High-Power Operation of Quantum-Dot Semiconductor Disk Laser at 1180 nm

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***Abstract*—In this letter, we report on a high-power operation of an optically pumped quantum-dot semiconductor disk laser designed for emission at 1180 nm. As a consequence of the optimization of the operation conditions, a record-high continuous-wave output power exceeding 7 W is obtained for this wavelength at a heat-sink temperature of 2 °C. A wavelength tuning over a range of 37 nm is achieved using a birefringent filter inside the cavity.**

***Index Terms*—Quantum-dot (QD) semiconductors, optical pumping, semiconductor disk laser (SDL), vertical-external cavity surface-emitting laser (VECSEL), wavelength tuning.**

I. Introduction

AMONG lasers in general, and semiconductor lasers in particular, semiconductor disk lasers (SDLs), also known as vertical-external-cavity surface-emitting lasers (VECSELs) [1], have attracted increasing attention during the last two decades in the scientific community. Beside their compactness, functionalities, and relatively low costs, SDLs are evolving as a key optoelectronic technology that can offer excellent beam quality [2], high brightness [3], and low-noise performance [4]–[6]. Furthermore, SDLs provide not only high-power multi-mode continuous-wave (CW) operation [7], [8], but also ultra-short pulsed emission [9]–[12] across a wide range of the electromagnetic spectrum, i.e, from the ultraviolet [13], [14] to the mid-infrared [15], [16]. The latter is enriched with successful exploitation of SDLs as a secondary source based on intra-cavity frequency-conversion processes. In particular, benefiting from their unique external-cavity geometry, SDLs are utilized for, e.g., the generation of higher harmonics [17], [18] and the difference frequency generation (room-temperature CW terahertz applications [19]–[21]). However, SDLs operating in the high-power regime are typically required for such non-linear intra-cavity applications.

Manuscript received December 01, 2014; revised December 01, 2014; accepted December 01, 2014. Date of publication December 01, 2014; date of current version December 01, 2014. This work was partly supported by the EU FP7 programme through the FAST-DOT project (contract No. 224338), and by the German Research Foundation (DFG) through GRK1782 and SFB1083 projects.

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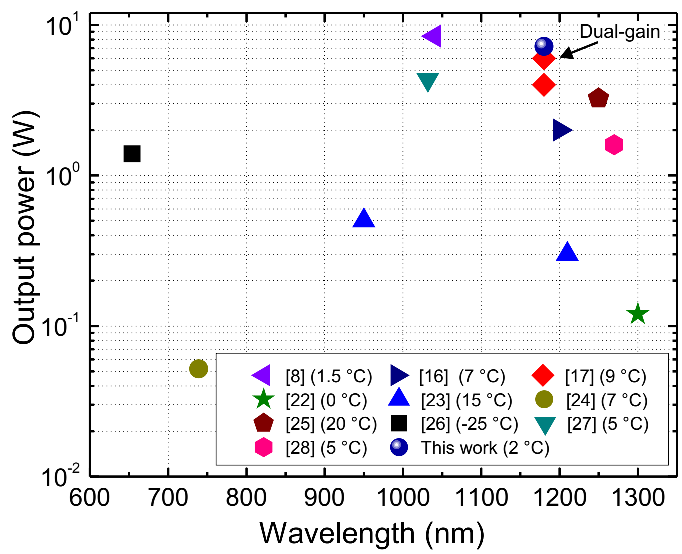

Fig. 1. Fundamental maximum continuous-wave output powers of QD-SDLs to date reported in the literature together with our present work. The corresponding temperatures are presented, each in brackets.

In this context, SDLs with quantum-dots-(QDs)-based active regions have generated an enormous amount of interest due to their potential for long-wavelength applications. In 2005, the first QD-SDL was achieved by Lott et al. [22] emitting near 1300 nm with an average output power of 120 mW. Three years later, QD-SDLs based on InAs/GaAs submonolayer (SML) and InGaAs Stranski-Krastanow (S-K) grown QDs gain material were demonstrated [23]. While for S-K samples, 300 mW output powers at 1040 nm and 1210 nm were reported, output powers of 1.4 W at 1040 nm and 0.5 W at 950 nm were achieved for SML samples. Further work led to an increase in the output power [18] and an extension of spectral coverage by QD-SDLs to red and near-infrared regions with a few tens of milliwatts at 730 nm [24] and multiwatts at 1250 nm [25], respectively. However, the highest output power for QD-SDLs has been recently obtained to be 8.4 W at 1040 nm [8]. A summary of remarkable fundamental maximum CW output powers of QD-SDLs to date is shown in Fig. 1.

In this letter, we report on a high-power operation of an optically pumped SDL based on (InGa)As S-K grown quantum dots and designed for emission at 1180 nm. The impact of the laser-cavity's parameters, i.e., the cavity length, the pump-spot width, and the transmittance of the output-coupler

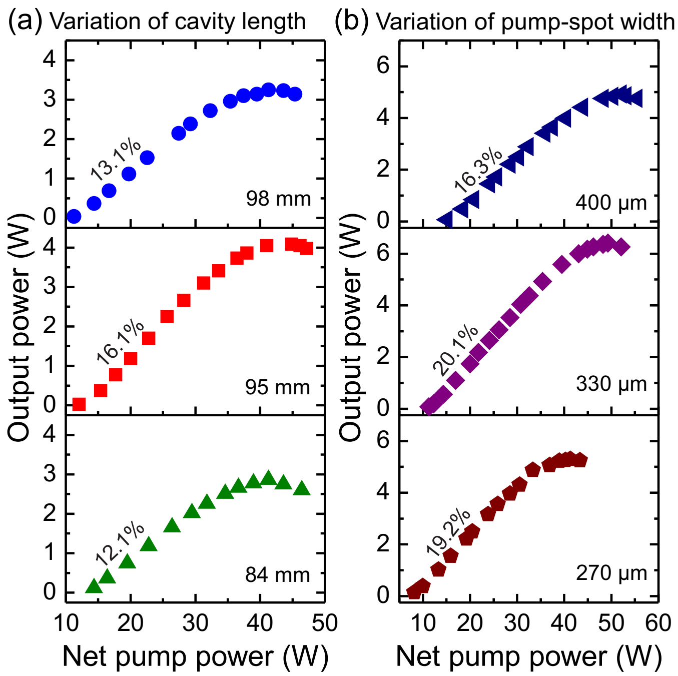

Fig. 2. (a) Output power characteristics measured for different cavity lengths, a pump-spot width of about 330 μm, and a heat-sink temperature of 15 °C. (b) Output power characteristics measured for different pump-spot widths, cavity length of 95 mm, and a heat-sink temperature of 5 °C. An OC mirror with 0.7%-transmission is used for all presented measurements. The inclined number in each subfigure in (a) as well as (b) represents the slope efficiency.

(OC) mirror, on the performance of the studied device is systematically investigated to achieve the optimization of the operating conditions. For the optimized aforementioned cavity parameters, the output power is recorded at various heat-sink temperatures. While QD-SDLs at 1180 nm with 4 W and 6 W output powers were previously reported employing a single gain-chip and double gain-chips, respectively [17], [29], we have obtained – using only a single gain chip – a maximum CW output power of 7.22 W at a heat-sink temperature of 2 °C. Moreover, the wavelength tunability is performed using a birefringent filter (BRF). The latter is inserted inside the laser cavity at Brewster's angle.

II. Experimental Setup

The structure of the SDL chip studied in the present work was grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. Firstly, a highly reflective distributed Bragg (DBR) reflector consisting of 35 pairs of GaAs/AlAs layers was grown on a 500-nm-thick-GaAs buffer. The active medium was grown on the top of the DBR and consists of 39 layers of S-K grown (InGa)As QDs, which are separated by 35-nm-thick-GaAs spacers. Each QDs-layer has a thickness of 6 nm. The QDs-layers are divided into 13 groups and placed at the anti-nodes of the optical standing wave. In addition, 83.4-nm-thick-GaAs spacer layers are placed between the groups of QDs. Then, the active region is capped by an $(Al_{0.9}Ga_{0.1})As$ window confinement layer with a thickness of 50 nm in order to prevent carrier recombination at the structure's surface. Finally, a 42.6-nm-thick-GaAs layer was grown on the top of the whole structure to avoid any oxidation. The above-described structure was designed for operation in the near-infrared spectral range at a wavelength of 1180 nm. More details on the structure's design can be found in the literature [18], [30].

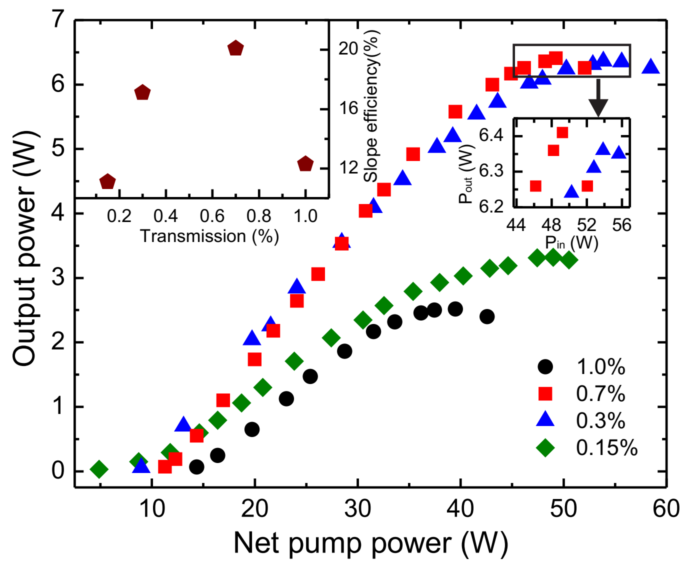

Fig. 3. Output power characteristics measured for for different OC mirrors, a pump-spot width of about 330 μm, a cavity length of 95 mm, and a heat-sink temperature of 5 °C. All OC mirrors have an equal curvature radius of -100 mm, but different transmissions. The left-hand inset shows the slope efficiency as a function of the transmission of the OC mirror. The right-hand inset shows a magnification of the encased area

The SDL chip is capillary bonded to an intra-cavity diamond heat-spreader, which is employed for thermal management, and mounted on a Peltier-cooled copper heat-sink. The excess heat, generated during laser operation, is dissipated via closed-cycle water cooling. The device is operated in a standard linear-cavity configuration, in which the resonator consists of the SDL-chip's DBR and a concave OC mirror. The SDL chip is optically pumped (OP) by a 808-nm fiber-coupled diode laser with a maximum CW output power of 120 W. The pump laser is focused onto the SDL chip under an incidence angle of 30°. At the aforementioned pump launch angle, the reflectivity from the diamond top surface and from the semiconductor-diamond interface for the pump wavelength was measured to be almost 10%. In this study, we used four OC mirrors of an equal radius of curvature of -100 mm and different transmissions of 0.15%, 0.3%, 0.7%, and 1%. Also, the pump spot width is varied systematically in order to find the optimum operation condition for obtaining high output power.

III. Results

In spite of the emission wavelength of an SDL, a critical parameter which can significantly affect the SDL devices performance is the mode-matching, i.e, the ratio, of the pump-spot width to cavity-mode width at the chips position. Besides, the transmittance of the OC mirror should be carefully chosen for the purpose of high-power operation. The cavity-mode width is typically determined from the cavity length in the case of a linear cavity as well as TEM_{00} laser mode for a given radius of curvature of the OC mirror. However, at the conditions of high-power SDL operation, a transversal multimode emission is expected [31] and, hence, the cavity-mode width cannot be directly estimated. Therefore, in the following, we introduce the impact of the variation of the cavity length, instead of the cavity-mode width, on the SDL's performance.

Fig. 2(a) shows the output power as a function of the net pump power for different cavity lengths and an OC mirror with a transmission of 0.7% at a heat-sink temperature of 15 °C. Here, the pump-spot width is set to about 330 μm and the cavity lengths are varied between 84 mm and 98 mm. The maximum output power of about 4.1 W, corresponding with the highest slope efficiency of 16.1%, is obtained for a cavity length of 95 mm. For the latter, on the other hand, the output power against the net pump power is shown in Fig. 2(b) for different pump-spot widths at a heat-sink temperature of 5 °C. In this case, the best performance of the studied device is observed for the pump-spot width of about 330 μm.

Next, we study the influence of the transmission of the OC mirror on the SDL's performance. Considering our above-mentioned findings, the cavity length and the pump-spot width are set to 95 mm and about 330 μm, respectively. However, the transmission of the OC mirror is varied between 0.15% and 1%. The corresponding experimental results are shown in Fig. 3, where the heat-sink temperature is set to 5 °C for all measurements. Although the thermal roll-over of our device in the case of an OC mirror with 0.3%-transmission sets in later than for 0.7%, a maximum output power of 6.41 W as well as the highest slope efficiency of 20.1% is obtained for the second case, cf. the insets of Fig. 3.

Subsequently, the impact of the heat-sink temperature on the performance of our studied device is investigated. Here, the above-determined optimal parameters for our cavity are used, i.e., the cavity length of 95 mm, the pump-spot width of about 330 μm, and the OC mirror with 0.7%-transmission. A clear enhancement in the SDL's performance is observed when the heat-sink temperature is decreased from 15 °C down to 2 °C, as it is shown in Fig. 4. This is represented by the variation of the corresponding slope efficiency which is plotted against the heat-sink temperature in the bottom-right inset of Fig. 4. Remarkably, we obtain a maximum output power of 7.22 W at a heat-sink temperature of 2 °C. To our knowledge, this record output power is to date the highest reported for QD-SDLs emitting in the wavelength region of 1180 nm. However, owing to the different gain medium and chip structure, this result cannot be compared to record output powers in excess of 20 W obtained for quantum-well SDLs emitting at similar wavelengths [32]. The top-left inset of Fig. 4 shows the optical spectrum of the laser, which is centered at 1180 nm, recorded at an output power of 6.5 W and 2 °C heat-sink temperature. The distinct periodically spaced peaks in the output spectrum are caused by an etalon effect introduced by the intracavity diamond heat spreader.

Finally, in order to tune the laser wavelength of our device, an 1-mm-thick BRF is inserted inside the cavity at Brewsters angle. By rotating the BRF, the wavelength is tuned over 37 nm around its central wavelength for an OC mirror with 0.15%-transmission. This is shown in Fig. 5. The output power at the central wavelength is almost 1.7 W and reduced at the wings of the tuning range. An example of the optical spectrum obtained after having inserted the BRF inside the cavity is presented in the inset of Fig. 5.

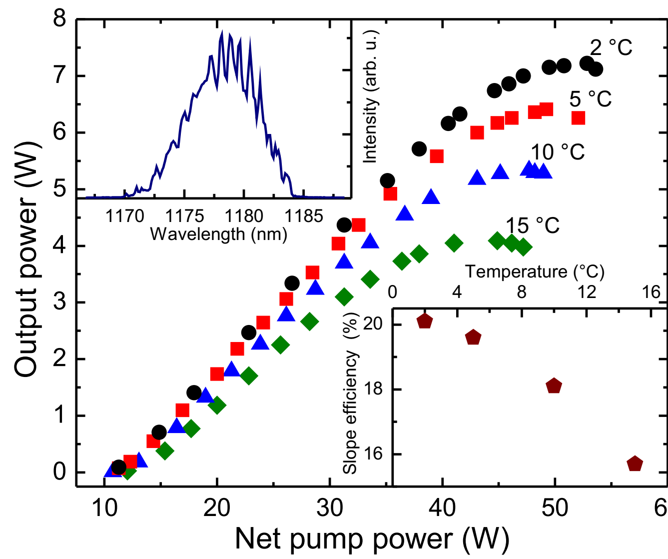

Fig. 4. Output power characteristics measured at various heat-sink temperaturesfor for a pump-spot width of about 330 μm, a cavity length of 95 mm, and an OC mirror with 0.7%-transmission. The bottom-right inset represents the slope efficiency as a function of the heat-sink temperature. The top-left inset shows the optical spectrum of the laser measured at an output power of 6.5 W at 2 °C.

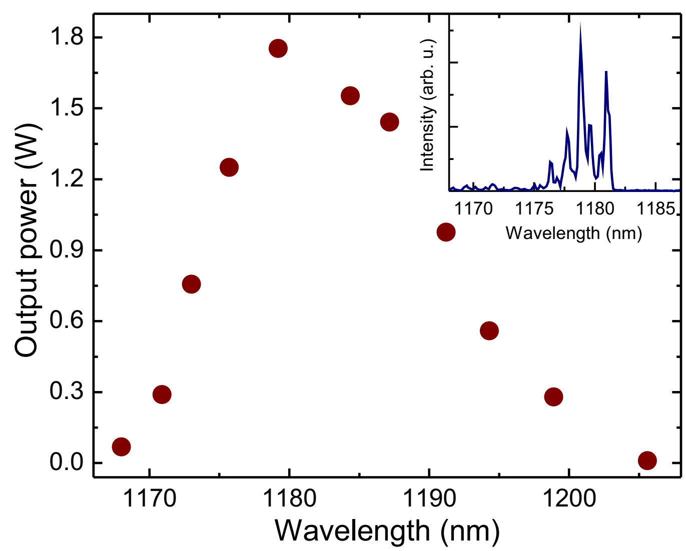

Fig. 5. Wavelength tuning characteristic measured using an 1-mm-thick BRF for an OC mirror with 0.15%-transmission at a heat-sink temperature of 10 °C. The inset shows the optical spectrum of the laser measured after having inserted the BRF inside the cavity.

IV. Conclusion

High-power operation of an optically pumped QD-SDL emitting at 1180 nm has been demonstrated. The cavity's parameters, i.e., the cavity length, the pump-spot width, and the OC mirror's transmittance, were systematically varied in order to reach the optimal performance of the studied device. The best performance is achieved for a cavity length of 95 mm, a pump-spot width of about 330 μm, and an OC mirror with 0.7%-transmission. The corresponding maximum continuous-wave output power up to 7.22 W is recorded at a heat-sink temperature of 2 °C. Besides, by rotating a birefringent filter inside the laser cavity, the emission wavelength became tunable over a range of 37 nm.

ACKNOWLEDGMENT

The authors would like to thank Dr. D. A. Livshits from Innolume GmbH for the fabrication of the QD structure and Prof. O. G. Okhotnikov from Tampere University of Technology for the preparation of the VECSEL.

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