Theoretical and Experimental Investigation of Quantum Dot Passively Mode Locked Lasers for Telecomm and Biomedical Applications

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Abstract. This thesis is focused on the experimental and theoretical study of novel quantum dot passively mode locked lasers. The motivation behind this endeavour was the fundamental need, of many scientific areas, for high power, ultra-short and time stabilized optical pulses, generated directly from highly integrated laser devices. Such devices could allow the study of ultra-fast chemical and physical effects, or alternatively could provide telecomm engineers and medical practitioners with hand-held lasers suitable for a variety of applications. The first step consists of a detailed mathematical investigation of the mode-locking mechanism so as to depict clearly the fundamental limitations associated with ultra-fast high power generation. Through numerical modelling a novel semiconductor material (quantum-dots) is successfully introduced, whereas the benefits of such an approach are presented. The major part of this thesis consists of a detailed experimental investigation of various quantum-dot based mode-locked semiconductor structures. Through this investigation various new effects were demonstrated, that allowed a deeper insight to new regimes of operation. These regimes that namely consist of multi-wavelength emission and mode locking, pulse-width narrowing with increasing current injection, Q-switching stabilization and feedback-free chaotic operation, unlock new areas of applications, present new design guidelines for highly integrated semiconductor lasers. Finally, these regimes originate from the unique properties of the quantum-dot material and were firstly observed and investigated during this thesis. Consequently, this thesis played a major role in the future development of this scientific field and led to more than 15 publications in peer-reviewed journals 4 conference papers and a book chapter.

1 Introduction

The introduction of laser systems during the 1960s allowed the generation of highly spectrally and spatially coherent electromagnetic radiation with immense impact into traditional scientific fields, whereas it allowed a radical expansion of newly emerging

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fields like bio-imaging/surgery, ultra-fast physics and high bitrate optical communications. Optical pulse generation was a highly sought achievement that could further expand the application areas of lasers. Traditional laser structures hinder such attempts due to their very large size and the complicated biasing schemes. On the other hand the semiconductor counterparts offered excellent integrating capabilities but their operating performance were significant inferior. In order to address this issue many novel ideas have been put into practice elevating some of the fundamental limitations of semiconductor pulsed lasers. During the last years novel material like quantum dots (QD) have been introduced offering further improvement compared to conventional semiconductor approaches. In detail QD materials offer three-dimensional confinement of carriers that in turn allow ultra-fast recovery time, low-linewidth enhancement factor, low thermal sensitivity and high saturation gain [1].

In this thesis the major effort was focused on exploiting the inherent advantages offered by the QD materials, aiming through device design of new laser structures and through identification of new regimes of operation, to further expand the capabilities of QD-based mode locked lasers. In detail a detailed numerical model that takes into consideration the unique band-structure of the QD material was developed, whereas by incorporating time-delayed differential rate equations the full behavior of a passive mode locking QD laser was modeled. Through modeling all the basic parameters that affect pulse quality and power were identified, thus the experimental and design efforts were focused on these aspects.

The experimental investigation allowed new regimes of operation that consisted of: Simultaneous dual wavelength mode locking from the two basic QD energy bands (ground-excited state) allowing the creating of two independent train of pulses from different wavebands [2]. Using the same concept dual wavelength mode-locking has been achieved from the ground state allowing tunable repetition rate of pulses [3]. Moreover, the ground state splitting effect allowed the identification of a new regime of operation that provided shorter pulses with increasing injection current in the presence of dual ground state emission [4-5]. This effect is very significant for the design of QD-lasers due to the fact that it allows simultaneous increase of the average power and reduction of the pulse width, a trend that cannot be achieved by conventional devices. The low linewidth enhancement factor of QD materials provided stimulation for a detailed experimental identification of the feedback tolerance of QD mode-locked lasers from both wavebands [6-8]. This study provided useful information about the isolation requirements of each energy-state, whereas it confirmed the strong dependence of pulse stability to the precise length of the external cavity. The significant tolerance of QD-lasers to optical-instabilities induced by feedback setup provided another urge to study the stability of the lasers under asymmetric pumping conditions. In this case optical instabilities and chaotic emission was achieved only by asymmetric current injection in the absence of complicated feedback setups [9]. Although these findings revealed an unstable operating regime it can allow the expansion of QD-lasers to new areas of applications like chaotic cryptography. Moreover, through controlled feedback, Q-switching elimination and wavelength switching was achieved. This process can remove the amplitude modulation that imposes serious restrictions to certain medical modalities [10]. Finally, by designing and evaluating QD-lasers with different structural parameters like, cavity length and width, number of QD layers, manufacturing guidelines was extracted and the parameters that allow multi-wavelength emission were investigated [11] whereas novel tapered structures were designed and constructed that allowed record level peak power [12].

2 Experimental Setup

In order to perform the above-mentioned experiments different experimental setups were employed. Nonetheless, in all cases some basic components were used. The different laser modules were mounted on a custom made 3-axis manipulator equipped with a vacuum pump and a thermoelectric cooler in a closed control loop, that provided thermal and mechanical stabilization. Optical power from the device was collected through a tapered single mode optical fiber with high numerical aperture also positioned through an independent 3-axis manipulator. Basic measurements have been performed with the help of a RF-spectrum analyzer with electrical bandwidth of 30GHz. The optical spectrum was evaluated through an optical spectrum analyzer with minimum resolution of 0.1nm, optical power measurements were performed through a large area InGaAs photodiode, while the temporal properties of the pulses were evaluated with the help of a background free optical autocorrelator based on second harmonic generation with a minimum resolution of 10fs. In fig. 1 the most elaborate experimental setup is presented that was used in order to study the feedback tolerance of each waveband. It consists of the laser module, a polarization controller aiming to optimize laser-external cavity coupling, a fiber coupler (90/10), where the 10% branch fed an optical isolator and all the measuring components (RF-Optical analyzer and autocorrelator), while the 90% of the coupler was fed to the external cavity. This cavity consisted of a free space section with various neutral density filters in order to tune the amplitude of the back-reflected optical power and a variable delay line, whose aim was to fine tune the length of the cavity. All the other characterization experiments were performed with the same experimental setup but with the absence of the external cavity module.

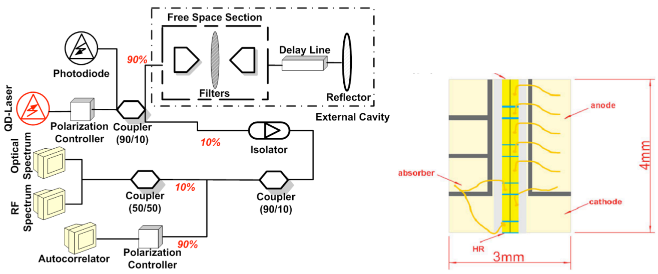

Fig.1. Fundamental experimental setup used to investigate feedback tolerance of each waveband of QD-mode locked lasers. Basic schematic of the laser structure.

The devices tested in this thesis consist of Fabry Perot laser structures that were grown by molecular beam epitaxy on a GaAs (100) substrate and contain self-assembled InAs/InGaAs QD Layers into 440 nm GaAs waveguide surrounded with $Al_{0.35}Ga_{0.65}As$ claddings. The back and front facets of the devices were high reflective coated (>99%)/low reflective coated (~10%), respectively, for the operating wavelength (1260 nm). Mode locking was achieved though reverse biasing part of the laser. The gain/absorption ratio is set to 85/15 for all devices under test. The length of the devices used in this paper varies from 2 mm to 4 mm, and the number of QD layers was 5, 10, and 15.

3 Results and discussion

A. Pulse Width Narrowing In the Presence of dual Ground-State Emission.

In this experiment, experimental results related to the existence of dual waveband emission from the GS from a multi-section QD mode locked laser are presented. In particular, we demonstrate that under specific bias conditions, GS splitting (GSS) occurs and in turn enables the narrowing of the generated pulses with increasing injection current. This observation leads to pulses of simultaneous increased peak and average power with respect to the usual device operation, which is a desired feature for biomedical applications.
The device under test is a multi-sectional QD laser, where the absorber is split into to two sections (0.3 mm each of them) and reverse biased, while the rest are forward biased. The laser structure contains five self-assembled InAs/InGaAs QD layers. The laser chip has a total length of 4 mm and contains stripes with 6μm width. In fig. 2 corresponding optical spectra for different bias conditions are presented that demonstrate the GS splitting effect.

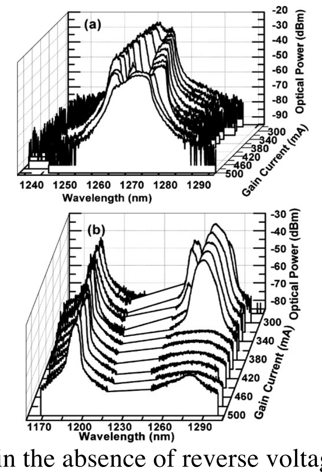

Fig.2. (a) Optical spectra in the absence of reverse voltage at the absorbing section and for various gain currents. (b) Optical spectra for V_{abs}=-7V.

This effect can be directly attributed to mode competition effects through the homogenous and inhomogeneous broadening. In particular, the splitting effect occurs in the GS when the injection current is high enough to enhance spectral hole burning

(SHB) at the center of the lasing spectrum. Carriers from these modes are reallocated through the inhomogeneous broadening to the outer modes, which initiate stimulated emission. The increase in the spectral separation of the two peaks with increasing current can be attributed to the fact that with increased modal gain a larger number of central modes are subject to SHB.

Pulse width evolution with the injection current is shown in Fig. 3. Although the pulse width is expected to increase monotonically with the current, in our case the opposite behavior is observed when double emission from the GS occurs.

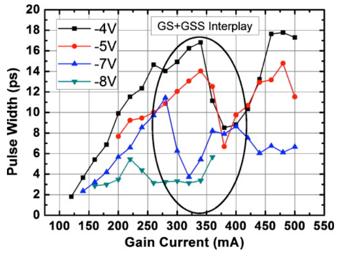

Fig.3. (a) Pulse width versus current injection for different reverse voltage at the absorbing section.

This temporal behavior of the emitted pulses was attributed to the fact that as injection current is increased thus more modes participate in the mode-locking mechanism. Although this effect theoretically can enhance mode locking in practice the larger number of modes tend to lock at different relative phases and consequently competition effects can destabilize mode locking. In our case the spectral splitting effect reduces the number of modes and thus reduces the competition effects. In particular this pulse-width reduction can lead to a significant increase in peak power.

B. Dual Ground-State Mode-Locking

Dual-wavelength mode-locked laser sources have been traditionally developed and investigated with other solid-state materials, most notably in Ti:Sapphire, fiber and most recently, ceramic lasers Research in this area has been motivated by the variety of applications for dual- and multiple-wavelength ultra-short pulses, such as time-domain spectroscopy, nonlinear optical frequency conversion and wavelength division multiplexing. In this context, the compactness, lower cost and direct electrical pumping associated with semiconductor lasers are very attractive features for reducing the footprint and complexity of the aforementioned applications, with the potential to also open up new avenues in ultrafast optical processing and optical interconnects.

By using the same device as described above but employing different bias conditions we tried to achieve simultaneous mode locking from the two independent sub-bands of the GS under splitting conditions. This regime of operation appeared when the reverse voltage at the absorbing section was kept below 3.5 V and the gain current was swept from the laser threshold up to 300 mA. The optical spectrum exhibited again two discrete GS sub-bands, while the RF spectrum had two discrete peaks centered around 10 GHz with separation in the order of 30 MHz. The two RF peaks correspond to two independent groups of modes that were phase locked. The slightly different repetition rate ($\Delta f \approx 30$ MHz) occurs due to the refractive index variation at each sub-band, which results to a slightly different effective cavity length. The absence of any side peaks in the RF spectrum apart from the two main peaks observed, imply that there is no amplitude modulation in the generated pulses (Q-switching) (fig.4).

Such monolithic lasers emitting mode locked pulses of two different GS sub-bands could be exploited for the realization of a low-cost terahertz pulsed source through beating in a photoconductor. Taking into account the spectral separation of the two sub-bands (2-14 nm), terahertz pulsed radiation in the (350 GHz-2.6 THz) band could be generated. Due to the different repetition rates of the optical pulses, the resulting terahertz radiation will be modulated by the difference $\Delta F_{rep} = F_{GS2}\text{-}F_{GS1}$, where F_{GS} are the repetition rates of the fundamental pulses.

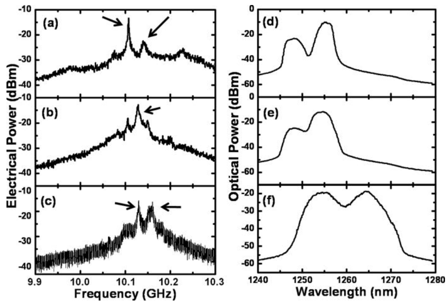

Fig.4. (a)-(c)RF spectra for increasing gain current and reverse voltage equal to -3.5V. (b) Corresponding optical spectra.

C. Dual Ground-Excited State Mode-Locking

In this case the structure used in the laser device was grown by molecular beam epitaxy on a GaAs substrate. The active region incorporated 5 layers of InAs QDs. A two-section QD laser diode was fabricated with a ridge waveguide 6μm wide, a total length of 2mm, while the saturable absorber was 300μm long, and was located near the back facet. The front and back facets were anti-reflection (~3%) and high-reflection (~95%) coated, respectively.

The dual-wavelength mode locking regime was obtained for current levels in the gain section between 330 and 430mA, and values of reverse bias between 6 and 10V in the saturable absorber section. A map depicting the different mode-locking regimes is represented in Fig. 5. It is noteworthy to point out that mode-locking involving solely the ES transition is observed both before and after the dual-wavelength mode-locking regime. Although these results present again simultaneous from transitions from different energy bands available in the QD materials it is worth mentioning that in this case mode-locking is not achieved though two discrete ground-sub-bands but from a different available transition (ES) thus the spectral separation of the two trains of pulses exceeds 80nm.

The exploitation of this mode-locked regime could enable a range of applications extending from time-domain spectroscopy, through to optical interconnects, wavelength-division multiplexing and ultrafast optical processing.

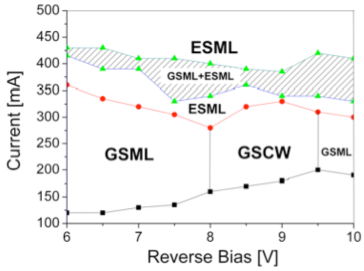

Fig.5. Mapping of the different operational regimes of a QD-passively mode locked laser versus current and reverse bias. The striped region corresponds to dual GS/ES mode locking.

D. Feedback Tolerance of QD Mode Locked Lasers and Chaotic Emission

The unique band-structure and carrier confinement of QD materials have triggered many attempts to study the line-width enhancement factor of such monolithic devices alongside their tolerance to feedback induce optical instabilities. During this thesis the first evaluation of pulse stability from both bands in the presence of optical feedback has been achieved. The experimental setup employed is described previously (fig.1). Two cases have been considered the first consists of single GS mode-locking while feedback effects were evaluated through calculation of the full-width at half maximum (FWHM) of the RF peak corresponding to the fundamental repetition rate. In fig. 6 the FWHM of the RF peak versus feedback strength is presented. It can be concluded that for feedback strength exceeding -34dB a radical increase in the FWHM is observed that corresponds to mode-locking deterioration, while for feedback larger than -25dB a complete coherence collapse is observed. On the other hand, if only ES mode-locking is present (higher gain current and reverse voltage) the system is more resilient to feedback instabilities and the increase of feedback strength even enhances the quality of mode locking by reducing the FWHM of the RF peak and consequently allow a more efficient phase locking of the longitudinal modes. Moreover as it has been shown numerically in the past for quantum well devices the exact external cavity length can play a dominant role in mode-locking stability and even further enhance mode locking if the external cavity round-trip is an integral integer of the intra-cavity round-trip.

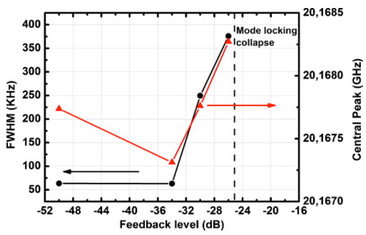

Fig.6. FWHM of the RF peak and the repetition rate for single GS mode locking.

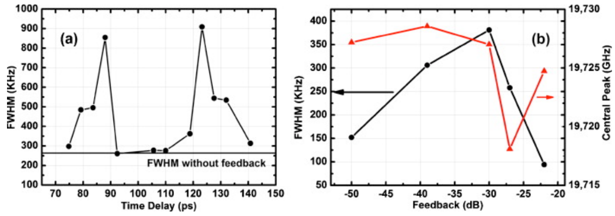

Fig.7. (a) FWHM for single ES mode locking versus cavity delay time. (b) FWHM and repetition rate versus feedback strength.

The main goal of the aforementioned approaches was to stabilize mode locking and investigate the isolation requirements for each waveband. On the other hand there are newly emerging applications that encourage coherence collapse and high spectral incoherence (multi GHz electrical bandwidth). Such applications like chaotic cryptography usually use controlled feedback related schemes that are quite complicated especially when high level of integration is required. In our case an alternative approach has been utilized in order to destabilize the laser. A two section monolithic laser was used where a different current density was employed at each section. The investigation revealed two regimes of operation. The first consisted of stable self-pulsations with low repetition rate. In this case the small section acted as an incomplete slow saturable absorber. The second regime manifest if the current was increased at both sections. In this case a significant increase in low frequency noise was observed with a 3dB bandwidth exhibiting 5GHz, whereas mathematical analysis of the collected experimental time-series revealed high complexity time-series with a correlation dimension exceeding 7. This operation regime originates from the different gain profiles of the two sections and the dynamic feedback induced due to the intra-cavity variations. Furthermore, this regime of operation allows the expansion of QD lasers into chaotic applications without the use of complicated feedback setups.

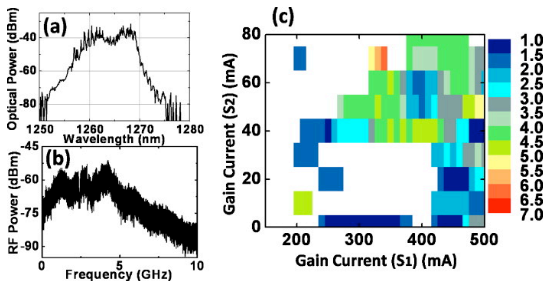

Fig.8. (a) Optical spectrum under coherence collapse (b) RF spectrum for the same regime (d) correlation dimension versus gain current of both sections exhibiting high complexity regimes.

E. Q-Switching Elimination and Wavelength Switching Through Controlled Feedback
In this part of the experimental investigation optical feedback was used in order to trigger wavelength switching. In particular through variation of parameters like feedback strength and external cavity length, wavelength switching under stable mode locked operation was achieved. One of the key benefits of this technique is the variation of the range that each regime of operation manifests (single GS/ES or dual wavelength emission), which in general is directly related only to the fabrication process. Furthermore through application of controlled level of optical feedback we were able to demonstrate stabilization of the ES mode locking and strong reduction of the pulse amplitude modulation effects (Q-switching), whereas significant reduction in device's current threshold was also recorded. In particular in fig. the RF spectrum for various level of optical feedback is presented. It can be clearly seen that by increasing the feedback strength the strong side-bands that imply amplitude modulation of the emitted pulses are strongly suppressed. The physical mechanism behind this effect is based on the fact that excess photons form the external cavity enhance stimulated emission and drive the laser beyond threshold, where the Q-switching effects tend to be dominant (fig.9).

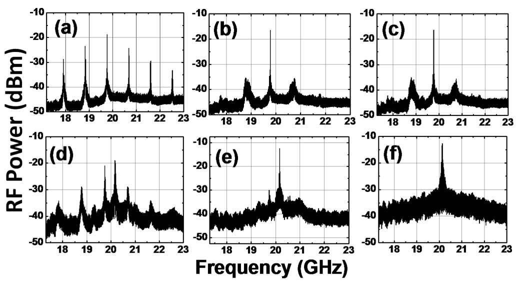

Fig. 9 RF spectra for the ES mode-locking of a 4mm QD device for various levels of controlled optical feedback.

F. Manufacturing Guidelines and Record Level Power Through Tapered Section QD-Mode Locked Lasers.

In order to exploit the advantages of QD-based pulsed sources, many efforts have focused on cavity optimization. These studies have focused on the effect of different fabrication related parameters like the number of QD layers and cavity length but were related to continuous wave (CW) operation. On the other hand, in the case of pulsed operation, most studies focused on the impact of the absorber/gain ratio to the mode locking performance. During this thesis we focus on the experimental identification of the impact of the number of QD layers on the quality of mode locking and the impact of excited state (ES) emission on the ground state (GS) mode locking was investigated for the first time.
In fig. 10 by comparing devices in terms of the number of QD layers independently of their length, a common behavior for all available lengths can be observed. The increase of number of layers from 5 to 10 induces an enhancement of the mode-locking performance in terms of pulse width, alongside an increase in the available range of bias conditions where mode locking is achievable. In particular, the dark grey regimes in the contour plots, which correspond to pulse widths smaller than 5ps,

are non-existent or difficult to achieve in the 5 QD layers (−7 V to −8 V and 100 mA to 200 mA), while the 10 layers devices exhibit a large range of bias conditions where such narrow pulses can be observed (−4 V to −8 V and 200 mA to 450 mA). It is of paramount importance to note that in the 5 QD layers case, the limited bias range that allows stable mode locking coincides with the early onset of ES lasing (high gain current). The increase of the QD Layers number from 10 to 15 does not result in a significant improvement of the pulse width, whereas in many cases, a degradation of system's performance can be observed (4 mm long devices).

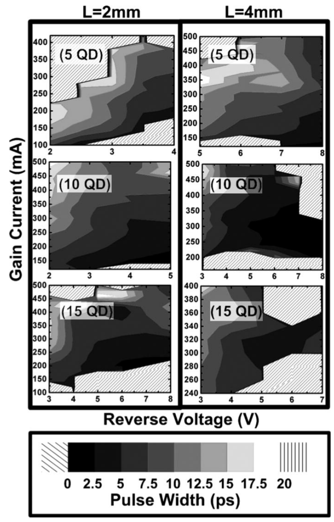

Fig.10. Contour plot of the pulse width versus gain current and reverse voltage for different laser structures.

In order to explain the experimental observed behavior, a standard mathematical formalism was employed that has been used in the past to evaluate the mode-locking performance of different QD laser structures. This approach treats mode locking from each state (GS-ES) as a simple net-gain modulation phasor with a time constant matching the characteristic round-trip of the cavity. Based on this approach, the formula predicted that a monotonical degradation of mode-locking quality should be observed by increasing the QD layers, due to the fact that differential gain increases dramatically for 5 QD layers, whereas remains almost constant for 10 and 15 QD layers devices. Although, these results confirm the experimental behavior of 10 to 15 QD layers, surprisingly in the case of 5 to 10 QD layers, the results are contradictory.

This discrepancy can be attributed to the fact that ES emission is present in the 5 QD layers devices due to early saturation of the GS and due to the absence of any additional frequency selection mechanism in the laser cavity that could suppress lasing from either band.

Finally by employing a tapered structure instead of the conventional rectangular structure gain saturation effects were suppressed due to increased waveguide width. Consequently, a significant gain elevation is observed that allowed sub-pico second pulses due to reduced self-phase modulation effects (fig.11) and a peak power of

7.5W directly from a monolithically integrated tapered mode-locked laser. Last but not least after the end of this thesis the tapered designs that were proposed were utilized for both laser and semiconductor optical amplifiers and the final peak power achieved after two stage amplifications reached the record level of 34W.

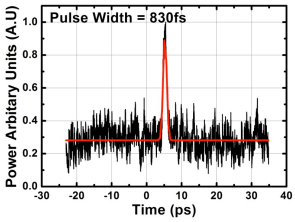

Fig.11. Autocorrelation trace for a two section tapered passively mode locked QD laser.

5 Conclusions

The results reported in this thesis have provided a deeper insight in the mechanism of passive mode locking in quantum dot lasers, whereas it revealed through experimental investigation new regimes of operations. These regimes consist of ground state splitting and the corresponding ability to dual mode lock the two tunable sub-bands, whereas by exploiting the same splitting effect a significant pulse width reduction was observed with simultaneous increase in the gain current and the emitted average power. Moreover, by exploiting the multi-wavelength capabilities of quantum dot devices, novel simultaneous dual wavelength mode-locking from the two main wavebands was achieved directly from a monolithic device.

Furthermore, an experimental evaluation of the feedback tolerance of both main energy-bands under pulsed operation was also performed for the first time, allowing the extraction of isolation requirements for pulses of each wavelength. This effort confirmed the low linewidth enhancement factor observed at the excited state alongside the strong dependence of pulse stability with the exact roundtrip of the external cavity. In the same context an alternative approach utilized in order to destabilize the laser operation was the utilization of inhomogeneous pumping in a two-section quantum dot Fabry Perot laser. This approach allowed coherence collapse and the generation of high complexity time series directly through the device without feedback related complicated setups. The beneficial role of feedback was also demonstrated by exploiting these dynamics in order to suppress Q-switching effects and allow wavelength switching. Finally, throughout this thesis several devices were designed and characterized. Through this process the impact of structural parameters like device length, width and number of quantum dot lasers on the quality of the pulsed operations were extracted, allowing clear guidelines for future devices. Last but not least through cavity optimization record level pulse widths and peak power were achieved that consist of 7.5W peak power directly from a tapered gain guided passively mode locked laser, and 34W through a two stage amplification process that employed tapered laser and semiconductor optical amplifier.

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