MIXSELs - a new class of ultrafast semiconductor lasers

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MIXSELs – A NEW CLASS OF ULTRAFAST SEMICONDUCTOR LASERS

A dissertation submitted to

ETH ZURICH

for the degree of

DOCTOR OF SCIENCES

presented by

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December 2008
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# Symbols and Abbreviations

### Symbols

<table>
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<th>Description</th>
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<tr>
<td>$\alpha$</td>
<td>absorption coefficient [m$^{-1}$]</td>
</tr>
<tr>
<td>$\alpha_{\text{led}}$</td>
<td>linewidth enhancement factor</td>
</tr>
<tr>
<td>$\beta$</td>
<td>two-photon absorption coefficient [m·W$^{-1}$]</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>relative confinement factor or gain enhancement</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>coefficient of thermal conductivity [W·m$^{-1}$·K$^{-1}$]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength [m]</td>
</tr>
<tr>
<td>$\xi_{\text{abs}}$</td>
<td>relative field enhancement in absorber region</td>
</tr>
<tr>
<td>$\tau$</td>
<td>delay, recovery time [s]</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>pulse duration [s]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>heat flux [W·m$^{-2}$]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>optical frequency [rad·s$^{-1}$]</td>
</tr>
<tr>
<td>$A$</td>
<td>amplitude of the slow recovery component</td>
</tr>
<tr>
<td>$c_0$</td>
<td>speed of light in free space [m·s$^{-1}$]</td>
</tr>
<tr>
<td>$D$</td>
<td>group delay dispersion (GDD) [s$^2$]</td>
</tr>
<tr>
<td>$d$</td>
<td>layer thickness [m]</td>
</tr>
<tr>
<td>$E$</td>
<td>normalized (complex) electric field amplitude</td>
</tr>
<tr>
<td>$E_t$</td>
<td>time varying electrical field [V·m$^{-1}$]</td>
</tr>
<tr>
<td>$E$</td>
<td>energy [J]</td>
</tr>
<tr>
<td>$E_p$</td>
<td>pulse energy [J]</td>
</tr>
<tr>
<td>$f_{\text{rep}}$</td>
<td>repetition rate [Hz]</td>
</tr>
<tr>
<td>$F$</td>
<td>fluence [J·m$^{-2}$]</td>
</tr>
<tr>
<td>$F_2$</td>
<td>induced absorption coefficient [J·m$^{-2}$]</td>
</tr>
<tr>
<td>$F_p$</td>
<td>pulse fluence [J·m$^{-2}$], defined as $E_p/(\pi w^2)$</td>
</tr>
<tr>
<td>$F_{\text{sat}}$</td>
<td>saturation fluence [J·m$^{-2}$]</td>
</tr>
<tr>
<td>$g$</td>
<td>gain</td>
</tr>
<tr>
<td>$H$</td>
<td>normalized magnetic field</td>
</tr>
</tbody>
</table>
Symbols and Abbreviations

- \( i \)  imaginary unit
- \( I \)  intensity [W·m\(^{-2}\)]
- \( L \)  cavity length [m]
- \( M^2 \)  beam quality factor
- \( n \)  refractive index
- \( N \)  carrier density [m\(^{-3}\)]
- \( P \)  power [W]
- \( r \)  radius [m]
- \( r \)  (complex) amplitude reflectivity
- \( R(z) \)  radius of curvature of the wavefront [m]
- \( R \)  intensity reflectivity
- \( R_{\text{lin}} \)  linear reflectivity
- \( R_{\text{ns}} \)  non-saturable reflectivity
- \( \Delta R \)  modulation depth
- \( \Delta R_{\text{ns}} \)  non-saturable losses
- \( \Delta R_{\text{pp}}(t) \)  time dependent response
- \( T \)  temperature [K] or intensity transmission
- \( w(z) \)  1/e\(^2\)-intensity beam radius [m]
- \( w_p \)  1/e\(^2\)-intensity beam radius of the pump [m]
- \( z \)  position coordinate (in direction of beam) [m]
### Abbreviations

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<th>Description</th>
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<td>AFM</td>
<td>atomic force microscope</td>
</tr>
<tr>
<td>AOM</td>
<td>acousto-optic modulator</td>
</tr>
<tr>
<td>AR</td>
<td>antiresonant</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>DBR</td>
<td>distributed Bragg reflector</td>
</tr>
<tr>
<td>FCA</td>
<td>free-carrier absorption</td>
</tr>
<tr>
<td>FWHM</td>
<td>full-width half-maximum</td>
</tr>
<tr>
<td>GDD</td>
<td>group delay dispersion</td>
</tr>
<tr>
<td>GTI</td>
<td>Gires-Tournois interferometer</td>
</tr>
<tr>
<td>HR</td>
<td>high reflector</td>
</tr>
<tr>
<td>MBE</td>
<td>molecular beam epitaxy</td>
</tr>
<tr>
<td>MIXSEL</td>
<td>modelocked integrated external-cavity surface emitting laser</td>
</tr>
<tr>
<td>ML</td>
<td>monolayer</td>
</tr>
<tr>
<td>MOVPE</td>
<td>metalorganic vapour phase epitaxy</td>
</tr>
<tr>
<td>PBS</td>
<td>polarizing beam splitter</td>
</tr>
<tr>
<td>PECVD</td>
<td>plasma enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>PL</td>
<td>photoluminescence</td>
</tr>
<tr>
<td>QD</td>
<td>quantum dot</td>
</tr>
<tr>
<td>QW</td>
<td>quantum well</td>
</tr>
<tr>
<td>RIE</td>
<td>reactive ion etching</td>
</tr>
<tr>
<td>ROC</td>
<td>radius of curvature</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SESAM</td>
<td>semiconductor saturable absorber mirror</td>
</tr>
<tr>
<td>SPM</td>
<td>self-phase modulation</td>
</tr>
<tr>
<td>STEM</td>
<td>scanning transmission electron microscopy</td>
</tr>
<tr>
<td>TBP</td>
<td>time–bandwidth product</td>
</tr>
<tr>
<td>TEM</td>
<td>transverse electromagnetic mode</td>
</tr>
<tr>
<td>TPA</td>
<td>two-photon absorption</td>
</tr>
<tr>
<td>VCSEL</td>
<td>vertical-cavity surface-emitting laser</td>
</tr>
<tr>
<td>VECSEL</td>
<td>vertical external-cavity surface-emitting laser</td>
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Publications

Parts of this thesis are published in the following journal papers and conference proceedings.

Journal papers


Conference papers


Abstract

Picosecond and femtosecond laser oscillators have enabled many breakthroughs in both fundamental science and industrial applications. However, so far these ultrafast lasers have not achieved the impact of continuous-wave lasers, which are used in various everyday life applications such as compact disk players, optical communication links or laser printers. One reason for the low market penetration is the complexity and cost of these sources. Currently, there are no suitable ultrafast laser sources for industrial high volume applications such as the optical clocking of microprocessors at gigahertz frequencies. Compact and reliable ultrafast lasers have also large potential in areas as diverse as biology, medicine, or metrology, which currently rely on bulky and complex ultrafast lasers such as titanium sapphire oscillators. In contrast to these laser systems, semiconductor lasers are ideally suited for mass production and allow a high level of integration which results in compact and simple devices.

In this thesis, we developed a novel type of ultrafast semiconductor laser. Our approach is based on the integration of a vertical external cavity surface emitting laser (VECSEL) and a semiconductor saturable absorber mirror (SESAM) into a single semiconductor structure. We refer to this class of devices as modelocked integrated external-cavity surface emitting lasers (MIXSEL).

The optically pumped VECSEL has received widespread interest in the past few years due to its capability of producing high average output powers in a diffraction-limited beam. The laser beam propagates vertically (perpendicularly) through the epitaxial layers. The total thickness of the epitaxial layers is small compared to the beam diameter of the pump laser allowing for very efficient heat removal. This makes the device power-scalable, i.e. the output power can be scaled upwards by increasing the pumped area, while the temperature difference in the semiconductor structure remains unchanged. Continuous wave output powers of up to 20 W in a diffraction limited beam have been obtained. Pulsed operation is obtained by modelocking with a SESAM inside the cavity.

The quantum well (QW) SESAMs used previously have a saturation energy comparable to that of the gain structure itself. Simulations and experiments show
that stable modelocking is only obtained if the absorber saturates stronger than the
gain. This has been realized by designing a cavity mode with a very small spot size
on the SESAM compared to the gain structure. This unfortunately makes integration
impossible.

A key challenge of this work was the development of saturable absorbers with
saturation properties that enable modelocking with similar mode sizes in the gain
and absorber layers. Semiconductor saturable absorber mirrors using quantum dot
(QD) absorbers exhibit a larger freedom of design than standard QW absorbers. The
dot density as an additional parameter in combination with the field enhancement
allows for an independent control of saturation fluence and modulation depth. I
present the first detailed study on the influence of QD growth parameters and post
growth annealing on the macroscopic optical SESAM properties. The nonlinear
reflectivity and the recombination dynamics were evaluated for a large set of QD-
SESAMs. We experimentally demonstrated for the first time that the dot density
allows to precisely adjust the modulation depth at constant saturation fluence.
Moreover, we showed that post growth annealing can reduce the saturation fluence
to values below 10 μJ/cm². By modelocking a VECSEL with a QD-SESAM (i.e. using
a folded cavity) we obtained more than 100 mW of average power at 50 GHz pulse
repetition rate using the same spot size on gain structure and absorber.

Optimization of the QDs required precise optical SESAM characterization. We
developed a new method to perform wide dynamic range nonlinear reflectivity
measurements. The measurement of the reflectivity has a very high accuracy of better
than 0.05% for pulse energies over a dynamic range of more than four orders of
magnitude. Even with this high accuracy, the setup is straightforward and has lower
demands on the electronic equipment compared to previous methods.

Using optimized QD-layers, we demonstrated the first VECSEL with integrated
saturable absorber. Our first MIXSEL generates 40 mW of average output power in
32-ps pulses at a repetition rate of 2.8 GHz. Improved cooling has increased the
output power to 185 mW. Advanced heat management will result in optically-
pumped MIXSELS with multi-Watt average output powers similar to our previous
modelocked VECSEL results with an external SESAM.

The final step towards even more compact and inexpensive ultrafast
semiconductor lasers is electrical pumping. We developed design guidelines for
electrically pumped VECSELS and MIXSELS. The realization of such devices will fill
a gap in the performance spectrum of today’s laser technology.


Der VECSEL hat, aufgrund seiner Eigenschaft hohe durchschnittliche Ausgangsleistung in einem beugungslimitierten Strahl zu erzeugen, in den letzten Jahren stark an Bedeutung gewonnen. Da der Laserstrahl vertikal (senkrecht) in den epitaktischen Schichten propagiert, wird eine effiziente Wärmeabfuhr durch die dünne Schichtstruktur hindurch gewährleistet. Dies wiederum ermöglicht die
Skalierung der Ausgangsleistung des Bauteils, das heisst die Ausgangsleistung kann durch die Vergrösserung der gepumpten Fläche erhöht werden, während die Temperaturdifferenz im Halbleiter unverändert bleibt. Im Dauerstrichbetrieb wurde mit diesem Konzept in einem beugungslimitierten Strahl bisher eine Ausgangsleistung von 20 W erzeugt. Durch Modenkoppeln mit einem SESAM innerhalb des Resonators wird ein gepulster Betrieb erreicht.

Früher verwendete SESAMs mit Quantentopfabsorbern (quantum well, QW) haben eine Sättigungsenergie vergleichbar mit derjenigen der Verstärkerstruktur. Simulationen und Experimente zeigen allerdings, dass stabiles Modenkoppeln nur dann realisierbar ist, wenn der Absorber stärker sättigt als der Verstärker. Durch den Bau von Resonatoren mit sehr kleiner Modenfläche auf dem SESAM im Vergleich zum Verstärker kann dies zwar umgesetzt werden, Integration ist dadurch jedoch ausgeschlossen.

Eine QD Optimierung erfordert eine sehr genaue SESAM Charakterisierung. Zu diesem Zweck wurde ein neues Verfahren zur nichtlinearen Reflexionsmessung mit einem großen Dynamikbereich entwickelt. Dieses weist mit einer absoluten Abweichung kleiner als 0.05% eine hohe Genauigkeit für Pulsenergien über einen Dynamikbereich von mehr als vier Zehnerpotenzen auf. Trotz seiner hohen Genauigkeit ist der Messaufbau unkompliziert und stellt im Vergleich zu früheren Messmethoden geringere Ansprüche an die elektronische Ausrüstung.


Die letzte Stufe hin zu kleineren und kostengünstigeren Kurzzeit-Halbleiterlasern ist das elektrische Pumpen. Es wurden bereits Richtlinien für den Entwurf von elektrisch gepumpten VECSELn und MIXSELn entwickelt, deren Umsetzung eine Lücke im Spektrum der heutigen Lasertechnologie schliessen wird.
Chapter 1

Introduction

A major breakthrough in optics was the first demonstration of coherent light emission from a Gallium Arsenide junction, the first laser diode, in 1962 [1]. One year later, H. Kroemer proposed the concept of the double-heterostructure laser, which formed the basis for the first continuous wave laser operated at room temperature [2]. Semiconductor lasers are ideally suited for mass production and widespread applications, because they are based on a wafer-scale technology, which allows a high level of integration. Not surprisingly, the first lasers entering virtually every household were semiconductor lasers in compact disk players. The semiconductor laser became a key component of many high volume products.

Today, lasers generating short pulses – referred to as ultrafast lasers – enable many applications in science and technology. Numerous laboratory experiments have confirmed that ultrafast lasers can significantly improve existing applications, for example increase telecommunication data rates [3], improve computer interconnects [4], and optically clock microprocessors [5-7]. There are also numerous new applications that only work with short pulses in areas as diverse as metrology [8], supercontinuum generation [9], and life sciences [10]. Currently, most of these applications rely on bulky and complex ultrafast solid-state lasers like titanium-sapphire based systems.

A highly promising application area for ultrafast semiconductor lasers are the optical interconnects in computers. Optical links have better data transmission capabilities than electrical systems, which made them the standard for long haul networks. Today, optical links are already being used for rack to rack connections...
having a distance range of 1-100 m. With Moore’s law saying that the number of transistors on an integrated circuit is increasing exponentially, doubling approximately every two years, the required bandwidth also increases exponentially. The electrical interconnects used now, have limited scaling properties, for example the communication of the processor with other parts in a computer (e.g. memory or graphics processing unit) takes place at a lower speed than the clock rate. Optical interconnects are very promising to take over this short distance communication. High speed optical connections have been demonstrated achieving 30 Gbit per second by direct modulation of a continuous wave laser [11]. With the combination of multiple lasers, more than 1 Tbit per second have been demonstrated. The next step is the use of the pulses from a modelocked laser, rather than shaping the pulses with a modulator. The short pulse durations, high peak power, wide spectral bandwidth, and low timing jitter lead to simplified synchronization and improved receiver sensitivity [12].

Clock distribution can also profit from pulsed laser sources. In an integrated circuit a clock signal is needed to synchronize the logic. The important parameters are skew, jitter and power. A large skew means a large time difference between the arrivals of clock pulses on different locations on the chip, while jitter is a measure for the variation of the pulse to pulse time. While for transistors the performance improves with scaling down the size, the copper clock interconnects have an increased delay for smaller wire cross-sections. An interconnect bottleneck is expected in the near future if scaling proceeds as planned. The main advantages brought by optics is a reduction of skew and jitter, lower sensitivity to temperature variations and less power consumption [4, 5]. A powerful modelocked laser would be an ideal source for optical clocking and enable further performance improvement of current microprocessors.

Another important application area is that of nonlinear frequency conversion, which allows to cover the whole visible spectral region with an infrared laser source. This is attractive for commercially important areas such as RGB laser projection. The laser projectors provide the broadest color gamuts available today. Ultrafast high power lasers can efficiently be frequency converted in a simple single pass through a nonlinear crystal due to their high peak power.
Most of these applications, in particular optical clocking and optical interconnects, require lasers that operate with high output power and multi-GHz repetition rate. Furthermore, it is important that the technology supports a high level of integration, so that the lasers are compact, reliable and suitable for cost-efficient mass production. In Figure 1.1 we compare several laser concepts which target such performance.

![Figure 1.1: Output power for different types of ultrafast lasers operating in the gigahertz regime (1 GHz = 10^9 Hz). To date, the available laser sources in this regime are either based on edge-emitting semiconductor lasers, harmonically modelocked (H-ML) fiber lasers, diode-pumped ion-doped solid-state lasers or vertical external cavity surface emitting semiconductor lasers (VECSELs). Above 100 GHz, the high-average-power edge-emitting lasers are also harmonically modelocked.](image)

Ultrafast edge-emitting semiconductor lasers are attractive because they can be fully integrated in one wafer. The highest output power to date is 250 mW at a pulse repetition rate of 4.3 GHz [13]. Unfortunately, it appears difficult to achieve high average power at pulse repetition rates well above 10 GHz because gain guiding at higher current densities gives rise to higher-order transverse modes. In addition, edge-emitting semiconductor lasers have strongly asymmetric beam profiles, which often need to be corrected with precisely mounted lenses. Typically, the same epitaxial layer forms both the gain (with a forward-biased section) and the saturable absorber (with a reverse-biased section), and can therefore not be optimized independently. The long interaction length in the device introduces significant
dispersion and nonlinearities. It is also challenging to fabricate an edge-emitting laser cavity length with a very precise pulse repetition rate and have this laser synchronized to an external reference clock.

Other interesting ultrafast sources are either based on diode-pumped solid-state lasers or fiber lasers. Solid-state lasers modelocked with semiconductor saturable absorber mirrors (SESAMs) [14-16] have achieved up to 2 W at 10 GHz and up to 160 GHz repetition rates with 110 mW. However, gain material and absorber material are different and cannot be manufactured simultaneously, which results in higher complexity and costs. Also electrical pumping is not feasible. This is also the case for modelocked fiber lasers. Moreover, fiber lasers are not fundamentally modelocked at high repetition rates. Instead, harmonic modelocking (H-ML) is used, where multiple pulses simultaneously circulate in the cavity at once, which is susceptible to pulse drop out and higher noise levels.

Our approach is based on the vertical external cavity surface emitting laser (VECSEL). In a VECSEL, the light is emitted in a perpendicular direction through the epitaxial surface, in contrast to edge-emitting lasers, where the beam propagates along the epitaxial layers. This approach enables a very efficient heat removal, resulting in high output powers with good beam quality at the same time. The highest continuous wave output powers reported today are 20 W with an $M^2 < 1.2$ [17] and 30 W with an $M^2 < 3$ [18], both based on optical pumping. Using electrical pumping, fundamental transverse mode operation with up to 500 mW has been demonstrated, in multi-mode operation, 1 W of average output power can be achieved [19].
Semiconductor lasers have a number of compelling advantages compared to other choices of laser material: the lasing wavelength can be engineered over a broad range by choosing the right material composition, see Figure 1.2. VECSELs have been reported at many wavelengths: 390 nm with InGaN wells [20], 660 nm with InGaP wells [21], 850 nm with AlGaAs wells [22], 980 nm with InGaAs wells [23], 1.3 μm with GaInNAs wells [24], 1.5 μm with InGaAs wells [25], and 2.3 μm with GaInAsSb wells [26].

![Figure 1.2 Bandgap energy as function of the lattice constant for different III-V semiconductor alloys at room temperature. Solid lines and closed dots indicate a direct bandgap, whereas the dashed lines and open dots indicate an indirect bandgap.](image)

The first passively mode-locked VECSEL was demonstrated in 2000 by Hoogland et al., they obtained 21.6 mW average output power in 22-ps pulses at a repetition rate of 4 GHz [27]. In the following years, large progress in output power and pulse duration has been made. To date, ultrafast VECSELs [28] have been successfully reported with average output powers of up to 2.1 W [29], pulse repetition rates of up to 50 GHz [30] and pulse durations below 300 fs [31, 32]. All these results had diffraction-limited, circular output beams. So far, these ultrafast VECSELs have at least three cavity elements, the gain structure, the output coupler and a SESAM for the generation of pulses. Since VECSELs are semiconductor lasers, the integration of a semiconductor saturable absorber in the gain structure should be feasible even though a straightforward integration from the separate device elements does not work and a new concept had to be developed.
In this thesis, I describe a novel ultrafast semiconductor laser, which is based on the integration of the saturable absorber into the VECSEL gain structure. The integration scheme is shown in Figure 1.3. The typical cavity for mode locking a VECSEL with a quantum well SESAM is shown in (a). It has a folded v-shaped geometry and consists of the SESAM as the end mirror, the gain structure as the folding mirror, and an output coupler. Stable modelocking requires significant absorber saturation, which is achieved by focusing the beam on the quantum well absorber. Due to the different mode areas, integration into one thin semiconductor structure is not feasible. We resolved the saturation issue by studying and developing QD absorbers, which enabled the first passively modelocked VECSEL with similar mode area on SESAM and gain structure (b). The simplification of the cavity design enabled us to achieve record high repetition rates from a modelocked VECSEL. The QD absorbers properties made integration into the VECSEL gain feasible (c). We refer to this new class of devices as modelocked integrated external-cavity surface emitting lasers (MIXSELS).

![Figure 1.3: Integration scheme, progressing from conventional VECSEL-SESAM modelocking with (a) large mode area ratios and thus limited to large cavities, (b) modelocking with identical mode areas on gain structure and SESAM, making high repetition rate and integration possible. (c) absorber-gain integration in a single device. The MIXSEL contains two high reflectors (HR), a quantum dot (QD) saturable absorber, quantum well (QW) gain and an anti-reflection (AR) coating. The intermediate HR is to prevent the pump light from bleaching the saturable absorber.](image)

In the first part of this thesis I will focus on the design, fabrication and evaluation of optically pumped VECSELS, which is the basis of this work. Important design decisions like resonance and top coating are discussed. With simulations of the temperature profile it will become clear that for good performance the substrate must be removed. The processing steps required to achieve this are explained in detail as well. Continuous wave experiments show that a fully processed VECSEL is able to deliver a record high 20 W of output power in fundamental transverse mode
operation. Most of the properties like heat management and power scaling are also valid for the MIXSEL gain structure. Next, an overview of the passive mode locking mechanisms and saturable absorbers is given. The important properties of a SESAM, namely the saturation fluence, the modulation depth and the recovery time are discussed. Based on numerical simulations I will demonstrate that quantum well saturable absorbers are not well suited for integration and that quantum dot absorbers are an excellent alternative.

In the second part of this thesis, I will discuss the optimization of the quantum dot saturable absorber. First I will present a new method for wide dynamic range nonlinear reflectivity measurements. The method is used for SESAM characterization and has a very high accuracy (better than 0.05%), which is needed because the quantum dot absorbers have a very small reflectivity change. Using this accurate setup we were able to do the first systematic analysis of the influence of QD grow parameters on the absorber properties. The modulation depth is proportional to the dot density as expected, whereas the saturation fluence is constant. Post growth annealing has a positive influence on the absorber, we can reduce the saturation fluence to below $10 \mu J/cm^2$ and make the fast recovery component of the quantum dots more dominant.

In the last part, I will describe the first MIXSEL. I will discuss the integration concept and its challenges. Because we use a resonant field enhancement, high requirements are set on the growth accuracy of the MIXSEL and precise characterization is needed. The intermediate mirror in Figure 1.3(c) consists of two sections, the first reflects the pump light (which would otherwise saturate the absorber) and the second controls the enhancement in the saturable absorber. The number of layers influences modelocking stability, pulse duration and sensitivity towards growth errors. The first proof of principle experiment showed that the concept is working, 40 mW average power were obtained 35-ps pulses. By improved cooling, we obtained 185 mW average output power with 32-ps pulse duration at 2.8-GHz. The output power is limited because of the high temperature increase in the gain structure, which can be overcome by removing the substrate as done before for high power VECSELs. The next step towards more compact and cost efficient ultrafast semiconductor lasers for wide-spread applications will be electrical instead of optical pumping. The challenge is to achieve both good electrical and optical
properties, which are usually contradicting. I present our design approach, which targets an optimized balance of both properties.

The thesis is organized as follows: Chapter 2 focuses on optically pumped VECSELs. Chapter 3 contains an overview of the passive modelocking using a SESAM. In this chapter I will point out the advantage of quantum dots over quantum wells regarding the integration. In Chapter 4, a new method for wide dynamic range nonlinear reflectivity measurements is presented. In Chapter 5, I will show the influence of QD grow parameters on QD SESAMs properties and give design guidelines. In Chapter 6, the MIXSEL is presented, and in Chapter 7, the first steps towards electrical pumping are shown. Finally, Chapter 8 contains the conclusions and an outlook.
Chapter 2

Optically Pumped VECSEL

The vertical-external-cavity surface-emitting laser (VECSEL)\(^1\) has recently gained much interest for power scaling. In the past external cavities and optical pumping were perceived to be inferior. This changed with the paper published by Kuznetsov et al. in 1997 [23], in which the authors clearly showed the potential of the optically pumped VECSEL geometry. They obtained 0.52 W output power in a TEM\(_{00}\) transverse mode with 71\% fiber coupling efficiency into a single-mode fiber.

In a VECSEL, the light is emitted perpendicularly through the epitaxial surface, in contrast to edge-emitting lasers, where the beam propagates in the epitaxial layers. An important advantage of optically pumped VECSELs is their potential to convert fairly low-cost, low-beam-quality optical pump power from high-power diode laser bars into a near-diffraction-limited output beam with good efficiency, in wavelength regions which are not covered by established solid-state laser gain materials. CW output powers of up to 30 W with beam quality factor M\(^2\) of 3 have been reported from such optically pumped VECSELs [18], and electrically pumped devices have reached 0.5 W single transverse mode output power (i.e. M\(^2\) = 1) [19].

\(^1\) Also referred to as semiconductor disk laser (SDL) or optically pumped semiconductor laser (OPS).
The VECSEL cavity consists of at least two cavity elements, the simplest cavity, the straight cavity, is shown in Figure 2.1(a). The first element is the gain structure, which is pumped optically or electrically and the second element is the output coupler. A typical gain structure is shown in Figure 2.1(b), the three sections (from left to right) are the high reflector (HR), the active region with quantum wells (QWs) and the antireflection coating.

![Figure 2.1: Elements of a VECSEL: (a) the optical resonator is formed by the gain structure and the output coupler and (b) expanded view of the gain structure, which contains a high reflector (HR), an active region with quantum wells (QWs) and an antireflection (AR) coating.](image)

With the VECSEL geometry we obtain a heat flow that is close to one-dimensional. This makes the device power-scalable, i.e. the output power can be scaled upwards by increasing the pumped area [33]. By scaling the pump power proportional to the pumped area on the gain structure, the maximum pump intensity does not increase. Therefore, the temperature rise in the semiconductor structure remains unchanged. The laser mode in the resonator can easily be adjusted with the output coupler and should match the pumped area. Other advantages are listed below [34].

Advantages of semiconductor lasers:

i) broad wavelength range (390 nm – 2.3 μm VECSELS have been shown);
ii) engineering allows special properties like low threshold or high efficiency;
iii) wavelength tuning > 100 nm is potentially possible;
iv) integration with other semiconductor devices is possible;
v) parallel fabrication enables inexpensive devices (wafer scale technology).
Advantages of optical pumping:
  i) no doping needed (easier growth and no free carrier absorption);
  ii) no $I^2R$ electrical power loss (less heating);
  iii) no carrier transport limitations (many QWs possible in large active region);
  iv) Gaussian gain profile makes good beam quality possible;
  v) power scaling.

Advantages of the external cavity:
  i) enables modelocking;
  ii) enables intracavity frequency doubling.

An additional advantage compared to edge emitting lasers is the reduced surface damage at high powers because of the larger spot sizes in VECSELs.

In Section 2.1 a method to compute the electromagnetic field in the structure is described. Section 2.2 the gain structure design is discussed. In Section 2.3 the fabrication and processing is described and in Section 2.4 characterization methods are discussed. In Section 2.5 the temperature rise is computed by using a simple analytical model and the result is compared to finite element simulations. Moreover, the influence of the temperature rise on the gain and cavity design is shown. In Section 2.6 the design of the optical cavity is given and in Section 2.7 typical continuous wave results are demonstrated.

2.1 Electromagnetic field computation

The gain structure typically contains around 100 layers with a total thickness of 10 $\mu$m. By assuming an incident plane wave, the electrical field in and outside of the structure can be computed using a well known transfer matrix algorithm for multilayer structures [35]. In this section the equations for normal incidence are derived and the modifications needed for non-normal incidence and absorption are given. The algorithm resulted in a flexible program used to design, analyze and characterize multilayer structures.
2.1.1 Matrix algorithm for dielectric multilayer structures

The structure (in our case the VECSEL gain structure) contains \( N \) layers with refractive indices \( n_j \) and thicknesses \( d_j \), a substrate with refractive index \( n_0 \) and a medium on top (most likely air) with refractive index \( n_{\text{air}} \). The layers are numbered \( 1 \) to \( N \) as shown in Figure 2.2. The complex electric and magnetic field amplitudes \( E_j \) and \( H_j \) are defined at the interfaces and we assume an \( \exp(-i\omega t) \) time dependence. To simplify matters, we first assume a field at normal incidence.

The electric and magnetic field can be split into forward and backward propagating waves, indicated with + and − signs, respectively

\[
E_j = E_j^+ + E_j^- \quad \text{and} \quad H_j = H_j^+ + H_j^-.
\] (2.1)

For simplicity we use dimensionless field quantities, with a free space impedance \( Z_0 = 1 \). In layer \( j \) with refractive index \( n_j \) the magnitudes of the electric and magnetic field are related by

\[
H = n_j (E^+ - E^-).
\] (2.2)

The minus sign arises because the backward propagating wave has a magnetic field in the opposite direction. After propagation through one layer, the field obtains a phase change \( \delta_j = n_j k_0 d_j \), with the vacuum wavenumber \( k_0 = 2\pi/\lambda \). For the electric field we write

\[
E_{j+1}^\pm = e^{i\delta_j} E_j^\pm.
\] (2.3)
Combining (2.1), (2.2) and (2.3), we can express $\mathcal{E}_{j+1}$ as function of $\mathcal{E}_j$ and $H_j$

$$\mathcal{E}_{j+1} = \mathcal{E}_{j+1}^+ + \mathcal{E}_{j+1}^- = e^{i\delta_j} \mathcal{E}_j^+ + e^{-i\delta_j} \mathcal{E}_j^- = \mathcal{E}_j \cos \delta_j + \overline{H_j \frac{i}{n_j}} \sin \delta_j. \quad (2.4)$$

A similar relation can be obtained for $H_{j+1}$

$$H_{j+1} = H_{j+1}^+ + H_{j+1}^- = e^{i\delta_j} H_j^+ + e^{-i\delta_j} H_j^- = E_j \sin \delta_j + \overline{H_j \cos \delta_j}. \quad (2.5)$$

Rewriting (2.4) and (2.5) in matrix notation results in

$$\begin{pmatrix} \mathcal{E}_{j+1} \\ H_{j+1} \end{pmatrix} = \begin{pmatrix} \cos \delta_j & (i / n_j) \sin \delta_j \\ \overline{in_j \sin \delta_j} & \cos \delta_j \end{pmatrix} \begin{pmatrix} \mathcal{E}_j \\ H_j \end{pmatrix}. \quad (2.6)$$

Once the electromagnetic field is known at a certain $z$ position within the structure, it can be computed anywhere else. Since there is only a backwards propagating wave in the substrate which we can assume to have an amplitude of 1, we can use (2.1) and (2.2) to obtain

$$\begin{pmatrix} \mathcal{E}_0 \\ H_0 \end{pmatrix} = \begin{pmatrix} 1 \\ -n_0 \end{pmatrix}. \quad (2.7)$$

This initial property enables us to compute the field in the complete structure using (2.6). Afterwards, the field is normalized such that the incident electrical field amplitude is 1 (i.e. $\mathcal{E}^- = 1$ in the medium on the top). The complex amplitude reflectivity $r$ can be computed with

$$r = \frac{\mathcal{E}_N^*}{\mathcal{E}_N} = \frac{n_{air} \mathcal{E}_N + H_N}{n_{air} \mathcal{E}_N - H_N}. \quad (2.8)$$

From $r$ we obtain the intensity reflectivity $R = |r|^2$ and phase change of the reflected wave $\phi = \arg(r)$.

The program is optimized to be as fast as possible. By using three-dimensional matrixes, the third dimension is formed by the wavelength, the algorithm can be executed more efficient on modern processors. By using optimized matrix libraries, data points can be computed in parallel.
2.1.2 Matrix algorithm for non-normal incidence and absorption

In the VECSEL cavity the gain structure is often used as folding mirror. A typical folding angle is 15°, which is below 5° inside the structure with higher refractive index. It is important to numerically take this into account for precise simulation results. Fortunately, the matrix algorithm can easily be adapted to compute the exact electromagnetic field. In this more general approach, $\mathbf{E}_j$ and $\mathbf{H}_j$ represent the tangential components of the electric and magnetic fields, which are continuous at the interfaces. In (2.2) we have to replace $n$ by $\eta$ which takes into account the angle and polarization

$$n \rightarrow \eta = \begin{cases} \frac{n}{\cos \theta} & \text{p-polarization} \\ n \cos \theta & \text{s-polarization} \end{cases} \, (2.9)$$

And the phase change in (2.3) becomes

$$\delta_j = n_j k_{0j} \cos \theta_j \, (2.10)$$

were $\theta_j$ is calculated by the Snellius law.

In real structures, materials can have absorption or gain (e.g. the active region absorbs the pump light and the QWs have gain). Precise analysis shows that the matrix algorithm can also be used with a complex refractive index

$$n = n_r + i \alpha / (2k_{0j}) \, (2.11)$$

with $n_r$ the real part and $\alpha$ the intensity attenuation coefficient. As a result of the complex refractive index the angle $\theta_j$ becomes complex as well.

2.1.3 Refractive index calculation

For the computation of the room temperature refractive index of the semiconductor materials we use the semi-empirical method proposed by M.A. Afromowitz [36]. To correct the refractive index for different temperatures, we use a linear temperature dependence with $2.8 \times 10^{-4}$ K$^{-1}$ for GaAs and $1.1 \times 10^{-4}$ K$^{-1}$ for AlAs [37]. For Al$_x$Ga$_{1-x}$As we interpolate between the two values.
To optimize the computation speed of the program, we reduce the number of refractive index evaluations. For example in a mirror structures many layers consist of the same material, by implementing a lookup table we have to compute the refractive index only ones for each material.

2.2 Gain structure design

In this section, we discuss how the design influences the important properties of the gain structure.

2.2.1 High reflector and antireflection coating

The purpose of the bottom mirror is to reflect the laser and the pump light. We normally design the optical cavity having a 15° angle on the gain structure (thus a 30° angle between incidence and reflected beam). For this angle, a reflectivity close to 99.99% is targeted for the lasing wavelength. For the pump we have larger angles, typically around 45°, which has the advantage that we can tune the pump angle over a broader range to optimize absorption. We design the mirror to reflect both wavelengths. This has two advantages, first we have a higher optical-to-optical efficiency due to the two passes through the active region and therefore more absorption, secondly there is less heating due to pump absorption in the mirror or in the heat sink, which also results in a higher efficiency and a higher maximum output power. For the pump wavelength, a reflectivity above 99% is usually targeted.
The high reflectivity at two wavelengths is realized by using a superlattice Bragg mirror, see Figure 2.3. The total optical thickness of one period of the superlattice is equal to an integer multiple $m$ of a both half-wavelengths. In our design, we choose $m = 5$. By increasing the thickness of first layer in the superlattice and decreasing the thicknesses of the others we control the relative reflectivity between the two wavelengths. We optimize the design for higher reflectivity at the laser wavelength than at the pump wavelength.

![Figure 2.3](image)

Figure 2.3: Part of the superlattice Bragg mirror. The total optical thickness of one period of the superlattice is equal to an integer multiple of both half-wavelengths. For our mirror we choose $m = 5$.

The materials used in the mirror are AlAs ($n = 3.0$) and Al$_{0.2}$Ga$_{0.8}$As ($n = 3.4$). Using GaAs ($n = 3.5$) we would have a larger refractive index contrast, resulting in an increased bandwidth and reflectivity, however GaAs absorbs the 808-nm pump light which leads to heating and reduces the efficiency. By adding 20% aluminum we can shift the bandgap to 735 nm.

The antireflection section is optimized to reduce the large reflection from the air/GaAs interface which is around 31%. The coating contains 12 alternating layers and is numerically optimized for low reflectivity. The objective function used for the optimization is chosen not only to have low reflectivity at the laser wavelength but also for broad wavelength range. We first use a Monte Carlo method that evaluates $10^5$ random layer structures, the best 1000 results are then locally optimized by a gradient method.

The simulated reflectivity curves of the optimized mirror structure and optimized antireflection section are shown in Figure 2.4. The mirror structure contains 8 periods of 10 layers with a reflectivity of 99.97% at 960 nm and 99.5% at 808 nm at an angle of 45°. The total thickness of the mirror structure is 6.2 µm, whereas the antireflection section has a thickness of only 803 nm.
2.2.2 Active region

The purpose of the active region is the conversion of photons. Optimization of the active region is a challenging task because of the high degree of freedom. The aspects to consider are: spacer versus inwell pumping, total thickness of the active region and the number and placement of quantum wells.

The two possibilities to absorb the pump light are inwell pumping and spacer pumping. Because of the smaller quantum defect, inwell pumping theoretically has a higher optical-to-optical efficiency and therefore a reduced heating. The pump wavelength has to be chosen close to the lasing wavelength (e.g. 940 nm for a 980 nm laser). Since the light is absorbed in the QWs instead of the barrier layers, the absorption is very low (≈15% for a single pass). Two methods can be applied to increase the absorption [38]. The first one uses additional optics to reimage the pump on the gain structure as in solid-state disk lasers [39]. The second one is to increase the electrical field in the QWs at the pump wavelength by designing a resonant structure. The pump absorption increases because absorption is proportional to $|\mathcal{E}|^2$. This method has high demands on the epitaxial process, pump diodes used and the angle of incidence of the pump. Moreover, a resonant structure has usually has a large group delay dispersion and small gain bandwidth (the negative aspects are explained in the next section), which makes inwell pumping unsuitable for
modelocked VECSELs. Our design is therefore based on spacer pumping. The active region consists of typically 5 nm thick In$_{0.13}$Ga$_{0.87}$As QWs and 130 nm thick GaAs spacer layers that absorb the pump light.

In the active region the electrical field forms a standing wave pattern as is shown Figure 2.5. The QWs are placed in the anti-nodes of the standing wave because here the interaction is the strongest. The total thickness of the active region has to be chosen, such that carriers are uniformly excited over the whole length. If the active region is too thick, the pump will be mainly absorbed in the upper layers, and in the worst case some QWs do not reach the transparency density. For 7 anti-nodes (the optical thickness is 7 times $\lambda/2$) homogeneous pump absorption is achieved by using a bottom mirror that also reflects the pump light.

![Standing wave pattern in the gain structure.](image)

Figure 2.5: Standing wave pattern in the gain structure. The gray curve is the refractive index and the black curve is the squared electric field, which has been normalized such that the incident wave has amplitude 1. The QWs are placed in the anti-nodes of the standing wave pattern.

To study the spectral dependence of the gain structure we define the gain enhancement $\Gamma$ as the average of the squared field in the QWs

$$\Gamma = \frac{1}{N_{QW}} \sum_{QWs} |E(z)|^2,$$

(2.12)

where $N_{QW}$ is the number of QWs. From the gain structure displayed in Figure 2.5 we obtain $\Gamma \approx 1$. For resonant structures without a top coating the gain enhancement is 4,
with a Bragg reflector on top it can be even higher (electrically pumped VECSELs typically have a gain enhancement above 4). The power reflectivity coefficient (i.e. $P_{\text{out}} = GP_{\text{in}}$) is

$$G(\lambda) = 1 + N_{QW} \Gamma(\lambda) g(\lambda, N) n_r d_{QW},$$  \hspace{1cm} (2.13)$$

where $g(\lambda, N)$ is the intrinsic QW gain as function of the wavelength and the carrier density, $n_r$ is the real part of the refractive index and $d_{QW}$ is the QW thickness. A higher gain enhancement results in a higher gain, however also a stronger saturation (smaller saturation energy).

The gain enhancement $\Gamma$ determines the gain of the entire structure and therefore the laser threshold and the optimum output coupling. Since $\Gamma$ is wavelength dependent, it can be seen as an intracavity filter, it has important consequences on the performance (e.g. output power and pulse duration) of a modelocked laser [40]. This will be discussed in more detail in the next section.

2.2.3 Resonance and group delay dispersion

The gain enhancement and the group delay dispersion (GDD) in a VECSEL play an important role in the pulse formation process. This is the main difference regarding the design of a continuous wave VECSEL compared to a modelocked VECSEL. A continuous wave VECSEL ideally has a high gain enhancement $\Gamma$ to be able to use a higher out coupling to reduce the significance of the intracavity losses (e.g. mirror losses and scattering). However, for a pulsed laser there are more requirements to take into account.

The gain structure is basically a Gires-Tournois interferometer (GTI) [41], formed by the reflection of the bottom mirror and the reflection from the top layers. The dispersion can be adjusted with the total thickness of the active region. The GDD coefficient can be computed by

$$D(\omega) = \frac{d^2 \phi(\omega)}{d\omega^2},$$  \hspace{1cm} (2.14)$$

with $\phi(\omega)$ as computed with the transfer-matrix algorithm and $D$ the dispersion coefficient expressed in $\text{fs}^2$. The second derivative is computed numerically. In Figure 2.6(a) the GDD is shown for three different cases. The light-gray curve
displays the GDD for a resonant gain structure, which does not contain an antireflection section, therefore the surface reflectivity is determined by the GaAs/air interface (31%). The dark-gray curve is the antiresonant case, which has the same design as the resonant structure, except for the extra $\lambda/4$ GaAs layer on top to change the resonance. The dashed black curve is the GDD of a structure with antireflection section. Here, the reflection is significantly reduced to values below 1%. The GDD has zero crossings both for resonances and antiresonances of the GTI.

![Figure 2.6: GDD and gain enhancement as function of wavelength. The light-gray solid curve is the resonant case, the dark-gray curve is the antiresonant case and the dashed black line is the structure with antireflection section.](image)

In Figure 2.6(b), the field enhancement factor $\Gamma(\lambda)$ is shown for the three different gain regions. The maximum field intensity at the design wavelength 965 nm is obtained for resonance ($\Gamma = 4$) and the minimum field intensity for antiresonance ($\Gamma = 4/n^2 \approx 0.3$). In case of the gain structure with the antireflection coating the field enhancement is in between, one can show that $\Gamma = 4/n \approx 1.1$. By designing the QWs at arbitrary positions in the structure, i.e. not in the anti-nodes, we can obtain arbitrary values for $\Gamma$, however these structures are more challenging to grow.

As mentioned before, the gain enhancement can be seen as an intracavity filter and has a strong influence on the pulse duration. A 1-ps pulse has at least a 1-nm FWHM bandwidth. Therefore, the gain structure must have an almost flat response in this region to maintain the optical spectrum over many roundtrips. For the resonant structure the effective gain spectrum is narrower than the intrinsic gain spectrum, whereas the antiresonant and coated structure the effective gain is broader since the curvature of the gain enhancement is opposite.
Taking into account all of the above considerations, optimal modelocking conditions are obtained with antireflection coated gain structures. The GDD is close to zero at the design wavelength, the gain enhancement is moderate and the gain spectrum is even broader than the intrinsic gain spectrum.

2.3 Fabrication

VECSELs are grown on semiconductor wafers using standard techniques, such as metal-organic vapor-phase epitaxy (MOVPE) and molecular beam epitaxy (MBE). Depending on the choice of heat spreader, additional processing is necessary. The choice of heat sink approach is crucial for the performance of the VECSEL. The most used geometrical approaches are shown in Figure 2.7.

![Figure 2.7: Three different approaches for heat removal. (a) The as-grown structure is directly (without processing) soldered on a heat sink. (b) Better thermal properties are obtained by soldering the epitaxial layers directly on a heat sink and removing the substrate by selective etching (the dotted part). (c) Better thermal properties are also obtained by bonding a transparent heat spreader on top of the structure.](image)

In Figure 2.7(a), the most trivial approach is shown. We can use the as-grown structure by cleaving and soldering it onto a heat sink. No processing is needed, which makes this method is ideal for fast testing of the devices. Better thermal performance is obtained with the device shown in Figure 2.7(b). Etch-stop layers grown between the substrate and the actual gain structure enable substrate removal, resulting in a gain structure directly in contact with the heat sink [33]. The active region is now separated only by a 6 µm mirror from the heat sink. Of course, for this approach, the structure has to be grown in reverse order. An alternative is shown in Figure 2.7(c), where a transparent heat sink (e.g. diamond or silicon carbide) is mounted on top of the sample. In this case, the heat sink is even closer to the active region. The heat sink can be capillary bonded with water, methanol or another suitable liquid to the
semiconductor structure [42]. This intracavity heat sink works excellent for continuous wave lasers, however for modelocked lasers one should be aware of the additional Fabry-Pérot effect. Possible solutions are using very thin heat sinks (smaller than 50 μm), using wedged heat sinks or using very good antireflection coatings. The structures used in this thesis are either as-grown or thinned with the layers grown in reverse order.

2.3.1 Growth

The gain structures used in this study are grown on (100) undoped GaAs substrates using a VEECO GEN III molecular-beam epitaxy (MBE) machine. The III-V semiconductor compounds needed for the gain structure are: GaAs and In$_{0.13}$Ga$_{0.87}$As (active region), AlAs and Al$_{0.2}$Ga$_{0.8}$As (mirror and AR coating). We use four cells: one for gallium, two for aluminum (a high flux for AlAs and a low flux for Al$_{0.2}$Ga$_{0.8}$As) and one for indium. The As is provided using an arsenic cracker to break As$_4$ molecules into As$_2$ molecules. For thinned structures, etch-stop layers are needed and we need an additional compound, namely Al$_{0.85}$Ga$_{0.15}$As. The mirror and the antireflection coating are grown at 600°C, whereas the QWs are grown at a slightly lower temperature of 550°C. The temperature is measured using band-edge absorption.

2.3.2 MBE calibration

Before the growth of the gain structure, several test-structures are required. We need to calibrate the growth rate and the compositions of the different materials. To obtain the growth rate of AlAs and GaAs, we grow a 5-pair mirror with a $\lambda/2$ layer of GaAs on top. This forms a resonant structure with a minimum reflectivity at the resonance wavelength. This resonance wavelength depends more strongly on the thickness of the top GaAs layer. On the other hand, the total stopband position of the mirror is determined by both materials. By fitting the measured reflectivity with a simulated reflectivity we can clearly distinguish the growth rate of both materials. A second test structure is needed to obtain the growth rate of Al$_{0.2}$Ga$_{0.8}$As. The material composition is determined by observation of the photoluminescence. By increasing the Al content in AlGaAs the photoluminescence (PL) wavelength decreases.
Finally, we need a test structure for the QWs. Here we need to optimize QW thickness and Indium content for optimum emission wavelength. The emission wavelength is measured with a PL mapper (Accent RPM2000). The measurements are done at room temperature, which is different from the operation temperature. Assuming a PL shift of 0.3 nm/K, and a 50 K temperature increase, we obtain a wavelength shift of 15 nm between the cold and hot structure. To obtain lasing at 960 nm, the ideal room temperature PL is 945 nm. The test structure we use is shown in Figure 2.8(a). Two AlAs layers prevent the carriers from recombination at the surface or diffusion into the substrate. In the PL spectrometer, the structure is pumped at 532 nm, which is subsequently absorbed in the GaAs. Computations show that 50% of the pump light is absorbed between the AlAs barriers and 40% is reflected. A typical PL spectrum is shown in Figure 2.8(b). We see the main peak at 945 nm and a smaller peak at 870 nm from the GaAs substrate. In between a small bulge around 910 nm is visible, which is due to the light hole recombination. The barriers do not significantly influence the PL shape, hence the measured PL is assumed to be the intrinsic PL.

![Figure 2.8: A QW test structure is grown to optimize the wavelength. (a) The structure contains two AlAs layers as barriers. In between 50% of the 532 nm pump light is absorbed. The black line indicates the field intensity in the structure. (b) A typical PL spectra showing heavy hole (HH) and light hole (LH) recombination as well as the GaAs photoluminescence.](image-url)
To find the composition (i.e. Indium content) we grow several structures with different QW thicknesses and analyze them with x-ray diffraction and PL measurements. Once consistent parameters are found, we use the beam flux monitor (BFM) to measure the indium and gallium flux. To adjust the PL peak wavelength, we can change the QW thickness by changing the shutter time or by changing the indium content with adjustments on the indium flux. In most structures we used QWs with around 13% Indium.

### 2.3.3 Processing of thinned structures

If high power performance is targeted, thinned structures are required. For this the reverse-grown sample is soldered onto a heat sink, subsequently the GaAs substrate is removed. After the growth the samples are first cleaved in 4x4 mm pieces and metalized. The metallization sequence is 30 nm titanium, 200 nm platinum, 5 µm indium and 100 nm gold. The final gold layer protects the indium from oxidation in air during the time the sample is not processed.

Several suitable heat sink materials are listed in Table 2.1. Both thermal conductivity and thermal expansion are important properties. The thermal conductivity should be as high as possible and the coefficient of thermal expansion should be as close as possible to that of GaAs. For example CVD-diamond has the highest thermal conductivity, however cleaves have been observed after processing because the thermal expansion coefficients are quite different. All heat sink materials have to be polished and gold-plated before use. The size of the heat sink is 5x5x1 mm.

<table>
<thead>
<tr>
<th>material</th>
<th>thermal conductivity $\kappa$ [Wm$^{-1}$K$^{-1}$]</th>
<th>thermal expansion $\alpha$ [$10^{-6}$/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>45</td>
<td>5.8</td>
</tr>
<tr>
<td>copper</td>
<td>400</td>
<td>17</td>
</tr>
<tr>
<td>CVD-diamond</td>
<td>1800</td>
<td>1.6</td>
</tr>
<tr>
<td>copper-tungsten W-10</td>
<td>180</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 2.1: Thermal properties of GaAs and suitable heat spreader materials.
For soldering we use a fluxless process under vacuum ($10^{-5}$ mbar) as described in [43]. The vacuum is needed to prevent oxidation of the indium during the soldering. The melting point of indium is at 157°C. The semiconductor sample is placed on top of the heat sink and a pressure of about 300 kPa is applied while the temperature is increased to 200°C.

After soldering, we remove the substrate. The different steps are shown in Table 2.2. In the first step the major part of the substrate will be removed. Three alternatives to do this are: mechanical lapping, chemo-mechanical etching with bromine or wet-etching with citric acid. The mechanical lapping is the fastest because the samples can be done in parallel, however the mechanical force can damage the samples. Bromine etching is also fast, however the samples have to be processed in sequence. For citric acid etching the least effort is needed, an etch rate of 7 nm/s gives a total etch time of about 23 hours, while maintaining a flat surface. All these methods have been used successfully. At the end of this step there is approximately 50 μm substrate left.

The following steps all use a very selective etching solution to stop on the next layer. First, the remaining of the substrate is removed by jet etching with a H$_2$O$_2$/NH$_4$OH (600 ml/24 ml) solution [44], the selectivity between GaAs and Al$_{0.85}$Ga$_{0.15}$As is approximately 30. To remove the Al$_{0.85}$Ga$_{0.15}$As layer we use HF, which has a very good selectivity. The next GaAs layer is removed with the citric-acid/H$_2$O$_2$ solution described in [45]. The last AlAs layer is removed again with HF.

<table>
<thead>
<tr>
<th>material</th>
<th>removal step</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 μm GaAs (substrate)</td>
<td>≈ 550 μm lapping/etching</td>
</tr>
<tr>
<td></td>
<td>≈ 50 μm H$_2$O$_2$/NH$_4$OH</td>
</tr>
<tr>
<td>300 nm Al$<em>{0.85}$Ga$</em>{0.15}$As</td>
<td>0.7% HF</td>
</tr>
<tr>
<td>20 nm GaAs</td>
<td>citric acid solution</td>
</tr>
<tr>
<td>75 nm AlAs</td>
<td>0.7% HF</td>
</tr>
</tbody>
</table>

Table 2.2: Processing steps required to completely remove the substrate and etch stop layers.
During the processing, the heat sink is covered with wax, which is removed afterwards with trichloroethylene (TCE). After cleaning the structure is ready to use, a processed structure is shown in Figure 2.9.

![Figure 2.9: A processed gain structure. A few In droplets can be seen on the exposed rim of the copper heat spreader. Some leftover GaAs substrate resulting from the jet-etching process is visible around the edges.](image)

2.4 Characterization

Precise characterization of the final structure is important. The growth takes over 18 hours, so small drifts of the growth rate are not unusual. The goal of the characterization is to obtain the exact layer thicknesses and material compositions and compute optimal working conditions such as ideal laser wavelength (maximum gain and optimal GDD) and the ideal pump angle that maximizes the absorption.

The combination of several techniques gives the best results because all have some advantages and disadvantages. The use of scanning transmission electron microscopy (STEM) gives the best resolution however it is very time consuming (mainly because of the complicated sample preparation) and therefore only applied for important structures. Much faster but also less resolution is obtained with the scanning electron microscope (SEM). In combination with an optical reflectivity spectrum measurement good results are obtained. We also used X-ray diffraction (XRD, Seifert XRD 3003 PTS-HR), however we did not obtain sufficient accuracy. The GDD, which is important for modelocking, is measured with by scanning whitelight interferometry.
In most cases we use a combination of a SEM image and a spectrometer measurement. With the SEM we obtain good relative information between the layers (e.g. to see a drift in the Bragg mirror), however the absolute layer thicknesses depend on a calibration. The relative layer thickness data is used in a model we use to compute the reflectivity. The layers are scaled and fitted to a reflectivity measurement. Using this procedure we can take into account linear drifts of the cells. Both SEM and spectral analysis are discussed in this section.

2.4.1 Scanning electron microscopy analysis
The scanning electron microscope (SEM) is used to get an overall impression of the growth. Even though the specified resolution of our SEM (Zeiss ULTRA 55) is 1 nm, we could not see the QWs, because they only have 13% indium which makes the contrast very low. Nevertheless the SEM is very useful to determine the drift of the growth rate of the cells during the entire growth process. A typical SEM picture of a gain structure is shown in Figure 2.10. The structure is cleaved shortly before putting it in the SEM to prevent oxidization of AlAs layers. To obtain better resolution the sample is dipped in hydrochloric acid (HCl) for a few seconds.

![SEM image of a gain structure](image1.png)

Figure 2.10: An SEM image of a gain structure. The QWs are not visible. On the left the superlattice Bragg mirror to reflect pump and laser light. In the middle the active region, the QWs are not visible. On the right the antireflection (AR) coating. The structure is used as-grown, on the left the GaAs substrate is visible.

2.4.2 Reflectivity analysis
The reflectivity spectrum is used to obtain an accurate knowledge of the growth deviations. The spectrometer we use is a Varian Cary 5E UV-Vis-NIR. A single spectrum is not enough to obtain accurate information about the different materials, however together with the information obtained from the SEM image the layer structure can be reconstructed. A measured spectrum is shown in Figure 2.11. The
high reflectivity at 808 nm disappeared because of the absorption, and the peaks around 1200 nm and 1600 nm are due to the superlattice Bragg mirror.

![Spectral reflectivity measurement](image)

**Figure 2.11:** A spectral reflectivity measurement of a gain structure. The dashed gray line is the calculated design reflectivity, the solid black line is the measurement and the solid gray line is the fit. The fit is very good for longer wavelengths, however not very accurate for shorter wavelengths. This can be explained by: i) the resolution of the spectrometer is not high enough to resolve the fast oscillations and ii) our absorption model is not accurate enough below the bandgap.

### 2.5 Heat management and temperature effects

The VECSEL has a one-dimensional heat flow which allows scaling the output power by scaling the mode on the active region. The pump beam radius $w_p (\approx 100 \mu m)$ is much larger than the thickness of the semiconductor structure ($\approx 8 \mu m$) therefore the heat flux is only pointed in the negative $z$ direction as shown in Figure 2.12. Increasing the pump power proportionally with the pumped area ($\pi w_p^2$) results in a constant pump intensity in the center and therefore also a constant temperature increase.

There are several physical mechanisms causing the heating in the structure. A large contribution is due to the quantum defect between the pump (808 nm) and laser (960 nm) wavelengths, which makes up 18.8% of the absorbed pump power. This energy is converted into heat. Other causes are nonradiative recombination in the active region, pump transmission through the whole structure and losses (e.g. at interfaces or in crystal defects). A good approximation for the heat power is to start
with the absorbed pump power and subtract the light radiated from the structure [30]

\[ P_{\text{heat}} = (1 - R_{\text{pump}})P_{\text{pump}} - P_{\text{laser}} - P_{\text{spont}}, \]  

(2.15)

with \( R_{\text{pump}} \) the reflectivity at the pump wavelength, \( P_{\text{pump}} \) the total pump power, \( P_{\text{laser}} \) the laser output and \( P_{\text{spont}} \) the power radiated by spontaneous emission, which is proportional to the threshold pump power.

The temperature profile in the gain structure influences the performance of the laser. The gain peak wavelength will shift, and the refractive index change causes a thermal lens. Good knowledge of the temperature profile is important, and in this section results obtained with a finite element simulation and a simple analytical model will be compared. Moreover the influences on gain are discussed and a model to compute the thermal lens is given.

![Figure 2.12: Idealized heat flow in the gain structure. A one dimensional heat flow is assumed in the Bragg mirror and the solder junction, whereas a three dimensional heat flow is assumed in the heat spreader. A heat source with a Gaussian transverse distribution is assumed on top of the Bragg mirror.](image-url)
2.5.1 Temperature simulation

We use commercially available finite element software to compute the temperature increase in the gain structure. In the simulation we do not take into account every single layer, however we compute an effective coefficient of thermal conductivity for both the solder junction and the gain structure using

$$\kappa_{\text{eff}} = \frac{d}{\sum \frac{d_i}{\kappa_i}},$$

with $\kappa_i$ the thermal conductivity and $d_i$ the thickness of layer $i$, and $d$ the total thickness. We compute the temperature for two structures: the first structure is an unprocessed structure directly soldered on to a copper heat sink and contains three layers, a 2 mm thick copper heat sink ($\kappa = 400 \text{ Wm}^{-1}\text{K}^{-1}$), a 600 µm GaAs substrate ($\kappa = 45 \text{ Wm}^{-1}\text{K}^{-1}$) and on top the 8 µm thick grown layers ($\kappa_{\text{eff}} = 36 \text{ Wm}^{-1}\text{K}^{-1}$). The second structure is a thinned structure consisting of a 2 mm copper heat sink, a 2.5 µm thick solder layer ($\kappa_{\text{eff}} = 80 \text{ Wm}^{-1}\text{K}^{-1}$) and finally the 8 µm thick semiconductor stack. The temperature $T(r, z)$ is computed according to

$$\nabla \cdot (-\kappa \nabla T) = Q,$$

with $\kappa(z)$ the thermal conductivity, and $Q(r, z)$ the heat source. The heat source is limited to the active region, hence we neglect the losses and the transmission through the mirror structure

$$Q(r, z) = \begin{cases} \frac{1}{d_{\text{act}}} I_{\text{heat}}(r) & z \in \text{active} \\ 0 & \text{otherwise,} \end{cases}$$

with $d_{\text{act}}$ the thickness of the active region, and $I_{\text{heat}}(r)$ the heat intensity. The heat intensity has a Gaussian profile and we use the heat power computed with (2.15) to obtain

$$I_{\text{heat}}(r) = \frac{2P_{\text{heat}}}{\pi w_p^2} \exp\left(-2\frac{r^2}{w_p^2}\right).$$
Equation (2.17) is solved using cylindrical symmetry with the boundary condition \( \frac{\partial T}{\partial z} = 0 \) on the top and \( T = 0 \) on the bottom. In Figure 2.13 the result is shown for a pump spot of \( w_p = 80 \, \mu m \) and a heating power of \( P_{\text{heat}} = 1 \). For other heating powers the temperature can be scaled linearly. The structure on the left is an unprocessed structure with 600 \( \mu m \) GaAs substrate in between and has a maximum temperature increase of 100 K. The structure on the right is thinned and has a maximum temperature increase of 30 K.

![Figure 2.13: Finite element temperature simulation of two gain structures. On the left a structure with a 600 \( \mu m \) substrate, on the right a structure with the substrate removed. In both cases, the pump spot radius is 80 \( \mu m \) and the total heat power is 1 W, corresponding to 5 kW/cm\(^2\) (assuming a flat top profile).](image)

To compare different heat sink materials it is better to visualize the data in a different way. In Figure 2.14 the maximum temperature increase \( \Delta T \) is plotted as function of the pump spot radius, while the heating intensity is kept constant at 5 kW/cm\(^2\). We clearly see the limitations of the scaling, because at a certain radius the temperature increase in the heat sink dominates the temperature increase in the semiconductor structure. This radius, however, is strongly determined by the thermal conductivity of the heat sink material. One way to reduce the heating at higher radii is to lower the pump intensity, however this also reduces the efficiency because the laser operates closer to the threshold.
Figure 2.14: Maximum temperature increase as function of the pump spot radius for three different heat sink materials. The data points are obtained from finite element simulations assuming a 5 kW/cm² pump intensity.

### 2.5.2 Analytical temperature model

For a better understanding we use an analytical model. For the thinned approach the assumption of a one-dimensional heat flow is valid. We assume a heat flux in the negative \( z \) direction in the semiconductor layers and in the solder layers. If we model the heat sink as a semi-infinite body an analytic solution of the temperature increase exists. The total temperature in the semiconductor is found by adding the heat sink temperature, the solder layer temperature and the temperature increase in the solder layer (see also Figure 2.12)

\[
\Delta T(r) = \Delta T_{\text{HS}}(r) + \Delta T_{\text{solder}}(r) + \Delta T_{\text{semi}}(r).
\]

In the one-dimensional regions the temperature can be computed with a simple model. We assume that the heat flux is given by

\[
\tilde{\phi} = -I_{\text{heat}}(r)\hat{u}_z,
\]

with \( I_{\text{heat}} \) as defined in (2.19) and \( \hat{u}_z \) the unit vector in the \( z \) direction. The temperature increase is obtained by integration

\[
\Delta T(r) = -\int \frac{\phi(r)}{\kappa(z)} \, dz,
\]
which can be written as a sum over all layers

$$\Delta T_{\text{semi}}(r) = \sum_{\text{layer}} \frac{2P_{\text{heat}}d_{\text{layer}}}{\pi w_p^2 \kappa_{\text{layer}}} \exp\left( -\frac{2r^2}{w_p^2} \right).$$

(2.23)

The same can be done to obtain $\Delta T_{\text{solder}}$. In [46], the analytical solution of the temperature distribution is computed in a semi-infinite body with a Gaussian distribution of the heat source at the body surface. The solution is

$$\Delta T_{\text{HS}}(r) = \frac{P_{\text{heat}}}{\sqrt{2\pi w_p \kappa}} I_0 \left( \frac{r^2}{w_p^2} \right) \exp\left( -\frac{r^2}{w_p^2} \right).$$

(2.24)

The total temperature increase can now be computed by using Equation (2.20). Comparisons show that the simple model is close the simulation (error $< 10\%$, for 1 W heat power). The computed temperatures $\Delta T_{\text{HS}}$, $\Delta T_{\text{solder}}$ and $\Delta T_{\text{semi}}$ are shown together with the values obtained by the simulations in Figure 2.15, we assumed a constant heat intensity of 5 kW/cm². The deviation of the heat sink simulation from the analytical model is most likely because we used a finite heat sink during the simulation, which therefore has a smaller temperature increase.

![Figure 2.15: Comparison of the analytical model (dashed lines) with the finite element simulations (solid lines). The dark gray line is the temperature increase in the semiconductor region, the light gray line is the temperature increase in the solder layer and the black line is the temperature increase in the heat sink.](image-url)
2.5.3 **Temperature effect on gain**

The absolute temperature has strong influence on the gain of the structure. The two important contributions are: the shift of the intrinsic gain spectrum and the change of the gain confinement $\Gamma$ due to a change of the refractive index ($dn/dT$).

When heating the structure we observe a strong red shift. A typical value for the intrinsic gain shift is 0.3 nm/K. Typical simulated gain spectra are shown in Figure 2.16(a). A smaller shift is obtained due to temperature dependent gain confinement. Given the temperature profile computed in the previous section we can calculate the actual refractive index of the layers. Taking into account the temperature dependence of the refractive index (with the values given in Section 2.1.3), the mirror shifts to longer wavelength at a rate of 0.04 nm/K. The shift of the gain enhancement is similar as shown in Figure 2.16(b). The solid lines show the gain enhancement $\Gamma$ as function of the wavelength and the dashed lines show the product of $\Gamma$ and the intrinsic gain, i.e. the effective gain spectrum an incident pulse will experience, see also (2.13). Because the impact of the temperature on the gain is so large, the structure has to be designed for a specific operating temperature.

![Figure 2.16](image_url)

**Figure 2.16**: Temperature dependence of the gain. (a) Red shift of the intrinsic gain spectrum with increasing temperature and (b) gain confinement with increasing temperature.

Above a certain temperature the laser output power drops quickly. This thermal runaway can be explained as follows [40]. Above the threshold the gain is equal to the total cavity loss. By increasing the pump power the temperature increases, the QWs become less efficient and more carriers are needed to maintain the same gain [47]. With increasing carrier density and temperature, the Auger recombination rate rises, resulting in even more heating. At the same time the intrinsic gain peak is
shifted with respect to the gain enhancement decreasing the effective gain. Above a
critical point, the temperature rises uncontrollably, and the laser emission stops.

2.5.4 **Computation of the thermal lens**

The temperature increase due to the pumping modifies the refractive index within
the gain structure which causes a radial dependence of the reflected phase $\phi(r)$. The
Gaussian like shape has lens-like properties, therefore we call this effect a thermal
lens. For some cavity designs, when the focal length is comparable to the radius of
curvature of the output coupler, the thermal lens cannot be ignored, and it can even
become the dominant focusing element of the cavity [30]. In our computations we
ignore two other effects that cause a defocusing lens: i) transversal carrier
distribution and ii) thermal expansion of the heat sink. The transversal
inhomogeneous carrier distribution caused by the optical pumping changes the real
part of the refractive index because of the Kramers-Kronig relations. Using the
linewidth enhancement factor we estimate the maximum phase change below
75 mrad, which can be neglected.
From the temperature distribution and the influence of the temperature on the refractive index, we can compute $n(r, z)$. Then, we compute the complex amplitude reflectivity $r(r)$ a plane wave would experience as function of discrete values of $r$ using the matrix algorithm described in Section 2.1.1. We assume the refractive index to be constant within each layer along the $z$ direction. The resulting phase shift is shown in Figure 2.17(a).

By taking the numerical second derivative at the optical axis, a parabolic approximation of the phase profile is calculated, which allows to extract the focal length of the thermal lens by comparison with the phase profile of an ideal thin lens

$$\phi(r) = -\frac{k_0}{2f} r^2,$$

with $k_0$ the vacuum wavenumber and $f$ the focal length. From Figure 2.17(a) it becomes clear that at the $1/e^2$ radius (65 μm) the computed phase deviates strongly from the parabolic phase, therefore a strong thermal lens introduces aberrations which lead to inferior beam quality.
The dioptric power of the thermal lens was determined for a range of pump powers by measuring the output beam radius of the laser with a beam profiler at a fixed distance from the output coupler. Using the matrix formalism for Gaussian beams we calculated the thermal lens which would produce such an output beam for the given optical system. This works well as long as the beam quality factor $M^2$ is taken into account. The results are shown in Figure 2.17(b). The measurements and simulations agree better at higher pump powers, however by choosing another pump spot the slope changes resulting in better agreement also at lower pump powers.

### 2.6 Cavity design

The design of the external cavity is important since it determines the output power, repetition rate (in case of modelocking) and transverse mode quality. The electric field in the external cavity can be described very well with a Gaussian beam. The two parameters, the scaling parameter $\omega(z)$ and the radius of curvature of the wavefront $R(z)$ can be computed with the ABCD law [48].

In the following we consider a linear cavity geometry which applies also to the MIXSEL. The mode on the gain structure $w_g$ should match the pump spot $w_p$. Good beam quality ($M^2$ close to 1) will be obtained with the mode parameter $w_g$ close to $w_p$. For a too large pump spot ($w_p \gg w_g$) higher order transverse modes will have gain and the laser will run in multimode operation. On the other hand, for a too small pump spot ($w_p \ll w_g$) the laser will run single mode however not at maximum output power. Three factors determining the mode size are: the radius of curvature of the output coupler, the cavity length and the thermal lens of the gain structure.

---

$^{2}$ $\omega(z)$ is the same for all TEM_{mn} modes, only for the fundamental mode $\omega(z)$ is the 1/e^2 radius.
A challenge for combining high average output power with high repetition rate is to provide a sufficiently large $w_g$ despite the small cavity length. When reducing the length of the cavity (to obtain a higher repetition rate $> 30$ GHz) the mode size on the gain structure also decreases Figure 2.18(a). The figure shows the spot size of the laser mode on the gain structure as function of the cavity length for four different output coupler curvatures, black lines. As indicated by the gray lines, the thermal lens reduces the spot size even more. The largest spot size is obtained with a flat output coupler ($\text{ROC} = \infty$), where the mode is only controlled by the thermal lens.

![Figure 2.18: Influence of the thermal lens on the cavity mode size on the gain structure. Results for output couplers with four different radii of curvature (ROC) are shown. (a) The laser mode on the gain structure as function of the cavity length. At small cavity lengths it is challenging to obtain a large mode. (b) The laser mode on the gain structure as function of the thermal lens. For the $L = 5$ mm case, the mode decreases with the dioptric power of the thermal lens.]()

2.7 Typical cw lasing performance

For evaluation of our VECSEL gain structures, it is important to thoroughly evaluate the cw lasing performance and the thermal lensing. We use different laser test setups and evaluate the performance initially with a simple linear cavity with a curved output coupler (as discussed in the previous section). The structure is pumped under an angle of $45^\circ$. In order to have an almost circular pump spot on the gain structure, we use two cylindrical lenses to shape the pump. The standard test setup, which was also later used for the MIXSEL uses a commercially available 5 W free-space 808-nm laser, having a $M^2 < 20$ in both directions.
The gain structure temperature is stabilized using two Peltier elements connected with a PID controller. At low temperatures (< 5°C) dry nitrogen was used to prevent condensation on the chip.

In Figure 2.19 we show the output power of a standard VECSEL as function of the pump power and heat sink temperature. The structure used here is an as-grown structure, thus having a 600 μm substrate between the gain layers and the heat sink. The threshold is around 0.5 W. At higher temperatures (e.g. 15°C) a roll over is visible.

Figure 2.19: Output power as function of pump power and temperature. The VECSEL is clearly more efficient at lower temperatures. At higher temperatures, a rollover is visible.
In Figure 2.20 the peak wavelength is shown for the same pump powers and temperatures. Increasing the heat sink temperature leads to a red shift. Increasing the pump power also leads to a red shift because this indirectly increases the temperature.

Figure 2.20: Peak wavelength as function of pump power and temperature.

The output power of as-grown structures is usually limited below 1 W because of the bad thermal impedance of the substrate. Substrate removal dramatically increases the performance. Using a processed VECSEL we achieved record high 20.2 W continuous wave output power in a fundamental transverse mode [17]. As heat spreaders we used commercial chemical-vapor-deposition (CVD) diamonds with a thickness of 530 µm. The heat sink was temperature stabilized by a water-cooled high power Peltier element at –20°C. The gain structure was pumped with 55 W on a circular spot with a radius of 240 µm. The 50 mm linear cavity had an output coupler with a transmission of 0.7% and a radius of curvature of 500 mm. The 20.2 W continuous-wave output beam was almost diffraction limited (M² < 1.1) and had a center wavelength of 960 nm. The laser is very efficient with a slope efficiency of 49.1%, a pump threshold of 4.4 W and an overall optical-to-optical efficiency of 43.2%.
Chapter 3

Passive Mode Locking

There are several techniques to obtain short pulses directly from a laser. The obvious solution seems the direct modulation of the gain. Pulse durations as short as 40 ps have been shown by active modulation of the current through a VCSELs [49]. Much shorter pulses can be obtained by passive loss modulation. In general, we can distinguish between four different regimes of laser operation: continuous-wave (cw), Q-switching, cw modelocking and Q-switched modelocking (QML), see Figure 3.1.

![Figure 3.1: Different regimes of laser operation. The dashed lines represent the average power level which is equal in each graph.](image-url)

Q-switching is a technique to obtain short (typically nanosecond) pulses from a laser by modulating the intracavity losses. By changing the losses the quality factor Q of the resonator will change. Initially the losses are kept high to avoid lasing. During
this time the pump energy is accumulated in the gain medium. As the losses
decrease, the intracavity power builds up quickly saturating the gain. Q-switching
was first demonstrated in 1962 by McClung et al. [50]. Single longitudinal mode
operation using extremely short cavities has been shown to obtain pulse durations
below 100 ps [51].

Significantly shorter pulses can be obtained by cw modelocking. In this regime a
single pulse oscillates inside the cavity. Every time the pulse hits the output coupler a
part of the pulse leaves the cavity forming a periodic pulse train with a repetition
rate $f_{rep}$ given by

$$f_{rep} = \frac{c_0}{2L},$$

with $L$ the cavity length and $c_0$ the speed of light. In the case of cw modelocking
multiple longitudinal modes are involved. Since the pulse envelope is periodic in
time, the longitudinal modes have a frequency spacing exactly equal to the pulse
repetition rate. We distinguish between fundamental and harmonic modelocking. In
the case of fundamental modelocking a single pulse oscillates in the cavity, whereas
harmonic modelocking allows multiple pulses, thus enabling a repetition rate an
integer multiple of the fundamental case (3.1). Harmonic modelocking has several
disadvantages: it is hard to control the precise number of pulses, it is susceptible to
pulse drop out and has higher noise levels. The pulse energy fluctuates because
successive emitted pulses are not copies of a single cavity-internal pulse as in
fundamental modelocking (leading to higher intensity noise) and secondly the pulse
to pulse distance can vary (leading to higher timing jitter). In this work we focus only
on fundamental modelocking.

In the Q-switched modelocking (QML) regime, mode locking and Q switching
occur simultaneously. QML is often seen as instability in a solid-state laser, and the
pulse energies obtained by QML can easily damage intracavity elements like mirrors.
Especially for very high repetition rate solid-state lasers, it is challenging to avoid
QML, because of the low pulse energies and the small emission cross-section these
gain materials have [52, 53]. VECSELs have the potential to achieve high average
output power at high repetition rates. The high differential gain results in stronger
gain saturation, which limits the amount of energy that can be stored in the gain structure, which efficiently avoids QML.

In Section 3.1 three possible mechanisms of passive modelocking are discussed. In Section 3.2 saturation properties of a semiconductor saturable absorber are shown and in Section 3.3 the semiconductor saturable absorber mirror (SESAM) design is discussed. In Section 0 the stability region is addressed by simulations. Finally in Section 3.5 first modelocking results are presented using a saturable absorber suitable for integration in the VECSEL gain structure.

3.1 Mechanisms of passive mode locking

To enable modelocking a loss modulator is typically placed close to one end mirror inside the cavity to collect the laser light in short pulses around the temporal minimum of the loss modulation. In fundamental modelocking, only one pulse is circulating inside the laser cavity, and every time the short pulse hits the output coupler a small fraction is transmitted, producing an equidistant pulse train with a period defined by the round-trip time of a pulse inside the laser cavity. For example, for a repetition rate of 50 GHz we need a cavity length of 3 mm. In general, we distinguish between active and passive modelocking. In the first case, the loss modulator is actively driven with an electronic signal, in the second case, the loss modulator is a special material (i.e. a saturable absorber) that has lower loss for laser light with higher intensity. An incident laser pulse then produces its own loss modulation, thus referred to as passive modelocking. Passive modelocking has several advantages over active modelocking. No synchronization is needed between the loss modulator and the pulse repetition rate, furthermore, much shorter pulses can be generated because the dynamics in the saturable absorber are much faster than the switching speed of typical loss modulators.

Three common mechanisms for passive modelocking are shown in Figure 3.2: a fast saturable absorber in combination with weak gain saturation (e.g. a solid-state gain medium), a slow saturable absorber with weak gain saturation and a slow saturable absorber with strong gain saturation (e.g. dye or semiconductor gain). In all cases the net gain is positive during a short time window when the pulse passes.
3.1.1 **Fast saturable absorber**

A fast saturable absorber has a recovery time shorter than the pulse duration, therefore the loss can be approximated to be intensity dependent. An example of such a system is the Kerr lens mode locked (KLM) solid-state laser [54-56]. KLM uses a lens with an intensity dependent focal length (a Kerr lens) in combination with an aperture. In most cases, however, a soft-aperture is used, where the reduced mode size in the gain material improves the overlap with the pump beam and therefore the effective gain. A significant change in mode size is only achieved by operating the laser cavity near one of the stability limits of the cavity, making the laser more sensitive to mechanical vibrations and temperature changes. Another disadvantage is that KLM lasers are not self-starting, once running in continuous mode, the mode-locked operation has to be induced manually. This can be done by shaking a cavity mirror or using a SESAM. KLM has resulted in the shortest pulses directly generated by a laser oscillator with pulse durations below 6 fs [57, 58].

3.1.2 **Slow saturable absorber with constant gain**

For a slow saturable absorber the recovery time is slow compared to the pulse duration. The gain saturation is determined by the average power. As shown in Figure 3.2(b), the slow recovery of the absorber results in a net gain after the pulse. At first glance it seems that fluctuations behind the pulse are amplified and can lead

<table>
<thead>
<tr>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast saturable absorber</td>
<td>A lens with an intensity dependent focal length (a Kerr lens) in combination with an aperture.</td>
</tr>
<tr>
<td>Slow saturable absorber with constant gain</td>
<td>A lens with an intensity dependent focal length (a Kerr lens) in combination with an aperture.</td>
</tr>
</tbody>
</table>

Figure 3.2: Three typical modelocking mechanisms using a saturable absorber. (a) The recovery time of the saturable absorber is shorter than the pulse duration. In case of slow recovery we distinguish between (b) weak gain saturation, e.g. solid-state gain or (c) strong gain saturation, e.g. semiconductor gain.
to instabilities, however stable operation in this regime is possible, because the growing noise behind the pulse will be swallowed after some time by the pulse. The absorber only absorbs the leading edge of the pulse, causing the pulse to move backwards each roundtrip. Numerical simulations have shown that in this regime the pulses can be at least twenty times shorter than the recovery time [59].

By using additional stabilization, much shorter pulse durations can be obtained. Soliton pulses can be formed when self-phase modulation (SPM) and group delay dispersion (GDD) are balanced in the laser cavity. In this case the pulse duration is determined by the SPM coefficient, the total intra cavity GDD and the pulse energy. The saturable absorber is not required for the pulse shaping, it is mainly responsible for starting and stabilizing the modelocking process.

3.1.3 Slow saturable absorber with dynamic gain saturation

In the case of a slow saturable absorber with dynamic gain saturation, both gain and absorber saturate and have a slow recovery compared to the pulse duration. Stable modelocking requires the absorber to saturate at lower pulse energies than the gain, i.e.

$$\frac{E_{\text{sat,abs}}}{E_{\text{sat,gain}}} \ll 1.$$  \hspace{1cm} (3.2)

In this regime, the absorber losses drop faster than the gain and a short window is formed where the gain is higher than the losses, as is shown in Figure 3.2(c). This regime is typical for lasers where both gain and absorber are based on the same type of material.

The lasers described in this thesis all rely on mode locking with a slow saturable absorber and dynamic gain saturation. For starting and stabilizing the mode locking, we use semiconductor saturable absorber mirrors (SESAM), for which the absorber parameters can be custom-designed over a wide range to match the requirements for modelocking.
3.2 Semiconductor saturable absorber

Semiconductors are ideally suited as saturable absorbers. They saturate at intensities typically found in solid-state and semiconductor lasers. Engineering over a broad wavelength range is possible, moreover the recovery dynamics can be controlled, for example with the defect density [60].

The semiconductor (which can be bulk, QWs, or QDs) absorb the photons when the photon energy is larger than the bandgap. After 60 - 300 fs the carriers thermalize and form a thermal equilibrium among themselves. On a longer timescale, typically between 10 ps - 10 ns, depending on the mobility of the carriers and the defect density, the carriers recombine and the absorber is recovered. A semiconductor is completely saturated when the absorption is equal to the stimulated emission. The two time scales are very helpful. The longer time constant enables the self-starting, whereas the fast time constant reduces the pulse duration.

In this section I show a simple rate equation, which we used to derive the saturation function, used for fitting the nonlinear reflectivity measurements. Several corrections are made for better agreement with real SESAMs. Moreover I discuss the relation between the macroscopic SESAM parameters and the microscopic material parameters.

3.2.1 Nonlinear saturation by short pulses

We start the derivation with a rate equation valid for a semiconductor close to the quasi equilibrium [47], neglect carrier diffusion and assume a linear dependence between the amplitude gain and the carrier density $N$

$$\frac{dN(z,t)}{dt} = \Lambda - \gamma_{nr} N - B N^2 - a (N - N_0) \frac{2I}{\hbar \omega}. \quad (3.3)$$

The first term is the optical pumping rate $\Lambda$, which is zero in the case of a saturable absorber. The second term represents the nonradiative recombination due to capture by defects in the semiconductor with a decay constant $\gamma_{nr}$, and the third term is spontaneous emission with the parameter $B$. Because the pulse durations are sufficiently short, we neglect both recombination terms during the pulse interval. The third term represents absorption ($N < N_0$) or stimulated emission ($N > N_0$), with $a$ being the differential gain coefficient, $N_0$ the transparency carrier density and $I$ the
time dependent pulse intensity. The absorber is completely saturated when $N = N_0$. Rewriting (3.3) in terms of the intensity absorption $\alpha = -2g = -2a(N - N_0)$, instead of the dependent variable $N$ we obtain

$$\frac{d\alpha(z,t)}{dt} = -\frac{2a}{h\omega} \alpha(z,t)I = -\frac{1}{F_{\text{sat}}} \alpha(z,t)I,$$

(3.4)

with $F_{\text{sat}} = h\omega / (2a)$ the saturation fluence expressed in $\mu J/cm^2$. Our aim is to solve this equation in a thin slab with thickness $d$ as depicted in Figure 3.3 to compute the absorbed energy density.

![Figure 3.3: Thin slab with thickness $d$ used to model the saturable absorber.](image)

Still missing is the differential equation to govern the propagation and absorption of the pulse. By using a coordinate system moving with the group velocity (i.e. the pulse arrives at every given $z$ plane at the same time), the system of differential equations becomes

$$\frac{\partial I(z,t)}{\partial z} = -\alpha(z,t)I(z,t),$$

(3.5)

$$\frac{\partial \alpha(z,t)}{\partial t} = -\frac{\alpha(z,t)}{F_{\text{sat}}} I(z,t).$$

(3.6)

With the initial conditions $\alpha(z, 0) = \alpha_{\text{lin}}$ and $I(0, t) = I_{\text{in}}(t)$ this can be solved analytically (also shown in [61]). To solve the differential equations, it will be convenient to introduce an averaged absorption $\bar{\alpha}(t) = \frac{1}{d} \int_0^d \alpha(z,t)dz$. Equation (3.5) can be simplified by moving the intensity $I$ to the left hand side and integrating over the thin slab with respect to $z$, resulting in

$$I_{\text{out}}(t) = e^{-\bar{\alpha}(t)d} I_{\text{in}}(t).$$

(3.7)
This is exactly the result expected for a thin slab with constant absorption $\bar{\alpha}$ and thickness $d$. Substituting (3.5) in (3.6) and integrating over the slab gives

$$\frac{d}{dt} \frac{\bar{\alpha}(t)}{d} = \frac{1}{d} \frac{I_{\text{out}}(t) - I_{\text{in}}(t)}{F_{\text{sat}}}.$$  \hspace{1cm} (3.8)

Then we insert (3.7) in (3.8) and solve the equation by separation of variables, i.e. moving $\bar{\alpha}$ to the left side of the equality and integrating both sides with respect to $t$, which gives

$$\int_{\alpha_{\text{lin}}}^{\infty} \frac{d}{e^{-\bar{\alpha}} - 1} \alpha d\alpha = \int_{-\infty}^{\infty} \frac{I_{\text{in}}(t)}{F_{\text{sat}}} dt = \frac{F_{\text{in}}}{F_{\text{sat}}}.$$  \hspace{1cm} (3.9)

This basically relates the absorption after the pulse $\bar{\alpha}(\infty)$ with the input pulse fluence $F_{\text{in}}$. The saturated intensity transmission after the pulse, $T_{\infty} = \exp(-\bar{\alpha}(\infty)d)$ can be written as function of the input pulse fluence $F_{\text{in}}$

$$T_{\infty}(F_{\text{in}}) = \frac{T_{\text{lin}}}{T_{\text{lin}} - (T_{\text{lin}} - 1)e^{-F_{\text{in}}/F_{\text{sat}}}},$$  \hspace{1cm} (3.10)

with $T_{\text{lin}} = \exp(-\alpha_{\text{lin}}d)$ being the linear transmission. This expression is the optical transmission a small probe pulse would see after a strong pulse, and can be used for example in pump probe experiments, to obtain the saturation fluence $F_{\text{sat}}$. However, in many experiments one needs the transmission a pulse experiences itself. To obtain this, we compute $I_{\text{out}}$ from (3.7) and insert it in (3.8). After separation of variables we obtain $T_{\infty}(F_{\text{out}})$, together with (3.10) we eliminate $T_{\infty}$ and can compute the transmission of the pulse

$$T(F_{\text{in}}) = \frac{F_{\text{out}}}{F_{\text{in}}} = \frac{\ln\left[1 + T_{\text{lin}} \left(e^{F_{\text{in}}/F_{\text{sat}}} - 1\right)\right]}{F_{\text{in}}/F_{\text{sat}}}.$$  \hspace{1cm} (3.11)

This result is independent of the temporal shape of the pulse. Furthermore, it does not depend on the absorption parameters $\alpha$ and the thickness of the saturable absorber. Instead it depends on the linear transmission $T_{\text{lin}}$, which can be measured more easily.
3.2.2 **SESAM reflectivity**

The semiconductor saturable absorbers are integrated into mirror structures, resulting in devices that reflect more light for higher incident pulse energies. Three modifications on the model function are needed for better agreement with real SESAMs: the small nonsaturable losses, the induced absorption that causes extra losses at high pulse intensities and the finite spot size of the beam. In addition, we change notation since we typically use the saturable absorber in reflection, and write \( R \) instead of \( T \). Because of the reflection we obtain a standing wave in the absorber. When the absorber is much smaller than the wavelength, the standing wave effect can be ignored. The interference, however, can change the magnitude of the field. This only changes the *extrinsic* saturation fluence \( F_{\text{sat}} \) and the *extrinsic* linear reflectivity \( R_{\text{lin}} \) (more details are given in Section 3.3.2).

A real absorber always has some nonsaturable losses, which means that the reflectivity will never be 100\%, independent of the incident fluence. Several mechanisms that cause these losses are: transmission losses through the mirror, nonsaturable defect absorption, free-carrier absorption, Auger recombination and scattering losses from rough surfaces. The nonsaturable losses are taken into account by a multiplying with a maximum reflectivity \( R_{\text{ns}} \).

To take into account induced absorption at higher fluences the model function is multiplied with a correction factor \( \exp(-F/F_2) \), where \( F_2 \) is the induced absorption coefficient

\[
R(F) = R_{\text{ns}} \frac{\ln\left[1 + R_{\text{lin}}/R_{\text{tot}}(e^{F/F_{\text{sat}}} - 1)\right]}{F/F_{\text{sat}}} e^{-F/F_2} .
\]  

(3.12)

One source of induced absorption is two-photon absorption (TPA), in this case the induced absorption coefficient can be computed using [62]

\[
F_2 = \frac{\tau_p}{0.585 \int \beta_{\text{TPA}}(z) n^2(z) |\vec{E}(z)|^4 \, dz},
\]  

(3.13)

with \( \vec{E}(z) \) the normalized electric field in the structure, \( n \) the refractive index and \( \beta_{\text{TPA}} \) the TPA coefficient expressed in cm/GW. The induced absorption also depends on the pulse length \( \tau_p \), for fs-pulses the induced absorption is very strong and can be
approximated by TPA only, whereas for ps-pulses the induced absorption is weaker, however stronger than expected from TPA alone [62]. The physical origin of this additional induced nonlinear absorption in the ps-regime remains to be clarified.

Until now, $R$ and $F$ are still a function of the spatial coordinates $x$ and $y$. To obtain the reflectivity from a pulse with a Gaussian beam profile and the fluence defined as $F_p = E_p/\pi w^2$, we have to integrate (3.12) over the entire beam profile and obtain [63]

$$R^{\text{Gauss}}(F_p) = \frac{1}{2F_p} \int_0^{2F_p} R(F) \, dF, \quad (3.14)$$

which can only be computed numerically.

The influence of these three corrections is graphically illustrated in Figure 3.4(a). The dashed lines indicate the reflectivity without the induced absorption, as expected for long picosecond pulses (i.e. without induced absorption) and the solid lines show the effect of the induced absorption at higher pulse fluences. By integrating the model function according to (3.14) the measured reflectivity is more averaged, resulting in less steep slopes as indicated by the black lines. Although several assumptions in the derivation of the fit function are made, the model function has proven to be suited to describe the nonlinear behavior of real SESAMs. A typical SESAM measurement with a fitted model function is shown in Figure 3.4(b).

![Figure 3.4](image-url)

Figure 3.4: Corrections on the model function needed for better agreement with real SESAMs. (a) An absorber always has some nonsaturable losses and induced absorption at higher fluences (solid lines vs. dashed lines). Measured with a Gaussian beam the slope becomes less (black lines vs. gray lines). (b) These corrections result in good agreement with measurements.
3.2.3 **Semiconductor transparency**

In order to optimize the absorber properties like saturation fluence and modulation depth, a better understanding of the saturation is needed. We will see that the product of modulation depth times the saturation fluence is proportional to the transparency density \( N_0 \) and therefore strongly related to the density of states. The transparency density \( N_0 \) depends on the material composition, wavelength, temperature and confinement. For bulk GaAs at 300 K, the saturation requirements are depicted in Figure 3.5.

![Figure 3.5: Bulk GaAs transparent 10 nm above the bandgap. On the left the energy dispersion is shown using the effective mass approximation. In the middle the Fermi functions for conduction and valence band at transparency are given. On the right the density of states is shown. Note that at transparency the Fermi levels are separated by exactly the photon energy.](image)

On the left, the energy dispersion for bulk GaAs is shown using the effective mass approximation. Since the curvature of the valence band is less, the hole effective mass is heavier than the electron effective mass (approximately 7 times). The arrow labeled with \( \hbar \omega \) indicates the optical transition connecting identical \( k \)-points in both bands.
In thermal equilibrium the Fermi level is inside the bandgap. After pumping the semiconductor the thermal equilibrium is disturbed, however the conduction-band electrons and valence-band holes are in thermal equilibrium among themselves. A quasi-equilibrium is formed on a timescale 100 fs - 10 ps. The semiconductor is transparent if the probability for stimulated emission equals the probability for absorption. One can show that this condition is fulfilled when the separation between the quasi-Fermi levels equals the photon energy, i.e. 

$$E_{fc} - E_{fv} = \hbar \omega. \quad (3.15)$$

The number of electrons should equal the number of holes, i.e. $n = p$. The carrier densities are computed with density of states $D(E)$ and the Fermi functions $f_c$ and $f_v$ for conduction and valence band, respectively

$$n = \int_{E_c}^{\infty} D(E) f_c(E) \, dE \quad \text{and} \quad p = \int_{-\infty}^{0} D(E) [1 - f_v(E)] \, dE, \quad (3.16)$$

with the Fermi functions $f_c$ and $f_v$ depending on the Fermi energies $E_{fc}$ and $E_{fv}$ respectively. The Fermi levels can be computed by numerically solving (3.15) and (3.16). In the example above, we chose a wavelength of 863 nm, 10 nm below the bandgap. With the parameters listed in Table 3.1, we obtained a transparency density of $N_0 = 2.2 \cdot 10^{18} \, \text{cm}^{-3}$.

<table>
<thead>
<tr>
<th>property</th>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>bandgap</td>
<td>$E_g$</td>
<td>1.42 eV (873 nm)</td>
</tr>
<tr>
<td>electron effective mass</td>
<td>$m_c/m_0$</td>
<td>0.07</td>
</tr>
<tr>
<td>hole effective mass</td>
<td>$m_c/m_0$</td>
<td>0.5</td>
</tr>
<tr>
<td>photon energy</td>
<td>$\hbar \omega$</td>
<td>1.44 eV (863 nm)</td>
</tr>
<tr>
<td>carrier concentration</td>
<td>$N_0, n, p$</td>
<td>2.2-$10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>CB Fermi level</td>
<td>$E_{fc}$</td>
<td>1.47 eV</td>
</tr>
<tr>
<td>VB Fermi level</td>
<td>$E_{fv}$</td>
<td>0.034 eV</td>
</tr>
</tbody>
</table>

Table 3.1: Parameters used to compute the transparency density.
It turns out that the conduction band Fermi energy is inside the conduction band whereas the valence band Fermi energy is still inside the bandgap. Using the computed Fermi energies, the probability to find an electron in the conduction band is

\[ f_c(E_c + \Delta E_c) = 80\%, \quad (3.17) \]

and the probability to find a hole in the valence band is

\[ 1 - f_v(-\Delta E_v) = 20\%. \quad (3.18) \]

This means that the conduction band is stronger saturated than the valence band, as expected, because of the smaller density of states.

The fluence needed to obtain transparency can be computed by multiplying the transparency density by the photon energy and the thickness of the layer. Assume we have a 20 nm thick piece of GaAs, the transparency fluence \( F_t \) needed to generate these carriers is

\[ F_t = d N_0 \hbar \omega \approx 1 \text{ \mu J/cm}^2. \quad (3.19) \]

We can also express the pulse fluence needed for transparency in terms of (extrinsic) SESAM parameters. The absorbed pulse energy per area for a pulse with fluence \( F \) is equal to \( F [1 - R(F)] \), for a saturated SESAM \( (F \to \infty) \) we obtain using (3.12)

\[ F_t = \lim_{F \to \infty} F [1 - R(F)] = F_{\text{sat}} \ln \left( \frac{1}{R_{\text{lin}}} \right) \approx F_{\text{sat}} \ln (1 + \Delta R) \approx F_{\text{sat}} \Delta R. \quad (3.20) \]

Together with (3.19) we obtain

\[ F_{\text{sat}} \Delta R \approx d N_0 \hbar \omega, \quad (3.21) \]

which relates the SESAM parameters (which we can measure) with the intrinsic property the transparency density. For example a SESAM with 20 nm bulk GaAs as absorber having a modulation depth of 1% would have a saturation fluence of 100 \( \text{\mu J/cm}^2 \) according to (3.21).
There are several possibilities to reduce the saturation fluence and the modulation depth simultaneously, which all rely on the reduction of the density of states. One option is to operate closer to the bandgap. Wavelength dependent measurements on QW-SESAMs by Grange et al. have shown that the modulation depth $\Delta R$ is constant, whereas the saturation fluence $F_{\text{sat}}$ decreases for photon energies closer to the bandgap [64]. Another option is the choice of a material with a broad absorption edge like GaInNAs [65], which has a measured transparency fluence of $F_{\text{sat}} \Delta R = 20 \text{nJ/cm}^2$. In QW absorbers (3.21) can be written as $F_{\text{sat}} \Delta R \approx N_0 \omega$, with $N_0$ the two dimensional transparency density expressed in cm$^2$. One step further is using quantum dots to reduce the density of states even more. For QDs the product can be written as $F_{\text{sat}} \Delta R \approx \gamma N_0 \omega$, with $N$ the dot density and $\gamma$ the average carriers needed per dot to obtain transparency. For example $\gamma = 1$ at 960 nm and having a dot density of $N = 1 \cdot 10^{11}$ cm$^{-2}$ results in $F_{\text{sat}} \Delta R = 20 \text{nJ/cm}^2$, which is comparable to GaInNAs QWs. The presented QD-SESAMs in Chapter 5 have a transparency fluence of 36 nJ/cm$^2$.

### 3.3 SESAM design

SESAMs typically have a DBR and an absorber section. In some cases the SESAM has a dielectric top coating to enhance the electric field or reduce the group delay dispersion [66]. In this thesis we only consider the resonant and antiresonant case, without top coating. The difference between a resonant and an antiresonant device is the thickness of the section containing the absorber.

#### 3.3.1 DBRs

A distributed Bragg reflector (DBR) serves as high reflector. The DBR contains quarter-wave layers of a low-index material (AlAs, $n_{\text{AlAs}} = 2.96$ at 960 nm) and a high-index material (GaAs, $n_{\text{GaAs}} = 3.54$ at 960 nm). By increasing the number of pairs the bandwidth remains constant, however the reflectivity increases. One has to take into account that a resonant SESAM has a transmission up to 12 times higher compared to an antiresonant SESAM with the same number of Bragg pairs. The reflectivity for different structures is shown in Table 3.2. Since most of our SESAMs are resonant we have to use at least 30 mirror pairs, thus having 0.03% mirror losses, which is low for the laser cavity compared to the output coupling of $\approx 0.5\%$. 
<table>
<thead>
<tr>
<th>mirror pairs</th>
<th>antiresonant</th>
<th>resonant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R ) (%)</td>
<td>( T ) (%)</td>
</tr>
<tr>
<td>20</td>
<td>99.91</td>
<td>0.09</td>
</tr>
<tr>
<td>25</td>
<td>99.99</td>
<td>0.01</td>
</tr>
<tr>
<td>30</td>
<td>100.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 3.2: Reflectivity and transmission of resonant and antiresonant DBRs.

3.3.2 Resonance and group delay dispersion

On top of the DBR-mirror is the saturable absorber section. The absorber is embedded between spacer layers. The first spacer layer after the mirror is chosen such that the absorber is in the anti-node of the standing wave pattern of the electrical field, see Figure 3.6. The second spacer layer determines the field enhancement. By making the roundtrip phase change in the last layer \( \pi(2n - 1) \), the structure is antiresonant and by making the roundtrip phase \( 2\pi n \) the structure is resonant, see Figure 3.6.

![Figure 3.6: Refractive index pattern and field enhancement of an antiresonant SESAM (a) and a resonant SESAM (b).](image-url)
Like for the VECSEL gain structure, we also define an enhancement factor $\xi_{\text{abs}}$ for the SESAM

$$\xi_{\text{abs}} = |\mathcal{E}(z_{\text{abs}})|^2,$$

(3.22)

with $z_{\text{abs}}$ the position of the absorber. In the antiresonant SESAM the enhancement is $\xi_{\text{abs}} = 4/n^2 \approx 0.32$, while in the resonant case $\xi_{\text{abs}} = 4$. The (extrinsic) modulation depth is proportional to the enhancement factor $\Delta R \propto \xi_{\text{abs}}$ and the (extrinsic) saturation fluence is inverse proportional $F_{\text{sat}} \propto 1/\xi_{\text{abs}}$. The product $F_{\text{sat}} \Delta R$ remains constant.

In Figure 3.7(a) the field enhancement $\xi_{\text{abs}}$ is shown as function of the wavelength. The resonant structure is extremely wavelength sensitive, having the advantage that one can tune the modulation depth with the wavelength, on the other hand the structure is more difficult to grow, a 1% mismatch in the layer thickness during growth will shift the resonance by 10 nm. The gray line indicates the mirror reflectivity, which has a bandwidth of over 80 nm, the dashed line is the resonantly designed and the solid line is the antiresonantly designed structure.

In Figure 3.7(b) the group delay dispersion is shown. In the resonant case the reflected beam has a strong wavelength dependent phase and therefore a larger GDD. Furthermore, the resonant design has a higher electrical field inside the structure resulting in more two-photon absorption and a smaller $F_2$ parameter.
A nonlinear reflectivity measurement of an antiresonant and resonant SESAM, having the same saturable absorber is shown in Figure 3.8. The very accurate measurement setup is described in detail in Chapter 4, the laser source we used is a Ti:sapphire fs-laser. The difference in modulation depth, saturation fluence and induced absorption is clearly visible. The gray lines show the SESAM curves without induced absorption, thus the reflectivity for long ps-pulses.

Figure 3.8: Example of an antiresonant (solid curves) and a resonant (dashed curves) SESAM having the same saturable absorber. The black curves show the least-square fit. The gray curves show the fit function without induced absorption, thus the reflectivity obtained by long ps-pulses.

### 3.3.3 Modelocking instabilities

There are several challenges that can prevent stable mode locking. The most important instabilities in VECSELs are QML, harmonic modelocking and the tendency towards cw. The flexibility of the SESAM allows optimizing parameters for its specific application. The optimum parameters for the SESAM strongly depend on the laser system.

Hönninger et al. have studied the QML stability limits [53]. Stable cw mode locking is obtained if the pulse energy respects the inequality

\[
E_p^2 > E_{\text{sat,gain}} E_{\text{sat,abs}} \Delta R,
\]

where \(E_p\) is the pulse energy, \(E_{\text{sat,gain}}\) and \(E_{\text{sat,abs}}\) are the saturation energies of gain and absorber respectively and \(\Delta R\) the modulation depth. At high repetition rates this
is a major challenge because for the same average power the pulse energy $E_p$ decreases, especially for solid-state lasers with a small gain cross section and therefore a large gain saturation $E_{\text{sat, gain}}$. QML can be suppressed in many cases, if a SESAM with low modulation depth ($\Delta R < 1\%$) and low saturation fluence is employed [66, 67]. Semiconductor lasers have much weaker Q-switching tendencies due to their high differential gain and thus a small $E_{\text{sat, gain}}$.

Induced absorption can reduce modelocking instabilities towards QML [62]. However, the induced absorption can also limit the maximum achievable pulse energy, if the roll-over occurs at lower pulse fluence [68]. With the SESAM design we can adjust the magnitude of the induced absorption. The TPA can be computed with (3.13), where the two-photon absorption parameter $\beta$ strongly depends on the material. GaAs has a high two-photon absorption ($\beta_{\text{GaAs}} = 20 \text{ cm/GW}$), whereas AlAs has a negligible TPA according to [69]. The induced absorption parameter $F_2$ can be reduced by using more GaAs, instead of AlAs.

Especially at low repetition rates, multiple pulsing can destabilize the laser. Saarinen et al. observed that number of pulses circulating in the cavity increases with pump power [70]. At a certain pump level, two pulses with lower energy have a gain advantage over a single pulse with higher energy. Scaling to lower repetition rates is therefore limited by harmonic modelocking, as the QWs are not able to store much energy because of the short carrier lifetime and two equally spaced pulses will therefore have a higher gain than a single pulse.

Another type of instability is the tendency towards cw operation. To saturate the absorber sufficiently the pulse energy should be larger than the saturation energy of the absorber: $E_p > E_{\text{sat, abs}}$. Moreover, in a laser with dynamic pulse-to-pulse gain saturation the absorber additionally needs to saturate faster than the gain for stable modelocking: $E_{\text{sat, abs}} \ll E_{\text{sat, gain}}$. These two requirements can be solved by a saturable absorber with a small saturation fluence.
3.4 Pulse shaping simulations

In this thesis a MATLAB program was implemented to simulate the evolution of pulses in a modelocked laser. The purpose is to explore the parameter range for stable modelocking and find the ideal parameters to obtain short pulses. No attempt is made to be exhaustive, however emphasis is placed on a basic understanding. The simulation is based on numerical iteration of the pulse inside the cavity until a stable solution is found, similar to the simulations described by Paschotta et al. [71]. Neither transverse effects (no Gaussian intensity profile of the beam and a flat gain profile) nor longitudinal effects (no propagation of waves) are taken into account. A pulse, defined on a time grid \([-T/2, T/2]\), interacts with the cavity elements, one after the other. Starting with an initial pulse (which can be noise) numerous cavity roundtrips are simulated until a stable solution is obtained.

We use the slowly varying envelope approximation to describe the time evolution of the pulse

\[
\begin{align*}
\hat{E}(t) &= \text{Re}\{A(t)e^{iw_0t}\} \\
P(t) &= |A(t)|^2
\end{align*}
\]

with \(\hat{E}(t)\) the time varying electrical field, \(P(t)\) the instantaneous power and \(\omega_0\) the reference frequency. The discretization time step \(\Delta T\) is chosen between the optical period and the pulse duration. Supposed that \(A(t)\) is almost constant within \(\Delta T\) the error is negligible and the approximation is good.

The model contains cavity elements which describe the effect of gain, SESAM and output coupler, see Figure 3.9. The effect of an optical element is applied to the pulse by so-called operators in either time or frequency domain, whichever is more suitable. A fast-Fourier transform (FFT) is used to convert the pulse into the other domain. The following subsections describe the used operators.
3.4.1 Gain filter

The purpose of the gain filter is to simulate the spectral behavior of the gain. The gain filter determines the wavelength of the output pulses, it also influences the pulse duration, the smaller the bandwidth the longer the pulses. In the real devices the spectral gain is determined by the gain enhancement and the intrinsic gain, as shown in Equation (2.13). The band pass filter we use in the simulations has a parabolic shape centered at 970 nm with a FWHM of 5 nm. By doubling the gain bandwidth we could obtain 20% shorter pulses.

3.4.2 Gain and absorber saturation

For both gain and absorber saturation we use the same operator. The dynamic saturation is treated in time domain using a differential equation based on (3.3)

$$\frac{dg(t)}{dt} = g_0 - \frac{g(t)}{\tau} - g(t)\frac{P(t)}{E_{\text{sat}}}, \quad (3.25)$$

where $g(t)$ is the dimensionless wavelength-independent gain, $g_0$ is the small signal gain, $\tau$ is the recombination time constant and $E_{\text{sat}}$ is the saturation energy. The small signal gain $g_0$ depends on the pumping rate $\Lambda$, differential gain $a$, transparency density $N_0$ and the recombination rate $\gamma_{\text{nr}}$. For the gain structure we have a positive gain $g_0 > 0$, for the saturable absorber the small signal gain can be approximated with $g_0 = -\Delta R/2$. Because of the saturation of gain and absorption also the real part of the refractive index changes which causes a nonlinear phase change. The complex amplitude reflectivity of gain and absorber is computed using

$$r(t) = \exp[(1-i\alpha_{\text{lev}})g(t)], \quad (3.26)$$

with $\alpha_{\text{lev}}$ the linewidth enhancement factor. The phase change affects the frequency spectrum in a similar way as self phase modulation (SPM).
In case of strong saturation we can take advantage of this nonlinear phase change [71]. The gain structure and the SESAM have a different linewidth enhancement factor because they are used at a different operation point, moreover the sign of the phase change is opposite. We expect the phase change of the SESAM to be dominant because of the larger modulation. By applying the right amount of GDD, we enter a regime called soliton modelocking, in which much shorter pulses can be obtained and the pulse duration is determined by the SPM and GDD coefficients. Until now this theory is not experimentally verified.

### 3.4.3 Group delay dispersion

Group delay dispersion is important in a modelocked laser cavity, as it determines the pulse duration and shrinks the stability region. If not compensated properly the pulse duration will increase every roundtrip. Like the gain filter operator, the GDD will be applied in the frequency domain. The phase change as function of radial frequency is given by

$$\varphi(\omega) = \frac{1}{2} D(\omega - \omega_0)^2,$$

(3.27)

with $D$ the GDD coefficient expressed in fs$^2$. Although gain structure, SESAM and etalon (used for wavelength tuning) have wavelength dependent group delay dispersion, we implemented it as wavelength independent in order to change wavelength and dispersion independently.

### 3.4.4 Additional operators

In this section two operators are described that do not influence the final result but are important for the numerical stability and the pulse buildup.

The first operator needed is the noise operator. There are several sources of quantum noise in the cavity, for example gain and SESAM but also the output coupler is a noise source because of the discrete nature of the photons. We also have technical noise, caused by fluctuations of the cavity length. The noise sources are important because they initiate modelocking operation. The noise operator adds random (and statistically independent) complex amplitudes with a variance $\sigma^2 = P/2$ to the amplitudes of the time trace. Typical noise powers we use are around 1 nW.
Additionally we use a center operator to keep the pulse peak at $t = 0$. Because the SESAMs absorbs the leading edge of the pulse, the pulse shifts backwards, eventually resulting in a slightly lower pulse repetition rate. The center operator shifts the peak to the center and is applied only every 10 roundtrips to increase computation speed.

### 3.4.5 Simulation results

We did extensive simulations with the model. Normally we start iterating with an initial pulse shape close to the expected output pulse (e.g. a sech$^2$). However, the model is capable of simulating the complete buildup process as shown in Figure 3.10. The used saturation fluence is 500 and 10 $\mu$J/cm$^2$ for gain and absorber respectively. The cavity length is 3 cm, corresponding to 5 GHz. After 5000 roundtrips the average power is stabilized and the pulse duration is 0.9 ps.

![Figure 3.10: Simulated pulse buildup in a passively modelocked VECSEL, the repetition rate is 5 GHz. The output pulse is 0.9 ps. After 5000 roundtrips the average output power is stable.](image-url)
Stable modelocking is only possible when short pulses have a gain advantage over continuous wave operation. An important role is played by the saturation fluence (or for a given spot size the saturation energy) of the saturable absorber. A saturable absorber should saturate faster than the gain, e.g. a stable situation is depicted in Figure 3.11(a). The modelocking stability and pulse duration is studied as function of the ratio $E_{\text{sat,abs}}/E_{\text{sat,gain}}$, see Figure 3.11(b). The dots indicate the pulse duration for stable modelocking and the lines indicate the corresponding average powers. In the simulation we chose the spot size on both gain and SESAM to be 100 $\mu$m, and the saturation fluence on the gain was fixed at $F_{\text{sat,gain}} = 500$ $\mu$J/cm$^2$. We used a total cavity GDD of 500 fs$^2$. The simulations were done with two different modulation depths, $\Delta R = 0.5\%$ (black) and $\Delta R = 1\%$ (gray).

![Figure 3.11: Saturation of the gain structure and the SESAM. (a) The gray dashed curve is the power profile of the pulse, the black line is the gain saturation and the gray line is the SESAM, which saturates faster. (b) The average output power (lines) and pulse duration (dots) as function of the ratio $E_{\text{sat,abs}}/E_{\text{sat,gain}}$. Two different modulation depths are examined: 0.5% (black) and 1% (gray).](image)

The simulations show that the saturation fluence of the absorber should be at least ten times smaller than the saturation fluence of the gain. Higher modulation depth results in a larger stability region and makes shorter pulses possible, however if the SESAM is not completely saturated the average output power drops because of the larger losses.
3.4.6 Outlook

To reproduce the exact modelocking behavior of the VECSEL, an improved model and more accurate parameters are needed. Parameters like the saturation energy of the gain and the linewidth enhancement factors can be extracted from the real devices. There are several possibilities to improve the model. For example adding Auger recombination to the rate equation (3.3), which cannot be neglected at higher carrier densities. The spectral shape of the gain, which is assumed parabolic now, can be replaced with simulations of the intrinsic QW gain and multiplied with the gain enhancement $\Gamma$. To improve the material response, e.g. taking into account spectral hole burning, one can implement the response of the gain and absorber by using an infinite impulse response digital filter as shown before by Kreuter et al. [72].

3.5 Towards absorber integration

As shown in the previous section, the condition for stable modelocking is given by

$$\frac{E_{\text{sat,abs}}}{E_{\text{sat,gain}}} = \frac{A_{\text{abs}} F_{\text{sat,abs}}}{A_{\text{gain}} F_{\text{sat,gain}}} < 0.1,$$

with $A_{\text{abs}}$ and $A_{\text{gain}}$ the mode areas on gain and absorber. There are two possibilities to satisfy this inequality. In the past (with QW-SESAMs) we choose a smaller spot size on the SESAM than on the gain structure. However integration of both elements in a single structure is not possible due to the different mode areas. With low $F_{\text{sat}}$ QD saturable absorbers, we can resolve the saturation issue. An important milestone for operation with identical spot sizes was the demonstration of 100 mW average output power at 25 GHz [73], which was the crucial experiment that had to work before an integration of the absorber could be attempted.

3.5.1 Modelocking at 25 GHz

The experimental setup uses a standard v-shaped cavity with the QD-SESAM and output coupler as end mirrors and an InGaAs-QW VECSEL as folding mirror. We used a 0.7% output coupler with a radius of curvature of 200 mm, which gives mode radii of about 95 $\mu$m on both SESAM and gain structure. A 20 $\mu$m thick, uncoated fused silica etalon is used to tune the wavelength. Pumping the VECSEL with 3.2 W at 808 nm gives an average output power of 108 mW. The optical spectrum is centered at 952.2 nm and has a FWHM of 0.20 nm, see Figure 3.12. The repetition rate
is 25.3 GHz. The time bandwidth product is 0.331, which is 1.05 times the transform limit of a sech\(^2\) pulse. The intracavity pulse fluence is 2.2 \(\mu J/cm^2\).

![Figure 3.12: Dataset taken at a repetition rate of 25 GHz with 108 mW average output power. The center wavelength is 952 nm with a FWHM of 0.2 nm, together with the pulse duration of 4.9 ps, this gives a time bandwidth product is 0.331, which is 1.05 that of a sech2.]

### 3.5.2 Modelocking at 50 GHz

Improving the laser test setup enabled us to further increase the repetition rate [30]. The 3.7 W pump light is incident on the gain structure at a 45° angle in the vertical plane, which allows for a more compact cavity in the horizontal plane. We achieve 102 mW average output power at a 50-GHz repetition rate, the pulse characterization is shown in Figure 3.13. The longitudinal modes in the optical spectrum are clearly visible. The modes are spaced by exactly the repetition rate. An algorithm, taking into account the internal filter of the optical spectrum analyzer, computes the position and magnitude of the single modes, indicated in the graph with the circles. These circles are fitted with sech\(^2\) function to compute the FWHM of the optical spectrum. The flat output coupler has a transmission of 1.6%. The time-bandwidth product is 0.38, which is 1.2 times the transform limit. The mode radii on the gain
structure and on the SESAM were approximately 62 μm, from which one can calculate the intracavity pulse fluence to be around 1.1 μJ/cm². The M² was 1.25 and 1.13 in the horizontal and vertical axes, indicating that the beam quality was reasonably close to the diffraction limit.

Figure 3.13: Pulse characterization of a 50 GHz VECSEL. The 3.3-ps pulses have an optical spectrum centered at 958.5 nm and a FWHM of 0.36 nm.
Chapter 4

SESAM Characterization

Precise knowledge of the nonlinear optical reflectivity is required to optimize SESAMs for self-starting passive modelocking at record high repetition rates or pulse energies. In this chapter, we discuss a new method for wide dynamic range nonlinear reflectivity measurements and describe the pump-probe setup we use to measure the temporal response of the SESAMs. These methods were the basis of the QD-SESAM optimization presented in Chapter 5.

Previously, Haiml et al. demonstrated a measurement system for the optical characterization of semiconductor saturable absorbers [63]. The core of the setup is a beam splitter (an uncoated small-angle wedged glass plate) in front of the SESAM (see Figure 4.1). The reflection on the front side ($A$) is proportional to $P_{in}$ and the reflection on the back side ($B$) is proportional to $R \cdot P_{in}$. The reflectivity of the SESAM is $R = B / A$ and can be computed as function of the incident pulse fluence, which is changed by a variable attenuator through a combination of a half-wave plate, a polarizer and an acousto-optic modulator (AOM). The detectors must be able to measure voltages over at least four orders of magnitude with an accuracy of better than 0.1%. A lock-in detection with two separate lock-in amplifiers has to be used to reduce the influence of stray light and noise. The AOM is used for modulation of the incident beam required for the lock-in scheme. However, it is very challenging to achieve sufficient accuracy, because the required performance is close to the linearity limit of the lock-in amplifiers.
Here we present a new approach: instead of detecting $A$ and $B$ simultaneously by two different detectors, these signals are separated in time and measured with the same detector system. Despite the lower constraints on electronic equipment a higher accuracy is obtained. Instead of two photodiodes and two high-end lock-in amplifiers only one photodiode, a simple amplifier and an AD converter are needed. We achieve an accuracy of less than 0.05% for an incident pulse fluence varied over more than four orders of magnitude. Care has to be taken in the alignment, since parasitic reflections and scattered light can cause relatively large errors. To exchange the sample we set up two alignment laser beams to make the measurement very reproducible. So far the setup has been tested with two laser systems: a VECSEL at a high repetition rate and a thin disk laser generating pulses with high energy.

In section 4.1, we introduce the new measurement method and discuss design considerations for the separate parts. In Section 4.2, the computation of the measurement data is described, and in Section 4.3 we describe the alignment and calibration. The results of measurements with the two different laser systems are shown in Section 4.4. In Section 4.5 the pump probe measurement is described.

4.1 Measurement concept

The nonlinear reflectivity measurement system consists of several parts, a pulsed laser source, a variable attenuator, an isolator and finally the measurement section (see Figure 4.2).
The pulsed laser source typically is a modelocked laser with sufficient energy to saturate the SESAM under test. Ideally, we want to characterize the SESAM under identical conditions as inside a laser cavity that is passively modelocked by the same SESAM. The pulsed laser source should therefore operate at the same center wavelength and pulse duration. The pulse fluence incident on the SESAM should be at least 10 times $F_{\text{sat}}$ for a precise parameter extraction [63], but depending on the induced absorption (e.g. a large $F_2$) fluences of up to 50 times $F_{\text{sat}}$ can be required for a precise characterization. In a modelocked laser, the intracavity fluence on the SESAM is typically 3-10 times $F_{\text{sat}}$. So we need to achieve approximately the same or higher fluence than inside the cavity. This is usually obtained either by strong focusing onto the SESAM or employing a lower repetition rate of the evaluation laser. At high repetition rates, some SESAMs do not fully recover between the subsequent laser pulses, and an evaluation at the precise repetition rate may even be needed.

A wide-dynamic range attenuator can be realized in many ways, e.g. by graded neutral density filters, acousto-optical modulators (AOMs), or polarization splitters in combination with polarization rotation optics. Neutral density filter wheels, however, may cause thermal lensing at high average power levels. AOMs can introduce amplitude noise at stronger attenuation levels and are typically limited to two orders of magnitude of attenuation. In our setup, we choose to use the polarization method, which relies on two optical elements: one element rotates the linear polarization state, whereas the second element selects the desired polarization.
Polarization rotation can be achieved using for example a half-wave plate or a polarizing beam splitter (PBS). Because half-wave plates typically have a limited bandwidth, we prefer to use PBSs which have a bandwidth >100 nm. The dynamic range is determined by the extinction ratio of the first PBS.

The angle of incidence onto the SESAM is perpendicular, and hence some light is reflected back into the laser source. An isolator prevents such back-reflections from entering the laser source, which would lead to mode-locked instabilities. The isolator consists of two polarizing beam splitters PBS2 and PBS3 and a Faraday rotator. To obtain good isolation we used Glan Laser PBSs, which have a 250 nm – 2.3 µm wavelength range and a extinction ratio of 1:100,000.

The measurement part consists of a non-polarizing beam splitter cube (BS), a lens, a chopper wheel and a photo detector (PD). Instead of detecting A and B simultaneously by two different detectors (like Haiml et al [63]), the signals are separated in time and measured with the same detector system. The separation in time is achieved by a chopper wheel which simultaneously chops both arms and is put close to the 50:50 beam splitter. The signal is amplified and measured with an analog-to-digital (AD) converter and recorded with a computer. The chopper frequency is typically in the range of 100s of Hertz, and a low-cost 14 bit AD-converter is sufficient to measure photovoltages with 0.01% accuracy (when the photo-current amplifier is set to obtain a full-scale for the reference signal, 14 bits results in 0.006% resolution, averaging over more points can even increase this value).

In our measurement system, we lifted the chopper wheel such that the axis of the chopper wheel is a few centimeters above the beam heights, see Figure 4.3(a). During one chopper wheel cycle, four different states occur: 1. only reference beam measured, 2. both beams measured, 3. only sample beam measured, and 4. both beams are blocked. The signal in phase 4 corresponds to a background signal from photodiode dark current and environmental background light, which is then discriminated from the measurement signal in phase 1 and 3. In reference [63], a lock-in detection was required to reject the background signal.
The lens L1 focuses the incident beam onto the SESAM, typical beam radii are between 5 µm and 20 µm. We employ a photo detector with a large detection area (typically 7x7 mm) to measure a collimated beam with large beam radius.

4.2 Data evaluation

The PD signal is amplified by a computer-controlled variable pre-amplifier to use the full range of the AD converter. The absolute gain and the offset have no influence on the measurement accuracy, it is only necessary to provide a linear response. Since the reflectivity $R$ is encoded in only one optical/electrical signal the constraints on the amplifier have become negligible. This is in contrast to the method of Haiml et al., in which the same gain and no offset has to be achieved by both amplifiers [63].

The computer algorithm first detects the rising edges, the black dots in Figure 4.3(b), and then takes the mean value of the data points on the flat levels, the black lines in Figure 4.3 (b). As both beams are blocked in phase 4, we can precisely measure the offset of the photodiode. Level A and B are obtained by subtracting the signal level in state 1, and the nonlinear reflectivity is obtained as $R = B / A$. This is done for 500 periods in succession (takes approximately 5 seconds per fluence) and averaged to minimize detector noise and laser noise. This averaged reflectivity has a standard deviation of 0.01%. The incident fluence can be computed from the level A and the pre-amplifier gain setting. An accuracy of 5% for the fluence measurement is typically good enough, as this will afterwards result in an inaccuracy of 5% for the fitted saturation fluence $F_{\text{sat}}$.

![Figure 4.3](image-url)

Figure 4.3: The chopper wheel is lifted a few centimeters to block both beams at certain angles, which makes it possible to measure the photodiode offset (a) and the corresponding trace on the photodiode (b).
4.3 Alignment and calibration

In this section, we first give a guideline for the optical design and initial alignment, then describe the steps to prepare the setup for measurements: calibration of the reflectivity, alignment of the SESAM to make sure it is in the focus of the laser beam and the exchange of the SESAM.

The beam splitter as well as all the other optical components are slightly tilted to eliminate reflections from the interfaces hitting the photodiode. We observed up to 2% measurement error when parasitic reflections or scattered light reached the detector, preventing such reflections from hitting the detector is therefore particularly important.

To achieve an identical optical-to-electrical response of the detector from the sample beam and the reference beam, the setup is designed in such a way that both beams have an identical spot size on the photodiode. The beam that enters the reflectivity measurement part is collimated and has a waist (1 mm radius) on the reference mirror. The sample beam is focused onto the sample using lens L1. Both returning beams have the same $q$ parameter (beam width and divergence). The overlap of both backward traveling beams can be verified by using a camera at the detector position.

An obvious sanity check is the measurement of a HR instead of the SESAM in the sample arm, which should result in a flat response over the full dynamic range. Because the sample arm includes an additional lens, the response from this arm is typically a few percent lower than the response from the reference arm. We introduce a calibration factor such that the reflectivity $R = C \cdot B / A$ is constant. In case of systematic errors $C$ can be a function of the fluence $F$.

For a measurement, the SESAM has to be positioned at the waist at zero degree incidence. First the SESAM is aligned perpendicular to the beam without the lens L1 by using an aperture. Then the lens is inserted and the beam is aligned again to the aperture. The final alignment concerns the fine tuning of the SESAM position, which needs to be exactly in the focus of the laser beam. The SESAM is moved along the propagation direction and the beam waist is where the nonlinearity is the largest and thus the measured saturation fluence is the smallest, see Figure 4.4.
Figure 4.4: Saturation energy obtained from the fit function for different z-positions. The smallest saturation energy is obtained when the sample is in the focus. The gray line is a parabolic fit.

One has to be careful when replacing the sample, because slight misalignments can result in measurement errors. We therefore use two alignment beams from a laser pointer to memorize the sample position and tilting angle, see Figure 4.5: the first beam is reflected by the sample and is directly aligned to an aperture; the second beam propagates through two lenses (focal length 5 cm) with the sample in-between. A linear translation of the sample causes a deviation in the angle of the collimated output beam that is aligned to a second aperture. The first beam is sensitive to angular errors and has a reproducibility better than 30 mrad. The second beam is mainly sensitive to position errors and has a reproducibility of 10 µm which is well below the Rayleigh length (140 µm). We obtain a 0.02% reproducibility of the reflectivity measurement.

Figure 4.5: Two laser beams are used for the sample alignment.
4.4 SESAM characterization results

We use the model function (3.12) with finite spot size correction (3.14) to fit the measurement data. The model takes into account the absorption of photons, but neglects the recombination, which is a good model for a slow saturable absorber where the recovery time is longer than the pulse duration. But also SESAMs with a fast recovery can usually be described with the deducted nonlinear reflectivity curve.

To compare the model function with measurement data we define the distance $\sigma$ as the squared 2-norm of the difference between the measured reflectivity and the reflectivity of the fit curve. The best fit has the smallest $\sigma$.

We will show two results, the first with VECSEL source and the second with a solid-state thin disk laser source.

4.4.1 VECSEL source

The first setup was built for the characterization of low saturation fluence quantum dot SESAMs which are used to passively modelock VECSELs [30] and which have been integrated into the modelocked integrated external-cavity surface emitting laser (MIXSEL) [74]. The measurement was performed using a VECSEL with 1 W of average output power at 960 nm. The VECSEL is modelocked with a SESAM at 1.5 GHz and generates 6-ps-long pulses. We focused the beam with a 20 mm lens to a small spot with a 5.8 µm radius. The fluence range is only three orders of magnitude, from 0.2 – 200 µJ/cm$^2$ since we were limited by the maximum pulse energy available from this gigahertz repetition rate laser. A typical measurement, which takes approximately 2 minutes, is shown in Figure 4.6(b). A dielectric HR was used for calibration. The reference measurement on this mirror shows peak-to-peak variation (flatness) of only 0.049%, see Figure 4.6(a). The data is fitted with a logarithmic function (straight line on a semi-logarithmic axis) which is used to correct following measurements. The SESAM is a quantum dot SESAM with a resonant design [66]. At low fluences we have a linear response of the dots, whereas at higher fluence we increase the carrier population due to the rather long recombination time and therefore increase the reflectivity of the SESAM due to the decreased absorption and increased stimulated emission. Due to the rather long 6 ps-pulses there is no induced absorption (for the fit we use $F_2 = \infty$) and three orders of magnitude are sufficient for a good fit. From the fit we determine the modulation depth to be $\Delta R = 2.17 \pm 0.02\%$.
(the tolerance corresponds to standard deviation of the fit parameter), the nonsaturable losses $\Delta R_{ns} = 1.23 \pm 0.02\%$ and the saturation fluence $8.48 \pm 0.36 \mu J/cm^2$.

![Figure 4.6](image.png)

Figure 4.6: Measurement of a HR without calibration (i.e. $C = 1$), the flatness of the mirror is below $<0.05\%$ (a) and a typical SESAM measurement (b). Both measurements use a modelocked VECSEL as source.

### 4.4.2 Thin disk laser source

The second setup was built for the evaluation of high saturation fluence SESAMs operating at 1030 nm, which enabled the realization of passively modelocked thin disk lasers exceeding 10 $\mu$J pulse energy [68]. The SESAM has InGaAs quantum wells which absorb the laser light. At a sufficient fluence the carriers start filling the bands and the wells become transparent. The laser source is a modelocked Yb:Lu$_2$O$_3$ thin disk laser running at a lower repetition rate of 65 MHz [75]. The pulses are 570-fs long, which will cause induced saturable absorption at higher fluences. We used a lens with a focal length of 25 mm to obtain a 10.3 $\mu$m beam waist (radius) on the sample, which allowed measurements up to 6800 $\mu$J/cm$^2$. The HR flatness was improved by choosing $C(F)$ as a second order polynomial of $\log(F)$. The HR measured with this correction factor has a flatness of 0.055%, see in Figure 4.7. From the fit we obtained $F_{sat} = 54.7 \pm 1.4 \mu J/cm^2$, $\Delta R = 0.722 \pm 0.005\%$, $F_2 = 3.18 \pm 0.13 J/cm^2$ and very small nonsaturable losses $\Delta R_{ns} = -0.003 \pm 0.005\%$. The systematic error in the measurement of the nonsaturable losses $\Delta R_{ns}$ depends on the accuracy of the HR reference measurement (see section 4), therefore we can only conclude that $\Delta R_{ns} < 0.1\%$. The green curve in Figure 4.7 shows the same fit function with $F_2 = \infty$, i.e. the expected reflectivity for ps-pulses.
4.5 Pump-probe measurement

The dynamics of the SESAM are important for the pulse formation and need to be characterized precisely. In order to realize shortest pulse duration, fast recovery has to be achieved [71]. The recovery is measured with a time resolved differential reflection setup (also referred to as pump-probe setup). The pulsed laser beam is first split into a strong pump beam and a weak probe beam, as shown in Figure 4.8(a). The intensity ratio should be at least 10:1 to make sure that the probe pulses do not influence the measurement.

Both beams should overlap on the sample. We can achieve this by using a beam profiler and adjusting the two lenses in front of the sample. The temporal overlap is adjusted with a computer controlled translation stage. The pump beam hits the sample first under a small angle, after a variable delay the probe beam reflects off the sample and is measured with a photodiode.

Both pump and probe beams are chopped at several 100 kHz by acousto-optic modulators (AOMs). By chopping the pump we measure directly the modulation this beam induces on the sample. In addition, we chop the probe beam to suppress the scattered pump light that accidently hits the detector. The probe beam is detected with a lock-in amplifier at the difference frequency, which is 70 kHz.
Figure 4.8: The pump probe setup used for the measurements. (a) By modulating the pump we directly measure the reflectivity change of the SESAM. The probe beams is also modulated to suppress stray light from the pump beam. Lock-in detection at the difference frequency (70 kHz) makes the setup very sensitive. (b) A typical SESAM response.

A typical pump-probe signal from a QD-SESAM is shown in Figure 4.8(b). The laser source used for the measurement is a modelocked wavelength tunable Ti:sapphire laser with a 80 MHz pulse repetition rate. The 140-fs pulses (measured directly after the laser) are nearly transform limited with a time bandwidth product of 0.34. The pump spot has a diameter of 20 μm and the probe is slightly smaller and has a diameter of 15 μm, this results in fluences of 5.1 μJ/cm² and 0.16 μJ/cm² for pump and probe respectively.

The normalized pump probe response can be fitted well with the two time constants

$$
\Delta R_{pp}(\tau) = A e^{-\tau/\tau_{slow}} + (1 - A) e^{-\tau/\tau_{fast}},
$$

where $A$ is the amplitude of the slow component with time constant $\tau_{slow}$ and $(1 - A)$ the amplitude of the fast component with time constant $\tau_{fast}$. In the example above $\tau_{fast} = 0.77$ ps, $\tau_{slow} = 74$ ps and $A = 70\%$. The fast recovery is due to transitions in the dots, whereas the slow recovery is due to recombination. A more detailed discussion on the carrier dynamics is given in Chapter 5.
Chapter 5

Quantum Dot Optimization

The key towards the integration of saturable absorber and gain in the MIXSEL was the understanding and optimization of QD absorbers. For several years, there has been an increasing interest in quantum dot (QD) based SESAMs because the strong localization of the wave function leads to an atom-like density of states that enables novel SESAMs with tunable optical properties. QD saturable absorbers were first used to modelock semiconductor edge emitters in 1999 [76], two years later in 2001 the first QD-SESAM is reported by Garnache et al. [77]. Rafailov et al. reported fast recovery dynamics, which can be beneficial for achieving shorter pulse durations [78] and pulse durations as short as 114 fs have been shown [79]. Another advantage of the QD-SESAM is the lower density of states and the additional parameter of the dot density which allow for low saturation fluence at moderate modulation depth. This is challenging to realize with QW-SESAMs [66, 80].

QD-SESAMs were particularly successful for modelocking VECSELs. In contrast to diode-pumped solid-state lasers, a semiconductor gain material exhibits dynamic pulse-to-pulse gain saturation [81]. In order to achieve stable modelocking, the absorber needs to saturate at lower pulse energies than the gain. The gain structure in VECSELs typically consists of several QWs, with a saturation fluence similar to the QW used in standard SESAMs. Stable pulse formation is usually achieved by strong focusing onto the QW-SESAM (10-40 times smaller area than in the gain), which limits the geometrical size and restricts the maximum achievable repetition rate [28, 30]. The additional design freedom of QD-SESAMs supports lower saturation fluence to achieve modelocking with similar mode areas on SESAM and VECSEL. This
resulted in modelocked VECSELs with record-high repetition rates up to 50 GHz, presented in Section 3.5. Moreover, the similar mode areas enabled the integration of the QD saturable absorber directly into the VECSEL structure, which will be discussed in the next chapter.

In this chapter, we present a detailed study of the effect of QD growth parameters on the macroscopic optical SESAM parameters. The additional parameter of the dot density in combination with the field enhancement allows for an independent control of saturation fluence and modulation depth. We studied the effect of QD growth parameters on the macroscopic optical SESAM parameters, measuring both nonlinear reflectivity and recombination dynamics. Our MIXSELs currently use a lower growth temperature for the QD-region than for the gain region. We therefore also investigate the effect of post-growth annealing on the QD properties. Moreover, we present design guidelines for QD-SESAMs with low saturation fluence and fast recovery.

This chapter is organized as follows. In Section 5.1 we discuss the QD-SESAM design and growth and describe our set of samples. In the next section, we present the nonlinear reflectivity measurements and demonstrate that the dot density directly influences the total change of reflectivity. In Section 5.3 the recovery dynamics are discussed, which vary strongly according to the dot density. In Section 5.4, we measure the influence of annealing and present QD-SESAMs with excellent performance in terms of low saturation fluence. Finally, we discuss design guidelines for combining low saturation fluence, optimum modulation depth, and fast recovery.

5.1 SESAM design and growth

The relative field strength in the absorber section can be controlled by the design of the structure. Especially for lasers operating at high repetition rates, resonant designs were proposed. The enhanced field strength in the absorber section leads to a reduction of the saturation fluence [66], on the other hand it equally increases the modulation depth. By changing the field enhancement, the product \( F_{\text{sat}} \Delta R \) cannot be altered (see Section 3.2.3). If one does not change the density of states, the absorbed pulse fluence to obtain complete saturation stays the same and the product \( F_{\text{sat}} \Delta R \) is maintained. The only solution to reduce both \( F_{\text{sat}} \) and \( \Delta R \) is to reduce the joint
density of states. Using QWs, this is difficult; with QDs the number of states is simply proportional to the dot density.

5.1.1 QD-SESAM design

In this study, all presented SESAMs are antiresonant. In contrast to a resonant design, the electrical field in the QD layer is insensitive to small growth errors and a variation of the wavelength, which allowed us to study their optical properties over a range of more than 40 nm. An antiresonant design leads to a larger saturation fluence and lower modulation depth, and modelocking experiments with the same beam waist on SESAM and gain structure (which is necessary at higher repetition rates) is not possible. To overcome this, we introduce a new design which provides both resonant and antiresonant samples from one single growth run, see Figure 5.1(a). As-grown the SESAM is antiresonant, but we can make the device resonant by selectively wet etching the last AlAs and GaAs layer away. We experimentally verified that this procedure leads to a decrease of the saturation fluence approximately by a factor of 10, while the modulation depth increases by the same factor. The absorber enhancement as function of wavelength for both the resonant and antiresonant design is shown in Figure 5.1(b).

![Figure 5.1](image).

Figure 5.1: The design of the QD-SESAM. (a) The structure contains a 25-pair distributed Bragg reflector with a saturable absorber section grown on top. The antiresonant structure can be changed to a resonant structure by removal of the two top layers (with \(\lambda/4\) optical thickness). (b) Field enhancement for both designs as function of the wavelength. The resonant design has a higher field enhancement resulting in a larger modulation depth and smaller saturation fluence however has a stronger wavelength dependence.
5.1.2 **QD-SESAM growth**

The SESAMs were grown on (100) GaAs substrates using a VEECO GEN III molecular-beam epitaxy (MBE). The distributed Bragg reflector (DBR) is a 25 pair AlAs/GaAs mirror and has a theoretical reflectivity of 99.98%. On top of the DBR the QD section is grown: first a spacer is needed to place the QDs in the anti-node of the electrical field. We chose AlAs instead of GaAs since GaAs has a smaller bandgap and therefore the two-photon absorption is significantly stronger. The InAs QDs are embedded between two thin GaAs layers (20 nm thickness each). After the first GaAs layer the substrate temperature is decreased to the desired temperature and during the growth of the second layer the temperature is ramped up.

The InAs QDs are grown using Stranski-Krastanov growth, which depends on the following parameters: substrate temperature, arsenic pressure, growth rate in number of monolayers per second (i.e. ML/sec) and indium monolayer coverage (ML coverage). The indium coverage is controlled by the opening time of the indium source shutter, a longer shutter time results in higher ML coverage, which again results in a higher dot density [82]. For the study, we grew the QDs at temperatures of 380°C, 400°C and 430°C, all other layers are grown at 600°C. In our MBE, the growth temperature is measured using band-edge absorption.

5.1.3 **Influence of growth temperature**

During the evaluation, we observed an influence of the growth temperature on the recovery. However the ML coverage is the dominant effect and the general tendencies are similar for the sample sets with different growth temperature. Therefore, we focus our study on QD-SESAMs grown at 400°C. We compare 5 samples grown with a 30, 35, 40, 45 and 50 seconds Indium shutter time. With the used growth rate of 0.053 ML/sec we obtain 1.6, 1.9, 2.1, 2.4 and 2.7 ML coverage. QDs are formed when the thickness of the InAs layer exceeds 1.5 MLs [83], so the first sample is just above this threshold.

5.2 **Nonlinear optical reflectivity**

The antiresonant samples have a relatively small modulation depth (< 1%) and a high precision setup is needed to measure the nonlinear reflectivity. For this purpose we use the setup described in Chapter 4 which has an accuracy of 0.05%. The laser source is a modelocked wavelength-tunable Ti:sapphire laser with a 80 MHz pulse
repetition rate. The 140-fs pulses (measured directly after the laser) are nearly transform limited with a time bandwidth product of 0.34. The absolute reflectivity was calibrated with a dielectric high reflectivity (HR) laser mirror, which reflectivity was assumed to be 100%. In reality, the reflectivity of the HR was even below the SESAMs, causing slightly negative $\Delta R_{ns}$.

5.2.1 Influence of the quantum dot density

In Figure 5.2 and Table 5.1 we show nonlinear reflectivity measurements of our QD-SESAMs at a laser center wavelength of 960 nm. The measurement data (dots) is fitted (solid lines) with the model function (3.12) taking into account the finite spot sizes. The SESAMs behave as expected, by increasing the ML coverage (dot density) the modulation depth also increases. The modulation depth is proportional to the dot density, while the saturation fluence remains constant. The microscopic definition of $F_{sat}$ according to (3.4) is: $d \alpha / dt = -(I / F_{sat}) \alpha$, with $I$ the incident pulse intensity and $\alpha$ the (intensity) absorption coefficient of the QD layer. As a result, $F_{sat}$ only describes a relative change of the absorption given the incident intensity and this is independent of the number of dots. The rollover also remains constant, the $F_2$ parameter is between 405 and 483 mJ/cm$^2$. The rollover depends on the pulse duration of the laser and the design of the structure, i.e. the integrated intensity in the GaAs layers, which is similar for all structures [62]. Note that the measurements were done with a Ti:sapphire fs-laser, lasers operating in the ps regime have less induced absorption and therefore the rollover would occur at a higher fluence.
Figure 5.2: Nonlinear reflectivity measurements of QD-SESAMs done at 960 nm with 140 fs pulses, the upper curve has the smallest ML coverage (dot density) and therefore the smallest modulation depth. By increasing the dot density the modulation depth also increases while the saturation fluence maintains constant.

<table>
<thead>
<tr>
<th>ML</th>
<th>$F_{sat}$ (μJ/cm²)</th>
<th>$\Delta R$ (%)</th>
<th>$\Delta R_{ns}$ (%)</th>
<th>$F_2$ (mJ/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>66.5</td>
<td>0.26</td>
<td>-0.002</td>
<td>405</td>
</tr>
<tr>
<td>1.9</td>
<td>71.2</td>
<td>0.48</td>
<td>-0.042</td>
<td>457</td>
</tr>
<tr>
<td>2.1</td>
<td>70.7</td>
<td>0.74</td>
<td>-0.092</td>
<td>482</td>
</tr>
<tr>
<td>2.4</td>
<td>65.7</td>
<td>0.77</td>
<td>-0.032</td>
<td>443</td>
</tr>
<tr>
<td>2.7</td>
<td>78.4</td>
<td>0.88</td>
<td>0.004</td>
<td>483</td>
</tr>
</tbody>
</table>

Table 5.1: Nonlinear reflectivity measurements of QD-SESAMs done at 960 nm with 140 fs pulses.

5.2.2 Influence of the wavelength

We also investigated the wavelength dependence of the saturation parameters. A flat spectral response is important for realizing ultrashort pulses with broad optical spectrum. The flat spectral response is also needed for wavelength tunable modelocked lasers, which are for example important in biomedical applications. The saturation fluence and modulation depth have been measured for three different wavelengths (940 nm, 960 nm and 980 nm) and are shown in Figure 5.3.
The measurements show a slight reduction of the modulation depth for longer wavelengths. The photoluminescence (PL) peak of the samples is around 1050 nm so we have both ground state (GS) absorption and excited state (ES) absorption. By increasing the wavelength, we have less ES absorption and more GS absorption, since ES absorption is stronger than GS absorption the total absorption decreases [84]. The average saturation fluence is 51.4, 70.5 and 44.5 µJ/cm² at 940, 960 and 980 nm. We conclude that the wavelength and ML coverage have no strong influence on the saturation fluence, only by increasing the field enhancement the saturation fluence can be decreased.

![Figure 5.3](image)

Figure 5.3: Fit parameters as function of monolayer coverage and wavelength. (a) the modulation depth and (b) the saturation fluence. The error bars in the graph indicate the 95% confidence levels.

### 5.3 Recovery dynamics

The SESAM recovery influences the pulse duration in a modelocked laser. In order to realize shortest pulse duration, fast recovery has to be achieved [71]. For GaAs absorbers fast recovery has been achieved by low-temperature growth (below 350°C) to create point defects to trap the carriers [60, 85]. Low-temperature growth is not required for QDs to have fast recovery times. Rafailov et al. have measured recovery times of approximately 1 ps [78]. The pump probe response exhibits a large fast component which quickly drops to 20% of its original value and is followed by a slow component > 100 ps. These two clearly distinguishable recovery processes are also present in our samples. Moreover, we observed that the time constants and relative ratio strongly depends on the growth conditions.
5.3.1 Dot density and recombination

The five samples are measured at 960 nm and the results are shown in Figure 5.4. The normalized pump probe response can be fitted well with Equation (4.1), i.e. a double exponential fit with two time constants

$$\Delta R_{pp}(\tau) = A e^{-\tau/\tau_{\text{slow}}} + (1 - A) e^{-\tau/\tau_{\text{fast}}}$$

where $A$ is the amplitude of the slow component with time constant $\tau_{\text{slow}}$ and $(1 - A)$ the amplitude of the fast component with time constant $\tau_{\text{fast}}$. For fast recovery a small slow component ($A \approx 0$) is favorable. Another option is a strongly reduced time constant $\tau_{\text{slow}}$, e.g. like measured for the 2.7 ML sample in Figure 5.4.

![Figure 5.4: Pump probe measurements of the five samples with different ML coverage measured at 960 nm. The measurements are normalized such that the amplitude of the slow exponential decay is 1](image)

The slow component is determined by carrier recombination and carrier escape. The sample grown with 1.6 ML coverage has a slow component of approximately 500 ps which is the expected recombination time for InAs QDs [86]. The measurement shows that by increasing the ML coverage the recombination becomes faster, which can be explained by a higher defect density and thus a faster recombination [87], or a higher interdot transfer probability because of the smaller distances between the dots [88].

The fast processes are due to transitions in the dots. There are several processes that can explain the fast relaxation mechanism. Auger processes are much more
likely than phonon relaxation [89], and recovery times of 0.5 ps have been measured [90]. Another very fast process is thermal hole activation [91] where the hole is removed and stimulated recombination drops (a SESAM is saturated when the stimulated emission is equal to the absorption). We measured a fast relaxation time constant $\tau_{\text{fast}}$ between 0.7 and 1.2 ps.

### 5.3.2 Amplitude of the slow component

In Figure 5.5(a), the response is shown for the 1.6 ML sample pumped at different fluences ranging from 20 to 450 $\mu$J/cm$^2$. It is obvious that by increasing the pump fluence the sample saturates more and thus the peak becomes higher. At low pump fluences the normalized response is identical ($\tau_{\text{slow}}$, $\tau_{\text{fast}}$ and $A$ are constant). At higher fluences the shape of the recovery changes. For the extreme case (450 $\mu$J/cm$^2$) the reflectivity increases again after a time of 0.9 ps, which is different from the measurements at lower fluences. A second maximum is observed after a time of 14 ps. This is most likely caused by the carriers generated in the GaAs around the dots by two photon absorption which after a few picoseconds are captured in the dots. This agrees with the capture time of 31 ps measured by other groups [92]. TPA in pump probe measurements have already been reported in [93]. Please note that TPA is strongly reduced for longer pulses, and the variation of $A$ with pump fluence will be substantially lower. We expect that the normalized response would remain constant even at 450 $\mu$J/cm$^2$, if pump pulses $> 500$ fs would be used.

Figure 5.5: (a) Pump probe measurements of the 1.6 ML sample for different pump fluences, measured at 960 nm. For better visibility, the measurements are shown with an offset of 10 ps. (b) The amplitude of the slow component ($A$) as function of ML coverage measured at three different wavelengths. The measurements are done at 50 $\mu$J/cm$^2$. 
In Figure 5.5(b), the amplitude of the slow component $A$ is studied as function of ML coverage and wavelength. We used a constant pump fluence of 50 $\mu$J/cm$^2$, for which TPA is negligible. The smallest $A$, which means a dominant fast recovery process, is obtained for samples just over the QD formation threshold (1.5 ML). Increasing the ML coverage increases the significance of the slow component. At a longer wavelength (the black curve) a smaller $A$ is obtained, therefore this operation regime is preferable for short pulse operation. This is consistent with the findings presented in [78], an $A = 20\%$ is measured for a wavelength 30 nm below the PL peak.

5.4 Post-growth parameter optimization by annealing

A key element for realizing the first MIXSEL is the detailed study on post-growth annealing of QD saturable absorbers. In the MIXSEL design, the QD saturable absorber layer is placed in the middle of the structure and is annealed during several hours of subsequent growth at 550°C – 600°C. This changes the dot composition (indium out diffusion) and size, resulting in a blue shift of the absorption and PL emission wavelengths [94]. Post-growth annealing of SESAMs is also a simple way to optimize SESAM parameters without the need for expensive and time consuming growth. We therefore also studied the effect of post-growth annealing on our quantum dot samples.

The surfaces of the samples are capped with 100 nm SiO$_2$ by plasma-enhanced chemical vapor deposition (PECVD) before the annealing to avoid surface damage due to As evaporation. After the annealing the caps are removed with reactive ion etching (RIE). The samples are annealed at 625°C (temperature measured with a pyrometer having an accuracy of 5%) using rapid thermal annealing (RTA).

We first studied the effect of the annealing time by observing the shift of the PL peak wavelength as function of annealing time. During the first minutes, the PL wavelength strongly shifts to shorter wavelength by several tens of nanometers, afterwards we observe a linear shift of 4.7 nm/hour, the blue shift is shown in Figure 5.6. All presented measurements afterwards are for an annealing time of one hour. For longer annealing times, similar results are expected.
Figure 5.6: (a) Photoluminescence spectra of the 1.6 ML QD sample before and after annealing, the two peaks are ground state (GS) and wetting layer (WL). (b) Blueshift of the PL peak as function of annealing time for a QD sample grown at 400°C. The samples are grown without a DBR.

The PL of the annealed 1.6 ML sample showed a strong blue shift to a center wavelength of 953 nm after 1 hour of annealing at 625°C, with the result that the modulation nearly vanished and the saturation fluence was not measurable anymore. The modulation depth of the other samples with larger indium coverage remained nearly unaffected by the annealing, but their saturation fluence was strongly reduced. The reduction of the saturation fluence is the strongest for the samples with the least ML coverage, we observed a reduction by up to a factor of 9. The samples with higher ML coverage showed only a reduction by a factor of 1.3, see Figure 5.7(a). Additionally, we observed a clear decrease of the slow recovery component (reduction of $A$) with an average of 18%, which can be explained by the blue shift. In Section 5.3, a smaller $A$ was also observed at longer wavelengths, i.e. closer to the PL peak. The change of the slow recombination time constant ($\tau_{\text{slow}}$) is not consistent, the samples with 1.9 and 2.1 ML became slower and the samples with 2.4 and 2.7 ML became faster, see Figure 5.7(b).

In Figure 5.7(c) and (d) the result of the annealing is shown for the 1.9 ML sample. The saturation fluence reduces from 63.6 to 7.2 $\mu$J/cm$^2$, while the modulation depth stays constant at 0.5%. This gives a sample with $F_{\text{sat}} \Delta R = 36$ nJ/cm$^2$, a factor 10 smaller than InGaAs QWs and comparable to GaInNAs QWs operated within the band tail [64].
Figure 5.7: (a) The saturation fluence ($F_{sat}$, left axis) and modulation depth ($\Delta R$, right axis) before and after annealing as function of monolayer coverage. (b) The amplitude of the slow component ($A$, left) and recovery time on a logarithmic scale ($\tau_{slow}$, right) before and after annealing. (c) The nonlinear reflectivity measurement of the 1.9 ML sample and (d) the pump probe measurement. All measurements in this graph are performed at 960 nm. The as-grown data is shown in black, the annealed data in gray.

5.5 Discussion

We studied the effect of dot density and post-growth annealing on quantum dot SESAMs. QD-SESAMs have an additional degree of design freedom compared to quantum well SESAMs. We experimentally demonstrated that the modulation depth can be tuned with the ML coverage (i.e. QD density) while the saturation fluence is constant, as predicted by theory. Due to its inherent inhomogeneous size distribution, the dots have broader uniform spectral properties than quantum wells. Nevertheless, the modulation depth increases slightly when operated at shorter wavelengths due to excited state absorption. The pump-probe measurements show that higher dot density results in faster recombination most likely because of defect recombination. For fast recombination, a small amplitude of the slow component is preferred, but care has to be taken when evaluating the measurements since the amplitude depends on the pump fluence. To enhance the fast component, the quantum dots should be grown close to the QD formation threshold and operated at
a wavelength close to the PL peak. Post-growth annealing allows to further reduce the saturation fluence. Moreover, the fast component becomes even more dominating.

Modelocked high repetition rate VECSELs require SESAMs with low saturation fluence (< 10 µJ/cm²) and a modulation depth of typically 1%. For achieving short pulse durations, fast recovery is necessary. Our study shows that the optimum design parameters for this case are apparently obtained by growing around 2 ML InAs coverage and subsequent annealing. This gives also a small saturation fluence which is favorable for modelocking VECSELs, the small modulation depth can be increased by growing more than one absorber layer if necessary.
The main goal of this thesis was the development of a new type of ultrafast semiconductor laser. We refer to this class of devices as modelocked integrated external-cavity surface emitting lasers (MIXSEL). The MIXSEL concept appears suitable for cost-efficient wafer-scale mass-production. Unlike VECSEL-SESAM modelocking, the MIXSEL has a linear cavity, which is easier to align and can be scaled to higher repetition rates than a folded cavity. With a conventional folded cavity concept it appears very challenging to exceed a repetition rate above 50 GHz (i.e. a cavity length below 3 mm) due to mechanical restrictions [30]. We expect MIXSELS to operate at repetition rates of 100 GHz and higher.

The concept of the MIXSEL gain structure is shown in Figure 6.1. First the pump light is absorbed in the active region (1). The carriers thermalize in the GaAs and get captured by a QW (2). Stimulated emission provides gain (3) and once the gain is equal to the losses the laser starts lasing. The intermediate DBR prevent pump light from reaching the saturable absorber, which would otherwise be saturated from the pump light. The laser light reaches the saturable absorber that starts and stabilizes the modelocking (4).
The main challenges for the MIXSEL are:

i) the saturable absorber, the saturation fluence must be small enough to permit sufficient saturation by the pulses and must be smaller than the saturation fluence of the gain to obtain stable modelocking;

ii) the net gain, the linear cavity has only one bounce on the gain structure, moreover the QWs, which are grown after the dots should have good material quality;

iii) growth accuracy, the current design is very sensitive to growth deviations, an accuracy below 1% is needed.

The development of the quantum dot (QD) saturable absorber was the crucial step towards the MIXSEL. With the QD saturable absorbers, we can resolve the saturation issue described in Section 3.5. With the dot density and the optical design of the structure (moving from an antiresonant to a resonant design) we can reduce the saturation energy and keep the modulation depth around the 1%-level.

However, combining the two different key elements, the high-temperature grown VECSEL gain structure optimized for high gain, and the low-temperature grown QD-SESAM optimized for low saturation fluence and fast recovery, raises several additional challenges. Therefore, the first structures where tested as-grown...
allowing us to focus on the optimization of the QD saturable absorber and growth in
general instead of time-consuming processing, even if the expected performance in
terms of output power was limited.

In Section 6.1 the design of the MIXSEL gain structure is discussed and in Section
6.2 we describe the growth, the QD characterization is described in Section 0. In
Section 6.4 the used experimental setup is shown and the results are given in
Section 6.5. In Section 6.6 we discuss the power scaling and the challenges to obtain
higher repetition rates.

6.1 MIXSEL concept and design

A more detailed design of the MIXSEL gain structure is shown in Figure 6.2. The
structure is designed for a laser wavelength of 955 nm and a pump wavelength of
808 nm. The six building blocks are:

i) 30 pair AlAs/GaAs DBR at 955 nm;
ii) saturable absorber (single QD layer);
iii) 5 pair AlAs/GaAs DBR at 955 nm;
iv) 9 pair AlAs/Al0.2Ga0.8As DBR at 808 nm;
v) active region (7 x 7 nm In0.13Ga0.87As QWs with GaAs spacer layers);
vi) 11 layer AlAs/Al0.2Ga0.8As AR-coating with 10 nm GaAs cap layer.

Figure 6.2: The MIXSEL design. The black line is the field enhancement.
The structure is designed to have a high field enhancement in the saturable
absorber.
The bottom mirror is designed to reflect the 955 nm laser light. Since only little pump light reaches this mirror, we can neglect the pump light absorption and use the materials GaAs and AlAs. The 30 pair DBR result in a reflectivity of 99.97% (comparable to a resonant SESAM, see Table 3.2).

Section 2 and 3 contain the QD based saturable absorber and a mirror to tune the needed field enhancement. The QDs are embedded inside a 20-nm thick GaAs layer surrounded by AlAs. We kept the GaAs-layer as thin as possible to minimize residual pump light absorption. In the current configuration only 0.25% of the pump light is absorbed in these GaAs layers. The $\lambda/2$ resonant sub-cavity enhances the field and enables tuning of the saturation fluence. Ideal would be a saturation fluence of 5 $\mu$J/cm$^2$. For the required field enhancement we have to presume saturable absorber parameters. As reference we take an antiresonant QD-SESAM having a saturation fluence $F_{\text{sat}} = 70$ $\mu$J/cm$^2$ ($\xi_{\text{abs}} = 0.32$) comparable to the SESAMs presented in Section 5.2. To obtain the preferred saturation fluence we therefore need a 14 times higher field ($\xi_{\text{abs}} \approx 4.5$), which is obtained by a five pairs AlAs/GaAs DBR on top of the absorber section.

Section 4 is a mirror which reflects the pump light, and thus prevents the saturable absorber to pre-saturate and moreover increases the pump absorption in the active region. The used materials AlAs and Al$_{0.2}$Ga$_{0.8}$As do not absorb 808 nm light. The 9 pairs of the pump mirror have a reflectivity of 93%, the remaining 7% is absorbed in the bottom mirror.

The gain section consists of 7 In$_{0.13}$Ga$_{0.87}$As quantum wells with a thickness of 7 nm surrounded by GaAs spacer layers that absorb the pump light. Due to the intermediate mirror 90% of the pump light is absorbed in the active region.

Finally the anti-reflective (AR) coating has the same material compositions as the pump DBR. The purpose is to increase the gain enhancement and broaden the gain spectrum.
6.1.1 Field enhancement in absorber section

The dots are embedded in a $\lambda/2$ cavity between two mirrors, which acts as a Fabry-Pérot interferometer. Thus the field enhancement in the absorber can be controlled by the number of mirror pairs in the intermediate DBR. The field enhancements of a structure with one and a structure with five mirror pairs are shown in Figure 6.3.

![Diagram showing field enhancement and refractive index](image)

Figure 6.3: Influence of the intermediate mirror on the field enhancement in the absorber section. The gray curve is the refractive index and the black curve is the field enhancement in the structure. The upper graph shows a MIXSEL design with 5 pairs (black circle) and the bottom graph shows a design with only 1 pair, which has a reduced absorber enhancement.

The obtained field enhancement in the absorber section is 4.8 and 1.1 for structures with five pairs and one pair respectively. The wavelength dependence of the absorber enhancement $\xi_{\text{abs}}$ and gain enhancement $\Gamma$ is shown in Figure 6.4(a). At the design wavelength 955 nm the value of the gain enhancement is equal for both designs, however with extra pairs the bandwidth becomes smaller. Unlike the gain enhancement, the absorber enhancement is increased by almost a factor 5 because of the extra mirror pairs. The GDD of the structures is shown Figure 6.4(b), both structures are designed to have a zero-crossing at 955 nm, however the structure
with five mirror pairs has a steeper slope and is more sensitive to growth deviations and temperature effects.

![Figure 6.4](image)

In terms of wavelength dependence, using less pairs clearly has advantages: it has a broader gain bandwidth, smaller dispersion and less transmission through the bottom mirror, however, at the time the experiment was done, we did not yet have the annealed antiresonant QD-SESAMs with an $F_{\text{sat}} = 7.2 \, \mu\text{J/cm}^2$, as presented in Section 5.4. Therefore the design with 5 mirror pairs having an absorber enhancement $\xi_{\text{abs}} = 4.8$ was preferred to obtain a sufficiently low saturation fluence.

### 6.1.2 Growth sensitivity

The used design is, mainly because of the resonance, very sensitive to growth inaccuracies. To have a qualitative idea, we simulated the field enhancement and GDD for structures with small deviations of the growth rate. We applied random errors (all below 1%) to the growth rates of the materials GaAs, AlAs and Al$_{0.2}$Ga$_{0.8}$As. Within one computed structure the layers consisting of the same material have the same relative error. Moreover we assumed the errors between the different materials to be uncorrelated. The results for 25 random structures are shown in Figure 6.5.
Often, small growth rate deviations can be compensated by a slightly different wavelength, however this is not preferable. For the resonant structure with 5 intermediate mirror pairs the growth should be controlled to obtain an accuracy below 1%. The other presented design with only 1 mirror pair is less sensitive to growth deviations as shown in Figure 6.6. By using the saturable absorbers presented in Section 5.4, having an $F_{sat} = 7.2 \, \mu J/cm^2$, this design appears to be a promising alternative for future MIXSELS.
6.2 MIXSEL growth

The MIXSELS are grown on a VEECO GEN III molecular-beam epitaxy (MBE) machine. The materials needed are GaAs, AlAs and Al$_{0.2}$Ga$_{0.8}$As for the mirrors and antireflection coating and In$_{0.15}$Ga$_{0.85}$As and InAs for the QWs and QDs respectively. Because the temperature is very important for the formation of the quantum dots we use band-edge absorption measurement to obtain the substrate temperature. This only works with empty substrates, since the grown layers will modify the reflection and transmission spectrum. Therefore, we use thermocouples to measure and control the temperature during the growth. Because the measured temperature with the thermocouples and the actual substrate temperature can be more than 10 K different (depending on the mount and contact with the wafer), we calibrate the thermocouple before growth with the band-edge absorption measurement for the needed temperatures.

Since we use the structure as-grown the order of the growth is: bottom mirror, QDs, intermediate mirror, active region including QWs and antireflection coating. The QDs are grown at 430°C, the QWs at 520°C, and the rest of the structure is grown at 600°C.

This high growth temperature does not affect the QWs, however it anneals the QDs. This annealing changes the dot composition and size, resulting in a blue shift of the absorption and emission wavelength [94]. We could compensate for this by initially growing the QDs at a photoluminescence peak of 1100 nm, the annealing during the growth afterwards will shift the absorption peak to around 950 nm to match our lasing wavelength. This optimization is described in Section 5.4.
6.3 QD characterization

The characterization of the layer structure is similar to the methods used for a VECSEL gain structure, which are described in Section 2.4. The characterization of the QDs, size and saturation properties is described in this section.

6.3.1 QD size and density

Microscopic QD properties like the dot size and dot density have an effect on the macroscopic properties like absorption wavelength and modulation depth. First we have grown a special test structure containing a QD layer without cap. Using atomic force microscope (AFM) we can measure the dot density. A measurement of a QD test structure with a high QD density is shown in Figure 6.7. The QD density is approximately $5 \times 10^{10} \text{ cm}^{-2}$. The QDs are partially overlapping, increasing the dot to dot transport enhancing fast recombination.

![AFM topography of the QD absorber layer](image)

Figure 6.7: AFM topography of the QD absorber layer (measured with a standard AFM tip radius of 10 nm) grown under the same condition as in the MIXSEL but without cover layer and without annealing. The QD layer was grown at 430°C with $\approx 2$ monolayer InAs deposition.
Although the AFM gives detailed information, a complete grown MIXSEL cannot be analyzed. To analyze the QDs of a MIXSEL we use a scanning transmission electron microscopy (STEM). In Figure 6.8 we show a measurement of the MIXSEL. The thickness of the QDs is approximately 3.5 nm and the diameter is around 40 nm, the STEM image shows a high QD density as well.

![Figure 6.8: STEM image of the QD layer. It shows that the thickness is around 3.5 nm and the diameter around 40 nm, the density is very high.](image)

### 6.3.2 Nonlinear reflectivity measurements of MIXSELs

The QW emission wavelength was optimized for operation at 70-80°C. At room temperature, the QW band edge is typically around 945 nm. At longer wavelengths the QWs do not absorb, and a nonlinear optical reflectivity measurements of the QD saturable absorber can be done. For the working MIXSEL structure (SV028), the QW absorption extended into the accessible wavelength region of our measurement setup and could therefore not be precisely measured. However, another structure (SV024) did not show absorption and could be measured. We compare this structure with a resonant QD-SESAM for which we used the same growth conditions as for the SV024 MIXSEL structure, both have a QD growth temperature of 400°C. This QD-SESAM has a resonant design with the $\lambda/2$ sub-cavity on top and the QD-layer embedded inside thin ($\approx 20$ nm) GaAs layers like the MIXSEL. After the growth, the QD-SESAM was in-situ annealed for 5 hours at 600°C, which is similar to the annealing that occurs during the MIXSEL structure growth. Within the first hour of the annealing
process, the PL wavelength changes by 125 nm, then it changes linearly with time at 5 nm/hour.

The measured nonlinear reflectivity of the MIXSEL SV024 and the QD-SESAM is shown in Figure 6.9. The details of the measurement set-up are described in Chapter 4. For this measurement we used a VECSEL passively modelocked with a SESAM in a folded shaped cavity with a pulse duration of 6 ps, a maximum average output power of 2 W and at a pulse repetition rate of 1.5 GHz. The laser focused to a spot radius of 5 µm on the device under test and the center wavelength was at 957 nm.

![Figure 6.9: Nonlinear reflectivity measurement at a center wavelength of 957 nm of an annealed resonant QD-SESAM (gray curve) and a full MIXSEL SV024 (black curve) with the same QD layer (in both cases grown at 400°C).](image)

We measured a saturation fluence $F_{sat}$ of 9 µJ/cm² and 11 µJ/cm², a modulation depth $\Delta R$ of 2.5% and 2.6% and a nonsaturable loss $\Delta R_{ns}$ of 1% and 0.9% for the MIXSEL and QD-SESAM respectively. The measurement wavelength was slightly detuned from resonance with a lower electric field enhancement in the absorber (i.e. $\approx 2.5$ instead of 4). Here we clearly show that the additional growth of the MIXSEL structure does not degrade the saturable absorber parameters which would result in a significant increase in nonsaturable loss $\Delta R_{ns}$.

6.4 Experimental setup

The MIXSEL wafer is cleaved in 5x5 mm pieces and soldered to a copper heat sink, which is cooled down to -10°C using two Peltier elements. The continuous wave
pump source delivered 1.5 W at 808 nm and is focused to a circular pump spot with a radius of 80 μm. The gain chip was subjected to a flow of dry nitrogen across its surface to prevent condensation and freezing of humidity. This introduces some weak disturbance due to refractive-index fluctuations in the cavity and was partly responsible for the observed noise in the autocorrelation.

We used an output coupler with a radius of curvature of 60 mm. The beam radii on the gain structure and output coupler are shown in Figure 6.10. We expect a thermal lens about 20 cm which does not significantly influence the resonator mode. With the cavity length one can tune the mode radius on the gain structure which has to match the pump beam.

![Figure 6.10: Beam radius versus cavity length using an output coupler with a radius of curvature of 60 mm.](image)

The MIXSEL cavity is shown in Figure 6.11. A 25 μm fused silica etalon is used for wavelength tuning. The etalon has a free spectral range of 12.7 nm, a transmission between 88 – 100%. The maximum GDD is 2000 fs², however at resonance the GDD is zero. Since the etalon is always operated near 100% transmission the GDD of the etalon can be neglected.
6.5 Results

In this section the results are shown obtained by modelocking of SV028. The layer thickness characterization, as described in Section 2.4, showed that the AlAs layers where too thin (3 – 4%). As a result, the absorber enhancement factor would be 1.5 instead of the design value 4. From this structure we could not measure the saturation fluence directly, based on structures grown with comparable parameters we expect the saturation fluence to be between 15 – 30 \( \mu \)J/cm\(^2\) and a modulation depth between 1 and 2\%. Furthermore, the gain enhancement would be increased by a factor of two compared to the design, which has the advantage of a higher gain, but also a reduced gain bandwidth.

The lasing wavelength can be tuned between 953 nm and 956 nm with an intracavity 25 \( \mu \)m-thick fused silica etalon. This gives us some adjustments in the field enhancement ratio between absorber and gain and the cavity group delay dispersion. Stable modelocking was obtained with a 5.4-cm long straight cavity and a 0.35\% transmission output coupler. The laser delivered 40 mW average power in 35-ps pulses at a 2.8 GHz repetition rate. The optical spectrum had a FWHM of 0.11 nm (Figure 6.12). The computed intracavity pulse fluence is 23 \( \mu \)J/cm\(^2\), which is close to the expected saturation fluence of the absorber. Modelocking was also
observed without the etalon but with less stability. The limited output power and low optical-to-optical efficiency is caused by the high temperature increase, caused by the poor thermal conductivity of the 600 μm thick substrate.

![Figure 6.12](image)

Figure 6.12: Pulse characterization of an optically pumped MIXSEL with 40 mW average output power. (a) autocorrelation with sech²-fit, (b) optical spectrum, (c) microwave spectrum on a 10-MHz span with 100-kHz resolution bandwidth.

We simulated the temperature increase in the structure using a finite element method: for a pump spot of 80 μm and 1.5 W of pump power, we obtained a temperature difference of 110 K between the semiconductor surface and the heat sink which results in an absolute temperature of 100°C for a -10°C heat sink. To confirm that the temperature increase was the main limiting factor, we cooled the heat sink further down to -50°C and increased the pump power. We optimized the set-up with a larger pump spot of 110 μm and an output coupler with 0.7% transmission and we indeed observed stable modelocked operation with 185 mW average output power and 31.6-ps long pulses at 957 nm (Figure 6.13). The cavity was 52.4 mm long, corresponding to a pulse repetition rate of 2.86 GHz. The mode radius on the MIXSEL gain structure is 78 μm which gives an intracavity pulse fluence of 53 μJ/cm². The average output power was increased by a factor of 4 compared to the previous results. The result was limited by the maximum pump power available in our setup (4 W). The long pulse duration is likely due to the growth deviation, that causes a larger group delay dispersion and a smaller gain bandwidth.
Figure 6.13: Pulse characterization of an optically pumped MIXSEL with 185 mW average output power. (a) autocorrelation with sech²-fit for a 31.6-ps pulse, (b) optical spectrum, (c) microwave spectrum on a 100-MHz span with 1-MHz resolution bandwidth.

The results of the $M^2$ measurement are shown in Figure 6.14. The measurement is done behind a lens (with a focal length of 30 mm). The measured $M^2$ was 0.95 and 0.96 in horizontal and vertical direction. The accuracy of the used beam profiler is 5%, thus we can conclude that the $M^2 < 1.1$ in both directions, which is close to the diffraction limit.

Figure 6.14: Beam quality measurement of 185 mW result. The accuracy of used beam profiler is 5%, explaining the fit values smaller than 1. The output beam quality is close to the diffraction limit.
6.6 Towards higher power and repetition rate

The thick (i.e. 600 µm) substrate has a poor thermal conductivity, resulting in a high temperature increase (over 100°C), ultimately limiting the output power. This problem also arises with VECSELs and is usually solved by growing the layers in reverse order and substrate removal (i.e. thinned structure) [18, 33]. Without the thick substrate, the temperature increase can be reduced below 30°C as shown in Section 2.5.1, allowing for substantially higher output powers. An alternative is to use a diamond heat spreader on top, with a partially reflective coating this could serve as complete external cavity.

We expect that our MIXSEL design supports repetition rates of 100 GHz and even higher. The challenge is to further reduce the saturation fluence below 1 μJ/cm² (assuming the same intracavity power). At 100 GHz the period time is 10 ps, less than the current pulse duration. The current long pulses can be explained by the rather strong GDD and reduced gain bandwidth. Using optimized QD-SESAMs and VECSELs in a folded cavity we easily achieve pulse durations in the 1-2 ps region. Optimizing GDD and gain bandwidth should enable even shorter pulse durations.
A key element to obtain truly compact laser devices is electrical pumping. It makes the bulky pump laser and pump optics redundant, and simplifies alignment and packaging. For many applications, for example optical clocking of microprocessors, this is an essential requirement. Of course, there are not only advantages. Optical pumping is ideal for VECSELS because the carriers are generated exactly where they are needed, i.e. in the active region, and with a Gaussian lateral distribution. For electrical pumping the highest carrier densities are found close to the contacts, i.e. not in a Gaussian distribution. The choice of a good design is crucial to obtain good performance in terms of output power and beam quality.

In the following, we discuss a design for electrical pumping that provides a balance between the opposed optical and electrical requirements, and which is suitable for passive modelocking. The device structure is similar to the vertical-cavity surface-emitting laser (VCSEL). A VCSEL consist of two mirrors, a highly reflective mirror on the bottom, a partially reflective mirror on the top, and a gain region in between. The top contact is a ring allowing the light to escape. The EP-VECSEL has a very similar gain structure, however the top mirror has a lower reflectivity and lasing is only obtained with an external cavity. With the curved output coupler the transverse mode in the external cavity can be controlled, enabling TEM$_{00}$ mode operation with high output powers. Due to the small cavity length, typical mode
diameter of a TEM$_{00}$ VCSELs is between 5 - 20 $\mu$m, whereas the larger cavity of an EP-VECSEL can have single mode operation with diameters above 100 $\mu$m. An EP-VECSEL gain structure is shown in Figure 7.1.

![Figure 7.1: EP-VECSEL gain structure. The thick GaAs current spreading layer allows a Gaussian-like gain profile in the active region.](image)

The first EP-VECSEL has been demonstrated by Hadley et al. [95], they reported continuous wave operation with 2.4 mW output power in a TEM$_{00}$ transverse mode. The presented devices had a diameter as large as 100 $\mu$m. Ten years later, McInerney et al. demonstrated high power operation [19]. The laser had 1 W output power in multimode operation. Using a different external mirror configuration they were able to force the laser in single mode operation ($M^2 < 1.1$) and obtained 500 mW output power.

Integration of the external cavity has been reported with 10 mW continuous wave output power [96, 97]. The devices have a curved micromirror output coupler made of a glass substrate bonded directly onto the semiconductor structure. Modelocking of an EP-VECSEL has been shown by Zhang et al. [98], they obtained 50-ps pulses at 6 GHz using an output coupler SESAM in a linear cavity configuration. A small antireflection coated intracavity lens was used to focus onto the SESAM to obtain the required saturation. The long pulse duration is probably caused by a large resonant field enhancement in the gain structure, because the EP-VECSELs were optimized for cw-operation.
In this chapter, we discuss several design issues for EP-VECSELs, which we published in [99]. The numerical simulations of the carrier density were performed in the group of B. Witzigmann at the Integrated Systems Laboratory, ETH Zurich. In Section 7.1, the design requirements are described, in Section 7.2 the electrical issues are discussed and in Section 7.3 we show the optical design. Finally, in Section 0 we discuss the integration of the saturable absorber.

### 7.1 Design considerations

The design of an electrically pumped VECSEL is quite challenging since there are many constraints. A good design has the following properties:

1. **Power scalable**;
2. Gaussian shaped gain profile (to obtain single mode operation);
3. Low operation temperature (low thermal resistance and low electrical resistance);
4. Low optical losses and high optical gain;
5. Broad gain bandwidth and small GDD (required only for modelocking).

Moreover, it is advantageous if complicated growth and processing can be avoided using a simple structure. Some of the requirements given above are contradicting and it is important to find an optimized balance. For example to obtain a low resistance high doping of the mirror structure is required which leads to an increased free-carrier absorption (FCA) and thus higher optical losses.

### 7.2 Electrical design

One of the implications of electrical pumping is that current has to flow through the mirrors, making doping unavoidable. The electrical conductivity of a mirror is mainly limited by the potential barriers at the interfaces. Especially p-doped mirrors have a high resistance, mainly because of the lower mobility and the higher potential barriers and therefore a reduced tunneling probability [100]. Simulations show that p-DBR structures can be improved significantly with a grading between both materials [99]. A reasonable p-DBR has a 20-nm grading with a doping concentration of $N_A = 2 \cdot 10^{18} \text{ cm}^{-3}$ whereas an n-DBR with the same doping without grading has lower resistance and also smaller FCA losses.
The laser light emitted in the active region has to be coupled into the external cavity, which makes a central top contact impossible. A more sophisticated design of the top contact is necessary. A common solution is a ring contact on top of the device, see Figure 7.1.

The spatial carrier distribution in the active region is quite important because it defines the spatial shape of the gain. The carrier distribution was simulated in the group of B. Witzigmann at ETH Zurich. They used a standard drift–diffusion model, taking into account the heterointerfaces with a thermionic emission model. The simulations show that a p-doped bottom mirror with a small bottom contact gives the best carrier density profile, see Figure 7.2(a). Since the electron and hole distributions are similar, only the electron density is shown.

![Figure 7.2: Simulated carrier density for a small and a large device. (a) The n-DBR results in a high carrier concentration below the top contact, making it unsuitable for single transverse mode operation. The p-DBR has an almost flat profile for an unstructured bottom contact (i.e. the whole p-DBR is contacted), by reducing the bottom contact size to 5 μm a Gaussian like profile is obtained. (b) Scaling to larger devices still shows that the p-DBR with small bottom contact gives acceptable, flat-top carrier densities. For these devices the bottom contact is 25 μm and the top contact aperture radius is 50 μm.](image)

The n-DBR, which provides a lower resistance and easier growth compared to the p-DBR structure, yields an increased carrier concentration and thus inversion below the top contact, which is unsuitable for fundamental transverse mode operation with the field maximum in the center of the device. The use of a smaller bottom contact (in this case with a radius of 5 μm) does not improve the situation.
The p-DBR in combination with an unstructured bottom contact (i.e. the whole wafer is contacted) allows for a flat spatial carrier distribution in small structures, but it fails in confining the current for typical VECSEL device radii. In order to enable a better current injection to the device center, the bottom contact can be implemented as a central disk contact. The difference between p-DBR and n-DBR originates from the difference in electron and hole carrier mobilities. The hole mobility is much smaller than the electron mobility and there is hardly any carrier spread in the lateral direction. The electrons injected from the top ring contact follow the spatial hole distribution.

For power scalability with large apertures, a top current spreading layer is necessary. Both increasing the doping concentration and thickness of the current spreading layer lead to a decrease of the overall resistance. The FCA is proportional to the doping concentration $N_D$ and the thickness $d$ of the current spreading layer. Thus a fixed $d\cdot N_D$ value yields approximately the same optical loss. Simulations show that a more uniform radial carrier distribution is obtained for thicker layers having lower doping. Simulations of a larger gain structure with a bottom contact radius of 25 $\mu$m and a top contact aperture radius of 50 $\mu$m are shown in Figure 7.2(b).

### 7.3 Optical design

The optical losses in the EP-VECSEL structure with a thick n-doped current spreading layer have to be compensated by an active region with sufficient gain. The FCA coefficient is

$$\alpha = 5 \cdot 10^{-18} \text{cm}^2 \cdot n + 11 \cdot 10^{-18} \text{cm}^2 \cdot p,$$

with $n$ and $p$ denote the electron and hole densities in $\text{cm}^{-3}$, respectively. The losses in the current spreading layer alone are between 1 and 2%, which is comparable to the gain of a typical optically pumped VECSEL. For laser operation the losses in the current spreading layer have to be compensated to achieve sufficiently high net-gain. Therefore, an intermediate mirror is necessary to increase the gain enhancement. The computed electrical field in the structure is shown in Figure 7.3. The gain structure has a p-doped 30-pair bottom DBR with graded interfaces, an active region containing 6 QWs in two antinodes, a 5-pair intermediate n-doped DBR, a 6 $\mu$m thick n-doped current spreading layer and an antireflection section on top. With the 5-pair
intermediate mirror we get a 5.5 times higher gain enhancement, making the losses in the current spreading layer negligible.

Figure 7.3: Optical design of the EP-VECSEL gain structure. In the top graph a structure without an intermediate mirror is shown. The losses in the current spreading layer are dominating the gain of the QWs. In the bottom a structure with intermediate mirror is shown. The gain enhancement is 5.5 times higher, yielding a net-gain.

Similar to an optically pumped VECSEL, this device also has an antireflection coating. Because of the thick n-doped current spreading layer a Gires-Tournois interferometer (GTI) is formed by the reflection of the bottom mirror and the reflection from the top layers. The influence of the coating on the GDD is shown in Figure 7.4(a), the gray curve is without, and the black curve is with the antireflection section. The free spectral range of the GTI is very small (a resonance approximately every 10 nm). Note that the exact shape of the GDD is determined by the thickness of the current spreading layer. A deviation of 6 nm (which is 0.01%) will shift the complete curve by 6 nm, therefore it is hard to predict the exact shape of the GDD. With an additional antireflection coating the GDD is in the worst case around $10^4$ fs$^2$. 
Figure 7.4: GDD and gain enhancement with and without AR coating. (a) Without antireflection (AR) coating the GDD is too large (gray curve), for an AR coated structure the GDD can be limited below $10^4$ fs$^2$ (black curve), the computed GDD depends on the thickness of the current spreading layer, which cannot be controlled accurately. (b) The gain enhancement shows strong resonances without coating and is smooth with coating.

The gain enhancement for the structure without antireflection section has very pronounced resonances as shown in Figure 7.4(b). The positions of the peaks are determined by the thickness of the current spreading layer and the laser will most likely operate at the highest peak (in this example around 960 nm) which has a FWHM of 3 nm. The use of an additional antireflection section eliminates interference effects and shows a smooth curve with 13 nm FWHM bandwidth, which is comparable to our optically pumped VECSELs and should allow for short pulse operation.
7.4 EP-MIXSEL

The presented design is suitable to be directly modelocked using an external SESAM. Because of the high gain enhancement, the gain structure has a very low saturation fluence, and the SESAM must have an even smaller saturation fluence to obtain stable modelocking.

The QD absorber would ideally be integrated in the unpumped antireflection section. This section can be designed to obtain the required field enhancement in the absorber.
Chapter 8

Conclusion and Outlook

In this thesis, a novel type of ultrafast semiconductor laser has been presented. The modelocked integrated external cavity surface emitting laser (MIXSEL) is a combination of two key technologies: the vertical external-cavity surface-emitting laser (VECSEL) and the semiconductor saturable absorber mirror (SESAM). Because both devices are based on semiconductor technology, integration into a single device is possible. The full integration of these modelocked lasers is a very promising enabler of many applications for which other lasers are too expensive or too bulky.

Optically pumped VECSELs are power scalable because of the efficient heat removal. At the same time, single transverse mode operation can be maintained by using an external cavity. To design the gain structure, a good understanding of the underlying physics is essential. We have developed a numerical simulation tool that allows us to optimize the design by calculating the electrical field distribution inside the layers of the VECSEL structure. Field enhancement, dispersion and growth tolerances can easily be evaluated and optimized. Moreover, finite element analysis has been performed to study the thermal properties of the gain structure and the limits of power scaling. A one-dimensional heat flow is obtained when the pump spot is larger than the thickness of the semiconductor structure. In this regime the output power can be increased by increasing the mode area on the VECSEL, whilst keeping the pump intensity constant. The limits for power scaling are determined by the temperature increase in the heat sink. Absolute temperatures beyond a certain level reduce the efficiency and can even lead to damage of the structure. It is important to replace the GaAs substrate with a material that has a higher thermal
conductivity such as copper or diamond. By using a diamond heat sink, we obtained fundamental transverse mode operation with up to 20 W of cw output power, which is higher than obtained from previous VECSELs. Such a VECSEL can be an attractive alternative to other laser types, i.e. diode-pumped solid-state lasers or fiber lasers, because VECSELs can be cheaper and more compact. Furthermore, the gain structure can be engineered for wavelength regions which are not easily accessible with other laser gain materials.

Inserting a SESAM into a VECSEL cavity enables ultrashort pulse generation. The SESAM initiates and maintains stable passive modelocking. Similar to the VECSEL gain structure, the SESAM can be designed for operation over a broad wavelength range. In order to obtain stable modelocking, the absorber needs to saturate at lower pulse energies than the gain. The gain structure in VECSELs typically consists of several QWs, with a saturation fluence similar to the QW used in standard SESAMs. In this thesis, a numerical simulation software has been developed to simulate the pulse propagation inside a modelocked laser. Various physical effects such as dispersion, gain saturation, absorber saturation, and noise are taken into account. The software does not only permit to find the steady state solutions, but also simulates the pulse buildup from noise inside the laser. These simulations show that the saturation fluence of the SESAM should be smaller than that of the gain by at least a factor of 10. The saturation fluence can be reduced by increasing the field enhancement in the absorber layer. However, this also increases the modulation depth of the absorber, or more precisely: the product $\Delta R F_{sat}$ remains constant with this procedure. Since the modulation depth of a resonant SESAM with standard QW absorber layer would be too high, the only solution to reduce both $F_{sat}$ and $\Delta R$ is to reduce the density of states. This reduction of the product $\Delta R F_{sat}$ can be achieved by using QDs instead of QWs. We obtained over 100 mW of average power from a VECSEL mode-locked with a QD-SESAM. The generated pulses had a duration of 3 ps and a repetition rate of 50 GHz. This experiment was an essential step towards the integration of gain and absorber into one single structure, because it proved that modelocking with identical mode sizes on gain and absorber is feasible.

Optimization of the QD saturable absorber for integration into the MIXSEL required precise optical SESAM characterization. We present a new tool for the characterization of the nonlinear reflectivity of SESAMs with a higher accuracy and
lower constraints on electronic equipment compared to previous setups. Instead of two photodiodes and two high-end lock-in amplifiers, only one photodiode, a simple amplifier and an AD converter are needed. Despite the simple and cost-efficient approach, an accuracy of better than 0.05% is achieved over a dynamic range of more than four orders of magnitude.

We presented the first detailed study of the influence of the QD growth parameters and post growth annealing on the macroscopic optical SESAM parameters, which was determined by measuring both nonlinear reflectivity and recombination dynamics. With the QD density, the design of QD-SESAMs has an additional degree of freedom compared to QW-SESAMs. We experimentally demonstrated for the first time that the modulation depth can be tuned with the monolayer coverage (i.e. the QD density) whilst the saturation fluence remains constant, as predicted by theory. Due to the inherent inhomogeneous size distribution, the dots have broader uniform spectral properties than quantum wells, which is advantageous for short pulses or wavelength tuning. Pump-probe measurements show that the recovery of a QD-SESAM can be described by two clearly distinguishable recovery time constants. To enhance the fast component, the quantum dots should be grown close to the QD formation threshold and operated at a wavelength close to the PL peak. Post-growth annealing further reduces the saturation fluence. Moreover, the fast component becomes even more dominating. Our study shows that the optimum SESAM parameters are obtained by growing around 2 monolayer InAs coverage and subsequent annealing.

Using optimized QD-layers, we designed and demonstrated the first MIXSEL. Our design is optimized for low saturation fluence of the absorber and prevents the saturation of the absorber by the pump radiation. It uses an intermediate mirror between the absorber and the gain regions, which adjusts the field enhancement in the absorber section and simultaneously reflects the pump light. A large field enhancement in the absorber section increases the growth sensitivity. We numerically analyzed the tolerance towards growth error in terms of field enhancement, gain bandwidth and dispersion for different designs. Furthermore, we optimized the low temperature grown QD saturable absorber (400-430°C) for integration into the high temperature grown gain structure (600°C). Nonlinear reflectivity measurements on a MIXSEL confirmed similar saturable absorber
properties as for a low saturation fluence QD-SESAM. A critical task was the precise
growth evaluation, which involved various techniques such as AFM, TEM, SEM,
spectral reflectivity measurements, PL measurements and GDD measurements. Our
work resulted in the first demonstration of a MIXSEL. It generated 40 mW of average
output power in 32-ps pulses at a center wavelength of 960 nm. A higher output
power of 185 mW in 32-ps pulses was achieved by improved cooling. The 5.4-cm
long cavity results in a repetition rate of 2.9 GHz.

In future, better heat management (i.e. substrate removal) will result in
multi-Watt average output powers as previously demonstrated with VECSELs. The
current growth inaccuracies cause a large group delay dispersion and a small gain
bandwidth, which are likely responsible for the relatively long pulse duration.
Designs with less sensitivity towards growth errors are promising to increase the
gain bandwidth and reduce the GDD, which will result in shorter pulses. Such
integrated ultrafast semiconductor lasers operating at multi-GHz repetition rate and
Watt level output power would fill a gap in the performance spectrum of today’s
laser technology.

The next step towards even lower-cost and more compact ultrafast
semiconductor surface emitting lasers will be electrical pumping. This would result
in devices ideally suited for many applications such as telecommunications, optical
clocking, frequency metrology, microscopy, laser display – anywhere where the
current ultrafast laser technology is considered to be too bulky or expensive.
References


REFERENCES


Curriculum Vitæ

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Education
Apr. 2004 – Dec. 2008 PhD studies in the group of Prof. Dr. Ursula Keller, Institute of Quantum Electronics, Physics Department, ETH Zurich, Switzerland
Aug. 1997 – Aug. 2003 Master of Sciences in Electrical Engineering (Cum Laude) Eindhoven University of Technology, the Netherlands
Sep. 1996 – Jul. 1997 Electrical Engineering, Zuyd University, Heerlen, the Netherlands
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Apr. 2004 – Dec. 2008 PhD studies at the Institute of Quantum Electronics, ETH Zurich, Switzerland (development of ultrafast semiconductor lasers)
Sep. 2003 – Feb. 2004 Research scientist at the Department of Electrical Engineering, Eindhoven University of Technology (development of tools to simulate and visualize electromagnetic fields for educational purposes)
Sep. 2001 – Dec. 2001 Internship at the Politecnico di Torino, Italy (analysis and simulation of a multi-mode interference semiconductor optical amplifier based 2R regenerator)

Awards and Honors
Apr. 2007 Young Researcher Best Paper Award, European Conference on Integrated Optics, Copenhagen, Denmark
Nov. 1998 Civi Encouragement Prize, for excellent grades in electrical engineering, Royal Holland Society of Sciences and Humanities, the Netherlands
Oct. 1997 Scholarship for high potential students, Eindhoven University of Technology, the Netherlands
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