UNIVERSITY OF TWENTE

BACHELOR ASSIGNMENT

2015

Theoretical study of passively mode-locked semiconductor-glass lasers

Author: Yvan Klaver (S1346423)

summary

In this thesis we will theoretically investigate a passively mode-locked semiconductor-glass laser. This laser uses a mode-locking mechanism called the self colliding pulse mode-locking (SCPM). In order to find to optimize the design of the laser, different operating regimes of the laser are shown by changing the saturable absorber to active section ratio, the passive section length and the injection current density.

Contents

1	Intro	ntroduction					
2	Pass 2.1 2.2 2.3	sively mode-locked diode lasers SA-gain combination	4 4 5 8				
3	Physical model						
	3.1	Wave and Carrier model	9				
	3.2	Material gain model	10				
4	Simulation						
	4.1	The simulated set-up	11				
	4.2	Changing the length of the passive section	13				
	4.3	Changing the ratio of SA to the active section	13				
	4.4	Changing the SA reverse bias	13				
5	Results and Discussion						
	5.1	Different regimes	14				
		5.1.1 Stable regime	14				
		5.1.2 Switching pulses	15				
		5.1.3 Gain switching \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots	16				
		5.1.4 Multiple pulses	16				
	5.2	Stable pulse shapes	17				
	5.3	Sweep Results	18				
		5.3.1 Autocorrelation	18				
		5.3.2 Optical spectrum	20				
		5.3.3 Pulse FWHM and Peak intensities	20				
		5.3.4 Results for a cavity with a FSR of 2GHz	21				
	5.4	SA bias	22				
6	Con	Inclusion and Outlook 22					

1 Introduction

Mode locked laser (MLL) sources are powerful tools enabling both industrial and academic developments. Implemented in different ways, MLLs are of interest for a wide spectrum of applications. For example, high pulse repetition rates are preferable for optical communication and making optical clocks [1], short pulses provides excellent time resolutions and facilitate measurements of ultra-fast processes which can not be measured otherwise [2], also the feature of high peak intensities of many MLLs renders them suitable for studying various nonlinear optical phenomenon [3] and for material processing [2].

Among those MLLs, semiconductor based MLLs stand out in terms of easy integration with other components. A broad range of applications are ensured by the numerous choices of available materials. Where the change of materials enable different wavelengths.

Monolithicity of a crystal material means that it is grown as a single structure. Semiconductor MLLs that are monolithic suffer from detrimental phase noises due to the intrinsic amplitude-phase coupling which equivalently changes the cavity length. Along the phase noises the monolithic MLLs suffer from self-phase modulation.

MLLs need active materials, which are material that highly interact with the light. One can also add highly passive materials to a cavity which do not interact with the light.

Emerging active-passive integration opens up new possibilities of combatting the phase noise, additionally, extra intra-cavity component such as band-limiting elements can also be easily implemented.

Recently new developments such as the use of graphene-film as a saturable output coupler have been made [4], this has a repetition rate of 1.5 GHz and a pulse FWHM of 1ps. Similarly a monolithic mode-locked laser made from all active materials has been shown with another low repetition rate of 2.1 GHz [5].

For a low repetition rate active-passive integration is missing. In this report we wish to investigate the output properties of such a set-up and the effect of the dimensions on the laser performance. A sketch of the simulated hybrid laser is shown in figure 1.1. Here the active saturable absorber and gain is separated from the low loss glass waveguide.

Based on a travelling wave model named FreeTWM [6] we numerically investigate how to bring such a hybrid integrated active-passive mode locked laser into operation. By studying the influence of various important parameters on the laser output properties we identify different regimes of the temporal and spectral dynamics. Parameters such as length ratio of the saturable absorber (SA) to the active section, cavity length, the pumping strength and reverse bias on the SA are used. As end goal we wish to find set of parameters for a stable operating low repetition rate MLL.



Figure 1.1: A sketch of the simulated set-up. With an active section existing of a saturable absorber (SA) and a semiconductor optical amplifier (SOA) coupled into a low-loss waveguide ending in a loop mirror. The light is out-coupled at the SA.

2 Passively mode-locked diode lasers

In this section we recal briefly the working of a ML diode laser a short fundamental description of the used materials will be given. This will cover the properties of a semiconductor gain medium, absorption properties and start the behaviour of the gain-absorber combination.

2.1 SA-gain combination

Lets start with a scenario where a pulse of light is already stabilized and assume it travels in a cavity of gain medium with an SA-section in the middle. Depending on the saturation properties of the gain and SA medium three things can happen (see figure 2.1). The saturable absorber restores fast, which means an relaxation time that is much shorter than the pulse FWHM: $\tau_s \ll \tau_p$ (figure 2.1.a). The saturable absorber restores slowly, which means an relaxation time longer than the pulse FWHM (figure 2.1.b). Or it can be a slow saturable absorber with saturable gain (figure 2.1.c). This last variant might be most realistic for the situation of an SA-SOA (semiconductor optical amplifier) combination. As the population inversion, which is related to the gain, of the SOA is able to bleach due to the high pulse intensity. And the SA relaxation rate is relatively small, for the simulations we shall see 1ps pulses whereas the SA recovery time will for a realistic semiconductor not get much lower than 5ps.

What happens in all cases is that the pulse travels through the saturable absorber medium and lowers the losses by doing so, this makes energy wise a high intensity pulse most efficient to travel through the SA. Phase-locked modes are preferred and modelocking occurs.

After the pulse passes through the SA the SA either slowly restores (situation **b** and **c**) or restores immediately (situation **a**) depending on the relaxation time. By restoring the losses noise, that is low intensity variation created by spontaneous emission, will not survive the SA when the net loss is higher net gain. As example the figures of 2.1 show



Figure 2.1: Optical loss, gain and pulse plotted over time for a) a fast saturable absorber and b) a slow saturable absorber c) a slow saturable absorber and saturable gain. [7]

where the gain window takes place. For **a** and **c** the peak only takes place when there is net gain (gain > loss).

Why the slow SA at \mathbf{c} still works even though it looks as if it would prefer to have a tail as well has multiple factors. First higher intensity light lowers the loss of the SA more and it is preferred to have the power from the tail in the peak itself. Secondly (which rather explains the cause) the front gets delayed by the SA [2], which causes noise that trails behind the pulse to be added to the power of the pulse.

For the simulations that have been done we implemented the SA section at an end of the cavity (see figure 4.1) as this will cause Self-colliding pulse mode-locking (SCPM) [8] (see figure 2.2). When the pulse reflects at the end of the SA the counter-propagating part of the pulse that is reflected add up with the electric field of the pulse. This higher peak intensity makes it possible to increase the unsaturated SA absorbance and will create a more stable environment for the pulses [9].

Note that SCPM is different from the colliding pulse method (CPM), the signature of this method is that there are **two** counter propagating pulses bleaching the absorber which is positioned in the center of the gain medium instead of a **single** pulse bleaching an absorber placed at a facet. Which means the output repetition rate should be $2 \times FSR$ for a set-up with normal CPM. The reason for the SCPM to have an preference for a repetition rate of the same frequency as the FSR means that it prefers to have a single pulse travelling within the cavity.

2.2 Semiconductor optical amplifier dynamics

Stimulated emission is the key ingredient for amplification of light. Necessary for any type of laser. The semiconductor optical amplifier achieves the stimulated emission via a population inversion (generates electron hole pairs).

A sketch of the band structure and Fermi-Dirac distribution is given in figure 2.3. This



Figure 2.2: Sketch of intensities at the left facet for the left traveling wave (I_{-}) , the right traveling wave (I_{+}) which in this case is the reflected part and the summations $(I_{-} + I_{+})$. Please note that only the intensity envelope of the pulse is depicted here.

figure shows that the relation for stimulated emission in a semiconductor can be achieved when the Bernard-Duraffourg condition [10] is satisfied:

$$E_{Fc} - E_{Fv} \ge h\nu = E_2 - E_1 \ge E_g$$
 (2.1)

This relation states that in order for stimulated emission to be possible the stimulating photons needs to have enough energy to enable a transition of electrons across the band gap (E_g) , but not more energy than the difference between the Fermi-levels of the conductance (E_{Fc}) and the valence band (E_{Fv}) . If a photon has an energy that is under the band-gap energy no transition of the electron can happen, neither from valence to conductance (absorption) nor the other way around (emission). The material is transparent to light with photon energy lower than the band-gap energy. However if the energy is above the Fermi-level difference the chance of absorbing the photon is higher than emitting a photon.

Figure 2.4 shows typical examples of the gain spectra as expected for increasing population inversions generated by increasing injection currents. This picture shows the Bernard-Duraffourg condition as photons with energies lower than the the energy gap have a gain of zero (the material is transparent). And for photons with the energy higher than the Fermi-level difference the gain is negative (absorption). The picture as well shows an relative blue shift of the peak gain with the inversion.

To maintain a certain population inversion density, N, there is some injection current density on the active region (J) needs to at least balance out the spontaneous recombi-



Figure 2.3: Band structure and Fermi-Dirac distributions for an semiconductor in the state $E_{Fc} - E_{Fv} > E_g$. In the band picture k is the electron wave vector. And in the distribution graph, $W_v(E)$ and $W_c(E)$ denote the Fermi-Dirac occupation probability distributions for electrons respectively for the valence and the conductance band. [10]



Figure 2.4: Typical gain spectra of a semiconductor amplifier at different inversion populations. Note that the axis for frequencies starts at band-gap energy. [11]

nation rate of carriers. Which is compensated by:

$$J = eR(N) \tag{2.2}$$

Here e is the elementary charge and R(N) the recombination rate which can be approximated as a cubic polynomial:

$$R(N) = \frac{N}{\tau_s} + BN^2 + CN^3$$
(2.3)

Here the different recombination types are described in each term. The spontaneous light emission is determined by the factor B, which describes the radiative bimolecular (band to band) recombination. Next to this and other recombination types (see formula

2.3) such as linear recombination and Auger recombination [10]. Having the factor $\frac{1}{\tau_s}$ and C respectively. The power of the terms are defined by the amount of minority carriers involved by the recombination. So for instance Auger recombination includes three minority carries.

2.3 Absorber dynamics

A semiconductor can exert gain as well as absorption on light depending on the wavelength and the inversion population. So for an absorber material one can use the same semiconductor material.

For the semiconductor to become absorbing one can implement it without any injection current. This will increase the absorption without having stimulated emission (of any significance that is).

In reality one will apply a reversed biased voltage on the semiconductor in order to tune parameter τ_s from eq.(2.3) which is the relaxation time of the absorber. Note that the reverse bias also causes the so called quantum confined stark effect [12] which causes, at the same time, a red shift of the peak absorption wavelength (see figure 2.5).



Figure 2.5: Absorption spectra for different reverse voltages applied to a semiconductor for tuning its absorption properties. Note that the axis for wavelengths starts at band-gap frequency. [12]

It is of course a very convenient property of a semiconductor junction that the relaxation rate is tunable simply with an external bias. However, one has to be aware that the associated red shift does change a lot about the dynamics of the absorber. This will namely change the net gain curve of a absorber/gain combination.

The semiconductor functions as an saturable absorber (SA). This means that its absorbance of light becomes less the higher the intensity of the light is. The absorption of light mainly happens by exciting the electrons from the valence band to the conduction band. See it as emptying the valence band and filling the conductance band. This creates a inversion which lowers the chance to absorb because less electrons from the valence band are available to excite to the conductance band. Thus with more light being absorbed the absorbance becomes less, the SA is bleaching. After a certain amount of time, mainly determined by the relaxation time τ_s of eq.2.3 the inversion created by a light pulse will vanish and an saturated absorber becomes an unsaturated SA.

3 Physical model

To used model simulates one dimensional spatial points of material that follow the Maxwell-Bloch equations[6]. This tool consists of a few physical models whereof a brief explanation will be given.

3.1 Wave and Carrier model

A main feature of the FreeTWM model is that it uses a Slowly Varying Approximation (SVA) around the optical carrier. This in combination with the approximation of a spatial distribution perpendicular to the propagation direction that is uniform over time and the propagation direction, describes the electric field as

$$\mathcal{E}(\vec{r},t) = \Phi(\vec{r}_{\perp}) \{ E_{+}(z,t)e^{i(q_{0}z-\omega_{0}t)} + E_{-}(z,t)e^{-i(q_{0}z-\omega_{0}t)} \} + c.c.$$
(3.1)

Here the electric field is described by a spatial distribution $\Phi(\vec{r}_{\perp})$ and slowly varying electric field envelopes $E_{+}(z,t)$ and $E_{-}(z,t)$ which are travelling to the right and left respectively. *c.c.* Gives the complex conjugate. By performing the SVA around the optical carries (ω_0, q_0) using this new description, the following equations can be deduced from the Maxwell-Bloch equations [6]

$$(\partial_t \pm \partial_z) E_{\pm}(z,t) = i P_{\pm} - \lambda(z) E_{\pm}(z,t) - i \kappa_{\pm}(z) E_{\mp}(z,t)$$
(3.2)

$$\partial_t D_0(z,t) = J(z) - R(D_0) - is(P_+ E_+^* + P_- E_-^* - c.c.)$$
(3.3)

$$\partial_t D_{\pm 2}(z,t) = -(R'(D_0) + 4\mathcal{D}q_0^2)D_{\pm 2}(z,t) - is(P_{\pm}E_{\pm}^* - E_{\pm}P_{\pm}^*)$$
(3.4)

$$R(D) = A(z)D + B(z)D^{2} + C(z)D^{3}$$
(3.5)

These expressions consist of: an approximation to the wave equation (3.2) where it includes loss $\lambda(z)$ and gain via the polarization P_{\pm} .

The recombination rate from (2.3) which is described in section 2.2 is now presented in normalized form in (3.5).

The first-order component of the carrier density (3.3) which is the quasi-homogeneous part of

$$D(z,t) = D_0(z,t) + [D_{+2}(z,t)e^{2iq_0z} + D_{-2}(z,t)e^{-2iq_0z}] + h.o.t.$$
(3.6)

Here D(z,t) is expressed as the approximation of the carrier density. For validity of accuracy for its current purpose one can again refer to [6]. The quasi-homogeneous part $D_0(z,t)$ described by (3.3) is dependent on the injection current density J(z), the recombination rate of this component $R(D_0)$, and light induced recombination which is described by the last part of (3.3). The last term is scaled by a factor of s, which is a

normalization factor such that $\tilde{E}_{\pm} = \sqrt{s}E_{\pm}$ and $\tilde{P}_{\pm} = \sqrt{s}P_{\pm}$.

The second component $D_{+2}(z,t) = D_{-2}^*(z,t)$ of equation (3.6) is describing the presence of a weak carrier density grating. Such gratings arise from so called spatial hole burning where standing waves in a laser cavity cause the anti-nodes to decrease the carrier density faster than the nodes as the electric field induces recombination. Please note that the weak grating component only contains carrier frequency part of the electric field. And that the slow envelope still has its own contribution in equations (3.3) and (3.4).

3.2 Material gain model

So far there are equations describing the electric field (E_{\pm}) and the carrier density (population inversion: D_0), these are linked by the polarization of the material (induced spatial density of dipole moment) which acts as the source or sink term in the wave equation of the field. The polarization within this model can be described as

$$P_{\pm}(z,t) = \chi_0(z) \left\{ \int_0^{+\infty} ds \chi[s, D_0(z,t-s)] E_{\pm}(z,t-s) + D_{\pm 2}(z,t-s) \frac{\partial \chi}{\partial D}[s, D_0(z,t-s)] E_{\mp}(z,t-s) ds \right\} + \beta(z)\xi_{\pm}(t) \quad (3.7)$$

Where the last term $\xi_{\pm}(t)$ is some white noise independent of D_0 and $\chi_0(z)$ is the maximum saturated gain ($\chi(z,t)$ is normalized to this value in this model). Note that the second kernel $\frac{\partial \chi}{\partial D}$ again occurs due to the SVA. The integration kernel that lies within equation (3.7) might be the most complex part of this model. As it consists of the summation over the energy bands. The valence and conductance band are assumed to have a quasi-Fermi distribution of electrons and holes respectively, see figure 2.3.

However it is important to realise that the approximation of the convolution made in [6] no longer corresponds to the generation of the kernel in the current version of the program. One now has to be referred to [13]. In this article J. Javaloyes and S. Balle describe equation (3.7) with a new approximation, which gives the macroscopic polarization based on the Bloch equation as

$$P(t) = \frac{-id^2}{\pi W \hbar^2} \int_0^\infty ds R(s, t-s) E(t-s)$$
(3.8)

with the convolution kernel (R(s,t)) as

$$R(s,t) = \mathcal{I}_c(s,t) + \mathcal{I}_v(s,t) - \mathcal{I}_0(s)$$
(3.9)

Where the first two terms are contributions of the conductance $\mathcal{I}_c(s,t)$ and the valence band $\mathcal{I}_v(s,t)$. And the last term is a correction term due to empty bands. Again the kernel is a summation over contributions from all bands, so see equation 3.9 as a summation in two parts. One part over the conductance band and one over the valence band, with a correcting term for the empty bands in between. These parts are described as

$$\mathcal{I}_0(s) = \frac{m}{\hbar} \frac{1 - e^{-i\Omega_T s}}{is} \tag{3.10}$$

$$\mathcal{I}_{c,v}(s,t) = \int_0^{\Omega_T} d\omega \frac{e^{-i\omega s}}{1 + \exp\left(\omega/\gamma_{c,v} - \beta F_{N,H}(t)\right)}$$
(3.11)

where the top-band frequency is $\Omega_T = \frac{\hbar k_m^2}{2m}$ with k_m as the edge of the Brillouin zone. This defines the state of maximum allowed energy for the described semiconductor crystal. $\gamma_{c,v} = \frac{k_B T}{\hbar} \frac{m_{c,v}}{m}$ are the effective thermal broadening of the electrons and holes respectively. Note that in equation (3.10) the mass $m = (m_e^{-1} + m_h^{-1})^{-1}$ is the reduced mass of the electron-hole pair, the inverse thermal in (3.11) energy is $\beta = (k_B T)^{-1}$. and $m_{c,v}$ is the effective mass of the conductance and valence band. Equation (3.11) which contains the time-dependent quasi-Fermi levels $F_{N,H}(t)$ for electrons and holes respectively. These are related to the instantaneous densities of electrons and holes by

$$N(t), H(t) = N_t^0 \frac{\gamma_{c,v}}{\gamma} \ln\left(\frac{1 + e^{-\beta F_{N,H}(t)}}{e^{-\beta E_{c,v}(k_m)} + e^{-\beta F_{N,H}(t)}}\right)$$
(3.12)

Where the N(t) and H(t) are the instantaneous densities of electrons and holes respectively. The polarization decay rate is given by γ and the transparency carrier density by $N_0^t = \frac{m\gamma}{\pi W \hbar}$. With W as the quantum well width.

4 Simulation

This section explains the simulations done. First describing the set-up followed by the explaining the changed parameters.

4.1 The simulated set-up

Let us first explain the schematic set-up of the laser to be simulated. This set-up is chosen for maximum simplicity and is essentially what is to be validated in an according experiment. In all simulations we consider a structure (see figure 4.1) that exists of two parts, an active part: the saturable absorber (SA) and the semiconductor optical amplifier (SOA/gain-medium), and a passive part: the glass wave-guide.

Defined are the lengths L1 and L2, in the simulations L1 is a fixed length. Important is to know that the travelling wave is implemented in a way that expresses optical lengths as time intervals as well. This means that, for instance, the physical length L_1 is expressed as the travelling time interval $\Delta t = \frac{L_2}{n_g}$ where n_g is group velocity index. For the simulations we will assume that active section contains a group index of $n_g \approx 3.6$ while for the passive section the group index does not need to be specified as it is considered lossless and having zero group velocity. And thereby provides a certain delay time for feedback into the active part.

The set of parameters as shown in table 4.1 will be used in all the simulations. The parameters are based on earlier simulations done based on a InGaAsP/InP structure[14],



Figure 4.1: Schematic picture of the simulated PML. The loss of the passive section is lumped in the reflectivity R_2 . L1 is the length of the active section (SA+SOA) and L2 is the length of the passive section.

[6]. These gain and SA properties are available for use in an experimental set-up along with a separated glass waveguide.

Because we are investigating the case that active and passive section are separated, the coupling between the active and passive section dominates the loss. For all sweeps the total loss of the passive section, thus the reflectivity R_1 will be kept the same.

Symbol	Value	Unit	Meaning
λ_0	1.55	$\mu { m m}$	Emission wavelengths (SVA expansion point)
n_g	3.6	-	Effective group index
$ au_c$	12.5	\mathbf{ps}	Travel time through active part
$2\alpha_i$	15	cm^{-1}	Internal losses
$2\chi_{0,SOA}$	424	cm^{-1}	Saturated gain factor for the SOA
$2\chi_{0,SA}$	1272	cm^{-1}	Saturated gain factor for the SA
γ	5	THz	Polarization decay rate
γ_c	0.8	rad $\times~\mathrm{THz}$	Electron thermal distribution width
γ_v	8	rad $\times~\mathrm{THz}$	Hole thermal distribution width
Ω_g	5	rad $\times~\mathrm{THz}$	Bandgap detuning (w.r.t. SVA point) of the SA
Ω_T	90	rad $\times~\mathrm{THz}$	Top band frequency
\mathcal{D}	12	$\mathrm{cm}^2 \mathrm{~s}^{-1}$	Ambipolar diffusion constant
A	1×10^8	s^{-1}	Non radiative recombination (SOA only)
B	7×10^{-10}	${\rm cm}^3~{\rm s}^{-1}$	Spontaneous recombination
C	1×10^{-29}	${\rm cm}^6~{\rm s}^{-1}$	Auger recombination
$ au_{SA}$	10	\mathbf{ps}	Absorber recovery time

Table 4.1: Table of the parameters used in the active sections

Next to that we consider that the reflectivity of both facets is fixed at the values as indicated in figure 4.1, R_1 30% at the left facet and R_2 9% at the right facet. Setting the value of R_1 this means that it has 70% output, for R_2 however the other 91% is loss and this facet has no output.

4.2 Changing the length of the passive section

To get understanding of the influence of the length of the passive section with regard to the active section we have performed calculations in which we sweep the passive length. The length of the active section has been set to 12.5 ps for all simulations and the passive section has been swept from 12.5 ps to 237.5 ps. This includes a free spectral range (FSR) of the complete cavity of 20, 10, 5 and 2 GHz. For the first characteristics the SA ratio to the active section is fixed to 4.5%.

We will discuss the output of the simulation in time domain and the output in the frequency domain. In order to identify the injection current range of the operation per passive length, the injection current is swept as well. This is done as the operation range might change drastically. Increasing the relative injection current range means increasing the usability the laser.

4.3 Changing the ratio of SA to the active section

Another variable will be swept, this is the ratio of the SA to the active section. This is done for all the different lengths that are simulated. We expect to see an influence on the duration of the generated pulses as the SA has the effect to reduce the FWHM of the pulse while the SOA increases the FWHM. We expect to see an increase of the lasing threshold current (the current at which lasing starts happening) with the SA to active ratio as the SA increases the losses.

4.4 Changing the SA reverse bias

As stated in section 2.3, applying a reverse bias put on the saturable absorber shortens the relaxation time, τ_s . However applying a reverse bias does as well tune the band-edge of the SA. Although there is a theory [15] for the relation between the relaxation rate and the reverse bias, the QCSE is very dependent on dimensions, structure and material of the SA. As a result there is no good measured reference for these values, rendering the reverse bias relaxation rate relation useless for our case. As we wish to use the relation between the band-edge shift and the relaxation rate.

As a result we swept the band-edge shift and the relaxation rate independently from one another. The band-edge detuning Ω_g (see table 4.1) and the absorber recovery time τ_{SA} are therefore swept from 1 THz to 4 THZ [16] and 5 ps to 30 ps [17] relatively. Next to these parameters the injection current J are swept from 20×10^8 to $90 \times 10^8 s^{-1}$. This range is determined by simulations doe earlier by the sweeps of SA to active ratio and passive length sweeps. Due to the many degrees of freedom the full exploration of which is not possible in terms of computation time, we decided to have a few parameters set. Based on results from section 4.2 and 4.3, the cavity FSR is set to 2GHz and the SA to active ratio to 6%.

5 Results and Discussion

This section introduces the main results that have been gathered from the simulations. We start by analysing time traces of the output intensity or optical spectra in obtained in selected cases. After that the pulses with low variation of shape over time (stable pulses) are isolated and fitted. Finally the results of the sweeps for SA active ratio and FSR are analysed followed by the SA bias sweep.

5.1 Different regimes

In most simulation repetitive output results is found for different regimes in the simulated set-ups.

5.1.1 Stable regime

Let us first discuss the regime we consider stable mode-locking. A time-trace, optical spectrum and RF spectrum from a simulation in that regime is given in figure 5.1.



Figure 5.1: Results of a simulation with a FSR of 5GHz, SA-to-active-length ratio of 4.5% and an injection current of $50 \times 10^8 \text{ s}^{-1}$. (a) output intensity time trace (b) optical spectrum (c) RF spectrum and (d) a zoom on the time trace.

It can be seen that the pulses are almost identical in shape and time interval, in this case a single pulse is travelling through the cavity and has an almost identical shape

each time it reaches the out coupling facet. In the RF spectrum (figure 5.1 (c)) one can see that the repetition rate corresponds to the FSR as the dominating frequencies are multiples of 5 GHz. This is what one would normally expect from an mode-locked laser that is based on the SCPM (see 2.1)

5.1.2 Switching pulses

With multiple pulses one can have the issue of mismatched timing and too low gain which will leave not enough time for the SOA to recover the gain between two subsequent pulses(see figure 5.2). For obtaining steady state operation the inversion needs to be recovered each time a pulse travels through this medium and this is done with an constant injection current.

In figure 5.2 (b) can see that if more than a single pulse is generated per roundtrip time, the second, additional pulse forms just before an initially present, first pulse. This is probably because the gain/population inversion is highest just before the pulse arrives and gives the possibility for spontaneous emission to grow towards a significant pulse. When this pulse travels through the gain this will bleach inversion population of the gain and reduce the growth of the initially present, first pulse. When the original pulse travels through the SA it experiences a net loss while the new pulse still has more gain than loss. And so one pulse dies out while another starts, we observe this phenomenon when the injection current is just above the stable region and happens for longer regions at higher FSR. The reason for the relation with injection current is the high population inversion in the gain before arrival of the travelling pulse (high enough to start a new pulse). The reason for the relation with the FSR most likely originates from the smaller interaction between the pulse and the gain medium.



Figure 5.2: Results of a simulation with a FSR of 5GHz, SA-to-active-length ratio of 4.5% and an injection current of $57.5 \times 10^8 \text{ s}^{-1}$. (a) output intensity time trace and (b) an zoom into a single instability at the time trace.

5.1.3 Gain switching

The pulses that start from spontaneous emission can as well be observed just before the laser starts mode-locking (see figure 5.3). In this case the starting of a new pulse happens when there are no pulses travelling through the cavity. The principle of starting the pulse is the same as in section 5.1.2. The difference is that there is not enough injection current to maintain the inversion for gain when the pulse travels through. The pulse travels through the gain medium reducing the gain quicker than the injection current build. This causes the same pulse to die out instead of a second pulse.

When comparing figure 5.2 and 5.3 note that the FSR is different as the described phenomenon only has an significant region for an current sweep with the FSR at 20GHz. For larger passive sections the region of injection currents where the switching happens gets smaller, for 2GHz for instance this phenomenon is not even observed. The reason being the same as in section 5.1.2, where the interaction between the pulse and the gain medium reduces when increasing the passive length.



Figure 5.3: A simulation output with a FSR of 20GHz, SA-to-active-length ratio of 4.5% and an injection current of $40 \times 10^8 \text{ s}^{-1}$. (a) output intensity time trace and (b) an zoom into a single burst.

5.1.4 Multiple pulses

Opposing to the Gain switching which mainly takes place at the lower FSR, at higher FSR with high injection current multiple pulses form inside the cavity but are still stable. See figure 5.4 as an example, where three pulses are travelling in the cavity at the same time. In time domain one can see that there are three pulses distinguishable purely from their difference in peak intensity. In frequency domain the fact that they are distinguishable is represented by the presence of the FSR frequency (5 GHz) even though the 15 GHz component is most dominant. This means that the time trace repeats with a rate of 15GHz but has extra overlap every three pulses causing a 5GHz component in the frequency domain.



Figure 5.4: A simulation output with a FSR of 5GHz, SA-to-active-length ratio of 4.5% and injection current of 90×10^8 s⁻¹. (a) time trace and (b) the RF spectrum.

5.2 Stable pulse shapes

The following section will focus on the temporal shape of the pulses in obtained the simulation where pulses after start-up of the laser will be analysed.

Let us analyse the pulses of the stable regime (figure 5.1). In figure 5.5 in order to show stability of the pulses, that is low change of the pulse shape over time, all the pulses of the latter half of the simulation are overlapped. This area has been marked red and has a small surface indicating low variety in shape of the pulse.



Figure 5.5: All pulses in the last half (50ns) of a simulation output with a FSR of 5GHz, SA-to-active-length ratio of 4.5% and an injection current of $50 \times 10^8 \text{ s}^{-1}$. The average pulse has been fitted with a Gaussian, sech² and Lorentzian fit based on average peak height and FWHM.

On the average pulse there have been made a fits whereof the transform-limited timebandwidth product is known. In our case the SA is slow compared to the pulse width, thus based on a analytical solution provided by Haus [18] one expects a sech²-shaped pulse that is indicating the formation of solitons. However Haus has already stated that this is not what one generally finds in experiments [19]. In [19] different electric-field envelope shapes are proposed.



Figure 5.6: All pulses in the last half (50ns) of a simulation output with a FSR of 5GHz, SA-to-active-length ratio of 4.5% and an injection current of 50×10^8 s⁻¹. The resulting region has been fitted with a sech² and asymmetrical fit with b = -0.29.

The shape for an asymmetric pulse of [19] seems to fit well on figure 5.6. The asymmetric pulse fit describes the electric field envelope as follows:

$$E(u) = \frac{V_A^{1/2}}{(\cosh^2 u + b \sinh u \cosh u + bu)^{1/2}}$$
(5.1)

Where V_A is the saturation energy normalized of the saturable absorber, b a fitting parameter and u is given by:

$$\frac{t}{\tau} = u(1 + b \tanh u) \tag{5.2}$$

Here t is time and τ is a time fitting parameter. By applying this fit with different values of b but set parameters of peak intensity and FWHM of the simulated peak width, the best fit is found.

When multiple pulses are observed, that is a higher repetition rate then the FSR, a small pulse shapes in the tail of the main pulse (see figure 5.7). Normally intensity variations in the tail is not able to survive for a long time as the front of the pulse travels slower than the tail. However this tail seems not only to be stable, the tail seems to be present in all of the pulses (which in the case of the simulation used for figure 5.7 is two subsequent pulses, thus a repetition rate of 10 GHz).

5.3 Sweep Results

5.3.1 Autocorrelation

It is noticed that for larger cavities multiple pulses occur (for lower injection currents) and in higher amounts.

In order to find instabilities and the repetition rate a intensity auto-correlation for this different sweeps, that is in this case injection current sweeps, has been plotted in dB. The



Figure 5.7: Result for all pulses in the last half (50ns) of the simulation with FSR 5GHz, SA to active ratio of 7.5% and injection current of $110 \times 10^8 \text{ s}^{-1}$. The resulting region has been fitted with a Gaussian, Soliton and Lorentzian fit based on average peak height and FWHM.

figure shows as well the lower stability of the pulses, this can be seen by the width and decay of the maximum values of the intensity autocorrelation vs injection current. For instance a wide line shows when the spacing of the pulses is not equidistant or multiple pulse trains that are not exactly in phase (this might also create dark spots in the line).

The auto-correlation for a 5 GHz cavity in figure 5.8 (a) shows that, instabilities represent themselves as a non-zero correlation-amplitude around the autocorrelated pulse. When the laser is having no output at low injection currents, white bands occur in the intensity auto-correlation. The picture shows as well the absence of the switching as described in section 5.1.3 at low injection currents for this particular set-up.



Figure 5.8: The simulation output sweep with FSR 5GHz, SA to active ratio of 4.5%. With (a) the normalized intensity autocorrelation and (b) the optical spectrum.

In general the transition between different quantities of pulses, which is a higher repetition rate, seem to be non existent. In the sense that at certain regions it will pulse in either the lower or higher quantity of the transition. However the transition from a single pulse in the cavity to a double pulse in the cavity seems to have region where the pulses are unstable. As example is figure 5.8, there is a transition from one to two pulses around 60×10^8 s⁻¹.

In this particular sweep around 130×10^8 s⁻¹ there is a switch between 3 and 4 pulses. For a cavity with higher FSR these switches occur more.

5.3.2 Optical spectrum

In figure 5.8 (b) the optical spectrum is plotted. Note that here the envelope of the spectrum is plotted, the envelope of the optical spectrum gives information about the shape of the pulse but not the carrier frequency nor low frequency changes. One observes broadening of the optical spectrum when increasing the injection current, until the number of pulses in the cavity increases. This broadening is an indication for reduction of the FWHM of the pulses. This can qualitatively be understood as the pulses with higher intensities, which are generated by higher pumping current, the pulse narrowing properties by the SA becomes higher. When an additional pulse is formed the average power is divided over all pulses causing a lower peak intensity and less narrowing of the pulses. Thus the optical spectrum suddenly becomes smaller again.

Note that for a higher SA-to-active-length ratio the optical spectrum gets broader over the complete current density range but the threshold current increases as well.

5.3.3 Pulse FWHM and Peak intensities

As in the last section described the FWHM of the pulses and peak intensity should change over different injection currents. To investigate whether the expectations of the last section are justified figure 5.9 is introduced, where all of the peaks in the simulation after start-up are analysed on the peak intensity and full width half maximum.



Figure 5.9: Results of an simulation sweep with FSR 5GHz and SA to active ratio of 4.5%. With (a) the FWHM plot and (b) the peak intensity. The errorbar gives the absolute range of the values that were observed in the latter half of a single simulation.

In figure 5.9 the FWHM of the pulse shows what can be expected from the optical spectrum of figure 5.8. It decreases when the width of the spectrum increases and the switches of the number of pulses travelling in the cavity can be distinguished by sudden change in the width of the optical spectrum. The peak intensity correlates with the FWHM of the pulse in that it increases when the pulse duration shortens and drops when an additive pulse starts circulating. This drop can be explained, as was already described above, by the division of power over the amount of pulses and the correlation with the FWHM because of the total power of the pulse. Their relation means that an smaller pulse needs an larger peak intensity in order to maintain the same power. Of course this is only approximately as the total power should increase with the injection current.

To see how the FWHM and peak intensity change with the ratio SA to active section, we plotted the pulse FWHM and peak intensities vs. the injection current one can find in figure 5.10. This contains a range of SA-to-active-length ratios that were swept with a cavity for 10 GHz.



Figure 5.10: Values taken from the simulation output pulses of a sweep with a FSR of 10 GHz. With (a) being the pulse FWHM vs. injection current and (b) the peak intensity vs. injection current. The errorbar gives the absolute range (max deviation from average) of the values that were observed in the regime after start-up of a single simulation.

5.3.4 Results for a cavity with a FSR of 2GHz

In figure 5.11(b) it can be seen that this longer cavity at splits the energy in the cavity into multiple pulses at that are about equidistantly spaced, as the pulse repetition increases in quantities of 2GHz. This happens at lower injection currents and in higher quantities with respect to smaller cavity lengths.

The injection current region where the 2GHz cavity is stable whilst having a single pulse is very close to the threshold current, this has already been observed before with monolithic lasers [20]. This operation regime seems to be small as it is only about a seventh of the threshold current $(J = 5 \times 10^8 s^{-1})$. Using the following parameters one



Figure 5.11: (a) Optical spectrum over different injection currents and (b) an intensity autocorrelation of the 2GHz cavity with 4.5% SA to active.

can approximate the current for a experimental set-up. The gain medium parameters of the laser are based on a multi-quantum well (MQW) structure with four 6 nm quantum wells (QW) o 2 micron width. Approximating the normalisation parameter of J as $N_{tr} \approx 1 \times 10^{18} cm^{-3}$ results in a stable regime of 4 mA.

5.4 SA bias

A redshift of the the band-edge Ω_g seems to be causing a decrease in loss of the SA. The decrease in effectiveness of the SA lets small variations in the electric field pass through the SA. At a detuning of 2 THz the output does no longer find any stable regime. For instance in figure 5.12, during the current sweep for $\Omega_g = 2$ THz, $\tau_{SA} = 10$ ps even at the lowest lasing current $(J = 30 \times 10^8 s^{-1})$ there is no stable pulsing.

Note that the current at which the laser starts is lowered and the pulse peak intensity is a reduced with respect to smaller band-gap detuning. Due to the redshift the losses of the SA to decrease the unsaturated losses decrease as well. Letting more low variation electric field pass through the SA, which causes the total power to be spread over time instead of collected in a pulse.

6 Conclusion and Outlook

The goal was to simulate different regimes of operation of a semiconductor-glass PMLL based on change of dimensional parameters and the injection current. And a set of parameters for a optimized hybrid laser is found.

In this thesis we have shown different regimes of a numerically simulated passively mode-locked hybrid laser based on the self colliding pulse method by changing the saturable absorber to active section ratio, the passive section length and the injection current density. There has been observed stable mode-locking(see figure 5.1), switching



Figure 5.12: Intensity output time trace for the SA bias sweep with $\Omega_g = 2$ THz, $\tau_{SA} = 10$ ps and $J = 30 \times 10^8 s^{-1}$

pulses(see figure 5.2), gain switching (see figure 5.3) and multiple pulses (see figure 5.4). The change in the pulse properties: FWHM and peak intensity have been seen which correlate with the injection current and pulse quantity (dominating RF frequency).

For the interest in the 2GHz FSR cavity it is shown that the cavity is able to function in a current region of about 4 mA. The hybrid laser with parameters stated in table 4.1 is optimized for the SA to active ratio of 4.5%. Meaning 50 micron SA and about 1 mm SOA. Such a laser should be usable with available current sources.

References

- [1] Till Rosenband et al. "Frequency ratio of Al+ and Hg+ single-ion optical clocks; metrology at the 17th decimal place". In: *Science* 319.5871 (2008), pp. 1808–1812.
- [2] R. Paschotta and U. Keller. "Passive mode locking with slow saturable absorbers". English. In: *Applied Physics B* 73.7 (2001), pp. 653-662. ISSN: 0946-2171. DOI: 10.1007/s003400100726. URL: http://dx.doi.org/10.1007/s003400100726.
- [3] DAB Miller et al. "Nonlinear optics with a diode-laser light source". In: Optics letters 8.9 (1983), pp. 477-479.
- [4] Rose Mary et al. "1.5 GHz picosecond pulse generation from a monolithic waveguide laser with a graphene-film saturable output coupler". In: Optics express 21.7 (2013), pp. 7943–7950.
- Yan Li et al. "A Low Repetition Rate All-Active Monolithic Passively Mode-Locked Quantum-Dot Laser". In: *Photonics Technology Letters, IEEE* 23.14 (2011), pp. 1019–1021. ISSN: 1041-1135. DOI: 10.1109/LPT.2011.2151281.
- J. Javaloyes and S. Balle. Freetwm: a simulation tool for multisection semiconductor lasers. 2012. URL: http://nova.uib.es/ONL/Softwares/Softwares.html (visited on 06/15/2015).
- [7] "Ultrafast solid-state lasers". In: Landolt-Börnstein, 2007. Chap. 2 Short and ultra short pulse generation.
- [8] D.J. Jones et al. "Dynamics of monolithic passively mode-locked semiconductor lasers". In: Quantum Electronics, IEEE Journal of 31.6 (1995), pp. 1051–1058. ISSN: 0018-9197. DOI: 10.1109/3.387042.
- [9] K A Williams, M G Thompson, and I H White. "Long-wavelength monolithic modelocked diode lasers". In: New Journal of Physics 6.1 (2004), p. 179. URL: http: //stacks.iop.org/1367-2630/6/i=1/a=179.
- [10] Tunable Laser Diodes and Related Optical Sources. John Wiley & Sons, 2005.
- [11] Laser Physics. John Wiley & Sons, 2010.
- P.M. Stolarz et al. "Spectral Dynamical Behavior in Passively Mode-Locked Semiconductor Lasers". In: *Photonics Journal, IEEE* 3.6 (2011), pp. 1067–1082. ISSN: 1943-0655. DOI: 10.1109/JPH0T.2011.2172403.
- [13] J. Javaloyes and S. Balle. "Detuning and Thermal Effects on the Dynamics of Passively Mode-Locked Quantum-Well Lasers". In: *Quantum Electronics, IEEE Journal of* 48.12 (2012), pp. 1519–1526. ISSN: 0018-9197. DOI: 10.1109/JQE.2012. 2221684.
- [14] V. Moskalenko et al. "Theoretical Study of Colliding Pulse Passively Mode-Locked Semiconductor Ring Lasers With an Intracavity Mach-Zehnder Modulator". In: *Quantum Electronics, IEEE Journal of* 50.6 (2014), pp. 415–422. ISSN: 0018-9197. DOI: 10.1109/JQE.2014.2316339.

- [15] H. Schneider and K. v. Klitzing. "Thermionic emission and Gaussian transport of holes in a GaAs/Al_xGa_{1-x}As multiple-quantum-well structure". In: *Phys. Rev. B* 38 (9 1988), pp. 6160-6165. DOI: 10.1103/PhysRevB.38.6160. URL: http://link.aps.org/doi/10.1103/PhysRevB.38.6160.
- [16] Irina V. Kulkova. "Material Engineering for Monolithic Semiconductor Mode-Locked Lasers". PhD thesis. DTU Fotonik - Department of Photonics Engineering Technical University of Denmark, 2014.
- [17] J. R. Karin et al. "Ultrafast dynamics in field-enhanced saturable absorbers". In: Applied Physics Letters 64.6 (1994).
- [18] H.A. Haus. "Mode-locking of lasers". In: Selected Topics in Quantum Electronics, IEEE Journal of 6.6 (2000), pp. 1173–1185. ISSN: 1077-260X. DOI: 10.1109/2944. 902165.
- [19] H. Haus. "Theory of mode locking with a slow saturable absorber". In: Quantum Electronics, IEEE Journal of 11.9 (1975), pp. 736-746. ISSN: 0018-9197. DOI: 10. 1109/JQE.1975.1068922.
- [20] V. Tahvili M.S. Augustin L.M. Smit M.K. Bente E.A.J.M. Latkowski S. Moskalenko.
 "2.5 GHz extended ring cavity mode-locked laser with an integrated phase modulator for dual comb fourier transform spectroscopy". In: 19th Annual Symposium of the IEEE Photonics Society Benelux.