

# Low repetition rate SESAM modelocked VECSEL using an extendable active multipass-cavity approach

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**Abstract:** Ultrafast VECSELs are compact pulsed laser sources with more flexibility in the emission wavelength compared to diode-pumped solid-state lasers. Typically, the reduction of the pulse repetition rate is a straightforward method to increase both pulse energy and peak power. However, the relatively short carrier lifetime of semiconductor gain materials of a few nanoseconds sets a lower limit to the repetition rate of passively modelocked VECSELs. This fast gain recovery combined with low pulse repetition rates leads to the buildup of multiple pulses in the cavity. Therefore, we applied an active multipass approach with which demonstrate fundamental modelocking at a repetition rate of 253 MHz with 400 mW average output power in 11.3 ps pulses.

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**OCIS codes:** (250.7260) Vertical cavity surface emitting lasers; (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers.

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## 1. Introduction

Vertical external cavity surface emitting lasers (VECSELs) [1] combine the advantages of diode-pumped solid-state lasers (DPSSLs), such as excellent beam quality and a high-Q cavity, with the features of semiconductor lasers such as emission wavelength engineering, compactness and low-cost fabrication. VECSELs are ideally suited for modelocking using a semiconductor saturable absorber mirror (SESAM) [2]. Since the first SESAM modelocked VECSEL demonstration in 2000 [3], these ultrafast laser sources have experienced an impressive improvement in performance [4] and start to be a viable alternative to ultrafast Ti:sapphire lasers, fiber systems or DPSSLs. Similar to DPSSLs, the high-Q cavity results in a very low timing jitter noise of ultrafast VECSEL source [5, 6]. Pulse durations as short as 60 fs in pulse bursts [7], or 107 fs with 3 mW average output power in fundamentally modelocked operation [8] were obtained. In the sub-500-fs domain, the power levels reach up to 150 mW [9, 10]. In 2011, the first sub-picosecond VECSEL with more than 1 W of average output power was demonstrated [11]. Since then, the power levels in this pulse duration regime increased up to 2.35 W in 778 fs pulses from a spontaneously modelocked

VECSEL [12], and very recently to 682 fs pulses with 5.1 W average power from a standard SESAM-modelocked VECSEL [13]. The highest average output power was generated from a VECSEL with an integrated SESAM. This modelocked integrated external-cavity surface emitting laser (MIXSEL) [14] emitted 6.4 W average power in 28.1 ps pulses [15].

VECSELs exhibit a gain carrier lifetime that is several orders of magnitude lower than for typical ion-doped glass or crystal gain materials. This is a clear advantage for the realization of extremely high repetition rates, because Q-switching instabilities, as present in DPSSLs [16], are strongly suppressed. Ultrafast VECSELs with repetition frequencies as high as 50 GHz in the fundamentally modelocked [17] regime, and even 175 GHz in harmonically modelocked operation [18] were demonstrated. Furthermore, VECSELs support widely tunable repetition rates in the GHz-regime for applications such as optical sampling by laser cavity tuning (OSCAT) [19] in the femtosecond modelocking regime [20, 21].

The short gain lifetime, however, is a severe challenge for increasing the pulse energy by means of lowering the pulse repetition rate for a given average output power. For DPSSLs, longer cavities and therefore lower pulse repetition rates enabled pulse energies above 10  $\mu$ J at a few MHz repetition rate and peak powers in the Megawatt regime directly from SESAM modelocked DPSSLs without further amplification [22–24]. So far, the lowest repetition rate of SESAM modelocked VECSELs is around 340 MHz [25, 26] with no more than 15 mW average output power. The pulse energy was limited to a few nJ even for Watt-level average output powers. The semiconductor gain is able to store energy only for a limited time of a few nanoseconds. If the separation between the pulses becomes longer, two or more pulses have a gain advantage, which introduces modelocking instabilities or harmonic modelocking. The harmonic modelocking regime was studied in detail in [26]. The authors confirmed that strong saturation and fast recovery of the gain causes harmonic modelocking, and that the pump power has a strong effect on the pulse break up.

In this paper, we explore a new approach to suppress multiple pulse instabilities at low repetition rates while still providing a high average output power. The idea is to employ a cavity in which the pulse passes over the gain multiple times per cavity round trip, as opposed to twice per cavity round trip in a standard linear cavity of a SESAM modelocked VECSEL. This allows to use longer cavities for a given gain recovery time without the formation of multiple pulses in the cavity. The multipass technique has been employed in ultrafast thin-disk lasers (TDLs) for the first time in 2008 [22, 23] and is referred to as the active multipass principle. In the case of modelocked TDLs this approach is used to multiply the gain per cavity round trip. That allows for larger output coupling rates as high as 70%, which substantially reduced the intra-cavity power and avoids excessive self-phase modulation (SPM) in the cavity. Here we apply the active multipass approach to reduce multi-pulse instabilities and demonstrate a stable and self-starting SESAM modelocked VECSEL with a repetition rate of 253 MHz using four gain-passes per cavity round trip. In a similar cavity using only two gain-passes we could not observe a regime of stable modelocking. To the best of our knowledge this is the first report on an active multipass VECSEL cavity and we demonstrate the lowest pulse repetition rate obtained with a SESAM modelocked VECSEL so far. We achieve pulse durations of 11.2 ps at an average output power of 400 mW. Furthermore, our cavity is designed in such a way that it can be extended in a modular way to many more passes.

Low repetition rate SESAM modelocked VECSELs are very attractive candidates for numerous applications such as biomedical multi-photon imaging. First experiments with a SESAM modelocked VECSEL on living organisms were reported in 2011 [27]. High quality multi-photon images were obtained with a SESAM modelocked VECSEL operating at 500 MHz pulse repetition rate with 287 mW average output power and a pulse duration of 1.5 ps corresponding to a peak power of 400 W. Recently, peak powers in the Kilowatt-level were reported, e.g. 3.8 kW peak power and an average output power of 5.1 W at a repetition rate of 1.7 GHz [13]. We expect that the active multipass approach for VECSELs will result in even higher peak powers to drive numerous applications that currently rely on more complex and expensive ultrafast laser technologies.

## 2. Active multipass VECSEL cavity design

### 2.1 Active multipass cavity configuration

Our experimental setup is based on a modular and extendable resonator design as shown in Fig. 1. We use four passes through the gain per cavity round trip, i.e. twice as many as in a standard SESAM modelocked VECSEL. The total cavity length of 60 cm corresponds to a pulse repetition rate of 250 MHz and a cavity round trip time of 4 ns. A flat output coupler (OC) and a SESAM serve as the end mirrors and the VECSEL gain chip is placed as an active folding mirror in the middle of the cavity. The four gain-passes per cavity round trip are symmetrically arranged and temporally separated by 1 ns to minimize multiple pulse instabilities. The gain chip is pumped by a circular pump spot with a radius of  $\approx 150 \mu\text{m}$  at an angle of incidence of  $45^\circ$  using a fiber coupled 808 nm laser diode. Since the component density is very high for such a small-footprint cavity setup, it is vital to have a systematic alignment procedure for the overlap of the cavity mode and the pump spot. We realize this by facilitating an M-shaped sub-cavity as shown in Fig. 1(a) where M1 and M4 are 1-inch diameter high reflective (HR) dielectric mirrors with a radius of curvature (ROC) of  $-100 \text{ mm}$ . M2 and M3 are flat HR mirrors designed for  $45^\circ$  angle of incidence. The sub-cavity with two gain-passes is completed with a flat semiconductor distributed Bragg reflector (DBR) mirror. Once the two first gain-passes overlap with the pump spot, the DBR is removed and the resonator is expanded by M3, M4, the gain chip and M1, as shown in Fig. 1(b). Finally, the cavity is completed by the SESAM and the full cavity can be aligned systematically with the mirrors M2, M3 and the SESAM. In this way a perfect overlap of all four gain-passes can be easily obtained in a systematic manner. The beam evolution of the  $\text{TEM}_{00}$  laser mode is shown in Fig. 2(a). A typical thermal lens in the VECSEL gain chip of 100 mm is taken into account [17]. A 20- $\mu\text{m}$  thick fused silica etalon is used for intra-cavity wavelength tuning.

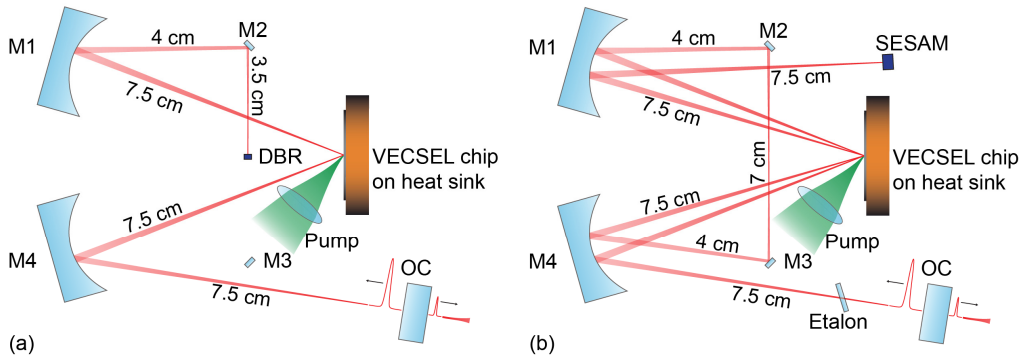


Fig. 1. Schematic of the multipass cavity design. (a) Sub-cavity with two gain-passes per cavity round trip used for alignment purpose, repetition rate 500 MHz (i.e. cavity length 30 cm). (b) Full multipass cavity with four gain-passes per round trip, repetition rate of 250 MHz (i.e. cavity length of 60 cm).

In our experiment, we achieved the best results with a standard resonant quantum-dot (QD-) SESAM with low saturation fluence (for details see section 3). In this case, we enlarged the SESAM mode waist to  $300 \mu\text{m}$  by using a mirror M5 with a ROC of  $-200 \text{ mm}$  instead of a second pass over M1 before the SESAM. M5 is placed at a distance of 9.5 cm from the gain chip and 4.8 cm from the SESAM, respectively, resulting in a total cavity length of 59.3 cm corresponding to a pulse repetition rate of 253 MHz. The simulated beam propagation for this case is shown in Fig. 2(b).

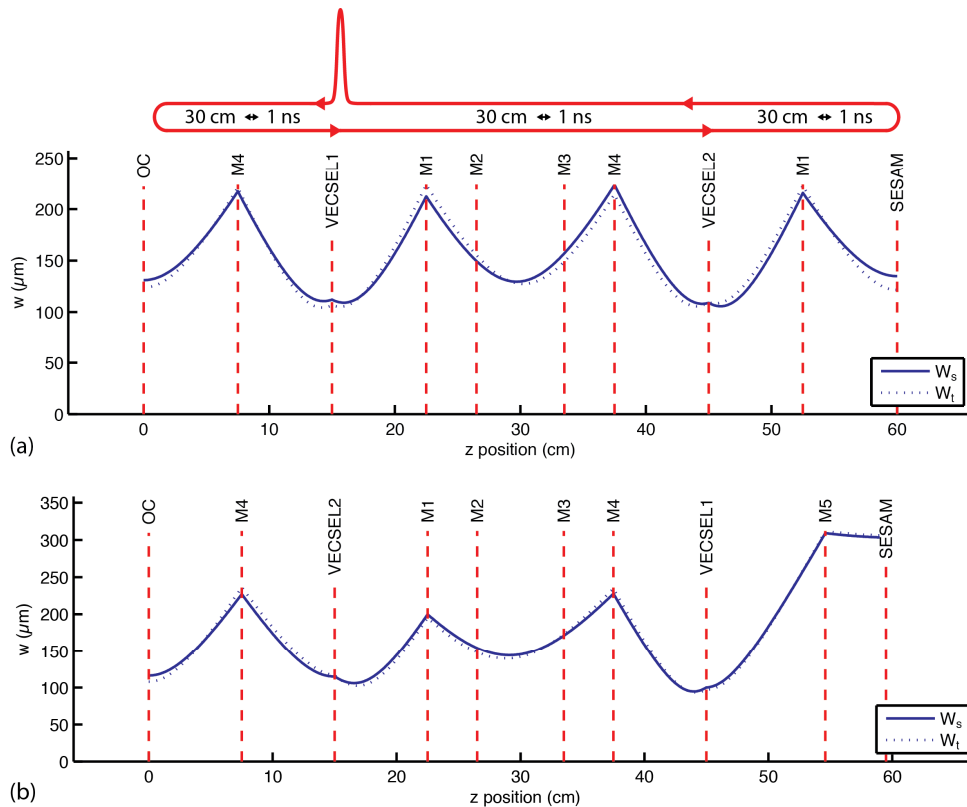


Fig. 2. Sagittal ( $W_s$ ) and tangential ( $W_t$ ) beam mode evolution as a function of the beam position. (a) 250 MHz cavity with small beam waist on SESAM ( $\sim 130 \mu\text{m}$ ) and (b) corresponding cavity with expanded beam waist on the SESAM ( $\sim 300 \mu\text{m}$ ).

## 2.2 Modular extendibility

The cavity is based on a modular design that theoretically allows for an arbitrary number of passes over the gain. In our design we can systematically extend the cavity by repeating the passes over the mirrors M2, M3, M4 and M1 such that the time between the gain-passes is always the same. This ensures stable fundamental modelocking without multiple pulse instabilities. To obtain true scalability, the resonator mode profile needs to be identical after every pass over the gain. We achieve this by implementing a unity-matrix transformation for Gaussian beams by placing mirrors M1 through M4 accordingly. The cavity section between the two intermediate gain-passes (i.e. the section between the positions indicated as “VECSEL1” and “VECSEL2” in Fig. 2) can be repeated and the additional beam waists, in particular the ones on the gain chip and SESAM, do neither change in size nor position. In this paper we present the results for four gain-passes, which allows us to demonstrate the active multipass cavity principle.

## 3. VECSEL gain structure and SESAM

The MOVPE grown VECSEL gain structure used for this experiment was grown in the FIRST cleanroom facility of ETH and is described in [28]. It consists of a highly reflective bottom mirror, the active region and an anti-reflection (AR) section on top. The mirror is a highly reflective  $\text{AlAs}/\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  super-lattice DBR for the laser wavelength at  $\sim 960 \text{ nm}$  under normal incidence angle and for the pump wavelength of  $808 \text{ nm}$  under  $45^\circ$  incidence angle, respectively. The active region contains 7 strain-compensated  $\text{In}_{0.13}\text{Ga}_{0.87}\text{As}$  quantum wells (QW) placed in the antinodes of the standing wave pattern of the electric field. GaAs

spacer layers between the QWs facilitate absorption of the pump light. The last element of the VECSEL is an AR-section on top of the structure to minimize reflections at the air-semiconductor interface. The VECSEL chip was grown in reverse order and flip-chip bonded on a chemical vapor deposition (CVD) diamond for optimal thermal management. The full fabrication of the structure is thoroughly described in [29].

We used a standard resonant QD-SESAM, as well grown in the FIRST cleanroom of ETH, consisting of a 30-pair AlAs/GaAs mirror, a single InAs QD absorber layer grown at 300°C and a quarter wavelength layer of silicon oxide coating (see [11]). With the rather low saturation fluence of 3.8  $\mu\text{J}/\text{cm}^2$  (measured at 965 nm) we used a 300  $\mu\text{m}$  beam waist on the SESAM according to Fig. 3(b). The modulation depth of the SESAM was around 1.2% with non-saturable losses of less than 1%.

#### 4. Experimental results

With the active multipass cavity described above we achieved a stable fundamental SESAM modelocked VECSEL with different OC transmissions (i.e. 0.5%, 1.5%, 2.5% and 4.5%). The highest average output power was obtained with a 4.5% OC. The VECSEL chip was pumped with 7.1 W and the copper heat sink underneath the diamond was thermoelectrically cooled and stabilized at a temperature of 3°C. With the cavity configuration simulated in Fig. 2(b), i.e. with a 300  $\mu\text{m}$  beam waist on the SESAM, we obtained up to 400 mW average output power in 11.2 ps pulses at a repetition rate of 253.2 MHz as shown in a measurement set in Fig. 3.

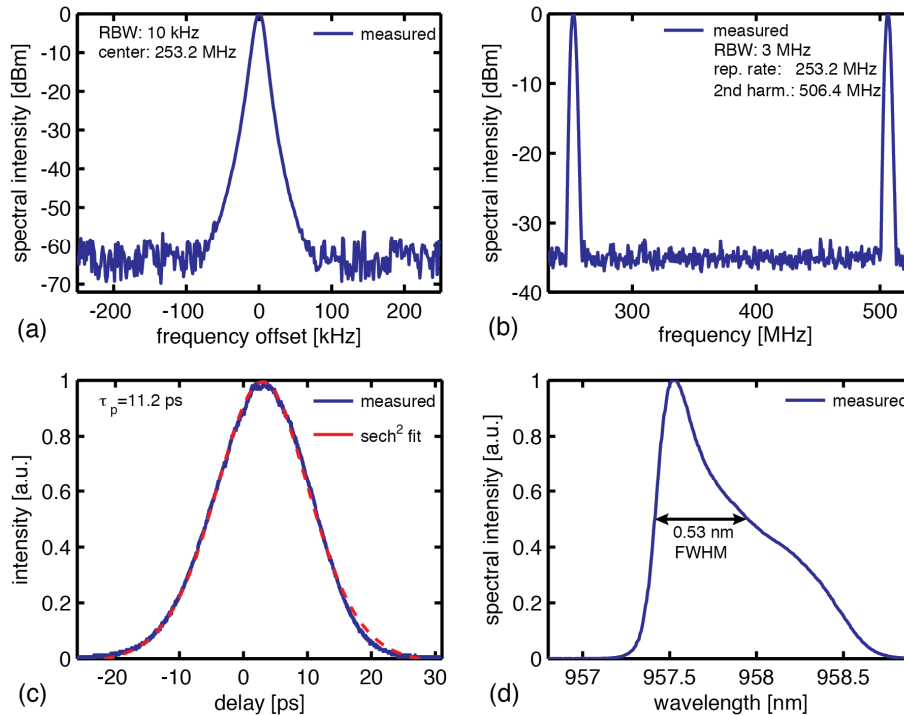


Fig. 3. Modelocking result for 400 mW average output power. (a) Microwave spectrum analyzer (MSA) signal centered around 253.2 MHz, span 500 kHz and resolution bandwidth (RBW) of 10 kHz, (b) MSA signal with span of 300 MHz and RBW of 3 MHz. (c) intensity autocorrelation signal (blue) and  $\text{sech}^2$  fit corresponding to a pulse duration of 11.2 ps. (d) Optical spectrum with FWHM of 0.53 nm corresponding to a time-bandwidth product (TBP) of 2.07.

The microwave spectrum analyzer (MSA) signal in Fig. 3(a) shows a clear 60 dB signal-to-noise peak at the repetition rate of 253.2 MHz recorded with a resolution bandwidth

(RBW) of 10 kHz. The MSA signal in a wider span is plotted in Fig. 3(b) showing the pulse repetition frequency at 253.2 MHz and the second harmonic at 506.4 MHz. The autocorrelation signal in Fig. 3(c) shows the measured second harmonic signal versus time and a  $\text{sech}^2$ -fit corresponding to a pulse with a FWHM of 11.2 ps. The wavelength is centered at 958 nm with a FWHM of 0.53 nm, see Fig. 3(d). The pulses are chirped with a time-bandwidth-product (TBP) of 2.07. The peak power of these pulses amounted to 124 W. With a fluence of about  $14 \mu\text{J}/\text{cm}^2$  the SESAM was operated at a saturation parameter of 3.7.

In order to confirm the stabilization effect of the four gain-passes allowing fundamental modelocking at low repetition rates, we studied a similar low repetition-rate cavity with only two gain-passes per cavity round trip. The beam waists and distances in the cavity were identical to the values in the multipass cavity. We realized this by bypassing the gain-pass at the position “VECSEL2”, see Fig. 2(b) with a DBR. Even with different SESAMs and OC transmissions we were not able to find any cavity configuration enabling stable modelocked operation. Most likely, the 3 ns time window between the gain-passes in the SESAM-arm of the cavity is too long compared to the gain carrier lifetime and leads to multiple pulse instabilities that severely destabilized the modelocking process.

## 5. Conclusion and outlook

We have successfully demonstrated the first active multipass cavity modelocked VECSEL to beat the lower repetition rate limit due to short semiconductor gain carrier lifetime. A record low pulse repetition-rate of 253.2 MHz for a fundamental SESAM-modelocked VECSEL was achieved with an average output power as high as 400 mW with 11.2 ps pulses. A peak power of 124 W was obtained making this new kind of modelocked VECSEL a very attractive candidate for compact pulse sources for biomedical applications. The demonstrated multipass cavity has only a footprint of around 15 cm by 15 cm. It is easy to align and stable modelocking can be achieved with various cavity configurations. Furthermore, it can be extended in a modular fashion to enable many more passes, in particular if the third dimension is incorporated for placing optical elements. This could be realized by employing a Herriott-type multipass cell [30], designed according to the extendable multipass cavity presented here. In principle this would allow pulse repetition rates in the sub-100 MHz range.

In these first proof-of-principle experiments, an intra-cavity etalon was used for wavelength tuning, which restricted the spectral bandwidth. Moreover, the dispersion of the gain structure and SESAM were not optimized for shorter pulse durations. Operation without etalon and the use of optimized SESAM and VECSEL structures should enable the operation in the femtosecond regime, increasing the peak power of the emitted pulses even more. Our approach is very promising to open up new application areas for modelocked semiconductor lasers that have been beyond their accessible repetition rate, pulse energy and peak power levels so far.

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