Femtosecond VECSEL with tunable multi-gigahertz repetition rate

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Abstract: We present a femtosecond vertical external cavity surface emitting laser (VECSEL) that is continuously tunable in repetition rate from 6.5 GHz up to 11.3 GHz. The use of a low-saturation fluence semiconductor saturable absorber mirror (SESAM) enables stable cw modelocking with a simple cavity design, for which the laser mode area on SESAM and VECSEL are similar and do not significantly change for a variation in cavity length. Without any realignment of the cavity for the full tuning range, the pulse duration remained nearly constant around 625 fs with less than 3.5% standard deviation. The center wavelength only changed ±0.2 nm around 963.8 nm, while the output power was 169 mW with less than 6% standard deviation. Such a tunable repetition rate is interesting for various metrology applications such as optical sampling by laser cavity tuning (OSCAT).

OCIS codes: (140.7260) Vertical cavity surface emitting lasers; (140.4050) Mode-locked lasers; (120.0120) Instrumentation, measurement, and metrology; (320.7100) Ultrafast measurements.

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1. Introduction

Tunable pulse repetition rates are interesting for various metrology applications, for example optical sampling by laser cavity tuning (OSCAT) [1]. A large change in repetition rate appears difficult to achieve in standard edge-emitting semiconductor lasers. Here we demonstrate a compact ultrafast semiconductor laser with which we continuously changed the repetition rate from 6.5 GHz to 11.3 GHz. This results in a delay of 65 ps, which corresponds to a cavity length change of approximately 9.8 mm. Moreover, the pulse duration and optical spectrum of the laser remained constant for such a variation of the repetition rate. Previous results on tunable pulse repetition rates at the gigahertz regime were demonstrated with a SESAM modelocked diode-pumped Er:Yb:glass laser, where the pulse repetition rate was changed from 8.8 to 13.3 GHz for telecom applications [2]. In comparison, here we report a broader repetition rate tunability with much shorter pulse durations (i.e. 625 fs instead of 1.8 ps), and with a much simpler cavity design (i.e. a V-shaped instead of a Z-shaped resonator) using a potentially cheaper laser technology with more wavelength flexibility.

The ultrafast semiconductor laser is based on an optically pumped vertical external cavity surface emitting lasers (VECSELs [3]) which combines the advantages of diode-pumped solid-state lasers (DPSSL) and semiconductor lasers. The semiconductor gain chip enables bandgap engineering and inexpensive mass production, while the external cavity allows for transverse mode control and the introduction of additional cavity elements, for instance to enable passive modelocking or non-linear frequency conversion. So far, all passively modelocked VECSELs were realized using semiconductor saturable absorber mirrors (SESAMs [4–6]). Repetition rates up to 50 GHz in 3.3-ps pulses [7] and average powers up to 2.1 W in 4.7-ps pulses [8] were reported from SESAM-modelocked VECSELs. Higher power levels up to 6.4 W in 28.1-ps pulses [9] were demonstrated with a modelocked integrated external cavity surface emitting laser MIXSEL) [10,11], in which gain layers and the saturable absorber are integrated into one single semiconductor chip. Such ultrafast VECSELs which are interesting for metrology applications, generate pulses as short as 107 fs with 3 mW average power in fundamental modelocking [12], and down to 60 fs in multipulse mode [13] and 784 fs with even more than 1 W average power [14]. The timing jitter of such lasers is very low and comparable to DPSSLs [15,16].

A very large pulse repetition rate tuning without any significant changes in the laser performance is challenging. So far, femtosecond VECSELs were realized using quantum wells (QWs) both for the gain layers and the saturable absorber. Such a configuration usually requires a smaller spot size on the saturable absorber than on the gain chip to achieve stable pulse formation [17]. Quantum dot (QD) SESAMs can achieve lower saturation fluences in comparison to standard QW-SESAMs, which allows for modelocking with the same mode radius on the gain and absorber sections. This is usually referred to as "1:1 modelocking" [17]. Furthermore, fast recombination dynamics can be achieved using QDs [18] and femtosecond operation at Watt-level was demonstrated with modelocked VECSEL using QDs in both the gain and absorber layers [14].

The free-space propagation in the external cavity of the VECSEL allows for simple repetition rate tuning by changing the cavity length. Very recently, a tuning range from 1 GHz to 1.2 GHz with 450-fs pulses and an output power of 45 mW was obtained from a QW-VECSEL modelocked with a QW-SESAM [19]. Using a QD-SESAM and 1:1 modelocking allows for a cavity design in which the mode sizes on the VECSEL and SESAM remain nearly constant for significant changes in the cavity length. Due to recent findings on the pulse forming mechanism in VECSELs [20], important parameters like pulse duration, output power and center wavelength can remain stable for a change of the cavity length. Here, we present a femtosecond QW-VECSEL modelocked with a QD-SESAM which can be tuned in repetition rate from 6.5 GHz up to 11.3 GHz. While tuning, the repetition rate, the pulse duration remained nearly constant at 625 fs ±3.5% standard deviation with an average output power of 169 mW ±6% for all repetition rates.

2. Cavity setup

2.1 QW gain structure

In our experiment, we used a QW gain structure which was grown by molecular beam epitaxy (MBE) on a GaAs substrate. The device consists of two $AlAs/Al_{0.2}Ga_{0.8}As$ distributed Bragg reflectors (DBRs). A 15-pair DBR at the bottom of the structure reflects the pump wavelength at 808 nm with a theoretical reflectivity of more than 99%, and a 30-pair DBR for the 950-nm laser wavelength is placed on top of it. It is designed for an angle of incidence of 10° and has a theoretical reflectivity of more than 99.9%. Between the two DBRs, an $Al_{0.2}Ga_{0.8}As$ spacer layer is positioned which allows for optimizing the pump absorption without changing the standing wave pattern of the electric field of the laser. According to our simulation, 95% of the pump power is absorbed in the active region which is located on top of the two DBRs. It consists of 7 indium gallium arsenide (InGaAs) QW layers, separated by GaAs spacer layers. The QW layers are positioned in the antinodes of the electric field of slightly different wavelengths around the center wavelength of 950 nm, in a similar way as reported in [14]. On top of the active region, an anti-reflection (AR) section is placed, which results in an extremely low dispersion of our structure [14]. It consists of 14 $AlAs/Al_{0.2}Ga_{0.8}As$ layers, a GaAs cap layer and a fused silica (FS) layer on the top. The FS layer was deposited using plasma enhanced chemical vapor deposition (PECVD). This AR section provides group delay dispersion (GDD) values of ±10 fs^2 over a range of 40 nm around the design wavelength. For better thermal management the QW-VECSEL gain structure was grown in reverse order, soldered onto a CVD diamond heat spreader (thermal conductivity >1800 $WK^{-1}m^{-1}$) and the GaAs substrate was removed by a chemical wet etching [21].

2.2 QD-SESAM

Modelocking was obtained by using a QD-SESAM with a standard resonant design and one QD absorber layer [22]. It was MBE-grown on a 600-µm thick GaAs substrate. The QD-SESAM has a DBR made of 30 pairs of quarter-wave layers of AlAs and GaAs. The absorber

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section itself is directly grown on the DBR where the QD layer is embedded in GaAs and placed in the antinode of the standing wave pattern of the electric field at 965 nm. This SESAM was characterized at a center wavelength of 965 nm [23,24]. A fast absorption recovery component in the order of 800 fs makes this QD-SESAM well-suited for femtosecond operation. The saturation fluence is 3.8 µJcm^{-2} with non-saturable losses of less than 1%, and a modulation depth of 1.2% (as reported in [14]).

2.3 Cavity configuration

For the experiment we used a standard V-shaped cavity in which the gain structure forms an active folding mirror. The end mirrors are the QD-SESAM and the curved output coupler (Fig. 1a). The temperature of the heat sink of the QW-VECSEL was adjusted to −20 °C while the gain structure was pumped at 3.3 W with a commercial 30-W 808-nm fiber coupled diode. The pump was focused on the gain structure under an angle of 45° and the pump spot radius amounted to 120 µm. The angle of incidence of the laser on the gain structure was about 10°. While the short arm between the QD-SESAM and the gain structure was kept constant at 4 mm, the length of the long arm between the gain chip and the output coupler was varied between 9.2 mm and 19 mm using a translation stage. Therefore, the possible cavity lengths correspond to repetition rates of the modelocked laser between 6.5 GHz and 11.3 GHz (Fig. 1b). Using a radius of curvature (ROC) of 100 mm for the output coupler results in a cavity configuration for which the laser mode on the gain structure remains nearly constant for such changes in cavity length. Simulations of the cavity mode profiles show, that the radius of the laser spot on the gain structure changes only slightly from 102.5 µm for the 11.3-GHz-cavity to 113.4 µm for the 6.5-GHz-cavity. Furthermore, the radius of the laser spot on the QD-SESAM is nearly the same as on the gain structure, i.e. it changes from 101.8 µm (11.3 GHz) to 113.4 µm (6.5 GHz).

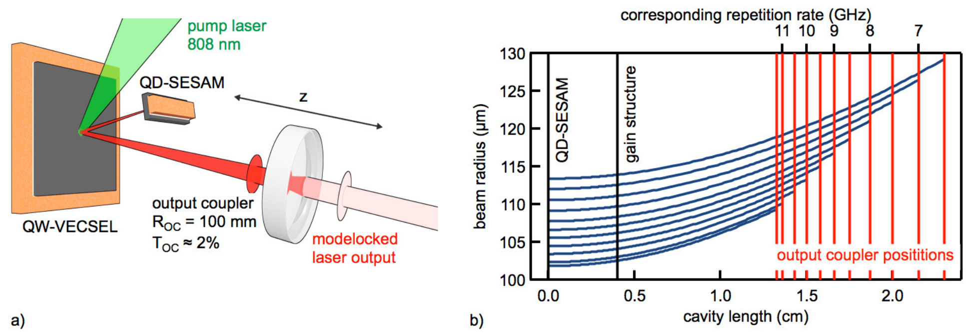

Fig. 1. a) Schematic overview of the V-shaped laser cavity, showing the pump geometry and the cavity elements: output coupler, QW-VECSEL and QD-SESAM. The repetition rate was changed by moving the output coupler in z-direction. T_{OC}: output coupler transmission. R_{OC}: radius of curvature of the output coupler. b) Simulated laser beam radii in the cavity (blue) for different cavity lengths and output coupler positions highlighted in red, also marked with the corresponding repetition rates. The two black lines indicate the positions of the QD-SESAM and the gain structure. The laser beam on the gain structure changes by less than +/−5% and is always smaller than the pump spot radius (120 µm).

This cavity setup allowed a change in repetition rate by simply moving the output coupler on a translation stage in z-direction during laser operation. It was not necessary to realign the laser after changing the cavity length.

3. Experimental results

With the laser cavity described above we achieved stable self-starting modelocking generating femtosecond pulses at continuously tunable repetition rates. Measurements for a repetition rate of 10 GHz are shown in Fig. 2.

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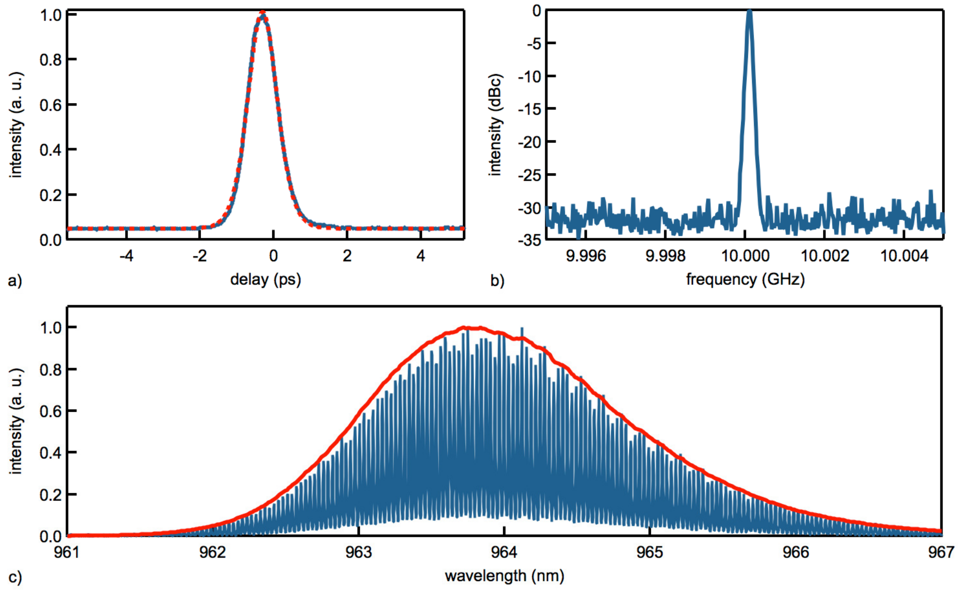

Fig. 2. Modelocking results obtained at a repetition rate of 10 GHz. a) Measured autocorrelation trace (blue) and fitted autocorrelation of a 607-fs sech^2-pulse (red). b) Microwave spectrum with a resolution bandwidth of 100 kHz and a span of 10 MHz showing a repetition rate of 10 GHz. c) Measured optical spectrum with a spectral width of 2.04 nm around 963.7 nm in red with a spectral resolution of 0.1 nm (32 GHz) and in blue with a spectral resolution of 0.01 nm (3.2 GHz), where the longitudinal cavity modes can be partially resolved.

While tuning the repetition rate from 6.5 GHz to 11.3 GHz without any realignment, the pulse duration remained nearly constant around 625 fs with less than 3.5% standard deviation (Fig. 3 red). Over the entire measurement for all cavity lengths, we measured only small changes in output power of less than 6% standard deviation around 169 mW (Fig. 3 blue). During the tuning, the center wavelength was extremely constant changing only about ±0.2 nm around 963.8 nm (Fig. 3 green) even though no etalon was used for wavelength stabilization. The time-bandwidth product in all cases was approximately 1.3 times the transform-limit of a sech^2-pulse. The laser was fundamentally modelocked. The beam quality was measured at 6.5 GHz and 10 GHz and M^2 values of less than 1.05 were obtained.

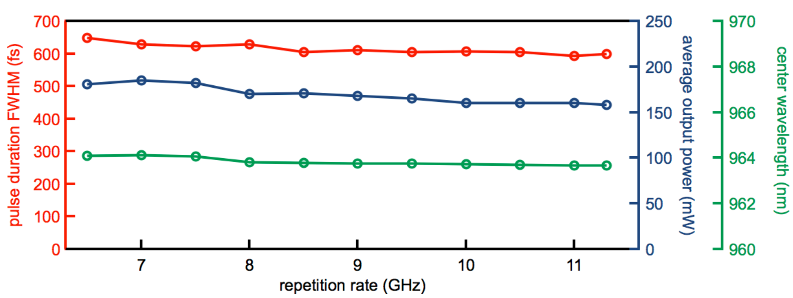

Fig. 3. The repetition rate was tuned from 6.5 GHz up to 11.3 GHz. During the tuning we measured only small changes in output power (blue), with less than 6% standard deviation around 169 mW, while the pulse duration (red) was nearly constant around 625 fs with less than 3% standard deviation. The center wavelength (green) was extremely constant changing only about ±0.2 nm around 963.8 nm.

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4. Conclusion

In summary, we demonstrated a femtosecond QW-VECSEL modelocked with a QD-SESAM which can be continuously tuned in repetition rate from 6.5 GHz up to 11.3 GHz. For all repetition rates, we obtained similar pulse durations around 625 fs with less than 3.5% variation while the output power was also extremely stable with 169 mW ±6%. In our design, the mode areas on VECSEL and SESAM are the same and remain nearly constant for a change in cavity length. This requires a low-saturation fluence SESAM, which can be realized by the use of QD absorbers. This performance is attractive for numerous applications, for example cost-efficient and compact pump-probe measurements using the OSCAT scheme.

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