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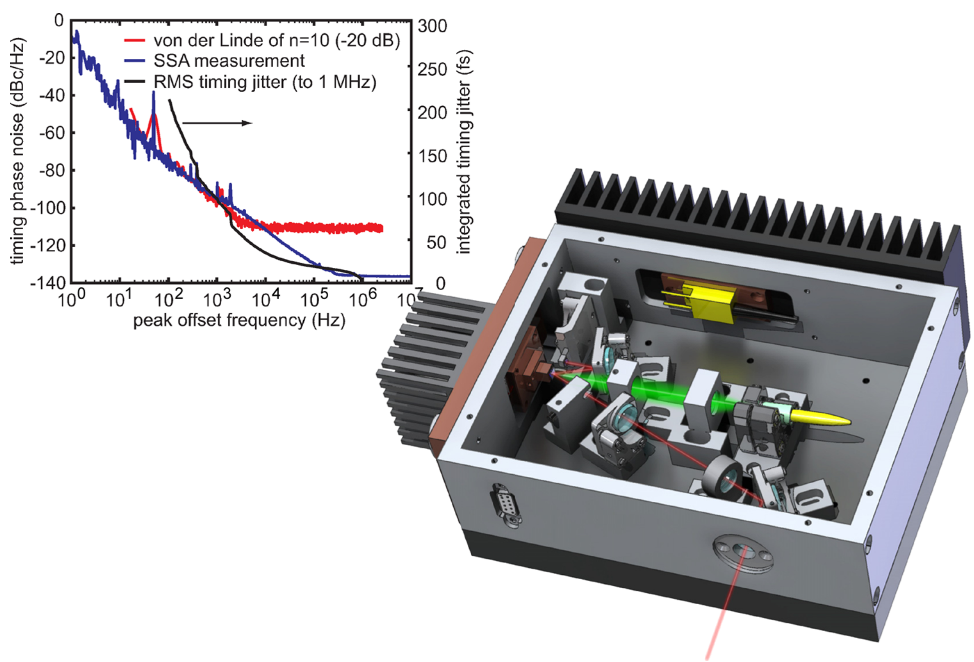

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Abstract: We present timing jitter measurements of an InGaAs quantum well vertical external cavity surface emitting laser (VECSEL) passively mode locked with a quantum dot semiconductor saturable absorber mirror (SESAM) at 2-GHz repetition rate. It generates 53-mW average output power in 4.6-ps pulses at 953 nm. The laser housing was optimized for high mechanical stability to reduce acoustic noise. We use a fiber-coupled multimode 808-nm pump diode, which is mounted inside the laser housing. No active cavity length stabilization is employed. The phase noise of the free-running laser integrated over a bandwidth from 100 Hz to 1 MHz corresponds to an RMS timing jitter of ≈212 fs, which is lower than previously obtained for mode-locked VECSELs. This clearly confirms the superior noise performance expected from a high-Q-cavity semiconductor laser. In contrast to edge-emitting semiconductor diode lasers, the cavity mode is perpendicular to the quantum well gain layers, which minimizes complex dispersion and nonlinear dynamics.

Index Terms: Photon sources, diode-pumped lasers, infrared lasers, mode-locked lasers, semiconductor lasers, ultrafast lasers.

1. Introduction

Ultrafast laser sources with low timing jitter are important for many applications, for example, in optical data transmission, optical sampling measurements, and in metrology. Diode-pumped solid-state lasers (DPSSLs) mode locked with semiconductor saturable absorber mirrors (SESAMs) [1], [2] benefit from high-Q cavities and moderate intracavity nonlinearities, resulting in a low quantum noise limit [3]. Nearly quantum-noise-limited timing jitter was achieved from passively mode-locked Er:Yb:glass lasers with 10-GHz repetition rate based on an enclosed cavity setup with high mechanical stability [4]. Vertical external cavity surface emitting lasers (VECSELs; see [5]) combine the advantages of DPSSLs and semiconductor lasers [6] and are therefore expected to be very attractive for many applications where the current commercial ultrafast lasers still seem to be too expensive. To date a large parameter range in performance has been demonstrated using SESAMs for stable and self-starting pulse formation. In fundamentally mode-locked operation, which is usually more stable than harmonically mode-locked operation, repetition rates up to 50 GHz were achieved at 102 mW average power in 3.3 ps-pulses [7]. The shortest achieved pulse duration is 60 fs, which, however, was realized in a multipulse mode with high instability [8]. Fundamentally mode-locked femtosecond VECSELs achieved 3 mW in 107 fs [9] and 1.05 W in 784 fs [10]. Furthermore, integration of the saturable absorber into the gain structure is feasible, enabling mode-locking from a simple and compact straight cavity setup. This type of laser is referred to as the mode-locked integrated external-cavity surface emitting laser (MIXSEL; see [11]). Recently, 6.4 W average power at 2.5 GHz in 28-ps pulses were achieved, which is higher than for any other mode-locked semiconductor laser [12].

Mode-locked VECSELs operate with high-Q cavities with typical intracavity losses (including output coupling) in the range of 1%–5%. In addition, the interaction length with the quantum well gain is very short due to the vertical propagation of the laser mode in the structure and therefore complex dispersion and nonlinear dynamics are kept low compared with edge-emitting diode lasers. The total thickness of a VECSEL structure is typically below 10 μm; therefore, the intracavity circulating pulse propagates mainly in air. This is in contrast to edge-emitting semiconductor lasers, where the interaction length with the semiconductor gain is much longer and the circulating pulse is significantly affected by complex material dispersion and nonlinearities, which tend to introduce instabilities. This makes VECSELs very similar to DPSSLs, which have demonstrated quantum-noise-limited performance [4].

Although mode-locked VECSELs are promising for low-noise operation, only few studies investigated their timing jitter so far. Wilcox *et al.* demonstrated a VECSEL passively mode locked with a quantum well SESAM operating at a center wavelength of 1043 nm with 2.3-ps pulse duration. In free-running operation, they measured an RMS timing jitter of 410 fs within a bandwidth of 1 kHz to 15 MHz. Active stabilization of the cavity length reduced it to 160 fs (measured in the same bandwidth) [13]. The main contributions to the timing jitter were in the low-frequency range. In subsequent experiments, Quarterman *et al.* achieved a timing jitter of 190 fs from a similar actively stabilized lasers generating sub-500-fs pulses in a bandwidth from 300 Hz to 1.5 MHz [14]. Baili *et al.* presented another method for active stabilization for which an additional actively modulated laser beam changed the saturation of the SESAM in VECSEL [15]. This reduced the free-running RMS timing jitter from 8 ps to 423 fs (bandwidth: 100 Hz to 10 MHz). In this paper, we present a mode-locked 953-nm VECSEL generating 4.6-ps pulses at a 2-GHz repetition rate. The laser is mode locked with a low-saturation fluence QD-SESAM, which enables a simple cavity design with similar spot sizes on gain and absorber. We optimized the cavity setup for maximum mechanical stability. Our free-running laser achieves lower timing jitter than previously reported even with active stabilization and demonstrates a comparable level of noise performance as DPSSLs.

2. Laser Design

The VECSEL gain chip was grown by metalorganic vapor phase epitaxy (MOVPE) on a GaAs wafer. It consists of a double-periodic 36-pair Bragg reflector for both the laser and pump wavelengths, on which the active region and an antireflective section are grown. The active region consists of seven 7.8-nm compressively strained $In_{0.13}Ga_{0.87}As$ quantum wells which are placed in subsequent field maxima of the standing-wave pattern. They are separated by spacer layers made of pump-absorbing GaAs and 17.7-nm tensile-strained $GaAs_{0.94}P_{0.06}$ layers for strain-compensation. The top section consisting of six $Al_{0.2}Ga_{0.8}As$/AlAs pairs is designed for minimum reflection of an 808-nm pump at an angle of incidence of 45° and a laser wavelength of 960-nm at 0°–10°. The structure was grown in reverse order for substrate removal. The GaAs substrate was replaced by a chemical-vapor-deposition (CVD) diamond heat sink. More details on the design and processing of the structure are described in [16], which reports a continuous-wave VECSEL with 20 W in fundamental transverse mode.

Stable self-starting mode locking is achieved with a QD-SESAM grown by molecular-beam epitaxy (MBE) on a GaAs substrate. It contains one single InAs QD-layer using Stranski–Krastanov growth, which is placed in a resonant structure (for details on the QD-SESAM growth; see [17]).

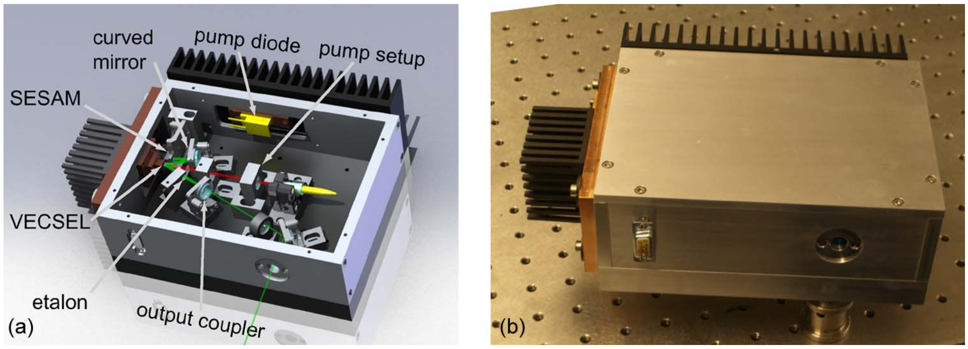

Fig. 1. (a) Z-shaped cavity design with the fiber-coupled pump diode. (b) Picture of the laser in the closed metal housing.

It has a saturation fluence of 19 μJ/cm^2, a modulation depth of 2.7%, and nonsaturable losses of 0.3% (measured with the setup described in [18]).

The 75-mm long standing-wave cavity is Z-shaped with a curved output coupler (radius of curvature (ROC) 60 mm, 0.9% transmission) and the SESAM as the end mirror. The two folding cavity components are the VECSEL gain chip and a curved mirror with an ROC of 60 mm [Fig. 1(a)]. The gain chip is optically pumped perpendicular to its surface by a fiber-coupled pump diode. The pump has a center wavelength of 808-nm and delivers a maximum power of 4.5 W in a multimode fiber (105-μm core diameter, NA 0.15). The intracavity beam radius on the VECSEL and SESAM are both approximately 90 μm. Operation with the same mode size on the SESAM as on the VECSEL is referred to as 1 : 1 mode locking and requires a SESAM with moderate saturation fluence [6].

In order to reduce technical noise due to vibrations of the cavity components, we built the cavity with improved mechanical stability. It is enclosed in an aluminum housing, which also contains the pump diode [see Fig. 1(b)]. Our laser is passively air-cooled, avoiding possible mechanical vibrations due to forced air or water cooling. The gain chip is temperature-stabilized to 17 °C by a thermoelectric Peltier element, which is cooled by a passive heat sink. The pump diode is not temperature-stabilized and its heat sink is thermally isolated from the main housing [see Fig. 1(b)].

At a pump power of 2.8 W, we obtain 53 mW in 4.6-ps pulses (see Fig. 2). The repetition rate is 2 GHz and the center wavelength is 953 nm. The output pulses are slightly chirped with a time-bandwidth product of 0.58 (1.8 times the transform limit of a sech^2-pulse). Please note that the laser setup was not optimized for efficiency, but for a simple cavity design, air-cooling, and stability (for example, the laser in [12] achieves 17% optical-to-optical efficiency). Furthermore, the VECSEL chip was not designed for perpendicular pump incidence, which leads to a reduced pump absorption. The laser is self-starting and runs stably over days.

3. Noise Performance

In the first step, we used the von der Linde method to evaluate the timing jitter performance [19]. We detected the laser output using a New Focus 1434 photodiode (25-GHz bandwidth) and an HP 8563E microwave spectrum analyzer. These experiments were performed with the first realization of the laser, which operated at a repetition rate of 1.88 GHz. In Fig. 3(a), the two-sided power spectral density of the 1st up to the 12th harmonic is plotted as a function of the peak offset frequency. In Fig. 3(b) we show the integrated sideband power (integrated over an offset frequency range from 100 Hz to 100 kHz on both sides) against the harmonic number n of the first 12 harmonics. The least square fit to (1) allows to determine the contribution of the amplitude noise P_A and the timing phase noise power P_T to the normalized power of the sidebands P_{sb}. According to (2), in which f_{rep} is the repetition rate of the laser, we obtain a free-running RMS timing jitter of $\sigma_T \approx 400$ fs.

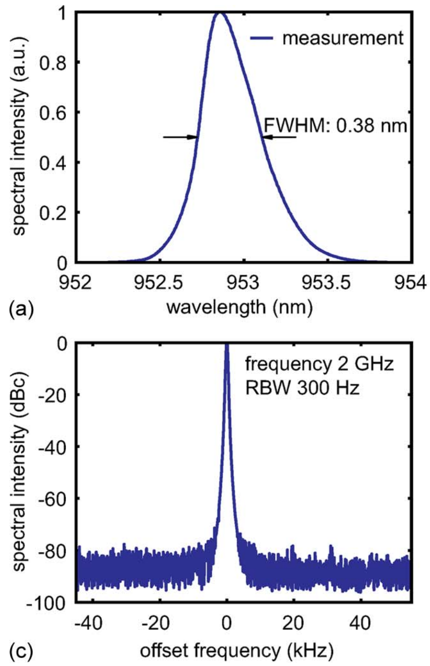

Fig. 2. Mode-locking results. (a) Optical spectrum, (b) intensity autocorrelation, and (c) and (d) microwave signal of the 4.6-ps pulses with 53 mW average power. RBW: resolution bandwidth.

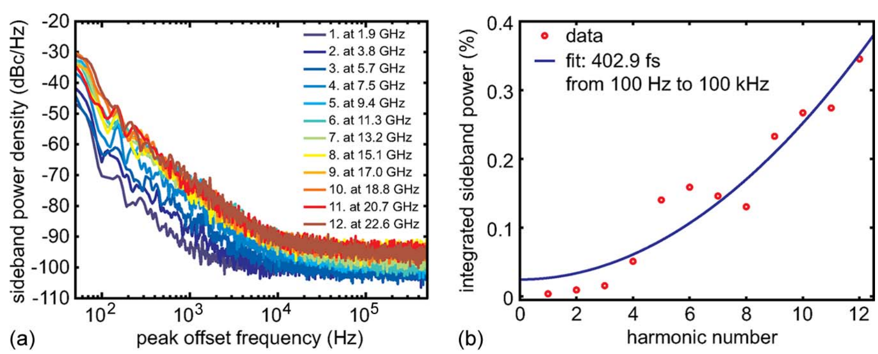

Fig. 3. (a) Sideband power spectral density of the first up to the 12th harmonic as a function of peak offset frequency measured with a microwave spectrum analyzer. (b) Integrated sideband power against harmonic number.

This value is an upper limit because the measurement was already system noise limited above 10 kHz [see Fig. 3(a)]

$$P_{sb}(n) = P_A + P_T \cdot n^2 \tag{1}$$

$$\sigma_T = \frac{\sqrt{P_T}}{2\pi \cdot f_{rep}}. \tag{2}$$

The measurements of the fifth and sixth harmonic show slightly increased noise. However, neglecting those points in the fitting procedure would change the RMS jitter only by less than 5%.

In a second step, we optimized the laser for operation at the targeted repetition rate of 2.0 GHz and characterized the timing jitter with an Agilent E5052B Signal Source Analyzer. We used the same 25-GHz New Focus photodetector with a Miteq amplifier (model AFS3). The optical power on

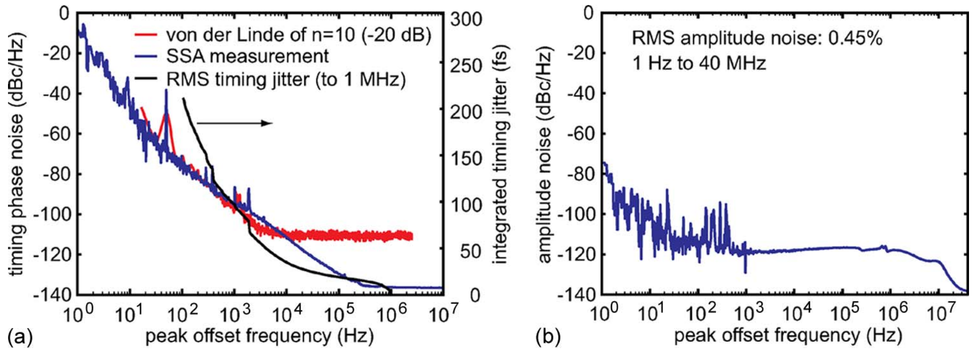

Fig. 4. Noise characterization. (a) Two-sided power density of the phase noise (dBc/Hz) and integrated timing jitter (fs) integrated from f_{low} to $f_{high} = 1$ MHz as a function of f_{low} and (b) amplitude noise with an integrated RMS amplitude noise of 0.45% in [1 Hz, 40 MHz].

TABLE 1

Overview of our timing jitter results (top four rows) and comparison with other lasers previously published

Laser	repetition rate	f_{min}	f_{max}	RMS timing jitter
VECSEL free-running	2 GHz	100 Hz	1 MHz	212 fs
	2 GHz	100 Hz	10 MHz	218 fs
	2 GHz	300 Hz	1.5 MHz	144 fs
	2 GHz	1 kHz	15 MHz	114 fs
VECSEL stabilized [14]	1 GHz	300 Hz	1.5 MHz	190 fs
VECSEL free-running [13]	897 MHz	1 kHz	15 MHz	410 fs
VECSEL stabilized [13]	897 MHz	1 kHz	15 MHz	160 fs
VECSEL free-running [15]	1.68 GHz	100 Hz	10 MHz	8 ps
VECSEL stabilized [15]	1.68 GHz	100 Hz	10 MHz	423 fs
Er:Yb:glass laser free-running [4]	10 GHz	100 Hz	1.56 MHz	190 fs
Er:Yb:glass laser stabilized [4]	10 GHz	6 Hz	1.56 MHz	26 fs

the photodiode signal was attenuated to approximately 1.5 mW, and therefore, the maximum photocurrent was limited to 200 μA. The fast measurement time enabled us to further optimize the operation parameters for low-noise performance. The measurement of the two-sided timing phase noise power spectral density and the amplitude noise power spectral density is shown in Fig. 4. For frequencies above 1 MHz, the phase noise signal is limited by system noise. We obtain an integrated timing jitter of 212 fs in a bandwidth of 100 Hz to 1 MHz.

The measurements are confirmed by a timing jitter measurement using the von der Linde technique [19] on a second laser setup with identical components. Here, the power spectral densities of the timing phase noise is derived from the noise sidebands around the 10th harmonic [19]. The measurement shows a similar noise spectrum to the results obtained with the Signal Source Analyzer [see Fig. 4(a)].

In Table 1, we compare our timing jitter results with other lasers. In reference [13] and [14] von der Linde measurements were performed, and in [4], an indirect phase comparison method was applied to measure the relative timing jitter of two independent lasers. In [15], a commercial jitter analyzer (Europtest PN9000) was used. The achieved values in this work are comparable with state-of-the-art free-running DPSSLs. Besides this, Table I shows that the main contribution to the timing jitter originates from acoustic noise in the sub-10-kHz regime. Further reduction of the noise level would therefore require even better mechanical stability or an active feedback loop for noise reduction. The performance is expected to be similar to previously mentioned DPSSLs, for which the jitter was reduced from 190 fs (100 Hz–1.56 MHz) to 26 fs (6 Hz–1.56 MHz) [4]. Aside from mechanical vibrations, a multimode pump can also introduce additional noise. This could be improved by changing to a single mode pump (as in [4]).

4. Conclusion

We have demonstrated a free-running SESAM mode-locked VECSEL, which achieves better timing jitter than any previous free-running or actively stabilized VECSEL. Special care was taken to achieve high mechanical stability of the laser setup. Furthermore, a simple laser design was realized by 1 : 1 mode locking with a QD-SESAM and the implementation of passive air-cooling. We characterized the timing jitter using two independent methods, the von der Linde method, and a commercially available Signal Source Analyzer. The RMS timing jitter is $\approx$212 fs in a bandwidth from 100 Hz to 1 MHz. A future active stabilization of the cavity length with a piezo actuator should significantly reduce the timing jitter, as the main contribution to the accumulated timing jitter occurs in the sub-10-kHz regime.

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