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# Sub-60-fs Timing Jitter of a SESAM Modelocked VECSEL

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**Abstract:** We present noise measurements of a pulse train emitted from an actively stabilized semiconductor-saturable-absorber-mirror (SESAM) modelocked vertical external cavity surface emitting laser (VECSEL). The laser generated 6-ps pulses with 2-GHz pulse-repetition rate and 40-mW average output power. The repetition rate was phase locked to a reference source using a piezo actuator. The timing phase noise power spectral density of the laser output was detected with a highly linear photodiode and measured with a signal source analyzer. The resulting RMS timing jitter integrated over an offset frequency range from 1 Hz to 100 MHz gives a value of below 60 fs, lower than previous modelocked VECSELs and comparable with the noise performance of ion-doped solid-state lasers. The RMS amplitude noise was below 0.4% (1 Hz to 40 MHz) and not influenced by the timing phase stabilization.

**Index Terms:** Photon sources, diode-pumped lasers, infrared lasers, modelocked lasers, semiconductor lasers, ultrafast lasers.

## 1. Introduction

Optically pumped vertical external cavity surface emitting lasers (VECSELs) compared with diode-pumped solid-state lasers (DPSSLs) offer much more flexibility for the laser operation wavelength because of band-gap engineering of the quantum-well gain section in the VECSEL. In addition, passive modelocked VECSELs with a semiconductor saturable absorber mirror (SESAM) [1], [2] do not suffer from Q-switching instabilities because of the much higher gain cross section of semiconductor lasers [3]. Since the first SESAM modelocked VECSEL in 2000 [4], such lasers have demonstrated outstanding performance in terms of average output power and pulse duration [5]–[9]. The full integration of the SESAM into the VECSEL structure was demonstrated with the modelocked integrated external-cavity surface emitting laser (MIXSEL) [10], [11] again with world-record performance generating multiwatt average output power with picosecond pulses at gigahertz repetition rates [9], [12]. Ultrafast laser sources with gigahertz repetition rates are important for applications such as optical data transmission [13], photonic signal processing [14], and frequency comb metrology [15]. The low-noise performance of DPSSLs have enabled new world records in data transmission rates [16] and frequency combs [17]. We expect very similar low-noise performance from ultrafast VECSELs because the interaction length with the quantum-well gain is very short and the cavity losses are very low compared with standard edge-emitting semiconductor lasers. It is well established that a high-Q cavity exhibits much lower noise levels [18], [19].

Diverse laser systems have shown very low timing jitter with different stabilization and measurement techniques [20]–[25]. These lasers operate at repetition rates in the megahertz regime or are harmonically modelocked for gigahertz operation. To achieve very low timing jitter, these laser systems are stabilized to an ultra-low-noise microwave oscillator [20], [21], a CW laser [22], [23], or an almost similar laser system [24], [25]. We demonstrate a passively and fundamentally modelocked gigahertz laser with a noise performance that is comparable with ion-doped solid-state lasers [26]. Only a limited number of studies on timing jitter from ultrafast VECSELs have been published to date. A quantum-well SESAM modelocked VECSEL generating 2.3-ps pulses at 1043 nm showed an RMS timing jitter of 410 fs (bandwidth: 1 kHz–15 MHz) in a free-running mode and 160 fs with active stabilization [27]. In subsequent experiments with an actively stabilized cavity and sub-500-fs pulse duration, a timing jitter of 190 fs (bandwidth: 300 Hz–1.5 MHz) was achieved [28]. A different approach of timing-jitter reduction of a modelocked VECSEL at the wavelength of 1530 nm was demonstrated by optically triggering the SESAM [29], reducing the RMS timing jitter to 8 ps in the free-running mode and to 423 fs with active stabilization (bandwidth: 100 Hz–10 MHz).

Here, we present world-record timing-jitter performance of a stabilized SESAM modelocked VECSEL generating 6-ps pulses at a repetition rate of 2 GHz and with 40-mW average output power at a center wavelength of 953 nm. Noise measurements of a similar laser in a free-running configuration showed an RMS timing jitter of about 212 fs in a bandwidth from 100 Hz to 1 MHz [30]. Active timing-jitter stabilization to an electronic reference source was achieved with a cavity length control loop using a piezo-electric actuator. After detection of the output pulse train with a highly linear photodiode (HLPD), the timing phase noise power spectral density (PSD) was measured with a Signal Source Analyzer (SSA). Integration over an offset frequency range of 1 Hz–100 MHz resulted in an RMS timing jitter below 60 fs.

## 2. Cavity Setup and Laser Performance

The laser is based on an InGaAs quantum-well VECSEL gain chip operating at 953 nm, passively modelocked with a quantum-dot SESAM. The VECSEL is optically pumped perpendicular to the surface using an 808-nm fiber coupled multimode diode laser operated at 2.1-W output power. The laser generates 6-ps pulses at 2-GHz pulse repetition rate and about 40-mW average output power. For good mechanical stability, all cavity elements and the pump diode are enclosed in a metal housing to reduce vibrations and air currents. To further minimize mechanical instabilities, we did not use water cooling, and therefore, the pump diode and the VECSEL chip are passively air cooled. Only the gain chip is thermally stabilized to a temperature of 15 °C using a Peltier element. The laser setup consists of a 7.5-cm-long Z-shaped cavity with a curved output coupler with a radius of curvature (ROC) of 60 mm and a transmission of 0.9%, the VECSEL gain chip, a highly reflecting folding mirror (ROC: 38 mm), and the SESAM as the end mirror [see Fig. 1(a)]. A 20-$\mu$m-thick fused silica etalon is placed between the VECSEL and output coupler for wavelength stabilization. Simulations of the cavity mode sizes show that the mode radius amounts to 90 $\mu$m on the VECSEL and 65 $\mu$m on the SESAM. In Fig. 2, the recorded optical spectrum [see Fig. 2(a)], intensity autocorrelation [see Fig. 2(b)], and the microwave signal [see Fig. 2(c)] are given.

## 3. Stabilization and Noise Measurement Setup

For the stabilization, part of the laser output is detected with a 25-GHz photodiode, amplified, and filtered with a 2.4-GHz low-pass filter (LPF) to filter out the higher harmonics. This remaining 2-GHz signal is stabilized to the 2-GHz reference signal from a synthesized signal generator (HP 8663A). We used a custom-designed phase-locked-loop (PLL) circuit with a double balanced mixer (MITEQ DM0104LA1) for analog phase detection. The output of the PLL circuit is connected to a piezo actuator (free stroke of 5.3 $\mu$m) mounted underneath the SESAM to control the cavity length [see Fig. 1(a)]. For the noise characterization, the other part of the laser output is detected with a HLPD [31], low-pass filtered, and amplified (Agilent 87405C) to measure timing phase noise with an SSA (Agilent E5052B). To increase the measurement sensitivity, we measured with ten correlations and

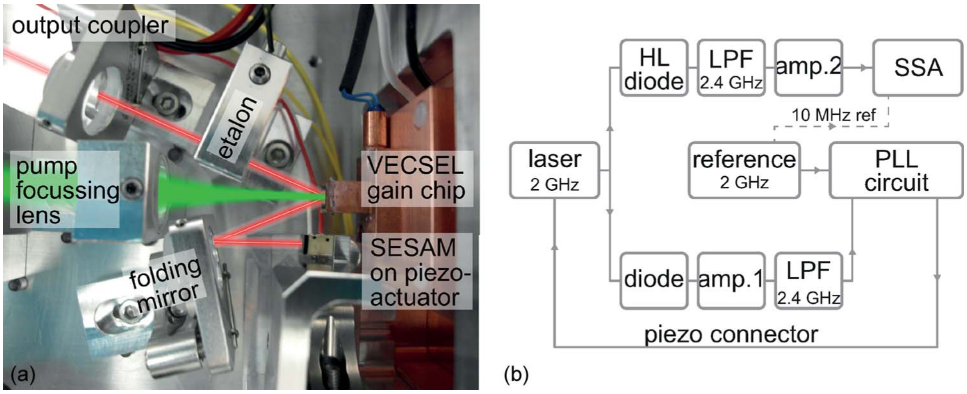

Fig. 1. Overview of the experimental setup: (a) laser cavity with output coupler (0.9% transmission ROC of 60 mm), folding mirror (ROC 38 mm) and (b) schematic overview of the stabilization and noise measurement setup. The electronic reference signal is provided by the synthesized signal generator (HP 8663A), the output of the laser is detected with a HLPD (DSC30S-HLPD, Discovery Semiconductor Inc.) and measured with a signal source analyzer (SSA Agilent E5052B).

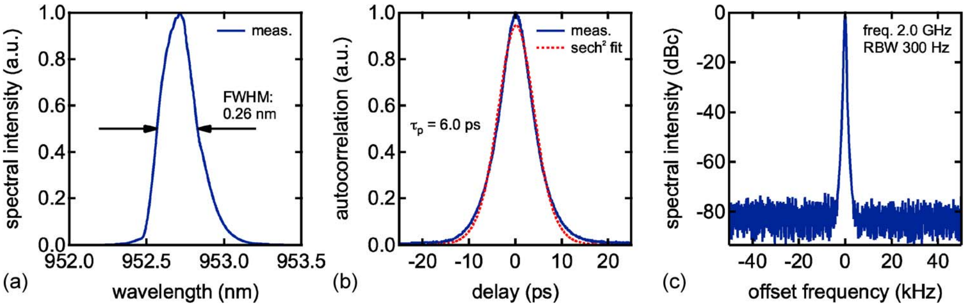

Fig. 2. Modelocking results. (a) Optical spectrum, (b) intensity autocorrelation, and (c) microwave signal of the 6.0-ps pulses at 2 GHz pulse repetition rate and about 40 mW average output power. RBW: resolution bandwidth.

used the 10-MHz reference of the signal generator for one channel in the SSA, which further increased the sensitivity in the range below 30 Hz (see Fig. 3).

## 4. Phase Noise Measurements

The single-sideband (SSB) phase noise PSD of the stabilized laser was measured and compared with the free-running laser and the reference oscillator (see Fig. 3). For the laser measurements, the output power was adjusted for a photocurrent of 1 mA from the HLPD, corresponding to a shot noise level of $-155$ dBc/Hz. This level is reached for offset frequencies above 10 MHz.

The RMS timing jitter $\sigma_T$ (see inset of Fig. 3) was calculated by integrating the phase noise PSD from the lower limit frequency $f_{\text{low}}$ to the higher limit frequency $f_{\text{high}}$ of 100 MHz. The corresponding RMS timing jitter was below 58 fs when taking the full bandwidth [1 Hz, 100 MHz] of the SSA, which is even lower than the RMS timing jitter of 89 fs from the reference source. This RMS timing-jitter value of the laser is an upper limit because, above 10 MHz, the measurement sensitivity is limited by the shot noise of the photodiode. The slight bump in the PSD between 1 MHz and 10 MHz is caused by amplitude to phase noise conversion in the detection setup. The original laser noise can be seen between 30 kHz and 1 MHz. Here, the laser has a lower phase noise level than the reference signal because, in this range, the noise level of the free-running laser is lower then the reference signal and the stabilization is limited to 10 kHz due to the loop bandwidth. In the range from 1 to 30 kHz the PSD of the stabilized laser is higher than the reference source, which potentially could be improved with a redesigned feedback loop. This could result in a minor improvement of less

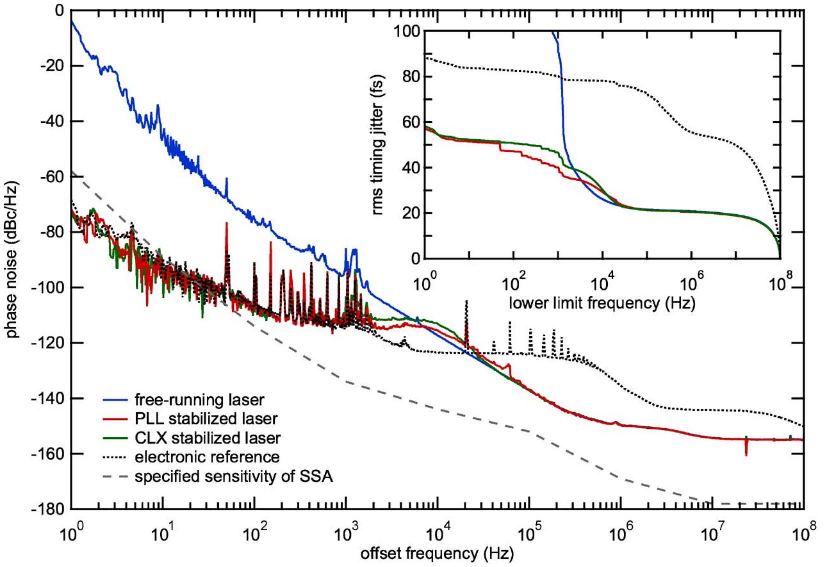

Fig. 3. Measured timing phase noise PSD (SSB) of the free-running laser (blue), the stabilized laser [two electronic circuits: PLL (red) and CLX (green)] and the reference source (dotted black). The specified sensitivity level of the SSA is given as well (dashed gray). Inset: RMS timing jitter integrated from the lower limit frequency to 100 MHz.

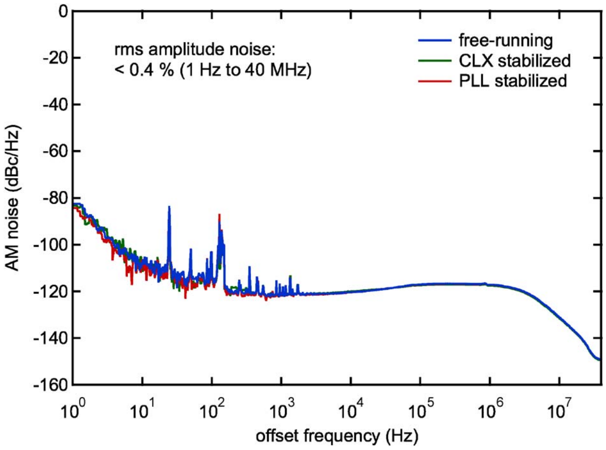

Fig. 4. Amplitude noise characterization of the free-running and the stabilized laser acquired with an Agilent E5052B showing no influence of the timing phase stabilization on the amplitude noise.

than 5 fs in the timing jitter in the [1 Hz, 100 MHz] bandwidth. Below 1 kHz, the laser follows the reference source, which limits the noise performance. A lower noise level can therefore only be expected in this range when locking the laser to a reference source with a lower noise level or to a second laser and measuring the relative timing jitter according to [24]–[26]. In the low offset frequency range below 30 Hz, the measured noise level is less than the specified sensitivity of the SSA. The sensitivity of the SSA is improved in this range by locking one local oscillator of the SSA to the 10-MHz reference signal from the reference source [see Fig. 1(b)].

We also measured the amplitude noise PSD (see Fig. 4) and determined the RMS amplitude noise to be below 0.4% integrated over a [1 Hz, 40 MHz] bandwidth. The amplitude noise was not stabilized and was not influenced by the timing-jitter noise stabilization. This was, in principle, expected because the timing jitter was stabilized with a simple cavity length adjustment, which does not affect passive modelocking with an intracavity saturable absorber.

TABLE 1

Overview of timing-jitter results and comparison with other fundamentally modelocked GHz lasers

| **source** | **repetition rate (GHz)** | **$f_{low}$ (Hz)** | **$f_{high}$ (MHz)** | **rms timing jitter (fs)** |
|---|---|---|---|---|
| VECSEL stabilized | 2 | **1** | **100** | **58** |
| | 2 | 100 | 100 | 47 |
| | 2 | 6 | 1.56 | 48 |
| | 2 | 1000 | 15 | 36 |
| | 2 | 300 | 1.5 | 39 |
| | 2 | 100 | 10 | 43 |
| reference source (HP 8663A) | 2 | 1 | 100 | 89 |
| VECSEL free-running | 2 | 1 | 100 | 34740 |
| | 2 | **100** | **100** | **201** |
| | 2 | 100 | 1.56 | 190 |
| | 2 | 1000 | 15 | 91 |
| | 2 | 300 | 1.5 | 131 |
| | 2 | 100 | 10 | 200 |
| VECSEL free-running [27] | 0.897 | 1000 | 15 | 410 |
| VECSEL stabilized [27] | 0.897 | 1000 | 15 | 160 |
| VECSEL stabilized [28] | 1 | 300 | 1.5 | 190 |
| VECSEL free-running [29] | 1.68 | 100 | 10 | 8000 |
| VECSEL stabilized [29] | 1.68 | 100 | 10 | 423 |
| VECSEL free-running [30] | 2 | 100 | 10 | 218 |
| | 2 | 300 | 1.5 | 144 |
| | 2 | 1000 | 15 | 114 |
| Er:Yb:glass laser free [26] | 10 | 100 | 1.56 | 190 |
| Er:Yb:glass laser stab. [26] | 10 | 6 | 1.56 | 26 |

Semiconductor edge emitting lasers with low-Q cavities often have a relaxation oscillation peak at a few gigahertz. However, the VECSEL operates in a different regime compared with both edge emitting semiconductor lasers and DPSSLs [32] with both a high-Q cavity and a short gain lifetime where no relaxation oscillations occur. We confirmed this by measuring the microwave spectrum with a resolution bandwidth of 3 kHz up to the fundamental peak at 2 GHz and could not detect any peaks from the laser down to the background of the microwave spectrum analyzer of $-120$ dBc/Hz. To exclude influence from the PLL circuit on the noise performance, the measurements were also performed with a commercially available CLX-1100 Timing Stabilizer from Time-Bandwidth Products (specially adapted for this setup at 2 GHz) leading to similar performance (see Figs. 3 and 4).

In Table 1 the calculated RMS timing jitter of the PLL stabilized laser is compared with the laser in free-running operation, previously reported VECSEL results, and a fundamentally modelocked 10-GHz DPSSL. Different integration bandwidths are given to compare with the published results.

## 5. Conclusion

We have demonstrated record low timing jitter below 60 fs integrated over a [1 Hz, 100 MHz] bandwidth from an optically pumped and actively stabilized SESAM modelocked VECSEL, which is comparable with the performance of SESAM modelocked diode-pumped ion-doped solid-state lasers. The pulse repetition rate of the laser, emitting 6-ps pulses at a repetition rate of 2 GHz, was stabilized to a reference source using a piezo actuator. The RMS amplitude noise was below 0.4% and not influenced by the timing stabilization. This result clearly demonstrates the great potential of SESAM modelocked VECSELs and MIXSELs with a noise performance in the same range as DPSSLs. This makes these lasers very attractive for cutting edge data transmission and frequency comb applications.

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