



Comparison of mode-locking performance in monolithic two-section InAs/InP quantum dot and InGaAsP/InP quantum well lasers

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Abstract: A common method to generate ultrashort pulses in a two-section laser diode is to pump the large section with gain current and apply a reverse absorber voltage to the small section, which acts as a saturable absorber. Ultrashort pulses detected in such a configuration are typically attributed to passive mode-locking. However, our results indicate that self-mode-locking is the dominant process for the generation of ultrashort pulses within the examined InAs/InP quantum dot laser and InGaAsP/InP quantum well laser, even in a passive mode-locking setup. To verify this, we controlled both laser sections with gain current only. The pulses detected in this setup were shorter than those observed in the passive mode-locking configuration. While the quantum dot laser was largely unaffected by the applied reverse voltage, the quantum well laser exhibited changes in behavior at medium and high reverse voltages, eventually preventing pulse generation. Additionally, we investigated repetition frequency tunability in pure self-mode-locking operation. Repetition frequency tunability was observed for both lasers: 47 MHz for the quantum dot laser and 86 MHz for the quantum well laser.

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1. Introduction

Mode-locked laser diodes (MLLDs) are versatile, cost effective and compact devices that are used in a wide range of applications. These include spectroscopic applications for material detection and testing such as terahertz time-domain spectroscopy [1], for optical communication [2,3], imaging [4], or optical clocks [5]. The compact design of MLLDs not only reduces production costs, but also enables applications as mobile systems [6,7]. A further advantage is the possibility to customize these devices in terms of emission wavelength, or pulse characteristics like pulse repetition frequency [8].

Some laser diodes with an emission wavelength around 1550 nm have the unique ability to generate ultrashort pulses by only applying gain current (I_G) [9]. This has been observed on single-section mode-locked lasers [10–12], which are also referred to as frequency-modulated (FM) lasers [13]. Pulses form by intrinsic nonlinear processes within the MLLD, notably due to spatial hole burning and four-wave mixing [12,14]. This process, which is also referred to as

self mode-locking (SML) has also led to measured pulse widths around 300 femtoseconds (fs) [15]. However, pulses generated by SML exhibit considerable chirp inducing the need for pulse compression. The dispersion properties of optical fibers (such as SMF-28) counteract that chirp at emission wavelengths around 1550 nm, so that the pulse experiences a compression. The fiber length plays a crucial role in achieving optimal pulse compression: if the fiber is too short, the pulse will not be fully compensated, if it is too long, the pulse will broaden again. It is therefore important to integrate optical fibers of suitable length into the setup [9,16].

Another technique for generating ultrashort pulses is passive mode-locking (PML), whose mode-locking process is also referred to as amplitude-modulation (AM) [17]. In 2007, PML was reported in an InAs/InP mode-locked quantum dot (QD) laser diode in the 1.5 μm regime for the first time [18]. Since then, pulse widths below 500 fs have been obtained [19]. With MLLDs, PML can be achieved directly on the device by dividing the laser chip into two sections [2,20]. The long section further serves as gain section and is electrically pumped with gain current (I_G), while a reverse absorber voltage (V_{Abs}) is applied to the short section, that acts as a slow saturable absorber [19,21,22]. The absorption of incoming light at the absorber section leads to the formation of free carriers. Thus, at higher light intensities, the absorber saturates, becomes transparent and forms a net gain window for ultrashort pulse formation [9]. Afterwards, the system recovers to its initial state, with the recovery time being equal to the recombination time of the free carriers when no V_{Abs} is applied. Applying an electric field via V_{Abs} accelerates the removal of free carriers from the active medium. As a result, the recovery time becomes shorter with increasing reverse voltage [2,21]. This removal of free carriers can be measured as a current flow at the absorber section and can serve as an indicator of the functionality and efficiency of the absorber.

In monolithic MLLDs, both the laser emission and the pulse formation processes due to SML or PML take place directly on the laser chip, which is often only a few hundred micrometers or a few millimeters long, enabling high pulse repetition rates. However, the pulses might exhibit chirp, which requires pulse compression. SML is thus a phenomenon observed in single-section FM lasers, while PML is attributed to two-section AM lasers. Previous studies on QD MLLD have observed switching between SML and PML regimes on two-section devices while varying absorber voltage and gain current settings [14,17] or have compared two-section devices with single-section devices [12]. We further found out that an InGaAsP/InP quantum-well (QW) two-section MLLD emits pulses primarily due to SML processes, even when a reverse absorber voltage is applied [23]. A higher V_{Abs} led to disruptive processes in the laser that prevented the formation of clean ultrashort pulse trains at all. In contrast, the best results were obtained when both sections of the MLLD were connected and pumped so that the laser operated like a single-section device, ensuring only SML processes were present.

This study focuses on a QD MLLD, which is structurally almost identical to the investigated QW MLLD, with the main difference being the active medium consisting of 7 stacked layers of InAs quantum dots in contrast to the QW MLLD with 4 x InGaAsP quantum wells. Previous publications on this QD MLLD have focused on its operating characteristics in a PML setup with applied V_{Abs} , including $V_{\text{Abs}} = 0$ V [24–26]. In contrast, this paper first investigates the QD MLLD's behavior when its two-sections are electrically connected, letting the device behave like a single-section laser. By this, single-section operation without saturable absorber and two-section operation with saturable absorber can be compared on the same laser chip. We further compare the behavior of the QD laser with that of the QW laser. The goal of this study is to determine which device performs better and whether pulse generation in the QD device originates in PML or SML processes. This includes an analysis of the MLLD's temperature stability, optical spectra's bandwidth, RF characteristics and pulse durations. Those properties are interesting for various applications. For instance, a narrow RF line width, temperature stability and a high repetition rate are of great importance for frequency comb applications, such

as dual comb spectroscopy [27,28]. Further applications like optical sampling by electronic repetition-rate tuning (OSBERT) [29] require the possibility of altering the repetition frequency (f_{rep}) of the laser by changing its electrical control parameters. Cherniak et al. have already shown in an extensive study that f_{rep} of the QD and QW MLLD can be tuned within a range of 20–25 MHz at fixed temperature and I_G by varying the applied V_{Abs} [24]. However, this option is no longer available when controlling the MLLDs as single-section device. Since the QW MLLD performed significantly better when pulse generation occurred solely through SML, our aim is to determine whether it is also possible to tune f_{rep} by varying I_G and temperature. This investigation is carried out with both the QD and the QW MLLD.

2. Devices and experimental setup

2.1. Devices

The MLLDs investigated here share a largely common design with the QD MLLD described in [23]: Both MLLDs have a total length of 840 μm , which is divided in two sections: a long gain section and a short 50 μm absorber section, separated by a 20 μm isolation gap [25,26]. The manufacturing process is identical for both devices, using metal-organic chemical vapor deposition (MOCVD) [30,31]. Moreover, both lasers have a 90% high reflection coating on the rear facet and a 10% anti-reflection coating on the outcoupling facet.

The key distinction between the two lasers lies in their active medium: while the QD device consists of 7 layers of InAs quantum dots, the active medium in the QW MLLD consists of 4x InGaAsP quantum wells.

For both lasers, the relative intensity noise (RIN) is as follows: RIN of all modes comparable ≈ -155 dB/Hz and RIN of single mode < -136 dB/Hz for a frequency > 5 GHz with both QD and QW lasers.

2.2. Experimental setup

For a conclusive comparison of the behavior of the QD and QW MLLD, the QD MLLD was operated under identical electrical control conditions as the QW MLLD, both in 1-Section Operation (1-SO), and 2-Section Operation (2-SO).

1-SO corresponds to an electrical setup configuration that exclusively enables SML: Both sections of the laser are connected via an SMA T-junction and driven with I_G , resulting in an equal current density in both sections. The MLLD thus behaves like a single-section device.

2-SO corresponds to a classic setup to achieve PML, in which the long section of the MLLD is supplied with I_G to act as gain section, and V_{Abs} is applied to the short section to realize a saturable absorber. However, the results with the QW MLLD showed that a 2-SO configuration does not necessarily lead to pulse formation caused by PML. For this reason, the terms 1-SO and 2-SO are used in the following as a neutral description of the electrical configuration to avoid confusion with the device's intrinsic pulse generation processes.

The following devices were used for device control: Thorlabs ITC 8052 as laser current driver and temperature control and Keysight E36311A power supply for applying the reverse absorber voltage. Data acquisition was performed using a Yokogawa AQ6315E optical spectrum analyzer (OSA), Coherent XPDV2120R high-speed photodiode in junction with Anritsu MS2760A-0070 electrical spectrum analyzer (ESA) for measuring the radio frequency (RF) spectra, and APE pulseCheck USB 150 autocorrelator (AC) for pulse characterization.

Fig. 1 shows the optical setup: First, the free-space laser beam is collimated using an aspherical lens (Thorlabs C660TME-C) and is coupled into a fiber using two mirrors and a fiber collimation package (Thorlabs F280APC-1550). By choosing an FC/APC fiber collimation package and adding an additional optical isolator (Thorlabs IO-4-1550-VLP), initial stability issues of the setup were successfully eliminated.

From this point on, the subsequent setup, both for the QW and QD MLLD, is entirely fiber-coupled. In the QD MLLD setup, 11 meters of optical fibers (SMF-28) are permanently installed, including a 2 m long fiber behind the fiber collimator, followed by a 5 m long fiber that is routed through a 3-paddle polarizer (Thorlabs FPC560). A polarization control is necessary as the AC requires linearly polarized light. Furthermore, two fiber beamsplitters are included with a length of 2 m each: a 90:10 beamsplitter (Thorlabs TW1550R2F1), with the 90% arm leading to the second 99:1 beamsplitter (Thorlabs TW1550R1A1), and the 10% arm being directed to the ESA. Since the AC requires high power for pulse detection, the 99% arm of the second beamsplitter is directed to the AC and the 1% arm is routed to the OSA.

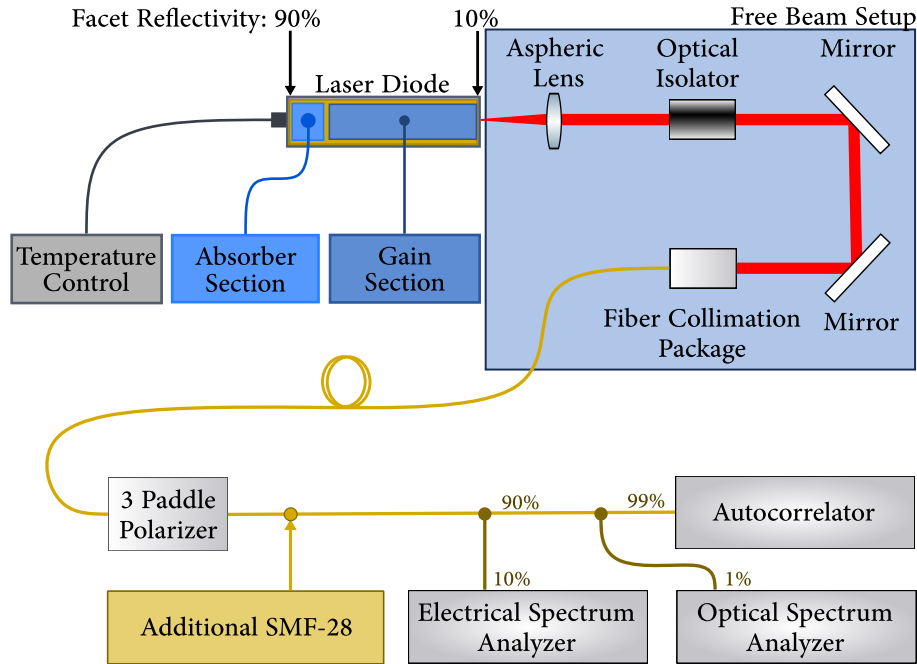


Fig. 1. Optical setup of the experiment with the QD MLLD. To a large extent, the same components, as well as control and measurement devices are used as in the experiment with the QW MLLD [23], to ensure the highest degree of comparability.

For dispersion compensation, additional SMF-28 fibers are required within the setup. These fibers are inserted at the junction between the 3-paddle polarizer and the first beamsplitter. Whenever fiber length values are mentioned in the following, they refer to the total fiber length (L_{Fiber}) in the setup, meaning the sum of the additional fibers and the permanently installed fibers in the setup.

A detailed description of the QW MLLD setup can be found in [23].

3. Experimental methods, results and discussion

3.1. Characteristic curves

Characteristic power-current (PI) curves were measured for the QD and QW MLLD. The power sensor (Thorlabs S132C) was positioned at the laser output after the aspheric lens, and parameters were varied in temperature (15°C to 40°C, steps of 1°C), I_G (0 mA - 400 mA, steps of 1 mA), and, in case of 2-SO, in V_{Abs} (-1.4 V - 0 V, steps of 0.1 V). However, the QW MLLD exhibited a thermal rollover at gain currents above 300 mA. To avoid damaging the laser diode, I_G was therefore set to a maximum value of 300 mA for the experiments with the QW MLLD.

The PI curves in 1-SO mode and at selected values of V_{Abs} in 2-SO mode at a temperature of 15°C are shown in Fig. 2(a) for the QD MLLD and (b) for the QW MLLD. Table 1 presents the values of the laser threshold current (I_{Thr}), the maximum average output power ($P_{\text{out,max}}$) and the curve's gradient ($\Delta P/\Delta I$).

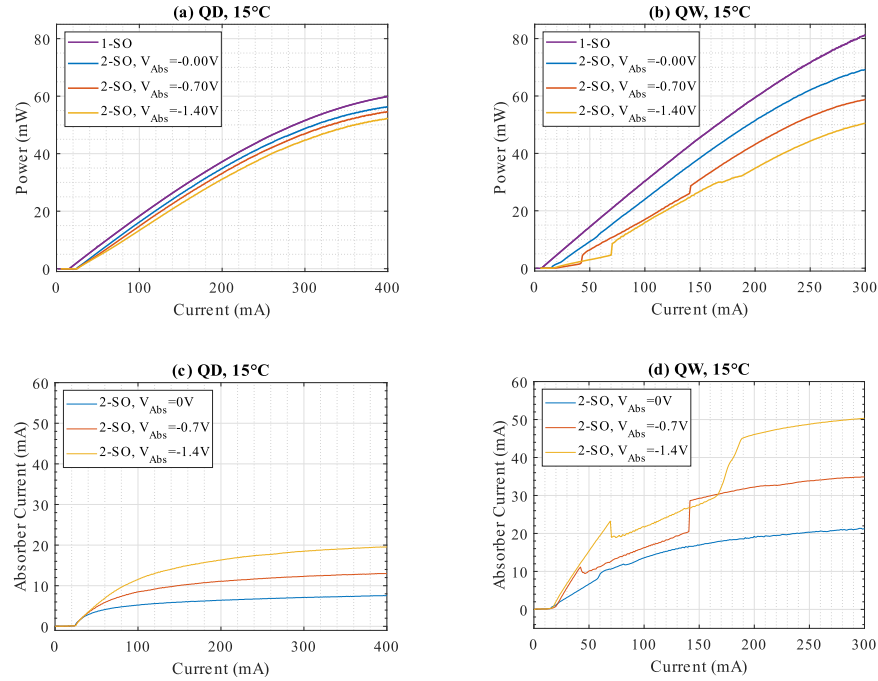


Fig. 2. Characteristic PI curves and absorber current for QD and QW MLLD, measured at 15°C . (a) PI curve of QD MLLD, (b) PI curve of QW MLLD, (c) absorber current of QD MLLD, (d) absorber current of QW MLLD

Table 1. Data from PI-curves, measured at 15°C at QD and QW setup, with I_{Thr} : Threshold current, $P_{\text{out,max}}$: Max. average output power and $\Delta P/\Delta I$: gradient of the curve after the laser threshold

MLLD	Setup	I_{Thr}	$P_{\text{out,max}}$	$\Delta P/\Delta I$
QD	1-SO	15 mA	60 mW	$0.20 \frac{\text{mW}}{\text{mA}}$
QD	2-SO, $V_{\text{Abs}} = 0 \text{ V}$	25 mA	54 mW	$0.20 \frac{\text{mW}}{\text{mA}}$
QD	2-SO, $V_{\text{Abs}} = -0.7 \text{ V}$	26 mA	52 mW	$0.19 \frac{\text{mW}}{\text{mA}}$
QD	2-SO, $V_{\text{Abs}} = -1.40 \text{ V}$	26 mA	49 mW	$0.17 \frac{\text{mW}}{\text{mA}}$
QW	1-SO	6 mA	81 mW	$0.31 \frac{\text{mW}}{\text{mA}}$
QW	2-SO, $V_{\text{Abs}} = 0 \text{ V}$	14 mA	69 mW	$0.28 \frac{\text{mW}}{\text{mA}}$
QW	2-SO, $V_{\text{Abs}} = -0.7 \text{ V}$	19 mA	59 mW	$0.25 \frac{\text{mW}}{\text{mA}}$
QW	2-SO, $V_{\text{Abs}} = -1.40 \text{ V}$	17 mA	51 mW	$0.19 \frac{\text{mW}}{\text{mA}}$

For the QD MLLD, the applied V_{Abs} has a minimal impact on the shape of the PI curves as well as on its gradient. However, the I_{Thr} value rises from 15 mA in 1-SO to 26 mA in 2-SO and $P_{\text{out,max}}$ decreases from 60 mW in 1-SO to 49 mW in 2-SO.

In contrast, the shape of the QW MLLD's PI curves and their respective gradients change significantly. With the QW MLLD, V_{Abs} has a significant influence on the MLLD's behavior.

The gradient not only decreases from $0.31 \frac{mW}{mA}$ in 1-SO to $0.19 \frac{mW}{mA}$ in 2-SO, at higher V_{Abs} , the curves also experience noticeable kinks. The laser threshold current of the QW MLLD is lowest, with 6 mA in 1-SO and rises up to 19 mA in 2-SO. Additionally, $P_{out,max}$ experiences a significant decrease with rising V_{Abs} , from 81 mW in 1-SO to 51 mW in 2-SO.

For identical operating parameters, it can be seen that $P_{out,max}$ is higher with the QW laser than with the QD laser. In principle, both types of lasers can achieve comparable output power values. In [25], $P_{out,max}$ for both devices reaches nearly 100 mW at identical gain currents (both operated at $20^\circ C$ and $V_{Abs} = 0$ V), measured by an Ulbricht sphere. Since the laser chips as well as their mounts and heat sinks are custom-made and can therefore slightly differ from one another, we attribute the differences in the measured values to the laser chip variation as well as the measurement method.

While measuring the PI curves in 2-SO mode, the absorber current was measured using the Keysight power supply. This was done to verify the electrical functionality of the absorber section, confirming that it is electrically connected and operational. The results are shown in Fig. 2(c) and (d), and confirm the observation of the PI curves: although the absorber current of the QD MLLD increases with higher values of V_{Abs} , the shape of the curves remains unchanged. In contrast, for the QW MLLD, the curves also show clear kinks and shape changes, until the shape of the curves converges at higher values for I_G and V_{Abs} . This behavior of the QW MLLD can be interpreted as follows: At low I_G values above the laser threshold, there is laser emission, but no mode-locking is present. As I_G increases, kinks appear. In the region between those kinks, it is assumed that both SML and PML processes are present within the device, but neither process is able to dominate. Up to this value of I_G , no frequency comb formation or emission of short pulses is observed. However, for low values of V_{Abs} , at values of I_G above the second kink, SML becomes predominant, eventually overtaking PML and fs pulses could be detected, while for high reverse absorber voltages a frequency comb forms, but no short pulse trains could be observed. This observation was further supported by measurements of the optical spectra, RF spectra, and autocorrelation in the QW MLLD [23].

Figure 3 shows both MLLD's behavior at a fixed V_{Abs} of -1.4 V at temperatures between $15^\circ C$ and $40^\circ C$ with steps of $5^\circ C$. For the QD MLLD, as seen in Fig. 3(a), reliable and consistent behavior is observed, even at higher temperatures, with $P_{out,max}$ decreasing as temperature increases. In contrast, the QW MLLD is much more temperature-sensitive, where a distinct rollover starting at a temperature of $35^\circ C$ can be observed in Fig. 3(b).

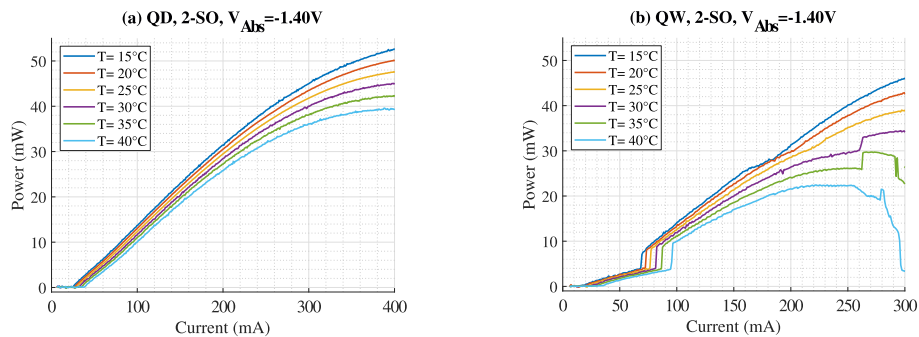


Fig. 3. PI curves measured at 2-SO and at $V_{Abs} = -1.4$ V between $15^\circ C$ and $40^\circ C$, with steps of $5^\circ C$. (a) QD MLLD, (b) QW MLLD

Based on the measurement of the PI curves and absorber current, it can be concluded that both lasers are functioning and are correctly electrically controlled in 1-SO as well as in 2-SO mode. However, the QW MLLD reacts more strongly to the applied V_{Abs} than the QD MLLD.

Furthermore, the QW MLLD has a lower I_{Thr} and higher $P_{\text{out,max}}$, while the QD MLLD has a significantly higher temperature stability.

3.2. Optical spectra

A systematic measurement of the optical spectrum was carried out at a heat sink temperature of 15°C , with changing parameter of I_G (150 mA to 400 mA, steps of 5 mA), and in case of 2-SO of V_{Abs} (-1.4 V to 0 V, steps of 0.1 V). No additional fibers were added to the setup, so that $L_{\text{Fiber}} = 11$ m.

In Fig. 4(a), for each measurement point, the 3dB bandwidth value of the optical spectrum was calculated, with the values of selected spectra given in Table 2, and the spectra shown in Fig. 4(b-e). The QD MLLD shows no major change in its behavior when the electrical control is changed from 1-SO to 2-SO. Even at higher values of V_{Abs} , there is no significant change in the shape of the spectrum or in the 3dB bandwidth value. As Fig. 4(b-d) show, the optical spectrum remains similar in shape at different values of V_{Abs} , closely resembling the spectrum in 1-SO operation. This becomes even more apparent in Fig. 5, where the optical spectra are shown for a fixed $I_G = 401$ mA in 1-SO and in all applied V_{Abs} in 2-SO.

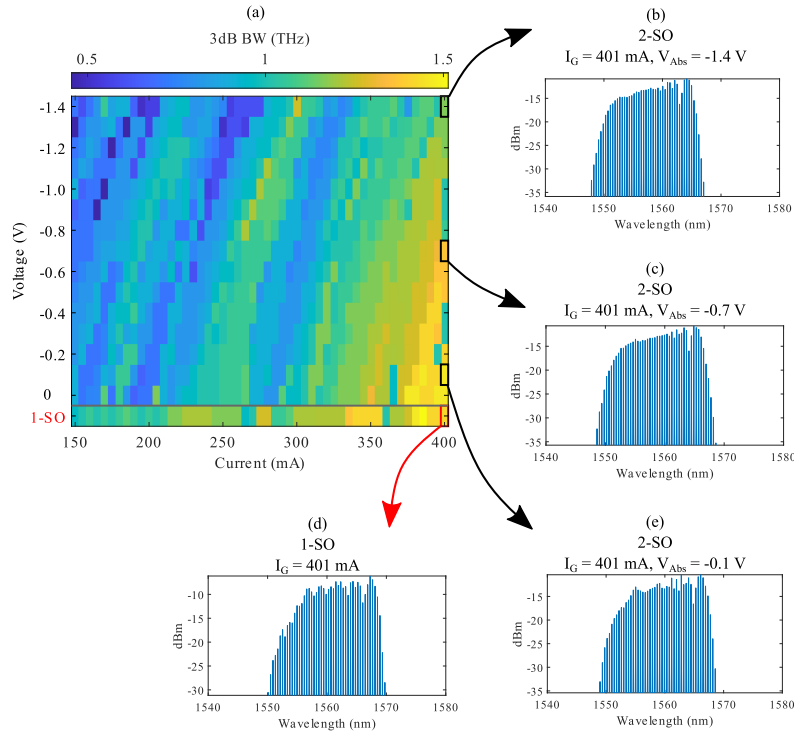


Fig. 4. Analysis of the QD's laser optical spectra, measured at a heat sink temperature of 15°C : (a) 3 dB bandwidth values of the optical spectrum at different gain currents at 1-SO setup (vertical axis label red) and at different gain currents and reverse absorber voltages at 2-SO setup. (b) 2-SO setup at $I_G = 401$ mA and $V_{\text{Abs}} = -1.4$ V (c) 2-SO setup at $I_G = 401$ mA and $V_{\text{Abs}} = -0.7$ V (d) 1-SO setup at $I_G = 401$ mA (e) 2-SO setup at $I_G = 401$ mA and $V_{\text{Abs}} = -0.1$ V.

A corresponding analysis of the QW MLLD's optical spectra is published in [23]. The QD MLLD's behavior is significantly different compared to that of the QW MLLD, where an increase

Table 2. QD MLLD's 3 dB bandwidth value of the optical spectra at selected operating points in 1-SO and 2-SO

Setup	I_G	V_{Abs}	3 dB Bandwidth
1-SO	401 mA	-	1.412 THz (11.5 nm)
2-SO	401 mA	-0.1 V	1.463 THz (11.9 nm)
2-SO	401 mA	-0.7 V	1.361 THz (11.0 nm)
2-SO	401 mA	-1.4 V	1.160 THz (9.4 nm)

in absorber voltage leads to a noticeable change in the spectrum's shape as well as a significant change of the 3dB bandwidth values.

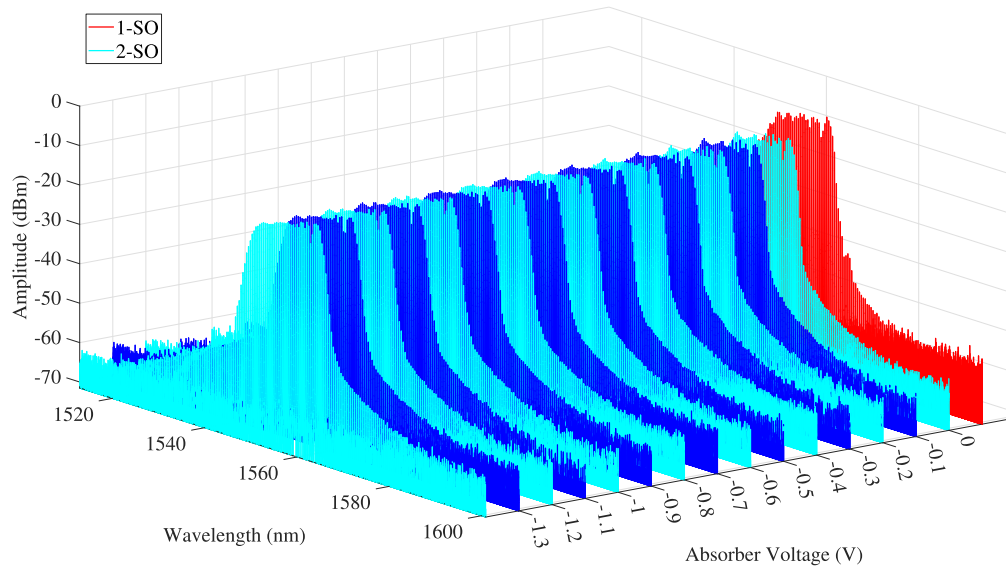


Fig. 5. QD MLLD: Optical spectra at 1-SO setup (red) and at 2-SO setup (all shades of blue) at all measured reverse absorber voltages. All spectra are measured at the same I_G of 401 mA.

3.3. Electrical spectra

The measurement of the electrical spectra was performed simultaneously with that of the optical spectra. Therefore, the same parameters were applied in terms of heat sink temperature, I_G , V_{Abs} and L_{Fiber} . The resolution bandwidth of the electrical spectrum analyzer was set to 30 kHz for both QD and QW laser measurements.

An analysis of the ESA measurement of the QD MLLD is shown in Fig. 6. The white areas indicate measured values for which no f_{rep} or -3 dB RF peak linewidth could be determined, either due to the absence of a clear peak in the signal or because the signal did not sufficiently separate from the noise floor. The repetition frequency is displayed in Fig. 6(a). For the QD MLLD, f_{rep} is slightly higher in 1-SO (between 50.40 GHz and 50.44 GHz) than in 2-SO (between 50.36 GHz and 50.41 GHz). It can also be seen that f_{rep} shifts to lower frequencies with increasing V_{Abs} . The analysis of the -3 dB RF peak linewidth in Fig. 6(b) shows no significant differences in behavior within 2-SO mode between higher and lower values of V_{Abs} , nor any significant variation in the device's behavior compared to 1-SO mode. For both modes of operation, the -3

dB RF peak linewidth remains below 150 kHz for the majority of measured values, with only a few exceptions exceeding this range. Additionally, a clear trend is observable: as I_G increases, the number of values with -3 dB RF peak linewidths above 100 kHz decreases, indicating stable operation.

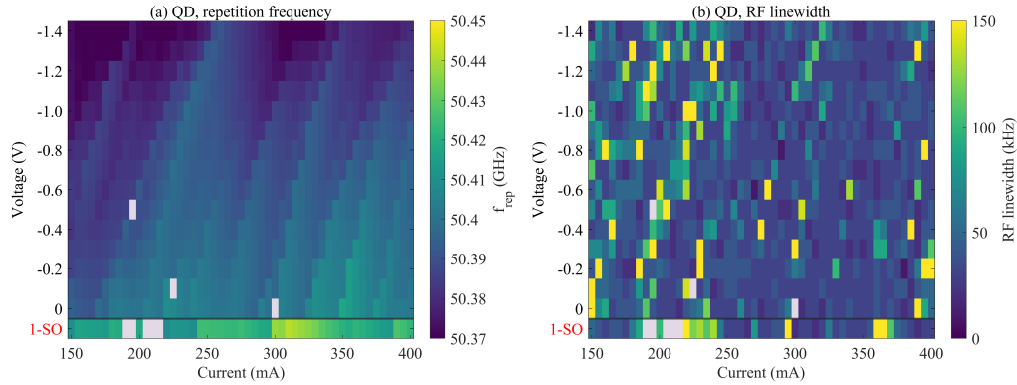


Fig. 6. Repetition frequency and -3 dB RF peak linewidth of QD MLLD in 1-SO and 2-SO mode, measured at a heat sink temperature of 15°C at I_G from 150-400 mA.

The analysis for the QW MLLD has already been discussed in detail in [23]. There, two clearly different regimes in 2-SO operation were observed: at low values of V_{Abs} , the RF signal resembles the signal in 1-SO operation, both in terms of f_{rep} and -3 dB RF peak linewidth. Higher values of V_{Abs} led to a change in the repetition frequency to lower values, and to significantly broader peaks.

After Cherniak et al. successfully demonstrated on both MLLDs that f_{rep} can be tuned in 2-SO mode solely by adjusting V_{Abs} at an operating point with constant temperature and I_G [24], we now analyze whether a similar tunability is possible in 1-SO mode. Since there is no absorber voltage in 1-SO mode, only temperature and I_G remain as adjustable variables. Figure 7 presents measured f_{rep} at various values of I_G , ranging from 150 mA to 400 mA for the QD MLLD and 150 mA to 300 mA for the QW MLLD, with a step size of 5 mA. In addition, the corresponding -3 dB RF peak linewidths are shown. The corresponding values of tunability, minimum value of f_{rep} , maximum value f_{rep} and its operation points are displayed in Table 3.

Fig. 7(a) shows the tunability of the repetition frequency at a temperature of 15°C of the QD as well as the QW MLLD. Significant differences in the device's behaviour are apparent: The QD MLLD shows tunability with linear regions that are interrupted by abrupt jumps in f_{rep} . Within a linear region, there is a trend for f_{rep} to decrease with increasing I_G . Regarding the minimum and maximum values of f_{rep} , the QD MLLD obtains a tunability of 35 MHz at 15°C.

The QW MLLD, however, shows an opposite trend to that of the QD device. In the QW MLLD, f_{rep} gradually increases with increasing I_G . It also encounters a higher tunability with 73 MHz at a temperature of 15°C. Both lasers preserve their behavior at a temperature of 25°C, with only minor changes within the tunability, as Table 3 shows.

Regarding the minimum and maximum f_{rep} values across all measured temperatures, a total tunability of 47 MHz is possible for the QD MLLD and 86 MHz for the QW MLLD.

As shown in Fig. 7(c) and (d), both the QD and QW MLLDs have narrow -3 dB RF peak linewidths: For the QD laser, the majority of values are below 150 kHz at both 15°C and 25°C. For the QW laser, the majority of values are below 300 kHz at both temperatures. However, it has to be noted that the QW and QD measurements were done in different campaigns and different video bandwidth (VBW) settings were used for the QD (30 kHz VBW) and QW (1 kHz VBW). Therefore, the -3dB peak linewidths of the QW laser could actually be even narrower and

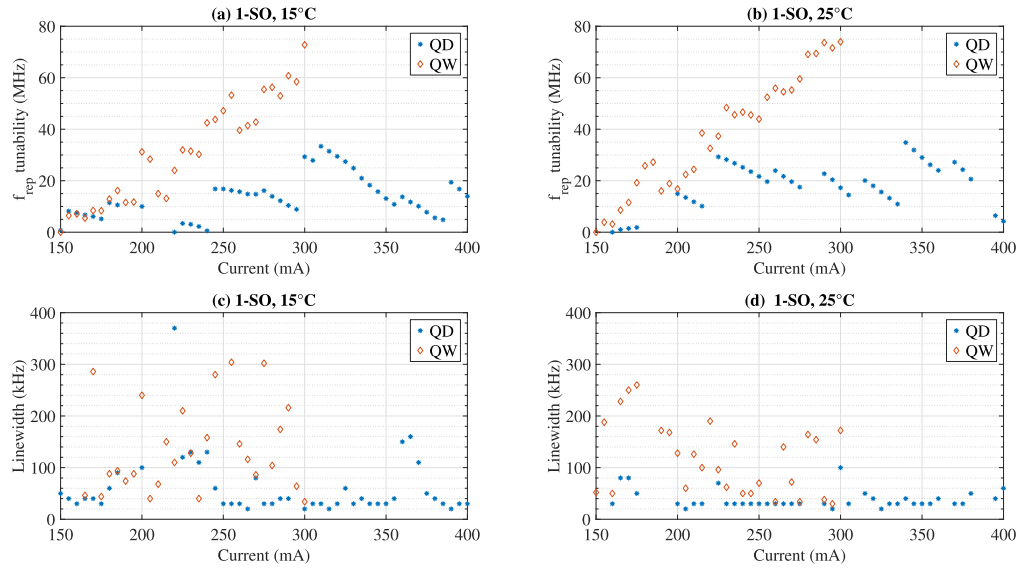


Fig. 7. Comparison of the QD and QW MLLD's f_{rep} tunability and -3 dB RF peak linewidth (a) f_{rep} tunability in 1-SO at 15°C, (b) f_{rep} tunability at 25°C, (c) -3 dB RF peak linewidth at 15°C, (d) -3 dB RF peak linewidth at 25°C.

Table 3. Tunability of the QD and QW MLLD's repetition frequency in 1-SO mode, dependent on the gain current and temperature

MLLD	Setup	Temperature	Tunability	min. f_{rep}	max. f_{rep}
QD	1-SO	15°C	34 MHz	50.408 GHz ($I_G = 221$ mA)	50.442 GHz ($I_G = 311$ mA)
QD	1-SO	25°C	35 MHz	50.394 GHz ($I_G = 161$ mA)	50.429 GHz ($I_G = 341$ mA)
QD	1-SO	15-25°C	48 MHz	50.394 GHz (25°C, $I_G = 161$ mA)	50.442 GHz (15°C, $I_G = 311$ mA)
QW	1-SO	15°C	72 MHz	51.166 GHz ($I_G = 151$ mA)	51.238 GHz ($I_G = 301$ mA)
QW	1-SO	25°C	73 MHz	51.172 GHz ($I_G = 151$ mA)	51.245 GHz ($I_G = 301$ mA)
QW	1-SO	15-25°C	86 MHz	51.164 GHz (18°C, $I_G = 151$ mA)	51.250 GHz (23°C, $I_G = 301$ mA)

comparable to those of the QD laser. However, a detailed quantitative study is out of the scope of this paper, and a more detailed investigation of the lasers' f_{rep} tunability and -3dB RF peak linewidth is subject of future studies.

3.4. Autocorrelation

The autocorrelation trace (ACT) measurements show that, for the QD MLLD, short ACTs are observed even at higher absorber voltages and elevated temperatures. In all cases, the same fiber length of 71 m for dispersion compensation was required.

Fig 8 shows that V_{Abs} has minimal impact on pulse duration, with the shortest ACT with a Full Width at Half Maximum (FWHM_{ACT}) of 588 fs, measured in 1-SO. However, even with the applied absorber voltage, as shown in Fig. 8(b-d), short FWHM_{ACT} of 626 fs to 722 fs were measured, even at elevated temperatures up to 37°C, as Fig. 8(d) demonstrates.

Lorentzian fits provide reasonable fits to the measured data, as can be seen in Fig. 8, providing pulse widths of (a) 294 fs (mse = 0.018), (b): 313 fs (mse = 0.018), (c): 322 fs (mse = 0.021) and (d): 361 fs (mse = 0.024).

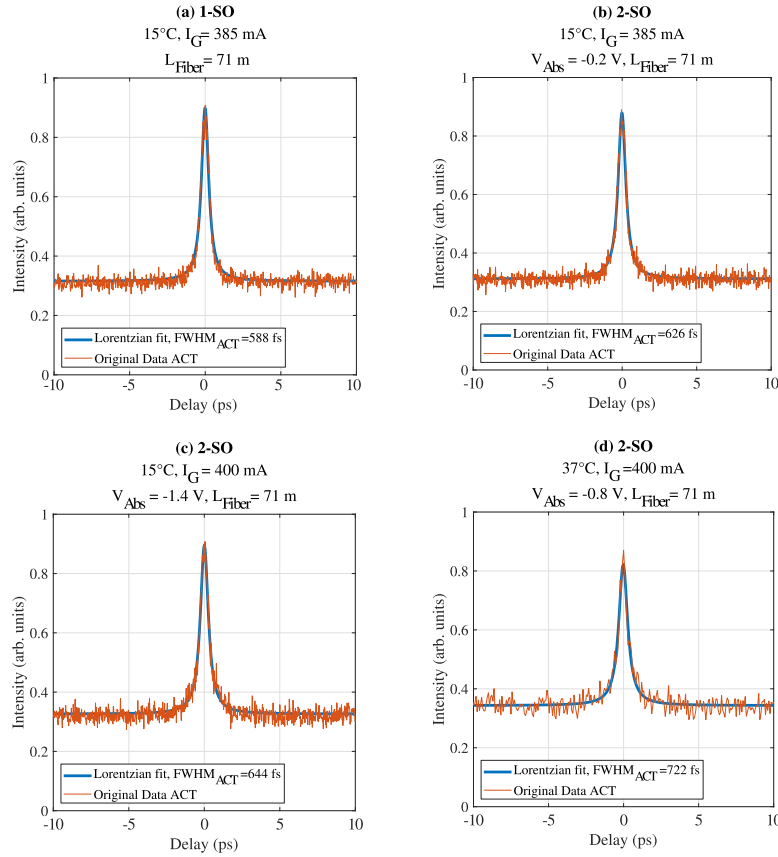


Fig. 8. Autocorrelation traces of QD MLLD, all measured with a total fiber length of 71 m. (a) 1-SO, $T=15^\circ\text{C}$, $I_G = 385$ mA, (b) 2-SO, $T=15^\circ\text{C}$, $I_G = 385$ mA, $V_{\text{Abs}} = -0.2$ V, (c) 2-SO, $T=15^\circ\text{C}$, $I_G = 400$ mA, $V_{\text{Abs}} = -1.4$ V, (d) 2-SO, $T=37^\circ\text{C}$, $I_G = 400$ mA, $V_{\text{Abs}} = -0.8$ V

However, we are aware that the assumption of a Lorentzian pulse shape may result in an underestimate of the actual pulse width, as the real pulse shape remains unknown. For a more precise estimate, we also calculated the inverse fast Fourier transform (IFFT) of the optical spectrum to calculate a transform-limited pulse. In the next step, the autocorrelation of that pulse was calculated and compared with the measured autocorrelation trace. Since the calculated and measured autocorrelation trace showed a high degree of agreement, we concluded that the pulse compression was almost ideal and that the correct fiber length was chosen for chirp compensation. Those calculations result in pulse widths ranging from 338 fs (Fig. 8(a)) to 487 fs (Fig. 8(d)). Fig. 9 shows the FWHM_{ACT} as a function of L_{Fiber} . Here, temperature, I_G and V_{Abs} were kept constant for each of the four measured operation points, only L_{Fiber} within the setup was varied. Starting with 55 m, L_{Fiber} was increased incrementally by 5 m, until 85 m was reached. At every fiber length, the ACT was measured and its FWHM_{ACT} was calculated by applying a Lorentzian fit, as it was equally done for the results showed in Fig. 8. For all four operating points, a broadening of the ACTs was observed when applying fiber lengths above and below 71 m. This makes $L_{\text{Fiber}} = 71$ m the optimal length for pulse compression since we obtained the shortest FWHM_{ACT}. The similarity of the behavior, in particular of 1-SO compared to the three different V_{Abs} applied in 2-SO stresses the conclusion that all four operating points of the laser

are subject to the same mode-locking process, namely SML. Although the absorber works in principle and can be controlled electrically, as Fig. 2 shows, the applied V_{Abs} is negligible for the pulse generation process. Rather, pulses solely form due to SML processes, which are hardly affected by V_{Abs} , even by higher absorber voltages.

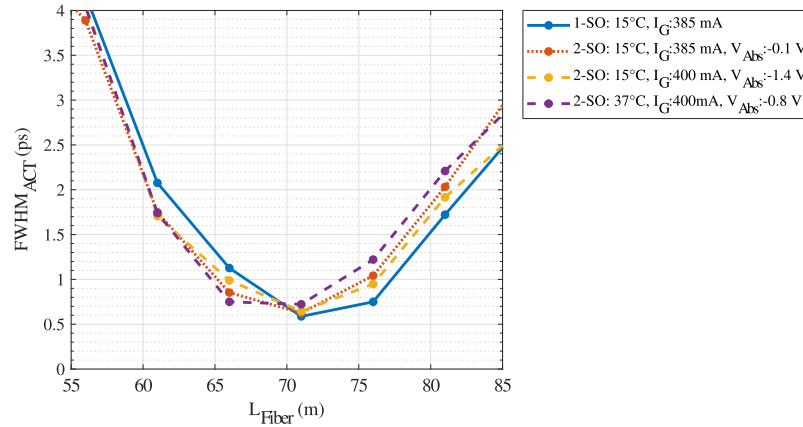


Fig. 9. FWHM values of the autocorrelation traces as a function of fiber length in 1-SO and at at four different measurement points in 2-SO mode.

4. Conclusion

The evaluation of the QD MLLD measurements consistently shows that the behavior of the QD MLLD does not change significantly between 1-SO and 2-SO mode, regardless of the applied V_{Abs} . This indicates that exclusively SML is present with no PML processes involved at all: In 1-SO and 2-SO mode, the optical spectra preserve their shape and properties and also the RF spectra show comparable behavior. The pulse width is smallest in 1-SO mode. However, the pulses maintain the same properties across the measured values of V_{Abs} , in particular an identical fiber length required for dispersion compensation of $L_{\text{Fiber}} = 71$ m.

This is a significant difference to the behavior of the QW MLLD, already analyzed in [23]. The QW MLLD reacted clearly at higher reverse absorber voltages, whereby the position of the change depends on I_G . At $I_G = 300$ mA, the change occurs between $V_{\text{Abs}} = -0.5$ V and $V_{\text{Abs}} = -0.6$ V. At low absorber voltages between 0 V and -0.5 V, ultrashort pulses could be detected which had the same characteristics as those in 1-SO, allowing the conclusion that these were generated by SML processes. For values at V_{Abs} between -0.6 V and -1.4 V, SML processes were disturbed and no sub ps pulses could be detected at all.

The tunability of f_{rep} in 1-SO mode demonstrates a clear difference between the two MLLDs: Both devices allow f_{rep} to change via temperature and I_G , but with opposing trends. The reason for this is currently unclear and requires further investigation through additional studies and simulations. With the QD MLLD, an increase in I_G leads to the formation of linear regimes, in which the repetition rate decreases as I_G increases. In contrast, for the QW MLLD, the repetition rate increases with increasing I_G . The maximum tunability in 1-SO mode is 47 MHz for the QD MLLD and 86 Mhz for the QW MLLDs.

In summary, it is not straightforward to say which laser has better properties or performs better. Both MLLDs are state-of-the-art devices that even improve their properties when connected in 1-SO mode compared to 2-SO mode. Both emit fs pulse trains, and are suitable for a wide range of applications. However, some of their properties differ: The QD MLLD has a better temperature

stability, while the QW MLLD's repetition frequency can be tuned over a significantly higher frequency range.

In addition, our results lead to a further conclusion: A PML setup, as here realized by 2-SO, does not automatically imply that PML is the process that generates ultrashort pulses. For both investigated MLLDs, pure SML, realized in a 1-SO setup, resulted in the shortest pulse duration and best operation. Within the QW MLLD, an applied V_{Abs} , even caused disturbed signals. This could also be valid for other MLLDs in the wavelength regime of $1.5\ \mu\text{m}$, if their material enables SML. Connecting such devices in a 1-SO setup may result in an improved signal and shorter pulse trains.

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