Self-mode-locked quantum-dot vertical-external-cavity surface-emitting laser

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We present the first self-mode-locked optically pumped quantum-dot semiconductor disk laser. Our mode-locked device emits sub-picosecond pulses at a wavelength of 1040 nm and features a record peak power of 460 W at a repetition rate of 1.5 GHz. In this work, we also investigate the temperature dependence of the pulse duration as well as the time-bandwidth product for stable mode locking.

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An optically pumped vertical-external-cavity surface-emitting laser (VECSEL), also named semiconductor disk laser, is a versatile type of laser whose emission wavelength can be tailored according to the demands of a specific application [1]. VECSELs can offer not only high average output powers in continuous-wave (CW) multimode [2] or single-frequency [3] operation, but also in a mode-locked (ML: also "mode locking") regime [4–6]. In addition, VECSELs can provide excellent output beam quality with M^2 values smaller than 1.2 [7,8]. Interestingly, ML VECSELs, which can be employed for a variety of applications ranging from material processing to biophysical imaging, have been demonstrated by exploiting various methods to establish pulsed operation.

Typically, external semiconductor saturable-absorber mirrors (SESAMs) are employed, which exhibit intensity-dependent absorption [9,10] and have to be designed carefully for each wavelength and application—a cost-driving and limiting factor in the development of ML VECSELs. These SESAMs, usually based on quantum-well (QW) or quantum-dot (QD) structures, can even be integrated directly into the chip, resulting in a so-called ML integrated external-cavity surface-emitting laser (MIXSEL) [11]. Since MIXSELs combine both QD and QW technology, this approach is rather complex. A SESAM-free mode-locking technique potentially produces higher output powers because of the absence of nonradiative absorption, which usually is a power-limiting factor in SESAMs. Besides semiconductor materials, graphene [12] as well as carbon nanotube [13] saturable absorbers have been employed for ML operation of VECSELs. However, mode-locking has also been reported to take place even without any additional saturable absorber—an effect called self-mode locking (SML) [14–17]. Different driving mechanisms for the phenomenon of SML were proposed [14–16], but up to now, it is still unclear which mechanism is in force.

Due to the nature of their density of states, QD-based semiconductor lasers have shown their potential for realizing low thresholds and high characteristic temperatures [18]. In addition, the QD gain layers inherently exhibit strong inhomogeneous gain broadening, ultrafast carrier dynamics, and low absorption saturation [19]. Previously, it was demonstrated that the carrier recovery time in such a QD structure is less than 1 ps [20]. VECSELs based on QD gain regions have been reported in CW operation at emission wavelengths between 654 nm [21] and 1300 nm [8,22]. Currently, the highest output power achieved is 8.4 W for 1040 nm [23].

In the year 2008, the first ML QD-VECSEL had been demonstrated to generate 18-ps pulses with an average output power of 27 mW [24], whereas the demonstration of a Watt-level femtosecond QD-VECSEL with 200 W peak power was achieved recently [10]. This elucidates the significant improvements in this field.

In this Letter, we report on the first passively self-mode-locked QD-VECSEL, emitting at 1040 nm. The self-mode-locked VECSEL device was set up in a standard linear cavity geometry in which the VECSEL chip itself and a curved output coupler (OC) formed the laser resonator with a total length of 97 mm [see Fig. 1(a)]. Mode locking was initiated by introducing a slit acting as the intracavity mode aperture. The slit was placed closely in front of the OC mirror, which exhibited a transmittance of 0.6% and a radius of curvature of 100 mm. Stable pulses of sub-picosecond duration with an average output power up to 750 mW have been obtained. This corresponds to a record peak power of 460 W at a repetition rate of 1.5 GHz. Moreover, we investigate the dependence of the time-bandwidth product (TBWP) on the heat sink temperature of the QD-VECSEL device.

The chip structure employed in this study was grown by molecular-beam epitaxy on a GaAs substrate and exhibited an antiresonant design. A ternary distributed Bragg reflector (DBR) is grown, which consists of 29.5 pairs of GaAs-$Al_{0.9}Ga_{0.1}As$. Furthermore, the DBR is transparent to the wavelength of the fiber-coupled 808 nm pump laser. The active gain medium in the structure consists of 35 layers of Stranski–Krastanow grown InGaAs QDs within GaAs spacers, organized as five stacks of seven QD layers each that are placed at the standing-wave electric field antinodes inside the cavity. Both QDs and the DBR are designed for an emission wavelength of 1040 nm. In order to prevent surface

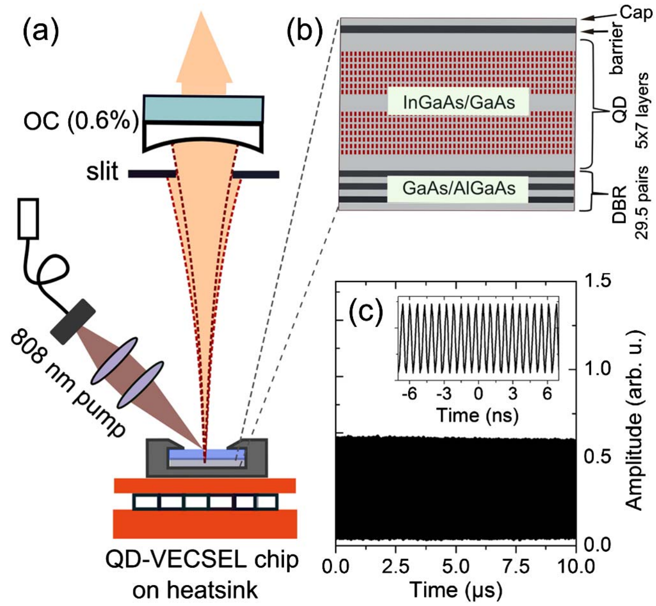

Fig. 1. (a) Schematic drawing of the optically pumped self-mode-locked QD-VECSEL setup. (b) Structure of the QD-VECSEL chip (top right). (c) Oscilloscope time trace of the VECSEL output for a time window of 10 μs and a few nanoseconds (inset), respectively.

recombination of the excited carriers and to avoid oxidation, the structure is capped by an $Al_{0.1}Ga_{0.9}As$ barrier layer followed by a GaAs layer. A schematic drawing of the VECSEL chip's structure is shown in Fig. 1(b).

The VECSEL chip is capillary bonded to an intracavity diamond heat spreader, which is employed for thermal management, and is mounted on a thermoelectrically cooled copper heat sink. The excess heat, generated during operation, is dissipated via closed-cycle water cooling.

Our VECSEL chip is optically pumped by an 808 nm diode laser under an incident angle of 30°. The pump optics is adjusted carefully to ensure good matching between the pump spot and the laser mode on the chip. The latter is estimated to have a radius of ~80 μm. Mode locking is initiated when the slit is moved or its width is varied [17]. Initially, ML operation was not stable and the resonator length was varied carefully by moving the OC in order to stabilize pulsing. Thereby, an improved operation is achieved at a certain cavity length (~97 mm). Stable ML operation was observed at a certain net pump power of about 16 W; otherwise, unstable mode-locking was observed. A representative long-span pulse train of the QD-VECSEL output is shown in Fig. 1(c): the signal was recorded for both a time window of 10 μs and a few nanoseconds (inset), respectively, via an InGaAs photodetector (PD) with a 3 dB bandwidth of 5 GHz and a digital oscilloscope with an analog bandwidth of 2 GHz.

Radiofrequency (RF) spectra measurements are presented in Fig. 2 with a signal-to-noise ratio of 45 dB at 1.5 GHz. For this, the PD is connected to an electrical spectrum analyzer exhibiting a bandwidth of 22 GHz (HP 8566A). Figure 2(a) presents an RF signal measured over a span of 6.5 GHz using a resolution bandwidth (RBW) of 100 kHz. The reduction in the amplitude of the fourth harmonic is attributed to the limited bandwidth of the PD. The corresponding RF spectrum of

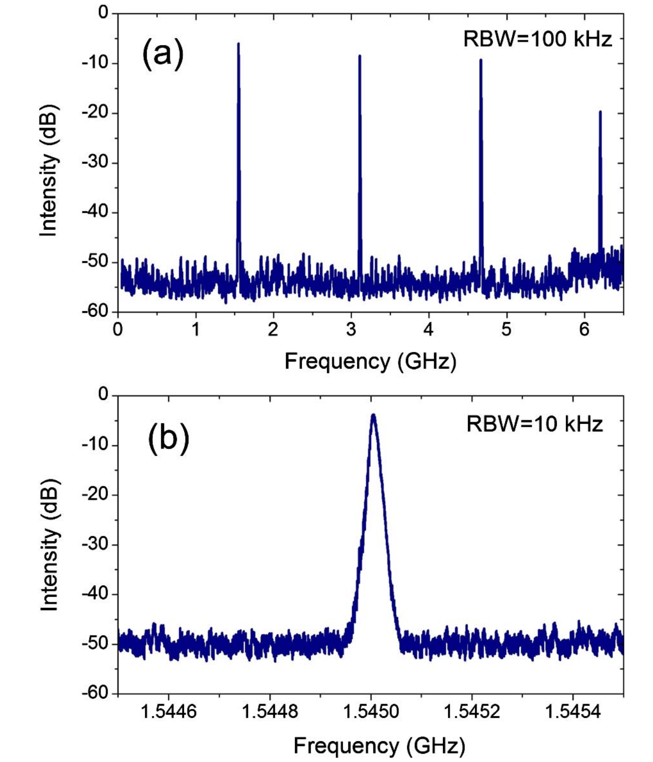

Fig. 2. RF spectra measured over (a) a span of 6.5 GHz and a RBW of 100 kHz, showing the first four harmonics, and (b) a span of 1 MHz and a RBW of 10 kHz. RF signal centered around 1.545 GHz.

the fundamental repetition rate measured over a span of 1 MHz using a RBW of 10 kHz is shown in Fig. 2(b). Here, a clear peak at 1.5 GHz is observed corresponding to the total cavity length of 97 mm.

In order to analyze the ML operation further, autocorrelation traces and optical spectra were recorded, which are presented in Figs. 3(a) and 3(b), respectively. Corresponding measurements were performed with an A.P.E. t5050 autocorrelator and an Ando AQ-6315A optical spectrum analyzer. The pulse durations are determined by assuming $sech^2$ shaped pulses in the autocorrelation traces. The optical spectrum of the laser is centered at 1038 nm. The distinct periodically spaced peaks in the spectrum are caused by the spectral filtering induced by the etalon, which is formed by the intracavity diamond heat spreader. The inset in Fig. 3(b) displays a CCD image of the TEM_{00} transverse mode profile of the laser output beam. The laser output is polarized linearly with a horizontal orientation.

As former investigations revealed, ML QD lasers exhibit strong temperature dependence of their mode locking properties [25]. Therefore, as the last part of our study, the performance of the self-mode-locked QD-VECSEL is investigated as a function of operation temperature. Pulse durations are measured in a stable ML regime for several temperatures. Figure 4(a) shows the expected increase of average/peak power (left/right axis) with decreasing temperature, with a peak power of 460 W obtained at 5°C. To our knowledge, this is the highest peak power obtained from a ML QD-VECSEL. Figure 4(b) depicts the decrease of pulse duration with

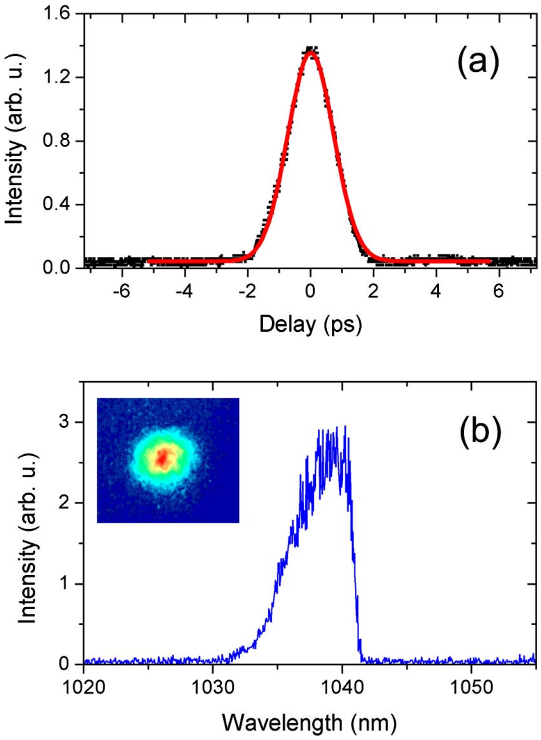

Fig. 3. (a) Autocorrelation trace of the self-mode-locked QD-VECSEL measured at 5°C. Black dots: experimental data. Red line: fit curve assuming a sech^2 pulse. (b) Corresponding optical spectrum. Inset: output beam profile in a false color map.

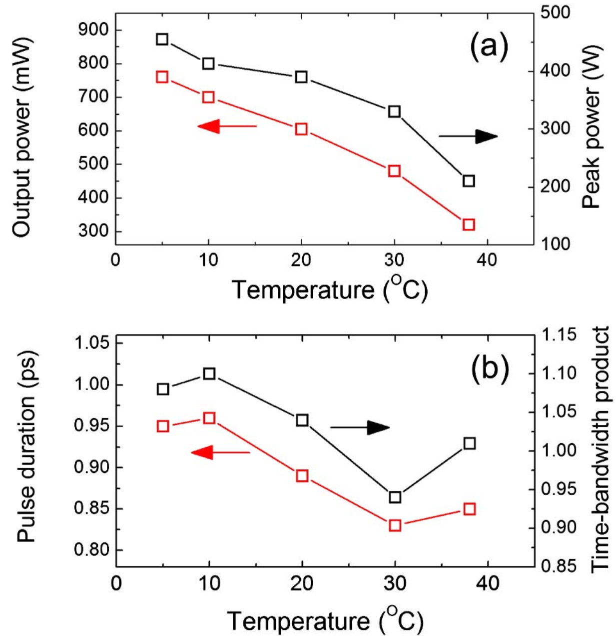

Fig. 4. (a) Average and peak output powers as a function of temperature (left/right axis). (b) Temperature-dependent pulse duration and time-bandwidth product for a sech^2-pulse shape. The optimum TBWP is 0.315.

increasing temperature (left axis). This trend might occur due to a temperature-dependent change of the dispersion inside the gain medium. Here, both output power and pulse duration measurements were performed at a constant net pump power of 16 W. In addition, a slight decrease of the TBWP could be observed as the temperature was increased, as revealed in Fig. 4(b) (right axis). The pulses measured are 3.0 to 3.4 times the transform limit of an ideal sech^2 pulse, confirming that the pulses are still strongly frequency-chirped due to the dispersion within the microcavity. The observed decrease of the TBWP in ML QD lasers has been investigated previously in the literature and several possible reasons have been suggested [25]: on the one hand, this feature implies an increase in the homogeneous linewidth [26], whereas on the other hand, it can be seen as the consequence of a decreased population inversion over the entire gain spectrum due to thermal coupling to the wetting layer, which would reduce the number of modes that reach the threshold [27]. It is worth to note that in our case, the decrease of TBWP is rather small compared with that in the references cited. We should mention that the present average output power and pulse durations are comparable with the results obtained using traditional saturable-absorber mirrors [10].

In conclusion, we have demonstrated the SML of an optically pumped QD-VECSEL. Sub-picosecond pulses with pulse duration as short as 830 fs at 1040 nm and a repetition rate of 1.5 GHz were obtained. Moreover, a record peak power of up to 460 W was demonstrated. A temperature-dependent study of the VECSEL's mode locking properties revealed that the pulse duration as well as the TBWP could be improved if the system is operated at increased temperatures.

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