Sub-300-femtosecond operation from a MIXSEL

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Abstract: Peak power scaling of semiconductor disk lasers is important for many applications, but their complex pulse formation mechanism requires a rigorous pulse characterization to confirm stable fundamental modelocking. Here we fully confirm sub-300-fs operation of Modelocked Integrated eXternal-cavity Surface Emitting Lasers (MIXSELs) with record high peak power at gigahertz pulse repetition rates. A strain-compensated InGaAs quantum well gain section enables an emission wavelength in the range of Yb-doped amplifiers at ≈1030 nm. We demonstrate the shortest pulses from a MIXSEL with a duration of 253 fs with 240 W of peak power, the highest peak power generated from any MIXSEL to date. This peak power performance is comparable to conventional SESAM-modelocked VECSELs for the first time. At a 10-GHz pulse repetition rate we still obtained 279-fs pulses with 310 mW of average output power, which is currently the highest output power of any femtosecond MIXSEL. Continuous tuning of the pulse repetition rate has been demonstrated with sub-400-fs pulse durations and >225 mW of average output power between 2.9 and 3.4 GHz. The strain-compensated MIXSEL chip allowed for more detailed parameter studies with regards to different heat sink temperatures, pump power, and epitaxial homogeneity of the MIXSEL chip for the first time. We discuss in detail, how the critical temperature balance between quantum well gain and quantum well absorber, the partially saturated absorber and a limited epitaxial growth quality influence the overall device efficiency.

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References and links


1. Introduction

Ultrafast optically pumped semiconductor disk lasers (SDLs) [1, 2] have emerged to high-power laser sources delivering short pulses at repetition rates from 100 MHz [3] up to 100 GHz in fundamental modelocking (i.e. with only one pulse per cavity roundtrip) [4]. Passive modelocking of vertical external-cavity surface-emitting lasers (VECSELs) with semiconductor saturable absorber mirrors (SESAMs) [5] has proven to be the most successful ultrafast SDL concept. SESAM-modelocked InGaAs-based VECSELs in the near-infrared around a center wavelength of \(\approx 1\) \(\mu\)m set the benchmark for ultrafast SDL performance [6]: pulses as short as 107 fs were demonstrated with 3 mW of average output power [7] and recently 400-fs pulses were achieved with record-high 4.35 kW peak power [8]. The next step towards even more compact devices was taken with the modelocked integrated external-cavity surface-emitting laser (MIXSEL) [9], in which the saturable absorber of a SESAM is vertically integrated into the gain structure of a VECSEL. MIXSELs have generated record-high average output power up to 6.4 W with an optical-to-optical efficiency of 17% [10]. However, the long >15-ps pulse durations limited the pulse peak power to 80 W. The development of a fast quantum well (QW) saturable absorber enabled the first femtosecond MIXSEL operation, however up to now only with a limited optical-to-optical efficiency of <1% [4, 11]. The simple straight linear MIXSEL resonator enables pulse repetition rate tuning between 15 and 100 GHz [4] and dual-comb modelocked operation [12].

More recently, SDLs have been also modelocked with graphene saturable absorbers which provide broad tunability and fast amplitude modulation, however, still suffer from low damage threshold, high saturation fluence and high non-saturable losses [13, 14]. In addition, “self-modelocking” was reported with high average power in femtosecond pulses [15]. This mechanism is the subject of ongoing theoretical investigations [16, 17] and still has to prove its suitability for clean and long-term stable modelocking operation. So far no stable modelocking in the sub-500-fs pulse duration regime has been demonstrated.

The greatest technological challenge for all ultrafast SDL concepts remains the combination of kilowatt pulse peak power and sub-200-fs pulse durations. These output parameters are not available yet (Fig. 1), but would be highly beneficial for a variety of
applications, such as multi-photon imaging [18] and self-referenced gigahertz frequency combs [19–22]. Due to their inherent advantages in manufacturing cost and packaging requirements, MIXSELS are very attractive for large scale industrial production within the ultrafast SDL family.

Here we present the latest achievements with femtosecond MIXSELS. The implementation of a strain-compensated active region enables longer device lifetimes and facilitates MIXSEL emission wavelengths in the technologically important regime of ytterbium (Yb)-doped amplifiers ≈1030 nm. With optimized designs and more precise dispersion control, we obtained the currently shortest pulses of a MIXSEL with a duration of 253 fs. The high average output power of 235 mW resulted in 240 W of peak power. This is the highest peak power from any MIXSEL to date and for the first time comparable to the performance of sub-300-fs SESAM-modelocked VECSELs (see Fig. 1). At 10 GHz repetition rate 279-fs pulses in 310 mW of average output power were obtained, which represents the currently highest output power of any femtosecond MIXSEL. Additionally, this novel femtosecond MIXSEL is continuously tunable in repetition rate. In a tuning range between 2.9 GHz and 3.4 GHz sub-400-fs pulses were generated with >225 mW of average output power.

Several parameter studies help to gather insights into the operation principle of the QW-absorber MIXSEL and the next steps for an improved modelocking performance are outlined. Besides reaching the optimum laser performance, the acceptance of ultrafast SDLs in industrial and scientific applications requires enhanced pump efficiencies. The challenges for combining short pulse durations and a high optical-to-optical efficiency with MIXSELS are discussed. With the technology moving from the source development towards applications, robust and long-term stable fundamental modelocking has to be proven rigorously. Based on experimental findings from this MIXSEL, we highlight some of the measurement difficulties, and suggest approaches which help to reduce the potential for misinterpretation of experimental measurements when characterizing pulses from ultrafast SDLs.

2. Laser design and fabrication

The layout of the MIXSEL semiconductor stack and the laser setup are derived from the structure described in [11], however several modifications have been applied. The layout and material composition together with the electric field distribution are depicted in Fig. 2(a). The MIXSEL is designed for operation around a wavelength of 1040 nm. The incident laser light is reflected by a 24-pair AlAs/GaAs distributed Bragg reflector (DBR), while the pump light is reflected by an intermediate 9.5-pair AlAs/Al_{0.15}Ga_{0.85}As DBR, designed for the pump wavelength of 808 nm. Compared to previous MIXSEL designs, the mole fraction of the high index Al_{x}Ga_{1-x}As compound in the pump mirror was decreased from $x = 0.20$ to $x = 0.15$ to...
enhance its intrinsic thermal conductivity and refractive index, but still preventing 808-nm pump light absorption. The intermediate DBR avoids uncontrolled absorber bleaching by residual pump light.

Fig. 2. a) MIXSEL layer stack similar to the structure described in [11], but with a strain-compensated active region and lower field enhancement in the active QWs; b) Measurement of structural GDD of unpumped structure at 20 °C (red circles) with superior GDD compared to previous MIXSEL structure [11]; c) Cavity layout consisting of MIXSEL structure, curved output coupler and a fused silica Brewster plate.

A single 14-nm thick In$_{0.2}$Ga$_{0.8}$As QW saturable absorber is positioned in the antinode of the standing wave pattern of the electric field intensity between the two DBRs. By embedding the QW into AlAs layers and with optimized low-temperature growth, the absorber exhibits the desired fast recovery times and low saturation fluences. The field intensity enhancement at the absorber position is designed to be around 1.4 (normalized to 4 outside the structure). A detailed characterization of the absorber type is presented in [11]. The active region comprises ten In$_{0.19}$Ga$_{0.81}$As QWs of 8.8 nm thickness. The compressive strain of the QWs is balanced by tensile strained layers of GaAs$_{0.94}$P$_{0.06}$. The active QWs are positioned pairwise on adjacent sides of the standing wave pattern antinodes in a fashion that has already been used for a previous MIXSEL structure [11]. According to guidelines derived from numerical pulse formation simulations, higher saturation fluences of the gain enable the generation of even shorter femtosecond pulses [32]. Therefore the average enhancement of the electric field in the QWs was decreased from 0.95 to 0.65 and flattened compared to previous structures [11] (less than 10% change over ± 20 nm around the lasing wavelength). The MIXSEL is finalized by a numerically optimized anti-reflection (AR) section, combining seven alternating layers of AlAs and Al$_{0.15}$Ga$_{0.85}$As and a single layer of fused silica (FS). Besides minimizing reflective pump light losses at the surface of the structure, the AR section ensures a flat GDD around the lasing wavelength. By minimizing deviations of the ideal layer thickness of the semiconductor and FS layers, the GDD can be kept reasonably flat over a large wavelength range (see Fig. 2(b)).

The structure was grown in reverse order on an undoped GaAs (100) substrate for subsequent flip-chip bonding. The etch-stop layer and the AR section were grown at 750 °C, while the active region was grown at 660 °C on an AIX 200/4 (AIXTRON SE, Herzogenrath, Germany) metalorganic chemical vapor deposition (MOCVD) machine. Afterwards, the wafer surface was cleaned using a hydrogen plasma source and transferred under ultrahigh vacuum conditions into a VEECO GEN III (Veeco Instruments Inc., St. Paul, MN, United States) molecular beam epitaxy (MBE) machine. The two DBRs for pump and laser light were fabricated with MBE at 580 °C growth temperature and the saturable absorber section in between was grown at 280 °C. After the epitaxy, the structure is cleaved, metallized and indium-soldered onto a 600-μm-thick polycrystalline diamond heat-spreader with a thermal
conductivity exceeding 2000 W m\(^{-1}\)K\(^{-1}\). After wet-chemical substrate and etch-stop removal the single layer of FS is deposited by plasma enhanced chemical vapor deposition (PECVD) [33].

A measurement of the GDD at room temperature (20 °C) and without optical pumping (Fig. 2(b)), performed with a setup described in [34], showed improved spectral flatness compared to the first femtosecond MIXSEL structure after processing [11]. With small GDD variations in the range of up to +100 fs\(^2\) shorter and more transform-limited pulses are expected.

3. Experimental results

The cavity layout remained unchanged for the following experiments, except for the cavity length and the radius of curvature (ROC) of the output coupler (OC). The transmission of the OC was \(T_{OC} = 0.55\%\). The MIXSEL structure and the curved OC formed a straight cavity (Fig. 2(c)). A 1-mm thick FS plate (Infrasil 1, 30° wedged, \(wzw\)-optic AG, Balgach, Switzerland) was included in the cavity at Brewster’s angle to obtain a laser output in a single linear polarization. The glass plate adds \(\approx 90\) fs\(^2\) of positive GDD to the total dispersion per cavity roundtrip. The MIXSEL chip was optically pumped under an angle of 45° by a commercial fiber-coupled 808-nm diode array, resulting in a circular pump spot with a radius of \(\approx 178\) µm on the device surface. The cavities were designed for laser mode waists on the MIXSEL structure in the range of 200 µm to ensure single transverse mode operation.

3.1 Scaling of mode locking performance

The MIXSEL chip was temperature-stabilized to –3 °C for the following experiments. We used an OC with a ROC of 500 mm for a cavity length of 44.8 mm, which corresponds to 3.35 GHz pulse repetition rate for fundamental mode locking (i.e., only one pulse per cavity roundtrip). With an incident pump power of 25.8 W stable and self-starting mode locking was obtained at an average output power of 235 mW. A pulse duration of 269 fs was measured with a second-harmonic intensity auto-correlation and a corresponding fit to a sech\(^2\)-shaped pulse (Fig. 3(a)). A long-range autocorrelation confirmed pedestal free operation in a 150-ps span (Fig. 3(a) inset). The optical spectrum features a bandwidth of 6.47 nm (full width at half maximum (FWHM)), centered at a wavelength of 1044 nm with no continuous-wave (cw) instabilities, typically revealed on a logarithmic scale (Fig. 3(b) with inset).

A microwave spectrum with a resolution bandwidth (RBW) of only 391 Hz in a 15-MHz span and >70 dB signal-to-noise ratio (SNR) indicates stable mode locking at 3.35 GHz pulse repetition rate (Fig. 3(c)). Furthermore all harmonics of the pulse repetition rate within the 25 GHz measurement bandwidth of the microwave spectrum analyzer are clearly visible (Fig. 3(d)). For the wide-span microwave spectrum a 22-GHz photodetector (Discovery Semiconductors Inc. DSC30S) was used without additional amplification. The pulses were characterized with a home-built second harmonic generation (SHG) frequency-resolved optical gating (FROG) apparatus [35] to assess their temporal and spectral phases. The autocorrelation trace indicates longer pulse durations than retrieved from SHG-FROG measurements, which is linked to an optical isolation stage before the autocorrelator to suppress back-reflections into the MIXSEL cavity. The isolation stage stretches the pulses with >5000 fs\(^2\) of positive GDD with significant contributions of higher order dispersion, which hinders staightforward compensation. The measured and retrieved SHG-FROG spectrograms are depicted in Fig. 3(e) + Fig. 3(f). The retrieved temporal intensity profile reveals a pulse duration of 253 fs.

The temporal phase is flat over the main part of the pulse, but increases for a satellite pulse of small energy (Fig. 3(g)). The retrieved spectral phase is flat and the retrieved spectrum (Fig. 3(h)) matches perfectly the measured spectrum (Fig. 3(b)). The FROG-error of the reconstruction for a grid size of 256 by 256 points is 0.0014 [36]. The corresponding time-bandwidth product (TBP) of the pulses is 1.40 times the ideal value for a transform-limited \(\text{sech}^2\)-shaped pulse. Therefore, the spectral bandwidth could support transform-limited pulses.
with a duration of \( \approx 180 \) fs. Fundamental transverse mode operation was confirmed with \( M^2 \) values of \(< 1.05\) in two orthogonal lab frame directions. This result marks a milestone of the MIXSEL technology, since it combines the currently shortest pulse durations with the highest pulse peak power of \( > 240 \) W. Therefore, the performance of MIXSELS is comparable to sub-300-fs SESAM-modelocked VECSELs for the first time (Fig. 1).

In a second experiment the repetition rate of the high-power sub-300-fs MIXSEL was scaled to 10 GHz. The length of the straight cavity is 15 mm and an OC with a ROC of 1000 mm was used for the experiment. Stable and self-starting modelocking at an average output power of 310 mW is obtained at an incident pump power of 23.1 W. The pedestal-free autocorrelation revealed a pulse duration of 292 fs (sech\(^2\)-fit, Fig. 4(a) with inset). The optical spectrum is centered at 1043 nm and offers a bandwidth of 5.75 nm FWHM (Fig. 4(b) with inset). A high SNR in a 10-MHz span microwave spectrum indicates stable modelocking at 10.02 GHz pulse repetition rate (Fig. 4(c)). Moreover, the second harmonic of the pulse repetition rate is clearly visible at a frequency of 20 GHz (Fig. 4(d)). The 6-dB signal

Fig. 3. 253-fs pulse generation from a MIXSEL at 235 mW average power: a) Intensity autocorrelation with corresponding sech\(^2\)-fit (inset: satellite-pulse free operation \( \pm 75\) ps around autocorrelation) – broadened due to an optical isolator; b) Optical spectrum centered around 1044 nm with a FWHM bandwidth of 6.47 nm, measured with a RBW of 0.1 nm (inset: optical spectrum on logarithmic scale); c) Microwave spectrum at 3.35 GHz in a 15-MHz span, measured with 391 Hz RBW; d) Large-span microwave spectrum (RBW: 300 kHz); e) Measured SHG-FROG spectrogram (grid size: 256x256); f) Retrieved FROG spectrogram (error: 0.0014); g) Retrieved temporal intensity profile of 253-fs pulse; h) Retrieved spectrum and spectral phase.

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reduction compared to the fundamental pulse repetition rate matches the installed amplifier specifications (Agilent 87405C, 2.7 dB harmonic loss at 20 GHz) and photodetector bandwidth (NewFocus 1444, −3 dB bandwidth: 20 GHz).

In Fig. 4(e) + Fig. 4(f) the measured and retrieved SHG-FROG spectrograms are shown. The retrieved temporal intensity profile yields a pulse duration of 279 fs (Fig. 4(g)). The temporal and spectral phases are flat and do not exhibit features (Fig. 4(h)). A small FROG-error of 0.0021 was calculated for the reconstruction on a grid size of 256 by 256 points [36]. Also for 10 GHz repetition rate $M^2$ values of < 1.05 were determined for two orthogonal lab frame directions. The TBP of the pulses is 1.3 times the ideal value for transform-limited pulses and the optical spectrum allows even for the generation of sub-220-fs pulses. This result marks the currently highest average output power of a femtosecond MIXSEL with 310 mW and results in a high peak power of 97 W at 10 GHz repetition rate.
3.2 Continuous repetition rate tuning of a femtosecond MIXSEL

Fast and reliable tuning of the repetition rate of pulsed lasers is an attractive feature, as it opens up the laser technology for a variety of applications. In asynchronous optical sampling (ASOPS) two femtosecond lasers with slightly different repetition rate drive pump-probe measurements without mechanical delay stages [37]. This scheme can be further simplified to OSCAT [38], where only a single laser with tunable repetition rate is sufficient to enable delay-stage free pump-probe measurements, used for compact and cost-effective measurement setups. For femtosecond SESAM-modelocked VECSELs continuous repetition rate tuning has been presented recently from 2.87 to 7.87 GHz [39] and from 6.5 to 11.3 GHz [31].

The straight resonator of a MIXSEL enables simple repetition rate tuning, as the mode-sizes on gain and absorber are changed identically with the cavity length. Pulse repetition rate scaling from 5 GHz up to 100 GHz has been presented previously for MIXSELS [4]. However, the exchange of the OC limited continuous tuning to intermediate ranges. Here, we present continuous repetition rate tuning between 2.9 GHz and 3.4 GHz from a MIXSEL with sub-400-fs pulse durations in combination with high peak and average output power. The simple straight linear cavity had an OC with a ROC = 500 mm. The semiconductor structure was stabilized to + 1 °C and a pump power of 24.5 W was applied (Fig. 5(a)).

![Fig. 5. Pulse repetition-rate tuning with high-power femtosecond MIXSEL: a) Schematic of MIXSEL cavity, where the distance between semiconductor structure and OC determines the pulse repetition rate for fundamental modelocking; b) Modelocking parameters for continuous tuning between f_{rep} = 2.9 GHz - 3.4 GHz: top: Sub-400-fs pulse durations (blue dots) and stable wavelengths (green squares); bottom: average power >225 mW (red squares) and peak power >175 W (gray circles).](image)

The cavity length was continuously tunable from 51.7 mm to 44.1 mm, covering a 500-MHz repetition rate span of fundamental modelocking between 2.9 GHz to 3.4 GHz. Multi-pulsing instabilities hindered even lower repetition rates, while for higher repetition rates adjustments of the pump power would have been necessary. For the tuning range, the change in cavity mode size on the MIXSEL structure is estimated by simulations to be less than 4%. The laser performance was recorded in repetition rate steps of 50 MHz and is shown in Fig. 5(b). For all indicated steps the laser average output power exceeded 225 mW with a maximum value of 285 mW at f_{rep} = 3.4 GHz. In combination with sub-400-fs pulse durations a high peak power of >175 W was obtained throughout the cavity length tuning. While the average power increases continuously for higher repetition rates, the pulse energy remains nearly constant over the tuning range. Since the pulse durations are decreased for higher repetition rates, the pulse peak power is increased towards higher repetition rates. The pulse

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formation in SDLs is strongly dependent on the degree of saturation of gain and absorber for near-constant structural dispersion, which is discussed in detail in [32].

4. Discussion

The ultrafast SDL technology is currently in the transition from initial proof-of-concept experiments towards reliable and reproducible sources. In this section we discuss the recent progress and challenges of the MIXSEL technology and operation. Those findings help to further optimize the next generation of SESAM-modelocked VECSELs and MIXSELs.

4.1 Homogeneity characterization

Introducing strain-compensation in the active region of a MIXSEL resulted in a structure with minimum crystal lattice distortions. Therefore, for the first time nearly all areas on the surface of the processed MIXSEL structure can be used for stable modelocking. Even after hours of operation the MIXSEL did not reveal any signs of degradation, typically observed previously without strain-compensation and associated with dark-lines in large area surface photoluminescence images [4, 11]. The influence of the lasing spot position on different modelocking parameters reveals further engineering efforts for design, semiconductor growth and post-growth processing.

The influence of the laser mode position on the chip surface on different modelocking parameters was studied. For an otherwise unchanged laser configuration, the lasing and pump beams (diameter \(0.4\) mm) were positioned on 18 different points, constituting a pattern with larger steps of 0.5 mm distance and smaller steps of 0.1 mm distance (Fig. 6(a)). An OC with a ROC = 500 mm was used for the experiments. The heat-sink temperature \(T_{hs}\) was stabilized to \(+1\) °C and a repetition rate of 3.35 GHz was chosen. Stable modelocking was found for all 18 points with average output powers ranging from 195 mW to 270 mW with a mean value of 247 mW and a standard deviation of only 7% or 18 mW (Fig. 6(b)). For an even more homogeneous average power distribution, the point defect formation during epitaxy has to be minimized, the contacting to the heat-spreader improved and the processed chip surface quality enhanced. Short pulse durations were found in a range between 255 fs and 355 fs with a mean value of 293 fs and a standard deviation \(\sigma = 30\) fs (Fig. 6(c)).

The pulse durations decrease significantly towards the edges of the chip, which can be directly linked to an even more optimized structural dispersion at these positions. Due to edge effects of the PECVD deposition process, the thickness of the final FS layer on the structure increases towards the outer parts of the chip, which leads for this particular chip to a dispersion closer to the design value. For stable modelocking, high pump powers from 23.2 W up to 26.9 W had to be used (mean value: 25.4 W, \(\sigma = 0.9\) W, Fig. 6(d)).
The MIXSEL operates reliably at sub-400-fs pulse durations at the probed positions on the surface and delivers high average output power. Numerical simulations indicate that, besides engineering efforts of various parameters of gain and absorber, the targeted pulse durations in the 100-fs regime require more advanced dispersion control of SDLs [32]. To this end, a strong focus has to be put on more precise FS deposition techniques, such as e.g. ion-beam sputtering, or structural designs that are less sensitive to layer thickness errors.

4.2 Temperature-dependence of modelocking performance

The earliest MIXSELs were based on quantum dot (QD) absorbers [9, 10]. Those absorbers have been optimized for low saturation fluences and moderate modulation depth [40]. QD compared to QW absorbers are less sensitive to temperature changes, which offers a more broadband operation range in terms of cooling and optical pumping. So far, however, the slow absorption recovery dynamics due to the annealing time during the MIXSEL growth limited further performance scaling towards shorter pulse durations. Alternatively, a QW-based absorber was developed for MIXSEL integration [11], which provides very fast absorber recovery, even after long annealing during the epitaxial growth, low saturation fluences and excellent reproducibility. However, the pronounced QW band-edge shift with temperature requires careful device design for vertical integration to obtain the spectral alignment of gain and absorber at the design wavelength (Fig. 7).

The influence of the heat-sink temperature \( T_{\text{hs}} \) on the MIXSEL performance reveals important aspects of the modelocking mechanism. The MIXSEL cavity used an OC with a ROC = 500 mm and remained unchanged at a pulse repetition rate of 3.35 GHz for the following experiments. The heat-sink temperature \( T_{\text{hs}} \) was changed in steps of 2 °C and stable modelocking operation was restored by adapting the pump power. Over a temperature range of 26°C between −15 °C and + 11 °C stable modelocking operation was found (Fig. 7(a)). A distinct plateau of maximum average output power is identified between −1 °C and + 7 °C with high average powers > 260 mW. For higher \( T_{\text{hs}} \) the pump powers necessary for obtaining stable modelocking decrease from \( \approx 32 \) W at \( T_{\text{hs}} = −15 \) °C to \( \approx 16 \) W at + 11 °C. At the same time, the center wavelength follows the behavior of the average power, covering a range of \( \approx 2.5 \) nm with higher lasing wavelengths for higher output power. The pulse durations nearly match perfectly the trend of the average output power in an inverse fashion, covering a span from \( \approx 430 \) fs down to \( \approx 325 \) fs. As one can assume nearly unchanged structural GDD during the study, the pulse shaping is governed mainly by saturation effects of absorber and gain.

The calculated pulse fluences \( F_p \) on the device are in the range between \( \approx 7 − 12 \) μJ/cm², which is close to the estimated absorber saturation fluence of \( \approx 10 \) μJ/cm² [11], but far below the gain saturation fluence (estimated \( F_{\text{sat,g}} \approx 70 − 100 \) μJ/cm²). Thus the influence of saturation on the gain is rather small. However, with increasing pulse fluences \( F_p \) around the current operation point, the absorber modulation (reflectivity contrast between unsaturated and saturated absorber) is not fully saturated and increases close to linearly. Therefore the absorber induces a stronger pulse shaping effect at higher pulse fluences on the device, which then leads to shorter pulse durations with SDLs. This effect is shown in Fig. 7(a) and was also confirmed in numerical simulations [32]. The influence of the changing thermal lens due to pump power variations on the output power is only minor, which is linked to the stable cavity configuration within a broad stability zone. Furthermore, effects of Kerr-lensing on the pulse shaping can be excluded for the MIXSEL cavity configuration, as the Kerr-induced mode-size changes amount to less than 0.05%, even for assuming the highest values for the recently measured nonlinear refractive indices [16, 17].

The variation in output power and pump power can be explained by the temperature-distribution in a MIXSEL, schematically depicted in Fig. 7(b). The two-dimensional representation is not to scale, but illustrates the most important parameters. Quantitative analyses in 3-D were performed in Refs [41, 42], but their validity is limited by the knowledge of the exact thermal resistivities of the contained components, such as the DBRs or the bonding layers.
The MIXSEL chip is cooled to the heat-sink temperature $T_{hs}$ and is optically pumped from the front-side. Thanks to the pump DBR, the pump light is almost entirely absorbed in the active region, which represents the region with the main heat load in such a device. The strongly elevated temperatures in the active region $T_{act}$ cause a temperature gradient towards the heat-sink temperature $T_{hs}$. Thus, the temperature in the integrated saturable absorber $T_{abs}$ is found in between both values. The temperature difference $\Delta T_{off} = T_{act} - T_{abs}$ is a critical design parameter in a QW-absorber MIXSEL, as it governs the spectral alignment of gain and absorber. The temperature offset $\Delta T_{off}$ can be adjusted by $T_{hs}$ and the active region temperature $T_{act}$, which is mainly related to the dissipated pump power.

![Diagram](image)

**Fig. 7.** Temperature-dependence of MIXSEL modelocking parameters: a) Distinct average output power maximum between $T_{hs} = -1 \, ^\circ C$ and $+7 \, ^\circ C$. The required pump power is reduced from $\approx 32 \, W$ to $\approx 16 \, W$; b) Schematic of temperature distribution in MIXSEL with temperature offset $\Delta T_{off}$ between active region and saturable absorber; c) Temperature-dependent spectral alignment of gain and absorber for QW-absorber MIXSEL unpumped and during operation.

Furthermore, the absolute temperatures in the gain and absorber sections should match the emission and absorption wavelengths that guarantee best overlap with the structural design to ensure ideal field enhancements and dispersion. The spectral alignment of gain and absorber is depicted in Fig. 7(c). Reflectivities below 100% are regarded as absorption from the saturable absorber (blue), while reflectivities above 100% represent gain from the active region (red). The gain curvature is approximated from recent measurements [43], while the absorption curvature is taken from a SESAM with the same absorber properties. Recent MIXSELS are designed for an active region temperature offset $\Delta T_{act} \approx 100 \, ^\circ C$ compared to $T_{hs}$. Therefore, the photoluminescence of the active layers is blue-shifted by $\approx 32 \, \text{nm}$ compared to $T_{hs}$.
the operation wavelength (InGaAs QW band-edge shift of 0.32 nm/°C). The saturable absorber is operated at the QW band-edge at a point with ≈2% modulation depth. Due to an approximate temperature offset $\Delta T_{\text{eff}}$ of ≈35 °C, the saturable absorber is designed for an operation temperature offset $\Delta T_{\text{abs}}$ ≈65 °C, which requires a 21-nm detuning in the un-pumped state relative to the operation wavelength.

Besides carrier excitation, the pump power is controlling the heat-load in the active region to balance the spectral offset between absorption and gain. In the novel MIXSEL structure the broadband and flat wavelength-dependent field enhancement does not restrict the intrinsic gain bandwidth of the active layers compared to previous structures. For a specific heat-sink temperature $T_{\text{hs}}$ stable modelocking is obtained in a regime of maximum gain, where the long wavelength parts of the gain are already slightly suppressed by thermal roll-over (Fig. 7(c)) [44]. Thus, the absorber modulation is enforced spectrally and modelocking instabilities, such as cw contributions at higher wavelengths, can be avoided. As the thermal roll-over is dependent on the material parameters of the gain, it was shown that the absolute roll-over temperature inside the semiconductor structure is nearly independent of the heat-sink temperature [44]. Hence, for higher heat-sink temperatures only a fraction of the pump power is needed to reach the point of maximum gain and the onset of thermal roll-over. The dependence of the output power on the heat-sink temperature resembles a complex interplay between optimum intrinsic QW performance, best overlap with the field enhancement of the gain and optimum carrier excitation levels with pumping. A more precise description requires further investigations.

For future MIXSEL structures $\Delta T_{\text{eff}}$ will be reduced by minimizing the absorber detuning by several nanometers. The required absorber modulation depth is then aligned to the gain at a lower pump power which should support increased device efficiency.

4.3 Stable fundamental modelocking versus “pulsation” with SDLs

With a high-Q cavity, a short gain lifetime in the nanosecond regime and a delicate pulse formation mechanism [45], SDLs are very susceptible to strong “pulsation”, that can be mistaken for clean fundamental modelocking if only limited laser diagnostics are available. Recently, the more established and robust SESAM-based modelocking has been replaced with novel saturable absorber schemes, such as graphene-based saturable absorber mirrors [13, 14] and “self-modelocking” based on based on nonlinear lensing effects, such as e.g. Kerr-nonlinearities, inside the SDL structure [15, 16]. However, passively modelocked SDLs, require rigorous pulse characterization in order to exclude instabilities of the fundamental modelocking process [46].

In the following we present two modes of operation of the MIXSEL: stable modelocking and strong “pulsation” that can be misinterpreted as stable modelocking with limited diagnostics. To illustrate this, we show how standard measurement techniques can appear to confirm stable modelocking in both the ‘pulsation mode’ and the stable fundamental modelocking mode of operation with our MIXSEL when certain measurement parameters are used. We then propose how to correctly identify these two regimes of operation.

The MIXSEL cavity was set up for a repetition rate of 3.35 GHz using an OC with a ROC = 500 mm. At a $T_{\text{hs}}$ of +1 °C the average output power of the MIXSEL was recorded for increasing pump power (Fig. 8(a)). At a pump power of ≈24.8 W, the average output power drops from ≈810 mW (mode of operation No. 1) to ≈249 mW (mode of operation No. 2). In both cases timing phase noise power spectral densities of the first harmonic of the repetition rate were recorded with a highly linear photodetector (Discovery Semiconductors Inc. DSC30S) and a commercial signal-source analyzer (Agilent E5052B) (Fig. 8(b)). The excessive phase noise in case No. 1 indicates modelocking instabilities. Those instabilities become even more evident in a microwave spectrum with a RBW of 1.56 kHz and high SNR of >60 dB (Fig. 8(c)). While for case No. 2 insignificant power in the noise side-bands can be identified, in case Nr. 1 a strong noise background is detected already 30 dB below the carrier level.
Fig. 8. Comparison of laser characterization for two selected laser modes of operation No. 1 (red circle) and No. 2 (blue circle): a) Power slope of the MIXSEL with the two characterized modes of operation indicated; b) Comparison of phase noise power spectral density for both cases; c) Microwave spectrogram for both cases with 1.56 kHz RBW and high SNR; d) Set of laser diagnostics for mode of operation No. 1; e) Set of laser diagnostics for mode of operation No. 2; f) and g): Wide-span microwave spectra for both characterized modes of operation (RBW: 300 kHz).
Typically three diagnostic tools are used for analyzing the laser modelocking. For mode of operation No. 1 an SHG-based intensity autocorrelation trace, an optical spectrum and a microwave spectrum were recorded with typical settings for the individual devices, presented in various publications of recent ultrafast SDLs (Fig. 8(d), top). The recorded data suggest modelocking with femtosecond pulse durations and a sech^2-shaped spectrum. However, by changing the settings and scales of the individual diagnostics (indicated red in graphs) an unstable pulsation mode becomes evident in the case No. 1 (Fig. 8(d), bottom). In the intensity autocorrelation trace a coherent peak is located on top of a broad plateau, spanning a large fraction of the delay range of the autocorrelator of ± 40 ps. In fundamental modelocking an autocorrelation trace must be free of any background.

The optical spectrum with a small RBW of 0.08 nm and without video averaging reveals a high level of noise in the spectral domain, strongly fluctuating for consecutive scan sweeps of the optical spectrum analyzer. In typical microwave spectra of ultrafast SDL results, 30 dBc SNR with an RBW of 100 kHz are presented to confirm stable modelocking. By reducing the RBW to below 10 kHz and increasing the SNR by appropriate amplification to over 40 dB, the modelocking instabilities can be easily identified with conventional microwave spectrum analyzers (Fig. 8(d), bottom right). In addition, we detect the instabilities in a 25-GHz bandwidth microwave spectrum with a RBW of 300 kHz (45-GHz photodetector without further amplification). In Fig. 8(f) a steady drop of harmonic signal (>10-dB loss of signal for harmonic no. 6) does not support “stable modelocking“ [46].

For comparison, the mode of operation No. 2 (i.e. stable modelocking) has been characterized with the same set of diagnostics (Fig. 8(e)). Here, a change in device settings and scales does not reveal modelocking instabilities. Those measurements suggests clean fundamental modelocking operation. The intensity autocorrelation trace is background-free, even on the largest available delay range. The optical spectrum remains unchanged when resolving it with the minimal bandwidth of 0.08 nm and without video averaging. The microwave spectrum does not exhibit excessive phase noise, even with a RBW of 3 kHz and 45 dB SNR. A 25-GHz microwave spectrum does not reveal a drop of harmonic signal or signal modulations (Fig. 8(g)).

Based on the detailed characterization we want to increase the awareness for the pitfalls in pulse characterization measurements with SDLs for the typical characterization tools: Stable multi-pulsing can be identified with an intensity autocorrelation, given that the pulse-spacing is shorter than half the delay range of the autocorrelator. For a spacing of the pulses longer than half the delay range of the autocorrelator, sampling oscilloscopes with sufficiently fast photodetectors can give indications of satellite pulses. Typical ultrafast SDLs operate in the gigahertz pulse repetition rate regime with sub-nanosecond distance in time. In many cases, the rise and fall times of photodetectors are not fast enough to resolve satellite pulses that are closely located to the main pulse. Furthermore, satellite pulses can be hidden by trigger-induced measurement artifacts in sampling oscilloscopes. Often, instabilities can be identified with conventional SHG autocorrelators. An autocorrelation trace with a short coherent peak on a broad plateau indicates a pulsation mode with several short pulses circulating in the cavity with indefinite spacing in the time domain. The width of the central coherent peak is a measure for the duration of the individual short pulses, while the width of the autocorrelation background determines the total length of the pulse sequence [47]. Only when excluding those pulsation phenomena rigorously, the pulse peak power can be calculated precisely.

When the optical spectrum should be recorded with the best available RBW, at best 10-20 times lower than the spectral bandwidth (FWHM), narrow-band modulations and large signal fluctuations for consecutive sweeps can help to identify modelocking instabilities.

A microwave spectrogram centered around the first harmonic of the repetition rate is an important measurement for revealing instabilities. In order to better detect potential modelocking instabilities, a high SNR of >45 dB in a sub-10-MHz span should be obtained for the smallest RBW (typically <10 kHz), before the jitter of the unstabilized repetition rate affects the measurement during a device sweep. Moreover, a large-span microwave spectrogram must feature the higher harmonics of the repetition rate. Any loss of the
harmonic signal or excessive harmonic modulation must agree with the bandwidth specifications of the photodetector, the amplifiers and the analyzer.

In addition, phase retrieval with e.g. a SHG-FROG can be used to identify instabilities. We were not able to record an experimental FROG trace for the mode of operation No. 1, while for stable modelocking excellent agreement between retrieved and measured FROG traces is obtained (Figs. 3(e)-(f) and Figs. 4(e)-(f)).

4.4 Efficiency limitations in modelocked operation

Despite the excellent performance of the presented MIXSEL structure, the low optical-to-optical efficiency ($P_{\text{out}}/P_{\text{pump}}$) in the order of $\approx 1\%$ is a real problem. The main goal for the ongoing MIXSEL development is a more efficient operation with higher average output power, while maintaining short femtosecond pulse durations. Here, we want to discuss the current limitations and present guidelines for future optimization.

In a first step, the pump light dissipation outside and inside the semiconductor structure has to be considered. The MIXSEL structure was finalized with an AR-section that ensures low GDD and moreover reduces reflective losses of the pump light at the interface between air and structure. Our current fabrication uncertainties are responsible for the reflection of approximately 15% of the incident pump light at the surface of the MIXSEL chip, which should be reduced to less than 2%.

Besides excitation of the laser medium, the optical pump acts as a heat source for the critical temperature balance between saturable absorber and gain (Section 4.2). Thereby modelocking is spectrally enforced at high pump excitation, when the long wavelength tail of the gain is already slightly suppressed by thermal roll-over in order to avoid modelocking instabilities, such as cw breakthrough or unwanted pulsation (see Fig. 7(c)). The spectral alignment of gain and absorber can be further engineered for ideal overlap at lower pump intensities, however the critical temperature balance cannot be circumvented with the current QW-based absorbers. A novel generation of saturable absorbers must offer the desired absorber parameters over a large spectral bandwidth and with reduced influence of the device temperature. Here we expect that QD-based absorbers can offer the desired parameters [40], however they need to be optimized for MIXSEL integration.

For future MIXSEL structures, we expect a combination of high gain and high gain saturation fluences at lower pump intensities by the implementation of more advanced carrier-distribution schemes for the individual QW gain layers. In addition, lower pump intensities minimize non-radiative loss from Auger recombination, reduce carrier loss at elevated gain temperatures and lower parasitic lateral lasing parallel to the stack layers as they reduce the available gain for modelocking operation.

Furthermore, cavity loss has to be reduced to allow for a larger output coupling rate, which is currently very low with only 0.55% transmission. The current MIXSEL fabrication scheme is based on two epitaxial techniques. Unwanted structural defects at the interface layers cause scattering loss, that can be avoided in a typical single-run fabrication scheme. Furthermore, the low degree of absorber saturation (absorber saturation parameter $S_a = F_p/F_{\text{sat,a}} < 1.5$) causes absorber losses in the order of $\approx 1\%$. Those are significantly larger than the OC transmission and the main contribution to parasitic device loss. Previously, MIXSELs with QW-based absorbers were operated with maximum $S_a \approx 3$ [4], while QD-absorber MIXSELS were operated with maximum $S_a \approx 14$ [10], both achieving watt-level average output power in picosecond pulses. The quasi-soliton pulse formation mechanism in SDLs [32, 45] relies on a balanced interplay of saturation-induced nonlinear phase shifts and positive GDD. For the formation of short sub-300-fs pulses the influence of the time-dependent nonlinear phase-changes has to be revisited in a more advanced theoretical model than previously presented [32]. Higher intracavity fluences would result in a larger absorber-induced phase change, potentially destabilizing the formation of a short femtosecond pulse and limiting the average output power.
5. Conclusion and outlook

We have demonstrated sub-300-fs operation from a high peak power MIXSEL at a center wavelength of 1040 nm with rigorous modelocking characterization.

The semiconductor structure was optimized according to the guidelines presented by Sieber et al. in [32]. A strain-compensated active region helped to increase the device lifetimes and allowed to scale the emission wavelength to >1030 nm. This novel MIXSEL generated 253-fs pulses in 235 mW of average output power. The combination of short pulse durations and a high average power leads to a peak power of 240 W, surpassing the previously highest result for a MIXSEL three times [10]. Therefore, MIXSELS achieve comparable performance than sub-300-fs SESAM-modelocked VECSELS for the first time (Fig. 1). At 10 GHz repetition rate we presented 279-fs-pulses in 310 mW of average output power, which represents the highest output power of any femtosecond MIXSEL to date. In addition, this MIXSEL is continuously tunable in repetition rate. In a tuning range between 2.9 GHz and 3.4 GHz sub-400-fs pulses were generated with >225 mW of average output power. Such lasers can be beneficial for pump-probe measurement schemes based on OSCAT.

We discussed the operation principle of the QW-absorber MIXSEL based on detailed parameter studies. The insights gained from those studies enable more optimized MIXSEL structures that achieve even shorter sub-200-fs pulses and kilowatt peak power with higher optical-to-optical efficiency in the near future. Such lasers are highly interesting sources for spectroscopy, imaging and gigahertz frequency comb metrology.

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