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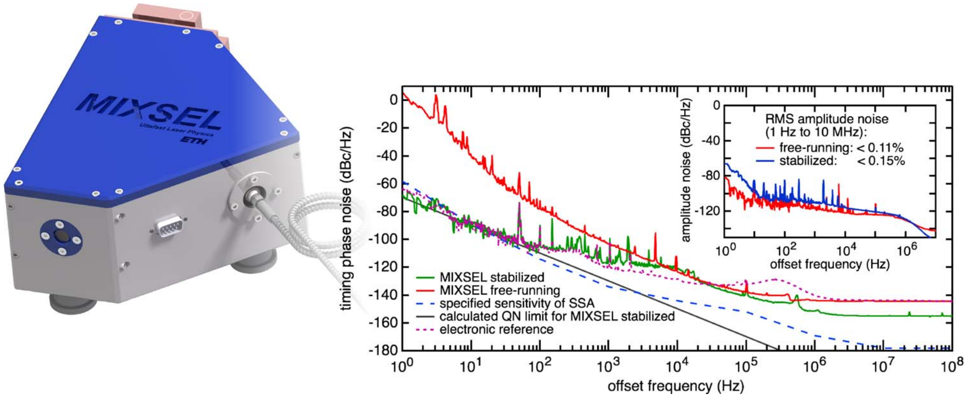

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Amplitude Noise and Timing Jitter Characterization of a High-Power Mode-Locked Integrated External-Cavity Surface Emitting Laser

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Abstract: We present a timing jitter and amplitude noise characterization of a high-power mode-locked integrated external-cavity surface emitting laser (MIXSEL). In the MIXSEL, the semiconductor saturable absorber of a SESAM is integrated into the structure of a VECSEL to start and stabilize passive mode-locking. In comparison to previous noise characterization of SESAM-mode-locked VECSELs, this first noise characterization of a MIXSEL is performed at a much higher average output power. In a free-running operation, the laser generates 14.3-ps pulses at an average output power of 645 mW at a 2-GHz pulse repetition rate and an RMS amplitude noise of $<$ 0.15% [1 Hz, 10 MHz]. We measured an RMS timing jitter of 129 fs [100 Hz, 10 MHz], which represents the lowest value for a free-running passively mode-locked semiconductor disk laser to date. Additionally, we stabilized the pulse repetition rate with a piezo actuator to control the cavity length. With the laser generating 16.7-ps pulses at an average output power of 701 mW, the repetition frequency was phase-locked to a low-noise electronic reference using a feedback loop. In actively stabilized operation, the RMS timing jitter was reduced to less than 70 fs [1 Hz, 100 MHz]. In the 100-Hz to 10-MHz bandwidth, we report the lowest timing jitter measured from a passively mode-locked semiconductor disk laser to date with a value of 31 fs. These results show that the MIXSEL technology provides compact ultrafast laser sources combining high-power and low-noise performance similar to diode-pumped solid-state lasers, which enable world-record optical communication rates and low-noise frequency combs.

Index Terms: Diode-pumped lasers, infrared lasers, mode-locked lasers, semiconductor lasers, ultrafast lasers.

1. Introduction

High power ultrafast laser sources with low timing jitter are required by numerous applications, for example in high-resolution optical sampling [1], frequency metrology [2], and high-class AD-converters [3]. In addition, modern ultra high-speed and high-bandwidth communication systems demand low-noise laser systems with gigahertz repetition rates [4] for which low-noise diode-pumped SESAM mode-locked solid-state lasers [5], [6] replaced fiber lasers. In comparison to the conventional bulk and fiber laser systems, the semiconductor disk laser technology can provide inexpensive wafer scale mass production at considerably lower costs, making this technology the most prominent candidate for widespread industrial applications [7].

Optically pumped vertical-external-cavity surface emitting lasers (VECSELs [8]), mode-locked with semiconductor saturable absorber mirrors (SESAMs [9], [10]), have recently shown remarkable progress with regard to high-power operation combined with femtosecond pulse durations [11]–[13]. The surface emitting disk geometry provides excellent beam quality, low intracavity nonlinearities and is power-scalable by simply increasing the laser mode area on the semiconductor disk [10]. Vertical integration of the saturable absorber of a SESAM led to the mode-locked integrated external-cavity surface emitting laser (MIXSEL [14]) combining the gain of VECSELs and the saturable absorber of a SESAM in a single semiconductor layer-stack. The absorber integration not only reduces the complexity of the laser system, but also reduces manufacturing costs and enables simpler device packaging. Stable and self-starting passive mode-locking can be achieved in highly compact straight cavities, which allow for straightforward repetition rate scaling by translating the output coupler in beam-direction.

After the first demonstration of a MIXSEL in 2007 with moderate output power [14], improvements of the quantum-dot (QD) saturable absorber and the thermal management resulted in a MIXSEL with a record-high average output power of 6.4 W in 28-ps pulses at a repetition rate of 2.5 GHz [25]. Even at a repetition rate of 10 GHz a very high average output power of 2.4 W in 17-ps pulses was obtained, which corresponds to the highest pulse energy of a mode-locked 10-GHz laser to date [15]. Most recently the first femtosecond MIXSEL has been demonstrated [16].

However, the noise performance of MIXSELs has not been characterized so far. In comparison to SESAM-mode-locked VECSELs [17]–[21] we would expect similar if not better performance. All semiconductor disk lasers (SDLs), such as VECSELs and MIXSELs, are typically operated with low-loss ($\approx$ 1–2%) cavities and repetition rates in the order of gigahertz (cavity roundtrip time of $<$ 1 ns). The photon lifetime in those cavities is typically in the order of 100 ns and therefore substantially longer than the semiconductor gain lifetime of a few nanoseconds (in comparison: the upper-state lifetime of commonly used rare-earth-doped gain media is in the order of a few microseconds to milliseconds). This configuration acts as a low-pass filter for spontaneous emission noise [22] and enables low amplitude noise operation. Furthermore, the much larger gain cross-section of the semiconductor material (in the order of 10^{-14} cm^2) compared to diode-pumped solid-state lasers (typically in the order of $< 10^{-19}$ cm^2) enables stable mode-locking at high repetition rates without unwanted Q-switching instabilities [23]. These Q-switching instabilities become even worse for the small intracavity pulse energies in the gigahertz repetition rate regime [24]. Nevertheless, for a 10-GHz SESAM mode-locked diode-pumped solid-state laser a nearly quantum-noise limited timing jitter was achieved by a stable mechanical setup and moderate intracavity nonlinearities [6]. For SDLs one can expect similar noise performance, as the interaction of the pulse with the semiconductor gain region is limited to a length of $\approx$ 1–2 micrometers compared to the propagation in the free-space cavity of several millimeters up to centimeters length. In addition, enhanced spontaneous emission noise arising from waveguide effects in mode-locked edge-emitting semiconductor lasers is not present in SDLs.

Different timing jitter measurements were performed for mode-locked VECSELs [17]–[21]. For a laser with a 2-GHz repetition rate, the lowest RMS timing jitter in free-running operation was 201 fs over an integration bandwidth of [100 Hz, 100 MHz] [17]. Active stabilization of the cavity length using a piezo actuator reduced the RMS timing jitter to record-low 58 fs [1 Hz, 100 MHz] [18]. For all results [17]–[21] the VECSEL gain chip was used as a cavity folding mirror which doubles the round-trip gain compared to a cavity configuration with the gain at the end of the linear cavity. In contrast, for the straight linear cavity of a MIXSEL the semiconductor structure forms one end mirror. Therefore, the laser setup can be reduced by at least one cavity component, which should give rise to an even better mechanical stability compared to a mode-locked VECSEL.

Here, we present a noise characterization of a high-power picosecond MIXSEL. In free-running operation at around a 2-GHz repetition rate, the laser generated 14.3-ps pulses with 645 mW of average output power with an excellent RMS amplitude noise of $<$ 0.11% [1 Hz, 10 MHz]. The average output power is therefore an order of magnitude higher than in all previous timing jitter

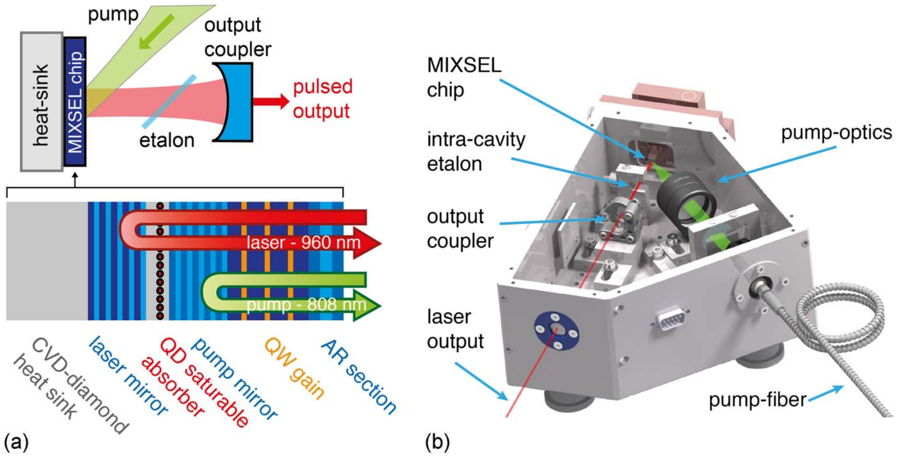

Fig. 1. (a) MIXSEL structure. The single quantum-dot (QD) saturable absorber is placed between distributed Bragg reflectors for pump and lasing wavelength. The active region is based on InGaAs quantum-wells (QWs), followed by an anti-reflection (AR) section. The MIXSEL chip is inserted in a straight cavity with an intracavity AR-coated 20-μm-thick fused silica etalon for wavelength tuning. The semiconductor chip is optically pumped under an angle of 45°. (b) MIXSEL housing to reduce external perturbation. The external 808-nm pump diode array is fiber-coupled to the housing.

measurements of SESAM mode-locked VECSELs [18]–[21]. We measured the single-sideband (SSB) timing phase noise power spectral density (PSD) with a commercial signal-source analyzer (SSA) and obtained an RMS timing jitter of 129 fs [100 Hz, 10 MHz] and 60 fs [300 Hz, 10 MHz]. These are the lowest timing jitter values of a free-running passively mode-locked semiconductor disk laser to date. Furthermore, in a slightly altered laser configuration, the repetition rate was actively stabilized to an electronic reference oscillator using a piezo actuator that changes the cavity length. In this configuration the laser generates 16.7-ps pulses at 701 mW of average output power. In the actively stabilized operation we measured an RMS timing jitter of 31 fs [100 Hz, 100 MHz] which represents the lowest value from a passively mode-locked semiconductor disk laser in this frequency range. Thus, these measurements confirm the superior performance of MIXSELs compared to SESAM mode-locked VECSELs for reasons discussed above.

2. Laser Design and Mode-Locking Performance

The MIXSEL [Fig. 1(a)] combines the quantum-well (QW) gain of VECSELs with quantum-dot (QD) saturable absorbers of SESAMs in a single structure, where the saturable absorber starts and stabilizes fundamental passive mode-locking. A single layer of self-assembled InAs QDs is placed between an AlAs/GaAs distributed Bragg reflector (DBR) for the laser wavelength and an intermediate AlAs/$Al_{0.2}Ga_{0.8}As$ DBR for the pump wavelength. The active region is based on seven $In_{0.13}Ga_{0.87}As$ QWs, which are embedded in GaAs for pump light absorption. On top of the layer stack an anti-reflection section minimizes the losses for pump and laser light at the interface between air and the semiconductor structure. The MIXSEL structure was grown by molecular beam epitaxy and flip-chip bonded to a diamond grown by chemical vapor deposition. Detailed descriptions about the structure and the flip-chip bonding are given in Refs. [15], [25].

For optimum laser noise performance we reduced environmental influences with a stable metal housing designed and manufactured especially for this laser setup [Fig. 1(b)]. In addition to improved mechanical and thermal stability, we reduced the unwanted airflow through the cavity with the closed housing. The MIXSEL chip is temperature-stabilized to minus 1 °C by a water-cooled Peltier element. Although water-cooling introduces additional vibrations of the housing, it is necessary to achieve high-power operation with any semiconductor disk laser. The laser is pumped at an angle of 45° with up to 35 W by a water-cooled industrial-grade fiber-coupled 808-nm-pump-diode-array (LIMO35-F100-DL808-LM) driven by a standard commercially available power supply (Delta

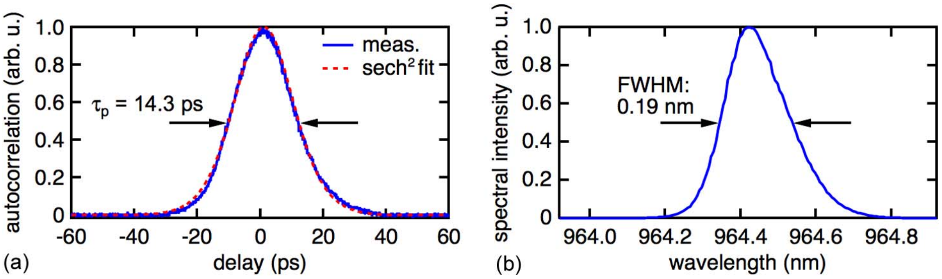

Fig. 2. MIXSEL results in free-running operation at 645 mW average output power: (a) intensity autocorrelation with fit to an ideal sech^2-pulse of 14.3 ps duration, (b) optical spectrum centered at 964.4 nm.

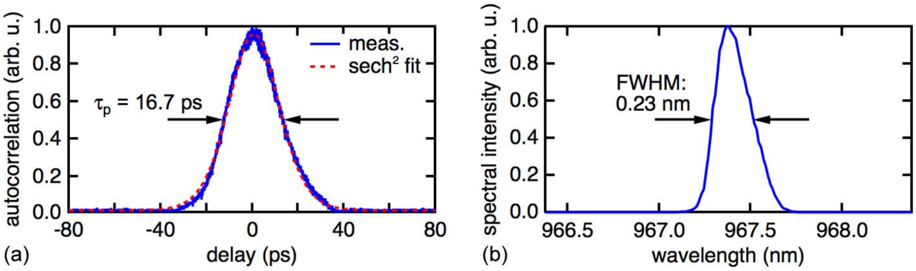

Fig. 3. MIXSEL results in stabilized operation at 701 mW average output power: (a) intensity autocorrelation with a fit to an ideal sech^2-pulse of 16.7 ps duration, (b) optical spectrum centered at 967.4 nm.

Elektronika SM7.5-80). All pump optics are mounted tightly on the housing baseplate to guarantee the maximum stability and to avoid drifts caused by linear translation stages or adjustable lens mounts which are usually employed at university-based lasers. The flat MIXSEL chip and a curved output coupler (OC) form a straight linear cavity (Fig. 1(a), top). The cavity mode radius of 168 μm on the gain chip was chosen to be slightly larger than the pump spot radius of 158 μm to suppress higher order transverse mode operation. A 20-μm-thick anti-reflection-coated fused silica etalon is inserted in the cavity to tune and stabilize the lasing wavelength. The intracavity etalon bandwidth should support sub-1-ps pulses, but the long recovery time of the integrated quantum dot saturable absorber limits the pulse duration to $>$ 10 ps [26], [27].

In free-running operation we used an output coupler with 0.5 inch diameter, 200 mm radius of curvature (ROC) and a transmission of 0.3%. At a pump power of 17.9 W, stable mode-locking at a repetition rate of 1.985 GHz was obtained, generating 14.3-ps pulses at an average output power of 645 mW and a center wavelength of 964.4 nm (Fig. 2).

For the active stabilization of the pulse repetition rate, as described in Section 3, a different output coupler with a transmission of 0.5% and a ROC of 200 mm was used. To reduce the weight load on the piezo, an output coupler with a diameter of 2.5 mm and a thickness of 2 mm was chosen [Fig 4(b)]. At a heat-sink temperature of minus 1 °C and a pump power of 23 W stable mode-locking at a repetition rate of 2 GHz was achieved (Fig. 3). In this configuration 16.7-ps pulses at an average output power of 701 mW were generated. In both configurations the laser was running stable over several hours of measurements without any signs of degradation.

3. Timing Phase Noise Characterization and Stabilization Setup

For noise characterization in both, free-running and phase-locked operation, a fraction of the laser output power is detected by a highly linear photodiode (HLPD, Discovery Semiconductors Inc. DSC30S [28]). The detector signal is low-pass filtered at 2.4 GHz to suppress harmonics of the repetition rate by 48 dB. After low-noise amplification (Agilent 87405C) of the signal to $+5$ dBm, the

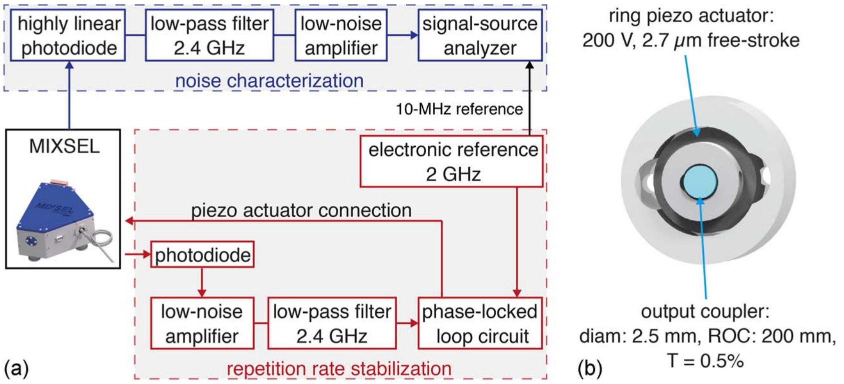

Fig. 4. (a) Schematic overview of the noise characterization and repetition-rate stabilization. The repetition-rate is stabilized to an electronic reference by a phase-locked loop (red section). For noise characterization (blue section) a part of the laser output is measured with a HLPD, low-pass filtered, amplified and the SSB timing phase noise PSD can be recorded with a commercial SSA. A stable common 10-MHz reference signal from the reference oscillator is used as a frequency reference for the SSA. (b) Output coupler (diam.: 2.5 mm, transmission: 0.5%, ROC: 200 mm) mounted on a ring piezo actuator (200 V, 2.7 μm free-stroke) for changing the length of the straight cavity.

SSB timing phase noise PSD was measured using a commercial SSA (Agilent E5052B) (Fig. 4(a), blue section). For an enhanced measurement sensitivity all timing phase noise measurements were performed with ten correlations [18].

To stabilize the pulse repetition rate of the laser, we used the piezo-controlled output coupler (OC) [Fig. 4(b)] to correct for any cavity length drifts. Therefore, an OC with a diameter of 2.5 mm was mounted on a piezoelectric ring actuator (maximum voltage: 200 V, free-stroke: 2.7 μm) to pass the transmitted light [Fig. 4(b)]. With the OC and its mounting plate weighing $\approx$ 230 mg, the -3 dB operation bandwidth of the utilized actuator was measured to be around 1 kHz.

For the active stabilization, the repetition rate of the laser was measured with a 25-GHz InGaAs photodetector (NewFocus Model 1414). After amplification and a 2.4-GHz low-pass filter, the signal is used for stabilization with a custom-made phase-locked loop (PLL) [18]. The PLL is based on a double balanced mixer (DBM, MITEQ DM0104LA1) and a specifically designed Proportional-Integral (PI) loop filter. The DBM is used as an analog phase detector and therefore seeded by the repetition frequency of the laser and a reference signal from a stable low noise electronic reference oscillator (Rohde&Schwarz SMF100A). The phase error signal was filtered by the PI loop filter and sent to the piezo actuator. For the repetition rate stabilization over a time frame of about 1 hour a driving voltage of only 30 V was needed, which corresponds to a utilized stroke of $\approx$ 400 nm. Note that the timing jitter is measured out-of-loop of the stabilization scheme. A stable common 10-MHz reference signal from the electronic reference oscillator is used as a frequency reference for the SSA.

4. Measured Timing Phase Noise Results

We measured the SSB timing phase noise PSD both in free-running and in actively stabilized operation with the measurement scheme presented in Section 3 (Fig. 5). For noise characterization of the laser in the different operation modes the photocurrent of the HLPD was chosen to be 0.6 mA in free-running and 1 mA in actively stabilized operation, which resulted in shot noise levels of -144.5 dBc/Hz and -154.9 dBc/Hz, respectively. The photocurrents were chosen for a minimum shot noise level. However, in free-running operation excess amplitude to phase noise coupling in the detection set an upper limit to the photocurrent.

From the SSB timing phase noise PSD the RMS timing jitter in different frequency ranges between the lower limit f_{low} and the higher limit f_{high} is calculated. For all measurements we used the full bandwidth of the SSA of ($f_{\text{low}} = 1$ Hz to $f_{\text{high}} = 100$ MHz), therefore timing jitter values for intermediate integration spans can be calculated. In free-running operation we measured an integrated RMS timing jitter of 129 fs between 100 Hz and 10 MHz, which is the lowest value for any

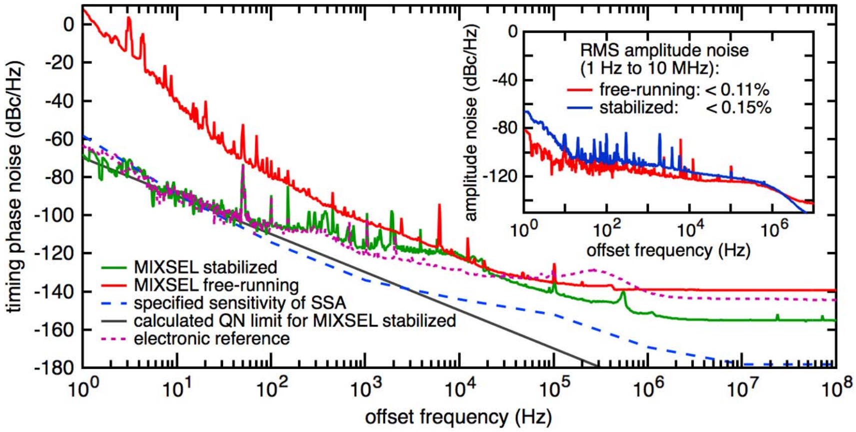

Fig. 5. Noise characterization of a high-power MIXSEL: SSB timing phase noise PSD of free-running (solid red) and actively stabilized (solid green) laser. For comparison the PSD of the electronic reference (dashed purple), the specified sensitivity of the SSA (dashed blue) and the calculated QN limit (solid gray) are given. Inset: RMS amplitude noise of the free-running laser was < 0.11% [1 Hz, 10 MHz] and of the stabilized laser was < 0.15% [1 Hz, 10 MHz].

free-running mode-locked semiconductor disk laser in this integration range (Fig. 5, red solid line). Furthermore, an excellent amplitude noise of < 0.11% was obtained between 1 Hz and 10 MHz in this configuration (Fig. 5 inset).

By phase-locking the repetition frequency to the low-noise electronic reference oscillator an integrated RMS timing jitter of 69 fs was measured for the integration between 1 Hz and 100 MHz (Fig. 5, green solid line). The integrated RMS timing jitter between 100 Hz to 10 MHz with a value of 31 fs is lower than for any stabilized mode-locked semiconductor disk laser reported until now. For frequencies up to 1 kHz the noise performance of the laser is limited by the electronic reference, which is in very good agreement with the measured actuator bandwidth. Between 1 kHz and 10 kHz the drop in actuator bandwidth causes deviations in the phase noise PSD from the electronic reference. The noise figure could be further improved with a piezo having a bandwidth greater than 10 kHz even when loaded with the relatively heavy output coupler. Note that the noise performance of the stabilized laser is better than the timing phase noise of the electronic reference oscillator for frequencies above 20 kHz. In addition, for frequencies below 10 Hz the measured timing phase noise PSD is below the specified sensitivity of the SSA (Fig. 5, blue dashed line), which limits the measurement accuracy in this frequency range. For illustration the quantum noise (QN) limit (Fig. 5, grey solid line) was calculated for the stabilized laser configuration according to Ref. [29] with the laser parameters given in Section 2 for a sech^2-pulse form and a saturated power small signal gain of 3% [30]. The theoretical QN limited timing jitter is found to be proportional to the pulse duration and inversely proportional to the square-root of the pulse energy [31]. Therefore, shorter pulse durations for otherwise similar laser parameters should support even lower quantum noise limited timing jitter. A detailed overview of the noise performance in both operation modes is found in Table 1, together with timing jitter values of previously reported mode-locked VECSELs and a 10-GHz diode-pumped solid-state laser. The integrated amplitude noise was < 0.15% [1 Hz, 10 MHz] for the stabilized laser configuration (Fig. 5, inset).

5. Conclusion and Outlook

We presented amplitude noise and timing jitter measurements of a free-running and an actively stabilized high-power MIXSEL at a repetition rate of 2 GHz. Record-low noise performance was achieved with and without stabilization, even though we used a water-cooled MIXSEL chip mount that can introduce mechanical vibrations. In free-running operation the laser generated 14.3-ps pulses at an average output power of 645 mW. By measuring the SSB timing phase noise PSD with an SSA, we obtained RMS timing jitters of 129 fs [100 Hz, 10 MHz] and 60 fs [300 Hz, 10 MHz],

TABLE 1

Results of timing-jitter characterization of free-running and actively stabilized MIXSEL compared to different passively modelocked lasers with gigahertz pulse repetition rates [18]. All lasers are operated in fundamental mode-locking, i.e., with only one pulse per cavity roundtrip

laser	repetition rate (GHz)	output power (mW)	f_{low} (Hz)	f_{high} (MHz)	RMS timing jitter (fs)
MIXSEL					
free-running	1.985	645	1	100	141721
			100	100	145
			100	1.56	128
			300	1.5	56
			1000	15	43.1
			100	10	129
stabilized	2.004	701	1	100	69
			100	100	32
			6	1.56	45
			300	1.5	24
			1000	15	25
			100	10	31
VECSEL					
free-running [17]	2	40	100	10	200
			100	100	201
stabilized [18]	2	40	1	100	58
			100	100	47
free-running [20]	0.897	40	1000	15	410
stabilized [20]	0.897		1000	15	160
stabilized [19]	1	40	300	1.5	190
free-running [21]	1.68	21	100	10	8000
stabilized [21]	1.68		100	10	423
Er:Yb:glass laser					
free-running [6]	10	15	100	1.56	190
stabilized [6]	10		6	1.56	26

which have been the lowest values for a free-running mode-locked semiconductor disk laser to date. In a slightly different laser configuration generating 701 mW of average output power in 16.7-ps pulses the repetition rate was stabilized. Phase-locking the repetition frequency to a low-noise electronic reference using a standard analog PLL greatly reduced the phase noise and resulted in an RMS timing-jitter of less than 70 fs [1 Hz, 100 MHz]. In the range between 100 Hz and 10 MHz we report the lowest timing jitter from a passively mode-locked semiconductor disk laser with a value of 31 fs. These record-low timing phase noise properties are also supported by an excellent amplitude noise of $<$ 0.15% [1 Hz, 10 MHz] for both the free-running and phase-locked operation with an average output power more than an order of magnitude higher than in all previous timing jitter measurements of SESAM-mode-locked VECSELs. Therefore, the excellent noise performance combined with high-power operation makes the MIXSEL a unique ultrafast laser source with adjustable pulse repetition rates in the gigahertz regime and high pulse energies [15]. Such a laser is ideally suited for applications in ultra high-speed optical clocking or high-resolution optical sampling.

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