High-Power Quantum-Dot Vertical-External-Cavity Surface-Emitting Laser Exceeding 8 W

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***Abstract*— We report on a record-high output power from an optically pumped quantum-dot vertical-external-cavity surface-emitting laser, optimized for high-power emission at 1040 nm. A maximum continuous-wave output power of 8.41 W is obtained at a heat sink temperature of 1.5 °C. By inserting a birefringent filter inside the laser cavity, a wavelength tuning over a range of 45 nm is achieved.**

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

I. INTRODUCTION

VERTICAL-EXTERNAL-CAVITY surface-emitting lasers (VECSELs) which are also known as semiconductor disk lasers (SDLs) have attracted much attention in recent years owing to their ability to combine high output-powers with diffraction-limited spatial beam quality and a widely accessible spectral range starting in the ultraviolet [1], [2] and reaching the mid-infrared [3], [4]. Novel structures based on quantum dots (QDs) embedded in this type of lasers [5] offer a number of the unique features such as broad gain bandwidth, ultrafast carrier dynamics, low temperature sensitivity, low threshold current and lower absorption saturation [6]. Moreover, their open architecture allows for numerous advantages such as passive modelocking using saturable absorbers [7]–[9] as well as even self-starting modelocking [10], [11] and intra-cavity frequency conversion [12]–[14]. Thus, these optically pumped systems have been employed for a variety of applications–scientific as well as industrial– such as spectroscopy, metrology, biophotonics, optical telecommunication, etc. [1], [3], [15]. It has been furthermore shown, that careful thermal management enables very high power operation for single-chip VECSELs with output powers exceeding 100 W [16]. Power scaling is also achieved by employment of multiple gain elements which can be exploited for frequency-doubled 532 nm devices with more than 60 W output power [17].

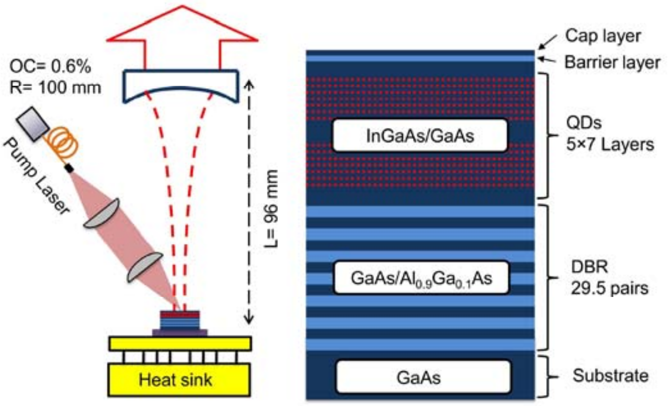

Fig. 1. Schematic illustrations of the OP-VECSEL cavity setup with a linear resonator (left), and the structure of the QD-VECSEL chip (right).

The chips constituting a VECSEL are not limited to periodic gain structures containing numerous quantum wells (QW), but also stacks of QDs layers are used which can be epitaxially grown under self-organization [18]. These QD-VECSELs provide as versatile systems as their similar QW pendants, with an even broader spectral gain and thus better tunability. However, their power output is significantly lower. Nevertheless, QD-VECSELs with up to a few Watts output power were demonstrated for various operation wavelengths in recent years; 1.39 W at 654 nm [19], 2 W at 1200 nm [20], 4.65 W at 1250 nm [21], 5.2 W at 960 nm [22], up to 4 W at 1180 nm [13], and 6 W at 1040 nm [13]. For the last two cases, wavelength tunabilities of 60 and 69 nm are reported, respectively [13].

In this letter, we report on a high performance operation of a QD-VECSEL designed for emission at 1040 nm. The output power is recorded for various pump spot widths and different heat sink temperatures. As a consequence of the optimization of the operation conditions, a maximum continuous-wave

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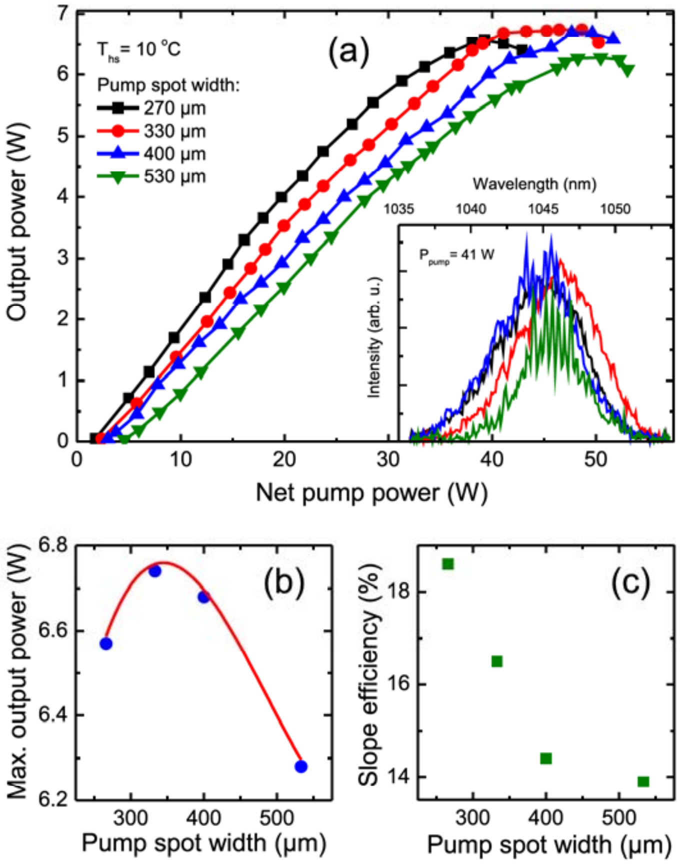

Fig. 2. (a) Input-output power characteristics for different pump spot widths, measured at a heat sink temperature (T_{hs}) of 1.5 °C. The inset in (a) shows the optical spectra of the laser for different pump spot widths, recorded at a net pump power (P_{pump}) of 41 W. (b) and (c) present the maximum (max.) output power and the slope efficiency as a function of the pump spot width, respectively. The red line in (b) serves as a guide to the eye.

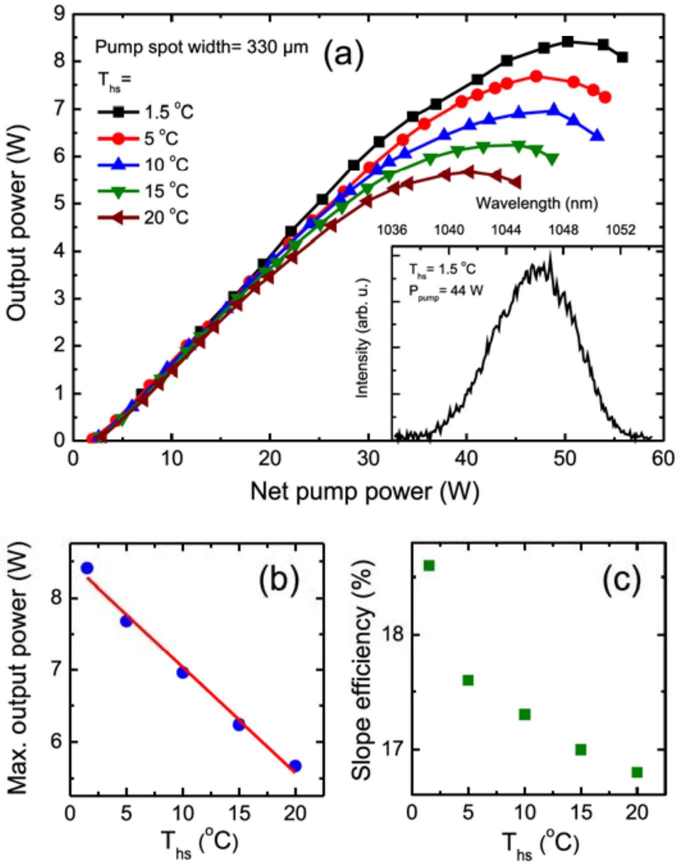

Fig. 3. (a) Input-output power characteristics for different heat sink temperatures, measured for a pump spot width of 330 μm. The inset in (a) shows the optical spectrum of the laser, recorded at a net pump power of 44 W at a heat sink temperature of 1.5 °C. (b) and (c) show the maximum output power and the slope efficiency as a function of the heat sink temperature, respectively. The red line in (b) denotes to a linear fit of the experimental data.

(CW) output power of 8.41 W is obtained for a pump spot width of 330 μm at a heat sink temperature of 1.5 °C. To our knowledge, this record output power is to date the highest reported for QD-VECSELs. Besides, a broad wavelength tunability up to 45 nm is achieved using a birefringent filter (BRF) which is inserted inside the laser cavity at Brewster's angle.

II. EXPERIMENTAL SETUP

The VECSEL chip structure exhibits an antiresonant design and was grown on a GaAs substrate by molecular beam epitaxy (MBE) and designed to emit at 1040 nm. After a 500-nm-GaAs buffer, a high reflectivity distributed Bragg reflector (DBR) consisting of 29.5 pairs GaAs/$Al_{0.9}Ga_{0.1}As$ is followed by the active gain medium. The latter consists of 35 layers of Stranski-Krastanow grown InGaAs QDs within GaAs spacer, organized as 5 stacks of each 7 QD layers that are placed at the standing-wave electric field maxima inside the cavity. Finally, the structure is capped by an $Al_{0.9}Ga_{0.1}As$ barrier layer followed by a GaAs layer in order to prevent surface recombination of the excited carriers and to avoid oxidation, respectively. A schematic drawing of the VECSEL chip's structure is shown on the right side of Fig. 1. The

is employed for thermal management, and mounted on a Peltier-cooled copper heat sink. The excess heat, generated during operation, is dissipated via closed-cycle water cooling.

A linear cavity configuration is used in our study, as shown on the left side of Fig. 1, in which the resonator consists of the VECSEL-chip's DBR and a concave output coupler (OC) mirror with a transmittance of 0.6% and a radius of curvature of 100 mm. The choice of this OC mirror is based on previous investigations, which indicated that by varying the overall output coupling an optimum performance can be obtained. In a study of a linear cavity configuration using three different transmittances of 0.15%, 0.3% and 0.6%, respectively, the best performance was revealed using a 0.6% transmittance. In addition, the optimum performance was obtained at a value of 0.6% in a similar investigation using several OC mirrors with transmittance in the range of 0.2% to 1% in steps of 0.2% in a single-pass V-shaped cavity, wherein the chip serves as an end-mirror such as in the linear configuration. We are confident that even finer tuning of the OC transmittance could still result in an increase of performance. The OC mirror opposes the gain mirror at an optimum distance of approximately 96 mm, resulting in a maximum of the laser output power

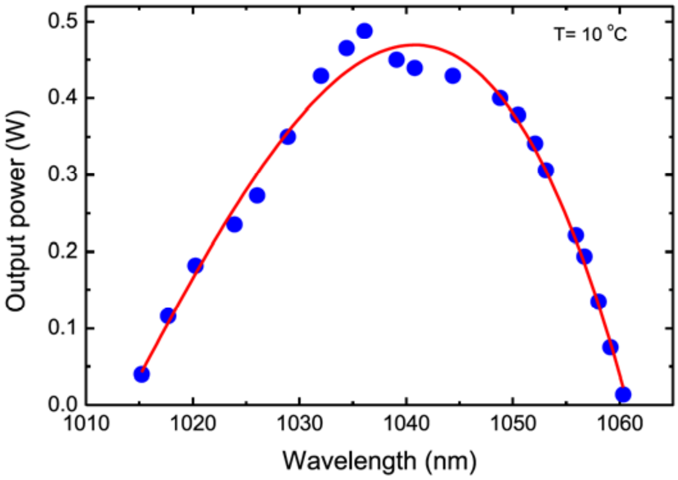

Fig. 4. Wavelength tuning characteristic, measured using a 0.6% output coupler (OC) and a birefringent filter (BRF) at a heat sink temperature of 10 °C. The BRF was inserted inside the cavity at Brewster's angle. The red curve serves as a guide to the eye.

The VECSEL chip is optically pumped (OP) by a 808-nm fiber-coupled diode laser with a maximum continuous-wave (CW) output power of 120 W. The pump laser is focused onto the VECSEL chip under an incidence angle of 35°. While the cavity-mode width at the chip's position and the OC are not changed for all measurements, the pump spot width is varied systematically between 270 μm and 530 μm in order to probe different mode matchings and power scaling effects.

III. RESULTS

In order to optimize the VECSEL's performance we first study the output power of the device for different pump-to-mode matchings which are given by the ratio of the pump spot width to the set cavity-mode width at the chip's position. Fig. 2(a) shows the output power as a function of the net pump power for pump spot widths ranging from 270 μm to 530 μm, measured at a heat sink temperature of 10 °C. While the thermal roll-over together with the threshold occur earlier for reduced pump spot widths, the maximum output power (before the occurrence of the thermal roll-over) exhibits a maximum for a pump spot width of 330 μm, as can be seen in Fig. 2(b). Moreover, the laser's emission wavelength near the thermal roll-over remains independent of the pump spot width (see inset in Fig. 2(a)). However, the slope efficiency, presented in Fig. 2(c), decreases when the pump spot width is increased. For pump spot widths larger than 400 μm its value remains nearly constant.

Subsequently, for a pump spot width of 330 μm, we measured the output power of the VECSEL as a function of the net pump power for different heat sink temperatures corresponding to 1.5, 5, 10, 15 and 20 °C, which are plotted in Fig. 3(a). An obvious increase in the maximum output power as well as the slope efficiency is observed when the heat sink temperature is decreased, as is shown in Figs. 3(b) and (c), respectively. A maximum output power and a slope efficiency

emission spectrum of the laser, which is recorded before the onset of thermal roll-over at a net pump power of 44 W and a heat sink temperature of 1.5 °C. Furthermore, the heat sink temperature dependence of the VECSEL output power is linear in this temperature range, as can be seen in Fig. 3(b), with an absolute slope of 0.15 W/°C. Hence, an output power of about 10 W could be achieved when the heat sink temperature is decreased to -10 °C.

Finally, we characterize the tunability of the output wavelength of our device. A BRF with a thickness of 1 mm is inserted inside the cavity at Brewster's angle in order to tune the wavelength. Fig. 4 shows the wavelength tuning characteristic, measured for a net pump power of 30 W and a pump spot width of 330 μm at a heat sink temperature of 10 °C. By rotating the BRF in its surface plane, the wavelength can be tuned from 1015 nm to 1060 nm, corresponding to a total range of 45 nm. In this experiment, the highest output power recorded amounts to 0.5 W at 1036 nm due to introduced optical losses.

IV. CONCLUSION

To summarize, we demonstrate high-power operation of a QD-VECSEL with optical output powers exceeding 8 W at 1040 nm. The input-output characteristics feature a clear dependence on the matching of the laser mode size on the gain mirror to the pump-spot width as well as a dependence on the chips temperature. Eventually, a maximum output power is obtained in the regime of transversal multimode operation for an optimized linear cavity of 96-mm length with a pump spot width of 330 μm at 1.5 °C. Moreover, the laser is tunable over a relatively large range of 45 nm when using a birefringent filter inside the cavity.We are confident that with further optimization of our QD-VECSEL device even higher output powers could be achieved in future studies.

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