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Modelocked quantum dot vertical external cavity surface emitting laser

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Abstract We report the first successful modelocking of a vertical external cavity surface emitting laser (VECSEL) with a quantum dot (QD) gain region. The VECSEL has a total of 35 QD-layers with an emission wavelength of about 1060 nm. In SESAM modelocked operation, we obtain an average output power of 27.4 mW with 18-ps pulses at a repetition rate of 2.57 GHz. This QD-VECSEL is used as-grown on a 450 µm thick substrate, which limits the average output power.

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1 Introduction and motivation

Optically pumped vertical external cavity surface emitting lasers (VECSELs) offer high output power, excellent beam quality and good efficiency [1]. They produced average output powers as high as 30 W with an M^2 value of 3 [2] or 20 W with an M^2 value below 1.1 [3]. The output power can be scaled up simply by increasing the mode area on the gain region and the pump power if the heat flow through the layer structure is nearly one-dimensional [4]. Moreover, semiconductor bandgap engineering can be used to obtain a large variation of emission wavelengths that are not covered by established solid state lasers. In addition, semiconductor lasers are ideally suited for mass production because they are based on a wafer-scale technology with a high level of integration.

In combination with a semiconductor saturable absorber mirror (SESAM) [5], VECSELs have been passively modelocked, and average output powers as high as 2.1 W [6], pulse repetition rates as high as 50 GHz [7] and pulses as short as 260 fs [8] were achieved. We recently introduced a new concept of ultrafast semiconductor lasers, where we integrated the saturable absorber and the active region into a single semiconductor based device. We refer to this new class of modelocked VECSELs as modelocked integrated external-cavity surface emitting lasers (MIXSEL) [9]. One key requirement was the development of quantum dot saturable absorbers that support the integration with the same laser mode size in the absorber and the gain. The MIXSEL platform has a high potential for applications in optical communication, optical clocking of multi-core microprocessors and compact supercontinuum generation for bio-medical applications. However, so far we always used quantum wells (QWs) for the gain section, and the pulse duration has been limited to the picosecond regime. Our motivation for using quantum dot (QD) gain structures within a MIXSEL or a modelocked VECSEL is the larger inhomogeneous broadening. Self-assembled InAs/GaAs QDs produce an inhomogenously broadened gain [10], which is wider compared to QWs and is less susceptible to temperature changes [11]. Previously, we have demonstrated with diode-pumped solid-state lasers that inhomogenous gain broadening relaxes the requirements on the saturable absorber and supports shorter pulse durations [12, 13]. With inhomogeneous broadening, the lasing bandwidth is increased at continuous wave (cw) operation because spectral hole burning enables many different axial modes to lase at the same time. Therefore,

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the saturable absorber only needs to provide sufficient self-amplitude modulation to phase-lock these modes without having to transfer the full energy from one axial mode to all other adjacent modes. We believe that the inhomogeneous broadening of QD-gain will enable sub-picosecond pulse generation of modelocked VECSELs and MIXSELs with fast quantum dot saturable absorbers [14, 15] in the near future.

VECSELs based on QD-gain regions have recently been reported in cw-operation at an emission wavelength of 1034 nm [16] and 1210 nm [17], where output powers of 1.4 W and 300 mW, respectively, were achieved using diamond heat spreaders.

Here, we report on the first passively modelocked QD-gain VECSEL. We employed a standard quantum well SESAM (QW-SESAM) and obtained self-starting stable pulses of 18-ps duration with an average output power of 27.4 mW at a pulse repetition rate of 2.57 GHz. The average output power of 27.4 mW is currently limited by the reduced thermal conductivity of the 450 µm thick GaAs wafer, onto which the VECSEL structure has been grown.

2 Laser cavity, QD-VECSEL gain structure and SESAM

We use a typical V-shaped laser cavity, which is shown in Fig. 1 [18]. The QD-VECSEL is pumped at 808 nm at an angle of 45 degrees. A QW-SESAM and a curved output coupling mirror constitute the end-mirrors of the laser cavity. The operation wavelength can be tuned by changing the angle of a 20-µm thick etalon. In this configuration the pulse passes the active region twice per cavity roundtrip.

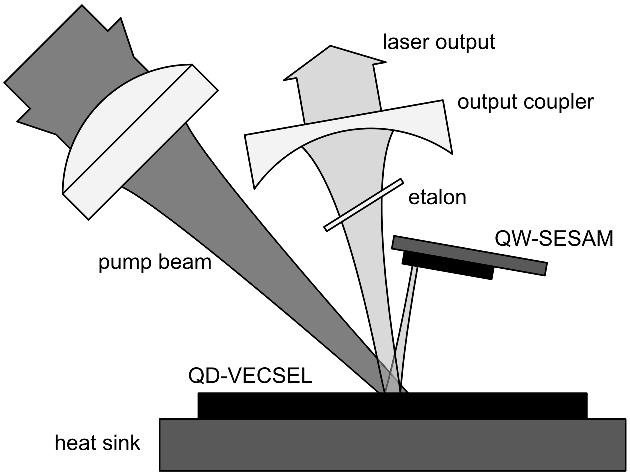

Fig. 1 Schematic of the laser setup. A V-shaped laser cavity is used with a quantum well SESAM (QW-SESAM) and the output coupler as the cavity end-mirrors. Inside the cavity we used a quantum dot gain VECSEL (QD-VECSEL) structure and a 20 µm thick etalon to tune the central wavelength of the laser. The 808-nm pump light is focused onto the QD-VECSEL structure under an angle of 45 degrees

The QD-VECSEL gain structure was grown by Innolume GmbH by molecular beam epitaxy (MBE) on a GaAs substrate of 450-µm thickness. The structure consists of a distributed Bragg reflector (DBR) centered around 1060-nm wavelength and an active QD region. The DBR is made of 29 pairs of quarter wavelength layers of GaAs and $Al_{0.9}Ga_{0.1}As$, which results in a high reflectivity at the laser wavelength (calculated 99.99%). The active region consists of five stacks of seven QD-layers embedded in GaAs, whereas the GaAs serves as absorbing medium for the pump radiation. In each stack, the seven QD-layers are separated from each other by 10 nm using GaAs spacers, and the five stacks are placed in five different antinodes of the standing wave pattern of the electrical field of the laser.

The QD stacks were formed by cyclic deposition of InAs (1/4 monolayer thickness) and GaAs (1/3 monolayer thickness) followed by short growth interruptions. The substrate temperature was kept as low as 510 to 520°C, monitored by an infrared pyrometer. No dislocations have been detected in the grown structure.

The SESAM used for modelocking the QD-VECSEL contains a QW saturable absorber in a standard anti-resonant design [19]. It was grown by MBE in the FIRST cleanroom facility at ETH Zurich and consists of a 30-pair AlAs/GaAs DBR centered at a wavelength of 1062 nm and a single InGaAs QW saturable absorber. The saturable absorption parameters of the SESAM were characterized with a high-precision nonlinear reflectivity setup [20]. At 1064-nm center wavelength, we determined a saturation fluence of 34 $\mu J/cm^2$, a modulation depth of 0.6% and nonsaturable losses of 0.2%.

The length of the laser cavity was 58.5 mm, which corresponds to a repetition rate of 2.6 GHz. The full folding angle of the cavity was 10 degrees. The dielectric output coupling mirror had 0.28% transmission at the laser wavelength and a radius of curvature of 60 mm. The round pump spot on the gain chip had 90 µm radius and the pump beam had an M^2 value of 12. The cavity geometry was chosen such that the laser mode radius on the SESAM was about 50 µm.

For our experiment, the QD-VECSEL structure was directly soldered onto a heat sink, and no further steps were taken towards improved thermal management [4]. During modelocked laser operation, the heat sink temperature was set to −20°C.

3 Experimental results and discussion

Fundamental modelocking with an average output power of 27.4 mW was achieved for a pump power of 1.56 W (Fig. 2). Pulses of 18-ps duration were measured with a second harmonic generation autocorrelator. We measured the optical

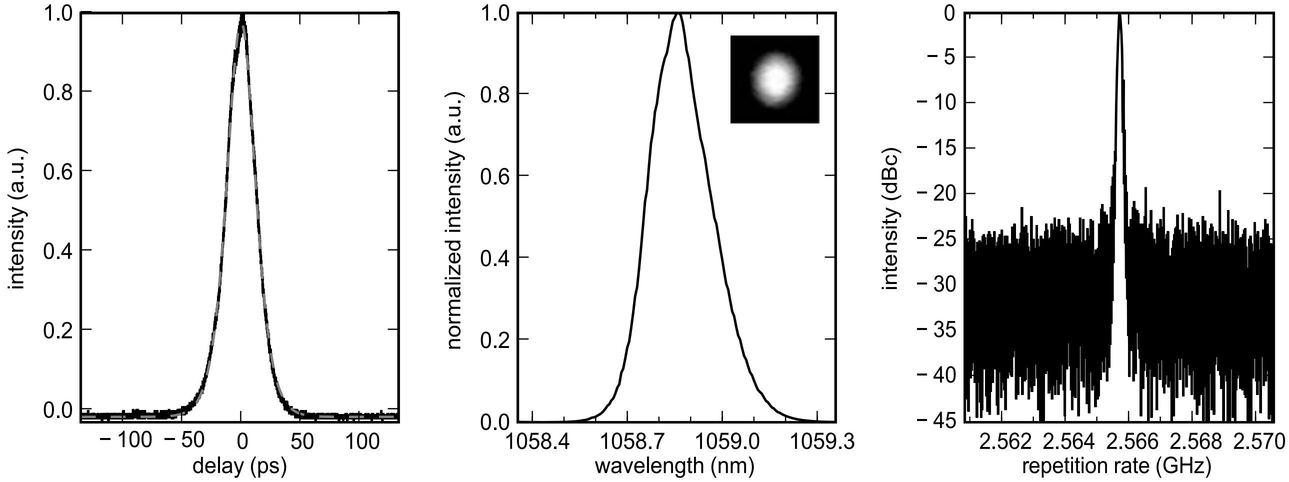

Fig. 2 The autocorrelation trace (*black*) and its fit (*gray dashed*), the emission spectrum with the beam profile as inset and the microwave spectrum are plotted for a pump power of 1.56 W on the QD-VECSEL. The deconvoluted pulse has 18 ps FWHM duration; the width of the optical spectrum is 0.22 nm, measured with a resolution bandwidth of 0.1 nm. The microwave spectrum shows a clear peak at 2.57 GHz, the spectral span was 10 MHz with a resolution bandwidth of 100 kHz

spectrum with an optical spectrum analyzer that had a resolution bandwidth of 0.1 nm and obtained an FWHM width of 0.22 nm. A simple deconvolution would result in an FWHM width of 0.2 nm and a time bandwidth product of 1 (i.e. about 3 times the transform limit of a sech^2 pulse). The microwave spectrum is measured over a span of 10 MHz with a resolution bandwidth of 100 kHz. We see a clear peak at 2.57 GHz, and additional measurements also clearly show the peaks for the higher harmonics of this frequency. In Fig. 2, also the beam profile of the laser beam is shown as an inset within the emission spectrum of the laser.

For pump powers higher than 1.56 W, a thermal rollover of the average power occurred. This roll-over is caused by the low thermal conductivity of the VECSEL structure. We did not optimize thermal management because this experiment was a proof-of-principle for modelocking a QD-VECSEL. Thus the 450 µm thick GaAs substrate has not been removed, and the average power is limited by thermal heat sinking [4]. The advantage of this structure is that almost no additional processing is required before the device can be used in the laser cavity.

We numerically simulated the temperature increase within our structure using a finite-element method for a pump spot of 90 µm and a pump power of 1.5 W. We obtained a difference in temperature between the active region and the heat sink of more than 100 K. Lasing experiments with cw-output of the VECSEL in a straight cavity setup also confirmed that the output power level is limited by the absolute temperature in the active region of the VECSEL. These numerical simulations furthermore show that the temperature difference between the heat sink and the active region can be reduced to 25 K for equally high pump powers if the 450 µm thick GaAs substrate is removed from the VECSEL and the grown structure is soldered directly onto the heat sink. We expect that such a QD-VECSEL will be power-scalable to several watts in analogy to QW-VECSELs. We would expect that a faster QD-SESAM and better dispersion management [21, 22] will ultimately result in shorter pulse durations.

4 Conclusion and outlook

We have demonstrated the first modelocked QD-VECSEL. Pulses of 18-ps duration with a repetition rate of 2.57 GHz were generated at a laser wavelength of 1059 nm. We could achieve an average output power of 27.4 mW. The average power performance of the laser can be further improved by optimizing the thermal properties of the VECSEL structure by substrate removal. The ongoing development of faster SESAMs using quantum dots and improved cavity dispersion management should allow the generation of femtosecond pulses in the near future.

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