41

Mode-Locked
Quantum-Dot Lasers

41.1 Introduction

Over the last three decades, laser physics has advanced dramatically. Starting from lasers operated in a continuous wave (cw) regime, scientists have developed techniques for generating periodic sequences of optical pulses with ultrashort durations—between a few picoseconds ($1 \times 10^{-12}$ s) and a few femtoseconds ($1 \times 10^{-15}$ s). To put this into perspective, 1 fs is the same as 1 s compared to 32 million years! Such ultrafast lasers have important applications in medicine, micromachining, optical communications, spectroscopy, and anything else that requires studying physics at extremely high powers or extremely short timescales. For instance, these lasers have been successfully adapted in eye surgery, because ultrashort pulses can make extremely precise cuts with minimum thermal damage.

However, despite the wide range of important areas that can benefit from ultrafast lasers, the use of these lasers is constrained due to several limitations. The ultrafast lasers currently available are often bulky, expensive, and difficult to operate. The ideal ultrafast laser would be a low-cost, handheld, and turnkey laser—features which could be offered by semiconductor lasers. Semiconductor lasers cannot yet directly generate the sub-100 fs pulses routinely available from crystal-based lasers, but they represent the most compact and efficient sources of picosecond and sub-picosecond pulses. Furthermore, the bias can be easily adjusted to determine the pulse duration and the optical power, thus offering, to some extent, electrical control of the characteristics of the output pulses. These lasers also offer the best option for the generation of high-repetition rate trains of pulses, owing to their small cavity size. Ultrafast diode lasers have thus been favored over other laser sources for high-frequency applications such as optical data/telecommunications. Being much cheaper to fabricate and operate, ultrafast semiconductor lasers also offer the potential for dramatic cost savings in a number of applications that traditionally use solid-state lasers. The deployment of high-performance ultrafast diode lasers would therefore have a significant economic impact, by enabling ultrafast applications to become more profitable, and even facilitate the emergence of new applications.

Novel nanomaterials such as quantum dots (QDs) have enhanced the characteristics of semiconductor lasers, greatly improving their performance. QDs are tiny clusters of semiconductor material with dimensions of only a few nanometers. At these small sizes, materials behave very differently, giving QDs distinctive physical properties of quantum nature—for instance, the emission wavelength or “color” depends on the size of the dot! These nanomaterials afford major advantages in ultrafast science and technology, and they can form the basis for very
compact and efficient lasers delivering short pulses of the order of hundreds of femtoseconds (Rafailov et al., 2007).

In this chapter, we show how QDs have enabled the generation of ultrashort pulses from compact optical sources based on semiconductor laser diodes. In Section 41.2, the necessary background information is presented on ultra-short-pulse generation from diode lasers. The concept of mode locking is introduced, and an overview of the mode-locking techniques available for semiconductor lasers is provided. The unique properties of QD materials and their suitability for ultra-short-pulse diode lasers are explained in Section 41.3. Finally, a summary of the state of the art in the field of QD mode-locked laser diodes is provided in Section 41.4. The chapter is finalized by a summary and an outlook on the future perspectives of this fascinating field.

41.2 Ultrafast Laser Diodes

41.2.1 Basics of Mode Locking

Mode locking is a technique that involves the locking of the phases of the longitudinal modes in a laser. This results in the generation of a sequence of pulses with a repetition rate corresponding to the cavity round-trip time. This well-established technique enables the production of the shortest pulse durations and the highest repetition rates available from ultrafast lasers, whether they are semiconductor or crystal-based laser systems. In a standing-wave resonator, the pulse repetition rate \( f_s \) is given by

\[
f_s = \frac{c}{2nL}
\]

where
- \( c \) is the speed of light in vacuum
- \( n \) is the refractive index
- \( L \) is the length of the laser cavity

In terms of Fourier analysis, there is an inverse proportionality between the duration of a mode-locked pulse and the corresponding bandwidth of its optical spectrum. The product of both the pulse duration \( \Delta \tau \) and the optical frequency bandwidth \( \Delta \nu \) is called the time-bandwidth product (TBWP). For a given frequency bandwidth, there is a minimum corresponding pulse duration—if this is the case and the optical spectrum is symmetrical, then the pulse is said to be transform-limited, and the TBWP equals a constant \( K \), whose value depends on the shape of the pulse, whether it is Gaussian, hyperbolic, secant, squared, or Lorentzian. By measuring the full-width at half maximum from an optical spectrum \( \Delta \lambda \), it is easy to calculate the TBWP of a given pulse:

\[
\Delta \nu \cdot \Delta \tau = K \Rightarrow \frac{c}{K} \Delta \lambda \cdot \Delta \tau = K
\]

Another important property of mode-locked lasers is that the energy that was dispersed in several modes while in cw operation, is now concentrated in short pulses of light. This implies that although the output average power \( P_{av} \) may be low, the pulse peak power \( P_{peak} \) can be significantly higher:

\[
P_{peak} = \frac{E_p}{\Delta \tau} \Rightarrow \frac{P_{peak}}{f_s} = \frac{1}{K} \frac{E_p}{P_{av}}
\]

where \( E_p \) is the pulse energy.

41.2.2 Mode-Locking Techniques in Semiconductor Lasers

In recent years, mode-locked laser diodes have been at the center of a quest for ultrafast, transform-limited, and high-repetition-rate lasers. To achieve these goals, a variety of mode-locking techniques and semiconductor device structures have been demonstrated and optimized (Vasil’ev, 1995). The three main forms of mode locking can be described as active, passive, and hybrid techniques, as outlined below.

Active mode locking relies on the direct modulation of the gain with a frequency equal to the repetition frequency of the cavity, or to a sub-harmonic of this frequency. The main advantages of this approach are the resultant low jitter and the ability to synchronize the laser output with the modulating electrical signal. These features are especially relevant for optical transmission and signal-processing applications. However, high repetition frequencies are not readily obtained through directly driven modulation of lasers because fast RF (radiofrequency) modulation of the drive current becomes progressively more difficult with increase in frequency.

The frequency limitation imposed by electronic drive circuits can be overcome by employing passive mode-locking techniques. This scheme typically utilizes a saturable absorbing region in the laser diode. In a saturable absorber, the loss decreases as the optical intensity increases. This feature acts as a discriminator between cw and pulsed operation and can facilitate a self-starting mechanism for mode locking. Most importantly, saturable absorption plays a crucial role in shortening the duration of the circulating pulses, as will be explained, thus providing the shortest pulses achievable by all three techniques and the absence of a RF source simplifies the fabrication and operation considerably. Passive mode locking also allows for higher pulse repetition rates that are determined solely by the cavity length.

Inspired by active and passive mode locking, the technique of hybrid mode locking meets the best of both worlds because the pulse generation is initiated by an RF current imposed in the gain or absorber section, while further shaping and shortening is assisted by saturable absorption. The next section explores in more detail the physical mechanisms behind passive mode locking.*

* From this point, mode locking will implicitly mean passive mode locking, unless otherwise stated.
41.2.3 Passive Mode Locking: Physics and Devices

So far, a simple frequency-domain picture for mode locking has been provided, where the relative phases are of primary relevance. A physical model for passive mode locking can alternatively and equivalently be described in terms of the temporal broadening and narrowing mechanisms.

Upon startup of laser emission, the laser modes initially oscillate with relative phases that are random such that the radiation pattern consists of noise bursts. If one of these bursts is energetic enough to provide a fluence that matches the saturation fluence of the absorber, it will bleach the absorption. This means that around the peak of the burst where the intensity is higher, the loss will be smaller, while the low-intensity wings become more attenuated. The pulse generation process is thus initiated by this family of intensity spikes that experience lower losses within the absorber carrier lifetime.

The dynamics of absorption and gain play a crucial role in pulse shaping. In steady state, the unsaturated losses are higher than the gain. When the leading edge of the pulse reaches the absorber, the loss saturates more quickly than the gain, which results in a net gain window, as depicted in Figure 41.1. The absorber then recovers from this state of saturation to the initial state of high loss, thus attenuating the trailing edge of the pulse. It is thus easy to understand why the saturation fluence and the recovery time of the absorber are of primary importance in the formation of mode-locked pulses.

This temporal scenario can be connected to the previously described frequency domain description of mode locking. The burst of noise is the result of an instantaneous phase locking occurring among a number of modes. The self-saturation at the saturable absorber then helps to sustain and strengthen this favorable combination, by discriminating against the lower power cw noise.

In practical terms, a saturable absorber can be integrated monolithically into a semiconductor laser, by electrically isolating one section of the device (Figure 41.2). By applying a reverse bias to this section, the carriers that are photogenerated by the pulses can be more efficiently swept out of the absorber, thus enabling the saturable absorber to recover more quickly to its initial state of high loss. An increase in the reverse bias serves to decrease the absorber recovery time, and this will have the effect of further shortening the pulses.

41.2.4 Requirements for Successful Passive Mode Locking

Ultrafast carrier dynamics are fundamental for successful mode locking in semiconductor lasers, particularly in the saturable absorber, because the absorption should saturate faster and recover faster. Indeed, the absorption recovery time is one of the determining factors for obtaining ultrashort pulses. In particular, for high-repetition-rate lasers, the absorber recovery time should be much shorter than the cavity period so that the absorber can return to a state of total attenuation prior to the incidence of each incoming pulse. The fast absorption recovery also prevents the appearance of satellite pulses within the window of the net gain. On the other hand, the gain recovery time should be shorter than the cavity round-trip time. Thus, for lasers operating at pulse repetition rates of 20 GHz or more, this means that the recovery times of both gain and absorption should be much shorter than 40 ps.

The saturation dynamics represents another crucial aspect for successful mode locking, as shown schematically in Figure 41.3. Such dynamics can be translated in terms of saturation fluence $F_{\text{sat}}$ or saturation energy $E_{\text{sat}} = A \cdot F_{\text{sat}}$, where $A$ is the optical mode cross-sectional area. The saturation energy is an indication of how much energy is necessary to saturate the absorption or the gain. Indeed, to achieve robust mode locking, the saturation

**FIGURE 41.1** A schematic diagram of the main components that forms a two-section laser diode (top). Loss and gain dynamics that lead to pulse generation (bottom).

**FIGURE 41.2** A schematic of a two-section semiconductor laser diode.
the absorber $E^a_{\text{sat}}$ should be as small as possible and smaller than the saturation energy of the gain $E^g_{\text{sat}}$:

$$E^a_{\text{sat}} = \frac{hvA}{\partial a/\partial N} < E^g_{\text{sat}} = \frac{hvA}{\partial g/\partial N}$$

where
- $h$ is Planck’s constant
- $v$ is the optical frequency
- $\partial a/\partial N$ and $\partial g/\partial N$ are the differential loss and gain, respectively

The special dependence of the loss/gain with carrier density in a semiconductor laser allows $\partial a/\partial N > \partial g/\partial N$, as shown in Figure 41.3.

This condition implies that the absorber will saturate faster than the gain for a given pulse fluence, thus enabling the creation of the net gain window as already mentioned. The ratio between saturation energies should also be as large as possible to ensure that the losses saturate more strongly than the gain.

### 41.2.5 Self-Phase Modulation and Dispersion

In a semiconductor material, both the refractive index and gain (or loss) depend on the carrier density and are thus strongly coupled. As the pulse propagates in the gain section,* the carrier density and thus the gain is depleted across the pulse, as the carriers recombine through stimulated emission. This leads to a dynamic increase of the refractive index, which then introduces a phase modulation on the pulse, changing the instantaneous frequency across the pulse. This phenomenon is called self-phase modulation (SPM) and is one of the main nonlinear effects associated with pulse propagation in semiconductor media.

To understand the mechanism of SPM, consider the simple and illustrative example of a plane wave $E(t, x)$:

$$E(t, x) = E_0 \exp(i\Phi(t)) = E_0 \exp(i(\omega_0 t - kx))$$

where
- $\Phi(t)$ is the time-varying phase
- $k$ is the wave vector
- $\omega_0$ is the optical carrier frequency
- $c$ is the speed of light
- $n(t)$ is the time-varying refractive index

The instantaneous frequency is the time derivative of the phase and thus can be written as

$$\omega(t) = \frac{\partial}{\partial t} \Phi(t) = \frac{\omega_0}{c} \frac{\partial n(t)}{\partial t} x$$

From this expression, it is clear that if the refractive index varies with time, then the instantaneous frequency of the plane wave will vary relative to $\omega_0$ and in a manner proportional to the temporal derivative of the index. The time dependence of this instantaneous frequency is called the frequency chirp. An up-chirp (down-chirp) means that the frequency increases (decreases) with time. An example of a frequency up-chirped pulse is illustrated in Figure 41.4.

SPM is not dispersive in itself, but the pulse will not remain transform-limited when it propagates in a dispersive material such as the laser medium. The effect of dispersion manifests itself in the variation of refractive index for different wavelengths which means that different spectral components will travel at different speeds. For an up-chirped pulse, the frequency is higher in the trailing edge than in the leading edge. When the pulse propagates through a material exhibiting positive (normal) dispersion, the trailing edge of the pulse propagates more slowly than the leading edge of the pulse and so this results in a temporal broadening of the pulse.

In a monolithic two-section mode-locked semiconductor laser, where a saturable absorber and a gain section coexist, the resulting chirp is a balance between the effects caused by the absorber and the gain. In the gain section, a frequency up-chirp results, while the saturable absorber helps to further

* In the following discussion, reference is made mostly to gain to simplify the description. However, all this reasoning can be applied equally well to the absorber.

† Up-chirp is also known as blue-chirp or positive chirp.
shape the pulse by contributing with a negative chirp. With a suitable balance between both sections, the chirp can be close to zero thereby leading to transform-limited pulses. Unfortunately, this is the exception rather than the rule, because this usually only occurs for a limited set of bias conditions and/or for given ratios of absorber/gain lengths. Therefore, up-chirp prevails for passively mode-locked lasers, leading to significant pulse broadening as the pulse propagates. The combined effect of SPM and dispersion impose the strongest limitation in the achievable shortest duration of pulses from mode-locked semiconductor diode lasers.

The mechanism of SPM implies that in addition to the original frequency $\omega_0$, there are now more frequencies inside the pulse envelope. This richer spectral content is not necessarily unhelpful because it can provide bandwidth support for shorter pulses, if the chirp of a pulse can be removed by provision of a suitable dispersion-induced chirp of the opposite sign. For up-chirped pulses, a dispersion compensation setup can be configured such that a negative (anomalous) group velocity dispersion is able to slow down the leading edge of the pulse and speed the blueshifted trailing edge to such an extent that at a certain point both edges propagate simultaneously and the pulse is shorter.

To routinely generate pulses that are nearly transform-limited, an alternative could be found in the choice of a material that exhibits lower coupling between refractive index and gain, as described by linewidth enhancement factor (LEF), or $\alpha$-factor:

$$\alpha = -\frac{4\pi d\alpha/dN}{\lambda}$$

A higher $\alpha$-factor implies a more significant coupling between gain and refractive index changes with carrier concentration and thus the possibility for higher levels of SPM and frequency chirp.

## 41.3 Quantum Dots: Distinctive Advantages for Ultrafast Diode Lasers

### 41.3.1 The Role of Dimensionality in Semiconductor Lasers

The history of semiconductor laser materials has been punctuated by dramatic revolutions. Everything started with the proposal of p-n junction semiconductor lasers in 1961, followed by experimental realization on different semiconductor materials (Basov et al., 1961; Basov, 1964). However, the lasers fabricated at that time exhibited an extremely low efficiency due to high optical and electrical losses. In fact, until the mid-1960s, only bulk materials were used in semiconductor devices, which were functionalized by introducing a doping profile. At the time, pioneers like Alferov and Herbert Kroemer independently considered the hypothesis of building heterostructures, consisting of layers of different semiconductor materials (Alferov, 2001).

The classic heterostructure example consists of a lower bandgap layer surrounded by a higher bandgap semiconductor material. Such design results in electronic and optical confinement, because a higher bandgap semiconductor also exhibits a higher refractive index. The enhanced confinement improved notably the operational characteristics of laser diodes, in particular the threshold current density, which decreased by two orders of magnitude.

But another revolution was about to come when it was realized that the confinement of electrons in lower dimensional semiconductor structures translated into completely new optoelectronic properties, when compared to bulk semiconductors. And how small should this confinement be? In order to answer this question, let us recall the concept of the de Broglie wavelength of thermalized electrons, $\lambda_\theta$:

$$\lambda_\theta = \frac{h}{p} = \frac{h}{\sqrt{2m^*E}}$$

where

- $h$ is the Planck’s constant
- $p$ is the electron momentum
- $m^*$ is the electron effective mass
- $E$ is the energy

In the case of III–V compound semiconductors, $\lambda_\theta$ is typically of the order of tens of nanometers (Saleh and Teich, 1991). If one of the dimensions of a semiconductor is comparable or less than $\lambda_\theta$, the electrons will be strongly confined in one dimension, while moving freely in the remaining two dimensions—this is the case of a quantum well (QW). A quantum wire is a one-dimensional confined structure, while a QD is confined in all the three dimensions. QDs are thus tiny clusters of semiconductor material with dimensions of only a few nanometers, surrounded by a semiconductor matrix that has a higher bandgap.

The spatial confinement of the carriers in lower dimensional semiconductors leads to dramatically different energy–momentum relations in the directions of confinement, which results in completely new density of states, when compared to the bulk case, as depicted in Figure 41.5. As dimensionality decreases, the density of states is no longer continuous or quasi-continuous but becomes quantized. In the case of QDs, the charge carriers occupy only a restricted set of energy levels rather like the electrons in an atom, and for this reason, QDs are sometimes referred to as “artificial atoms.”

For a given energy range, the number of carriers necessary to fill out these states reduces substantially as the dimensionality decreases, which implies that it becomes easier to achieve transparency and inversion of population—with the resulting reduction of threshold current density. In fact, this reduction has been quite spectacular over the years, with sudden jumps whenever the dimensionality is decreased (Alferov, 2001).
41.3.2 Quantum Dots: Materials and Growth

The group of QD materials that has shown particular promise is based on III–V QDs epitaxially grown on a semiconductor substrate. For instance, InGaAs/InAs QDs on a GaAs substrate emit in the 1–1.3 \( \mu \)m wavelength range, which could be extended to 1.55 \( \mu \)m. Alternatively, InGaAs/InAs QDs can be grown on an InP substrate that covers emission in the 1.4–1.9 \( \mu \)m wavelength range (Ustinov et al., 2003).

The remarkable achievements in QD epitaxial growth have enabled the fabrication of QD lasers, amplifiers, and saturable absorbers offering excellent performance characteristics. To date, the most promising results have been achieved using the spontaneous formation of three-dimensional islands during strained layer epitaxial growth in a process known as the Stranski–Krastanow mechanism (Goldstein et al., 1985; Ustinov et al., 2003). In this process, when a film A is epitaxially grown over a substrate B, the initial growth occurs layer by layer, but beyond a certain critical thickness, three-dimensional islands start to form—the quantum dots. A continuous film lies underneath the dots, and is called the wetting layer. The most important condition in this technique is that the lattice constant of the deposited material is larger than the one of the substrate. This is the case of an InAs film (lattice constant of 6.06 Å) on a GaAs substrate (lattice constant of 5.64 Å), for example.

In spite of being an extremely complex process, the Stranski–Krastanow mode is now widely used in the self-assembly of QDs. An advantage of this technique is that films can be grown using the well-known techniques of molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), and therefore the science of QDs growth has benefited immensely from all the previous knowledge gained with this technology. These are also good news for commercialization, because manufacturers do not have to invest in new epitaxy equipment to fabricate these structures.

Due to the statistical fluctuations occurring during growth, there is a distribution in dot size, height, and composition but, at the moment, epitaxy techniques have evolved to such an extent that the amount of fluctuations can be reasonably controlled, and can be as small as a few percent.

If the dots are grown on a plane surface, their lateral positions will be random. An example of such structure is shown in Figure 41.6. In the self-assembly process, there is no standard way of arranging the dots in a planar ordered way, unless they are encouraged to grow at particular positions in a pre-patterned substrate.

At present, the densities of QDs lie typically between \( 10^9 \) cm\(^{-2} \) and \( 10^{11} \) cm\(^{-2} \). The sparse distribution of QDs results in a low value of optical gain. Thus, the levels of gain and optical confinement provided by a single layer of QDs may not be enough for the optimal performance of a laser. In order to circumvent this problem, QDs can also be grown in stacks, which allows an increase in the modal gain without increasing the internal optical mode loss (Smowton et al., 2001), where the various layers are usually separated by GaAs barriers. The GaAs separators are responsible for transmitting the tensile strain from layer to layer, inducing the formation of ordered arrays of QDs aligned on top of each other. Further optical confinement is enabled through the cladding of such arrays within layers of higher refractive index and bandgap energy, therefore forming a heterostructure.

![FIGURE 41.5](image)

**FIGURE 41.5** Schematic structures of bulk and low-dimensional semiconductors and corresponding density of states. The density of states in different confinement configurations: (a) bulk; (b) quantum well; (c) quantum wire; and (d) quantum dot.

![FIGURE 41.6](image)

**FIGURE 41.6** Photographs of an InGaAs quantum dots grown on GaAs substrate: (a) A TEM image of a single sheet of quantum dots. (b) A TEM image of a cross section of an 8-layer thick stack of quantum dots in GaAs layers.
41.3.3 Broad Gain Bandwidth

A QD laser was proposed in 1976 (Dingle and Henry, 1976) and the first theoretical treatment was published in 1982 (Arakawa and Sakaki, 1982). The main motivation was to conceive a design for a low-threshold, single-frequency, and temperature-insensitive laser, owing to the discrete nature of the density of states. In fact, practical devices exhibit the predicted outstandingly low thresholds (Kovsh et al., 2004; Liu et al., 2005), but the spectral bandwidths of such lasers are significantly broader than those of conventional QW lasers (Rafailov et al., 2007). This results from the self-organized growth of QDs, leading to a Gaussian distribution of dot sizes, with a corresponding Gaussian distribution of emission frequencies. Additionally, lattice strain may vary across the wafer, thus further affecting the energy levels in the quantum dots. These effects lead to the inhomogeneous broadening of the gain—a useful phenomenon in the context of ultrafast applications, because a very wide bandwidth is available for the generation, propagation, and amplification of ultrashort pulses. The effects of inhomogeneous broadening on the density of states are schematically illustrated in Figure 41.7. However, it is important to stress that a highly inhomogeneously broadened gain also encompasses a number of disadvantages, because it partially defeats the purpose of a reduced dimensionality, by broadening the density of states. Indeed, the fluctuation in the size of the QDs has the effect of increasing the transparency current and reducing the modal and differential gain (Qasaimeh, 2003; Dery and Eisenstein, 2005). Therefore, much effort has been put into improving the dots uniformization by engineering the growth and post-growth processes (Ustinov et al., 2003).

The extremely broad bandwidth available in QD mode-locked lasers offers potential for generating sub-100 fs pulses provided all of the bandwidth can be engaged coherently and dispersion effects suitably minimized.

![FIGURE 41.7 Schematic morphology and density of states for charge carriers in (a) an ideal quantum-dot system and (b) a real quantum-dot system, where inhomogeneous broadening is illustrated.](image)

![FIGURE 41.8 Schematic of the energy levels in a QD material (a), and radiative transitions via GS—ground state (b) and ES—excited state (c). CB—Conduction band; VB—valence band.](image)

Indeed, it has been shown that there is usually some gain in narrowing/filtering effects in mode-locked QW lasers (Delfyett et al., 1998). With the inhomogeneously broadened gain bandwidth exhibited by QDs, there is support for more bandwidth and this can oppose the effect of pulse broadening that may arise from spectral narrowing. Additionally, due to the particular nature of QD lasers, many possibilities open up in respect of the exploitation of ground-state (GS) and excited-state (ES) bands,* as schematically represented in Figure 41.8. Such versatility has been successfully exploited in a multiple-wavelength-band switchable mode locking (Cataluna et al., 2006c). On the other hand, the interplay between GS and ES can be deployed in novel mode-locking regimes (Cataluna et al., 2006a). Using an external cavity, it is possible to set up tunable mode-locked sources that can operate in the wavelength range that extends from the GS to the ES transition bands (Kim et al., 2006a).

41.3.4 Ultrafast Carrier Dynamics

In the initial studies of QD materials, it was thought that their carrier dynamics would be significantly slower than those in QW materials due to a phonon bottleneck effect (Mukai et al., 1996). Interestingly, experiments have demonstrated quite the opposite. As a consequence of access to a number of recombination paths for the carriers, QD structures exhibit ultrafast recovery both under absorption and gain conditions (Borri et al., 2006). In two evaluations, the absorber dynamics of surface and waveguided QD structures were investigated by using a pump-probe technique (Borri et al., 2000; Rafailov et al., 2004b). This showed the existence of at least two distinct time constants for the recovery of the absorption. A fast recovery of around 1 ps is followed by a slower recovery process that extends over 100 ps (Rafailov et al., 2004b).

More recently, sub-picosecond carrier recovery was measured directly in a QD absorption modulator when a reverse bias was applied (Malins et al., 2006). Absorption recovery times ranged from 62 ps down to 700 fs and showed a decrease by nearly two orders of magnitude when the reverse bias applied to the structure was changed from 0 V to −10 V. This important observation provides significant promise for ultrafast modulators that can operate

* Ground and excited states are also available in quantum wells. However, the δ-like density of states associated with quantum dots enables an easier access to the ES, owing to the faster saturation of the GS in quantum dots.
above 1 THz and for the optimization of saturable absorbers used for the passive mode locking of semiconductor lasers at high repetition rates, where the absorption recovery should occur within the round-trip time of the cavity. Crucially, the shaping mechanism of the fast absorption recovery also enhances the shortening of the mode-locked pulses, and thus QD lasers have the potential for generating shorter pulses than their QW counterparts.

41.3.5 Low Absorption Saturation Fluence
QD-based saturable absorbers exhibit lower saturation fluence than QW-based materials due to their delta-like density of states. For example, in a QD one electron is enough to achieve transparency and two to achieve inversion. This characteristic facilitates the self-starting of mode locking at modest pulse energies. This feature is particularly important in high-repetition-rate lasers where the optical energy available in each pulse is small. Indeed, it has also been observed that the saturation power is at least 2–5 times smaller for a QD saturable absorber than for a QW-based counterpart when integrated in a monolithic mode-locked laser (Thompson et al., 2004a). In this paper, the authors pointed out that saturation would further depend on the density of dots, reverse bias, and inhomogeneous broadening.

41.3.6 Low Threshold Current and Low Temperature Sensitivity
As devices, QD diode lasers have the advantage of requiring a very low threshold current to initiate lasing (Ustinov et al., 2003). This attribute applies also to operation in the mode-locking regime, because most QD lasers exhibit mode-locked operation right from the threshold of laser emission. (Bistability between the non-lasing state and the onset of lasing/mode locking might be present, as has been shown experimentally (Huang et al., 2001; Thompson et al., 2006b) and numerically (Viktorov et al., 2006).) A low threshold current is clearly advantageous because this can represent a device that is compatible as an efficient and compact source of ultrashort pulses where the demand for electrical power can be very low. Furthermore, having a low threshold avoids the need for higher carrier densities for pumping the laser and this implies less amplified spontaneous emission and reduced optical noise in the generated pulse sequences.

Due to the discrete nature of their density of states, QD lasers also exhibit low-temperature sensitivity (Mikhrin et al., 2005), making them excellent candidates for applications where resilience to temperature effects is important.

41.3.7 Low Linewidth Enhancement Factor
One of the main motivations for the enthusiastic investigation of QD materials in the last few years has been the theoretically predicted potential for very low values of LEF, owing to the symmetry of the gain associated with QD structures. The possibility of a low LEF is very attractive for a number of performance aspects, such as lower frequency chirp in directly modulated lasers, lower sensitivity to optical feedback effects, and suppressed beam filamentation. The potential of a lower effect of SPM in QD lasers also held a promise for the generation of transform-limited pulses. However, disparate reports have been published in the last 3 years, with some reports of LEF values of nearly zero (Newell et al., 1999), and others with values of LEF similar (Ukhanov et al., 2004) or significantly higher than in QW structures (Dagens et al., 2005). Ultimately, the LEF is a characteristic that is highly dependent on the operation conditions of the laser, and as such, its meaning always needs to be contextualized for a set of particular conditions. This is a topic that is currently under intense investigation.

41.4 Mode-Locked Quantum-Dot Lasers: State of the Art

41.4.1 Pulse Duration
The first demonstration of a QD mode-locked laser was reported in 2001, with pulse durations of ~17 ps at 1.3 μm and repetition rate of 7.4 GHz, using passive mode locking (Huang et al., 2001). Hybrid mode locking at the same wavelength was demonstrated in 2003 by the Cambridge University group (Thompson et al., 2003); they reported an upper limit estimation of 14.2 ps for the shortest pulses measured at a repetition rate of 10 GHz. Later in 2004, the same group demonstrated Fourier-transform-limited 10 ps pulses at 18 GHz repetition rate, using passive mode locking (Thompson et al., 2004b).

In 2004, we demonstrated the generation of sub-picosecond pulses directly from a QD laser where the shortest pulse durations were measured to be 390 fs, without any form of supplementary pulse compression (Rafailov et al., 2004a, 2005). These pulses were generated by a two-section passively mode-locked QD laser and this was the first time that sub-picosecond pulses were generated directly from such a monolithic laser.

The generation of sub-picosecond pulses was reported later by several groups (Laemmlin et al., 2006; Thompson et al., 2006b). In one of these reports (in 2006), Thompson and coworkers demonstrated the generation of pulses as short as 790 fs, by using a flared waveguide configuration in a two-section QD laser (Thompson et al., 2006b). Because the beam mode size in the saturable absorber section was much smaller than that in the gain section, the ratio of saturation fluences in the absorber and gain sections was increased. This enhanced the pulse formation mechanisms and allowed for better pulse shaping and shortening.

There has also been much effort in designing QD-based mode-locked sources that could be deployed in the 1.55 μm band (Legeard et al., 2007). Ultra-short-pulse generation has been achieved from single-section lasers based either on InAs QDs (Renaudier et al., 2005) or quantum dashes (Gosset et al., 2006) grown on an InP substrate. These authors have suggested that there are no fundamental differences between the QDs and dashes in the context of mode-locked laser sources.
41.4.2 Toward Higher Pulse Repetition Rates

To achieve higher repetition rates in mode-locked lasers, it is necessary to decrease the cavity length. This poses a significant challenge to QD lasers because of their lower gain and the operation in short cavities may shift the emission to the ES band (Markus et al., 2003). To avoid this problem, a higher number of QD layers should be deployed in the active region. Using this simple approach, the highest repetition rate directly generated from a passively mode-locked QD two-section laser was 80 GHz (Laemmlin et al., 2006), when a 15-layer structure was used. Another method to boost the repetition rate of mode-locked lasers is to use colliding pulse mode locking. This technique is similar to passive mode locking, but the saturable absorber region is placed at the precise center of the gain section. Two counter-propagating pulses from each outer gain section therefore meet in the saturable absorber region, bleaching it much more efficiently than if just one pulse was present. This process can also result in shorter and more stable pulses. Owing to the device geometry, mode locking is achieved at the second harmonic of the fundamental (round-trip) frequency, and the pulse repetition rate is doubled. A variation of colliding pulse mode locking is harmonic mode locking, where more than two pulses circulate in the cavity, the number being equal to the harmonic. Colliding-pulse mode-locking was first demonstrated for QD lasers in 2005 (Thompson et al., 2005), resulting in a modest repetition rate of 20 GHz. Harmonic mode locking has also been demonstrated with repetition rates of approximately 40, 80, 120, and 240 GHz (Rae et al., 2006).

41.4.3 Temperature Resilience of Mode-Locked QD Lasers

Due to their delta-function-like density of states, QDs offer great potential for designing temperature-resilient devices. If their high-speed performance is also proven to be resilient to temperature, QD lasers can become the next generation of sources for ultrafast optical telecoms and datacoms, because the constraint of using thermoelectric coolers can be avoided, thus decreasing cost and complexity. In this context, we have demonstrated stable passive mode-locked operation of a two-section QD laser over an extended temperature range (from 20°C to 80°C) at relatively high output average powers (Cataluna et al., 2006b).

Additionally, to meet the requirements for high-speed communications, it is important to investigate the temperature dependence of the pulse duration. For instance, in communication systems with transmission rates of 40 Gb/s or more, the temporal interval between pulses is less than 25 ps and so the duration of the optical pulses should be well below this value at any operating temperature. We have shown that the pulse duration and the spectral width decrease significantly as the temperature is increased up to 70°C (Cataluna et al., 2007). The combination of all these effects resulted in a sevenfold decrease of the time-bandwidth product (the pulses were still highly chirped due to the strong SPM and dispersion effects in the semiconductor material).

To account for the decrease in pulse duration with temperature, a model for mode locking in QD lasers was used. It was found that the pulse durations are determined principally by the escape rate of the carriers in the absorber section, which lead to a decrease of absorber recovery time with increasing temperature, thus inducing a decrease in the pulse durations. This has been verified recently using ultrafast spectroscopy to probe the absorber recovery time as a function of temperature (Malins et al., 2007).

41.4.4 Mode Locking Involving Excited-State Transitions

It has been observed that laser emission in QD lasers can access the transitions in GS, ES or both (Markus et al., 2003), as represented in Figure 41.8. Furthermore, sub-picosecond gain recovery has been demonstrated for both GS and ES transitions in electrically pumped QD amplifiers (Schneider et al., 2005). In this reported work, the LEF was shown to decrease significantly for wavelengths below the GS transition, even becoming negative at ES thereby implying a potential for chirp-free operation for the range of wavelengths involved. Laser emission in the ES is also characterized by a higher differential gain than GS, with associated benefits for ultrafast QD lasers. We have demonstrated an optical gain-switched QD laser, where pulses were generated from both GS and ES, and where the ES pulses were shorter than those generated by GS alone (Rafailov et al., 2006). The potential for shorter and chirp-free pulses from ES transitions motivated us to investigate the mode-locked operation of QD lasers in this band. We demonstrated, for the first time, passive mode locking via GS (1260 nm) or ES (1190 nm) in a QD laser, at repetition frequencies of 21 and 20.5 GHz, respectively (Cataluna et al., 2006c). The switch between these two states in the mode-locking regime was easily achieved by changing the electrical biasing conditions, thus providing full control of the operating spectral band. It is important to stress that the average power in both operating modes was relatively high and exceeded 25 mW. In the range of bias conditions explored in this study, the shortest pulse duration measured for ES transitions was ~7 ps, where the spectral bandwidth was 5.5 nm, at an output power of 23 mW. These pulse durations are similar to those generated by GS mode locking at the same power level.

Although pulse durations from ES spectral band have been below expectations so far, it is our opinion that exploitation of the ES transitions—a unique feature of QD lasers—can lead to a new generation of high-speed sources, where mode locking involves electrically switchable GS or ES transitions that are spectrally distinct. This could enable a range of applications extending from time-domain spectroscopy, through to optical interconnects, wavelength-division multiplexing, and ultrafast optical processing.
41.5 Summary and Outlook

41.5.1 Critical Discussion

In this chapter, we have presented the physics and reported on the progress of ultrafast laser diodes based on QD materials. The results presented in the literature show that monolithic passively mode-locked QD lasers can currently surpass the performance of similar QW lasers in terms of pulse duration (Rafailov et al., 2005, Thompson et al., 2006b). There are other particular features where QD lasers have already been shown to have a superior performance, notably in the case of pulse timing jitter where record low values have been reported (Choi et al., 2006, Thompson et al., 2006a).

We strongly believe that the appeal of QD lasers also resides in the novel functionalities that are distinctive of QDs. These are the exploitation of an ES level as a means to achieve novel mode-locking regimes; the temperature resilience offered by the quantized density of states; lower threshold and higher output power levels; and access to the enlarged spectral bandwidths associated with the inhomogeneously broadened gain features. These characteristics are not only useful from an operational point of view, but also provide some insights into a more comprehensive understanding of the underlying physical mechanisms of mode locking in QD lasers.

41.5.2 Future Perspectives

Although there have been many advances in the control of the growth of QD laser having ultra-low threshold current and temperature resilience, it is not yet understood what is the most advantageous QD structure layout to be used in the regime of mode locking. In particular, it is not clear what is the optimum level of inhomogeneous broadening that results in shorter and higher peak power pulses. Therefore, it is relevant to investigate if and how the inhomogeneously broadened spectral modes are engaged coherently in the generation of ultrashort pulses and how that effect could be used to improve the performance of the lasers toward sub-picosecond pulse durations. Exploiting novel QD materials based on p-doped and tunnel injection structures could also bring advantages in minimizing the effect of any deleterious SPM effects in mode-locked lasers.

Comparison between theory and experiment of undoped and p-doped lasers has shown how this technique can improve the LEF (Kim and Chuang, 2006b). By tuning the level of doping, lasers can exhibit zero and even negative LEF at low current densities (Alexander et al., 2007). Tunnel injection QD structures can also be of great interest for use in mode-locked lasers, as the injection of cold carriers may bring many benefits to the operation of mode-locked lasers (Delfyett, 2006). The LEF has been recently calculated and has been demonstrated to be much less than that reported for other lasers (Mi and Bhattacharya, 2007). Selective excitation of population in these lasers has been demonstrated, which could lead to a mitigation of the inhomogeneous broadening effects and contribute to a narrower spectrum and the production of transform-limited pulses (Bret and Gires, 1964).

The ES spectral band can also be exploited in tunable lasers using QD materials where the inhomogeneous broadening is controlled so as to maximize the overlap between GSs and ESs. While in cw operation, QD lasers have been demonstrated with tunability ranges up to 200 nm (Varangis, 2000), by exploiting the gain available from the GSs and ESs. Combining this tunability with the possibility of generating ultrashort pulses, it will be possible to achieve a new generation of versatile lasers emitting pulses across a wide range of wavelengths—as if we had compressed many different lasers into a single laser! Such disruptive characteristics will offer endless possibilities and enable applications never seen before in science and technology.

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