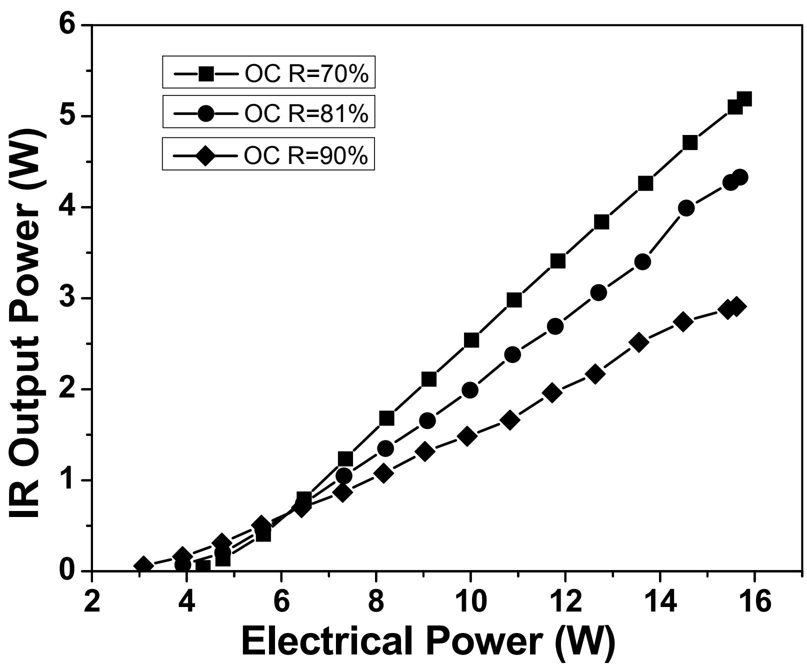

Figure 5 IR output power as a function of input electrical power by using OCs with reflectivities of R=70%, 81% and 90%.

4. IR OUTPUT POWER RESULTS

To estimate the IR-to-green optical conversion efficiency, we replaced the MgO: PPLN crystal by flat OCs with various reflectivities and measured the corresponding IR output power. OCs with reflectivities of 70%, 81%, 90% were used in this measurement, corresponding to 30%, 19%, 10% IR output coupling, respectively. The IR output power as a function of electrical power is shown in Fig. 5. At the pumping electrical power of 15.7 W, the IR output power generated by using OCs with R=70%, 81% and 90% was 5.19 W, 4.33 W and 2.91 W, respectively. Considering the CW green output power of 3.34 W at pump electrical power of 15.78 W, it was estimated that the SHG efficiency achieved was equivalent to the output coupling efficiency of an OC with transmission between 10% and 19% range.

5. CONCLUSION

In summary, we have demonstrated a high efficiency electrically pumped green VECSEL with the output wavelength at 532 nm. Compared with our previous result [16], we have improved the wall-plug efficiency to 21.2%. This value, to the best of our knowledge, is the highest efficiency that has been reported to date from an electrically pumped green VECSEL based on intracavity frequency doubling.

REFERENCES

[1] B. Rudin, A. Rutz, M. Hoffmann, D. J. H. C. Maas, A.-R. Bellancourt, E. Gini, T. Südmeyer, and U. Keller, "Highly efficient optically pumped vertical-emitting semiconductor laser with more than 20 W average output power in a fundamental transverse mode," Opt. Lett. 33, 2719-2721 (2008).

[2] 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, "1060-nm vertical-external-cavity surface-emitting lasers with an optical-to-optical efficiency of 44% at room temperature," Appl. Phys. Lett. 88, 91107 (2006).

[3] A. Garnache, S. Hoogland1, A. C. Tropper, I. Sagnes, G. Saint-Girons and J. S. Roberts, "Sub-500-fs soliton-like pulse in a passively mode-locked broadband surface-emitting laser with 100 mW output power," Appl. Phys. Lett. 80 (21), 3892 (2002).

[4] T. D. Raymond, W. J. Alford, M. H. Crawford, and A. A. Allerman, "Intracavity frequency doubling of a diode-pumped external-cavity surface-emitting semiconductor laser," Opt. Lett. 24, 1127-1129 (1999).

[5] E. U. Rafailov, W. Sibbett, A. Mooradian, J. G. McInerney, H. Karlsson, S. Wang, and F. Laurell, "Efficient frequency doubling of a vertical-extended-cavity surface-emitting laser diode by use of a periodically poled KTP crystal," Opt. Lett. 28, 2091-2093 (2003).

[6] A. Harkonen, J. Rautiainen, M. Guina, J. Konttinen, P. Tuomisto, L. Orsila, M. Pessa, and O. G. Okhotnikov, "High power frequency doubled GaInNAs semiconductor disk laser emitting at 615 nm," Opt. Express 15, 3224-3229 (2007).

[7] Kang Li, Aiyun Yao, N. J. Copner, C. B. E. Gawith, Ian G. Knight, Hans-Ulrich Pfeiffer, and Bob Musk, "Compact 1.3 W green laser by intracavity frequency doubling of a multi-edge-emitter laser bar using a MgO:PPLN crystal," Opt. Lett. 34, 3472-3474 (2009).

[8] M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, “Quasi-phase-matched second harmonic generation: tuning and tolerances,” IEEE Journal of Quantum Electronics, vol. 28, no. 11, pp. 2631–2654, 1992.

[9] G. D. Miller, R. G. Batchko, W. M. Tulloch, D. R. Weise, M. M. Fejer, and R. L. Byer, “42%-efficient single-pass cw second-harmonic generation in periodically poled lithium niobate,” Optics Letters, 22, 1834–1836, (1997).

[10] Y. Lu, Q. Xu, Y. Gan and C. Xu, "Field-Sequential Operation of Laser Diode Pumped Nd:YVO4/PPMgLN Microchip Green Laser,” IEEE Photon. Technol. Lett. 22, 990-992, (2010).

[11] J. F. Seurin, C. L. Ghosh, V. Khalfin, A. Miglo, G. Xu, J. D. Wynn, P. Pradhan, and L. A. D’Asaro, "High-power high-efficiency 2D VCSEL arrays," Proc. of SPIE Vol. 6908, 690808, (2008).

[12] Delai Zhou, Jean-Francois Seurin, Guoyang Xu, Alexander Miglo, Daizong Li, Qing Wang, Mukta Sundaresh, Sam Wilton, Joe Matheussen, and Chuni Ghosh, "Progress on vertical-cavity surface-emitting laser arrays for infrared illumination applications",Proc. of SPIE Vol. 9001, 90010E (2014).

[13] R. V. Leeuwen, J. F. Seurin, G. Xu and C. Ghosh, "High-power Pulsed Intra-Cavity Frequency Doubled Vertical Extended Cavity Blue Laser Arrays," Proc. SPIE 7193, 71931D (2009).

[14] J. G. McInerney and A. Mooradian, "Optimizing Electrically pumped Vertical Extended Cavity Surface Emitting semiconductor Lasers (E-VECSELs)," Proc. of SPIE Vol. 7919, 79190L (2011).

[15] H. Lindberg, S. Illek, I. Pietzonka, M. Furitsch, A. Plößl, S. Haupt, M. Kühnelt, R. Schulz, U. Steegmüller, T. Höfer, and U. Strauß, "Recent advances in VECSELs for laser projection applications," Proc. of SPIE, Vol. 7919, 79190D (2011).

[16] P. Zhao, B. Xu, R. V. Leeuwen, T. Chen, L. Watkins, D. Zhou, P. Gao, G. Xu, Q. Wang, G. Xu and C. Ghosh, "Compact 4.7 W, 18.3% wall-plug efficiency green laser based on an electrically pumped VECSEL using intracavity frequency doubling", Opt. Lett. 39, 4766-4768 (2014).