Ultrafast integrated semiconductor laser technology at 1.55 µm
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Ultrafast Integrated Semiconductor Laser Technology at 1.55 µm
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Filosofen zijn mensen die de hele dag nadenken over de zin van het leven. 
Ik weet niet wat de zin van het leven is,
maar volgens mij in ieder geval niet om daar de hele dag over na te lopen denken.

T. Maassen
1 Ultrafast Integrated Semiconductor Laser Technology at 1.55 μm

1.1 Introduction

Mastering fire and light is without doubt one of the greatest and most influential technological achievements in human (pre-) history. It allowed humans to break the natural cycle of the sunlight during the day and the darkness of the night. It was made possible to venture to otherwise uninhabitable territory, where the climate would be too cold otherwise. And it made possible numerous arts and crafts, such as metal working and cooking. As such it was essential for the start of what we would nowadays call our technological civilization. All in all mastering fire and light allowed the human race to take matters in their own hand and be less dependent on his surroundings and environment. The apparent impact of this is clearly underlined by the mythological Prometheus, who empowered the human race at the expense of their divine rulers.

The invention of the laser in 1960 by Theodore Maiman [1] and the laser diode two years later [2] have been proven to be some of the most significant breakthroughs for human technology in the last century. With applications ranging from optical storage and barcode scanners to industrial machining and optical fiber communication, the laser has been of huge impact on everyday life. Moreover the laser is present in almost every laboratory, with main applications in spectroscopy and (fluorescent) imaging. All of these applications make use of the characteristic features of laser output light, namely its coherence, uniform polarization and monochromaticity, i.e. very narrow linewidth of the optical spectrum. Moreover using techniques as Q-switching, gain-switching and modelocking extremely short and/or high peak power optical pulses can be created [3].

The work presented in this thesis focuses on semiconductor or diode lasers, operating at wavelengths around 1.55 μm, i.e. the near-infrared. The advantage of this wavelength range is threefold. First of all this is the wavelength of choice for optical fiber communications, as the optical fibers have a loss-minimum around this wavelength range [4]. Therefore the laser diodes operating in this range have a main application in optical fiber communication. Secondly because of this application in telecommunication and the corresponding research and development activities over the last decades, material quality and device manufacturing have reached a level of maturity that enables the fabrication of high quality devices with a high level of integration density using the InP/InGaAsP material system [5]. Moreover as a third point, in the development of the optical telecommunication, test and measurement equipment as well as many optical components are readily and extensively available and are often turn-key.

The work presented in this thesis focuses on ultrafast laser technology. Of course the speed of light itself can obviously be quantified as ultrafast, but more specific in this work it refers to the pulsed operation of the laser diodes and the associated devices that have been
developed for further pulse processing. Using the technique of mode-locking, pulse durations down to a few picoseconds and pulse repetition rates of over tens of Gigahertz are commonly generated by mode-locked laser diodes (MLLDs) [6] in laboratory situations. The main aim of the work presented here is to explore the possibilities of realizing a source that is able to generate pulses in the femtosecond range, i.e. down to 200 fs to 300 fs. This source can also include pulse processing or manipulation components on the same chip as the MLLD, i.e. the components are integrated.

As a last point of the focus of this work the technology has to be mentioned. All the devices presented in this thesis have been fabricated in the COBRA cleanroom, and they consist of components that represent state-of-the-art technology, but not experimental technology. Hence the results of this work represent a feasible technology platform, which can be compatible with the technologies as used by nowadays commercial foundries, like Infinera, Bookham and CIP. The theoretical work presented is mainly set up to serve as a tool for the device design.

In this introduction chapter, first the applications for these ultrafast integrated semiconductor lasers are discussed in the next section. In section 1.3 an overview is given of the approach in this work to generate the short pulses. This chapter is then concluded with a summary of the results of this work and the main conclusions.

1.2 Applications of ultrafast integrated MLLDs

The main advantages of ultrafast integrated MLLDs over their bulk or fiber optics counterparts are their small size and stability [7]. Moreover potentially lower fabrication cost, scalability of the production process and turn-key operation can significantly increase the feasibility of the application and implementation of ultrafast technology. On the downside the average power and optical bandwidth that can be generated by integrated MLLDs is limited. This also limits the pulse durations and corresponding peak powers that can be achieved. However in many applications these drawbacks are not significant and it is obvious that the integrated MLLD offers superior possibilities for numerous applications.

As mentioned above the field of optical telecommunication has stimulated a lot of research on integrated MLLDs, especially operating at wavelengths around 1.3 μm and 1.55 μm. As a result the main application area of these lasers is in this field, where they can function as a synchronized pulse source for wavelength-division multiplexed (WDM) systems and optical time-division multiplexed (OTDM) systems [8]. Also because of their short cavity and well defined pulse repetition rates, MLLDs can operate as optical clocks for clock extraction [9] and to define switching windows in e.g. OTDM demultiplexing [10]. The high stability of the optical spectrum associated with these well defined pulse repetition rates allows for more advanced optical networking applications, such as arbitrary pulse shaping [11,12], dispersion (pre-) compensation [13] and new modulation formats such as optical code-division multiple-access (O-CDMA) [14,15]. Especially for these last mentioned applications, the possibility for further integration of the MLLD with additional pulse processing components is very promising and often essential for large-scale implementation in optical networks [14]. Related to the developments of the fiber optic networks, MLLDs have an application in monitoring these networks, e.g. by optical time domain reflectometry [16]. And also applications like fiber radio can make use of MLLDs [17].
The advantages of small size and stability have also stimulated research on the application of MLLDs in fields where traditionally bulk or, more recently, fiber lasers were used. In the field of multi-photon bio-imaging first efforts are now being made to use MLLDs as the optical source [18,19]. Optical sampling is another promising application, e.g. for optical waveform measurement [20,21] or analog-to-digital conversion [22].

MLLD pulse repetition rates of tens of Gigahertz to over one Terahertz [23,24] far exceed what can be achieved by electronics and improved and new applications arise. One very promising application is to use MLLDs for optical interconnections to silicon CMOS chips for precise clock distribution, system synchronization and increased bandwidth, all at a reduction of the power dissipation [25,26]. Considering the Terahertz range these lasers can be used for the generation of Terahertz radiation, e.g. for imaging purposes, using photoconductive antennas [27].

All applications above make use of semiconductor mode-locked lasers, though the necessary specifications for the lasers can be different for the various applications. Moreover many of these applications can greatly benefit from added pulse processing components, which can be integrated on the same chip when semiconductor lasers are used. In the next section the approach of this work to create a platform for ultrafast integrated semiconductor laser technology, operating in the 1.55 μm wavelength range, is presented. The limits of what can be achieved within state-of-the-art technology are discussed.

1.3 Approach in this work – technology overview

The platform proposed in this work consists of a MLLD, a pulse chirper and a pulse shaper, all realized as separate components in the InP/InGaAsP material system, operating at wavelengths around 1.55 μm. This platform is schematically shown in Fig. 1-1. The MLLD is able to generate pulses, which are then spectrally broadened by a pulse chirper. The pulse shaper is then able to apply an arbitrary dispersive profile to the (chirped) pulse for further pulse compression or arbitrary shaping in general. In the following these three components will be discussed separately. An overview of the current state of the technology shows the viability of this platform for the applications as mentioned in the previous section. The discussion below is limited to fully integrated semiconductor based components.

Fig. 1-1 Schematic overview of the proposed sequence of components to generate femtosecond pulse trains. Pulses are represented by their temporal power profile. The greyscale shading is representative for the spatial distribution of the wavelengths, i.e. the pulse chirping. This chirp profile is also indicated by the dashed line.
1.3.1 MLLD

With the technique of mode-locking the phase of the longitudinal cavity modes of a laser are locked. This can be achieved actively by modulating the cavity gain or loss with an external source at the same frequency as the roundtrip frequency of the optical field inside the laser cavity. Another way to achieve mode-locking is in a passive way, where the modes are coupled by a self-driven internal nonlinear process. The most studied and widespread way to achieve passive mode-locking (PML) in laser diodes is by introducing a saturable absorber into the laser cavity [28,29]. Applying an added modulation to the absorber at the roundtrip frequency can stabilize this roundtrip frequency with a resulting lower timing jitter. This is called hybrid mode-locking. An extensive overview of mode-locking in laser diodes can be found in [6]. In the following the current state-of-the art in MLLDs is discussed with respect to pulse duration, power and repetition rate.

Sub-picosecond pulse durations of 0.79 ps have been achieved using hybrid mode-locking of a 20 GHz extended cavity laser [30]. Lower pulse durations have been reported for higher frequencies, e.g. durations down to 0.58 ps at 480 GHz [31], though at a decreased pulse extinction ratio. Using a separately optimized absorber waveguide structure, pulses down to 0.6 ps at 42 GHz have been achieved [32]. The gain medium in these lasers is (multiple) quantum well material. Development of quantum dot based gain material, especially operating at wavelengths of 1.3 μm, shows to be promising for reducing the pulse durations even further, i.e. down to 0.4 ps [33].

Optical output powers of MLLDs are generally lower than their bulk and fiber-optic counterparts, where power levels of 0.1 – 1 W are readily achieved [34,35]. In MLLDs the output powers are typically around a few milliWatts [36], but by optimizing the design for high-power operation average output powers of 250 mW and pulse energies of 58 pJ have been obtained [37]. Again quantum dot gain material proves to be promising in this respect as a gain medium for short pulses [38] and MLLD realized in this material have shown average output powers of 45 mW, with picosecond pulse peak powers over 1 W [33].

In PML in MLLDs the pulse repetition rate is limited at the lower values to about 1 GHz - 3 GHz, i.e. a value corresponding to carrier lifetime of the gain medium. At lower frequencies mode-locking instabilities may develop [37,39]. In harmonic mode-locking the pulse repetition rate corresponds to the cavity roundtrip time. As a result the repetition rate is related to the physical length of the cavity, which is about 2 mm for InP/InGaAsP laser diodes for 20 GHz operation. At these frequencies pulses with extinction ratios of over 25 dB have been reported [7,40], which are necessary values for high-speed TDM systems, where values of even 30 dB to 40 dB are required for pulse train interleaving [8,41]. Pulse repetition rates of over 1 THz at wavelengths around 1.55 μm can be obtained with intracavity reflectors to select the harmonic number, e.g. by distributed Bragg reflectors (DBR) [24]. Using photonic-bandgap reflectors record high repetition rates of 2.1 THz have been obtained for laser diodes operating at a wavelength of 0.86 μm [42]. The pulses obtained with these techniques however show a relatively poor extinction ratio due to the limited number of modes present in the optical spectrum.

As mentioned above the cavity length defines the pulse roundtrip time. There are two basic types of cavities, i.e. Fabry-Pérot (FP) type cavities and ring cavities. In FP cavities, the length is typically determined by the cleaved waveguide facets, which act as the mirrors and can be high-reflection (HR) coated to increase this reflectivity. Also DBRs can act as mirrors, which have the advantage that the cavity length can be lithographically and more precisely defined. The same advantage holds for ring cavities, but on the down-side an
output coupler has to be added. In [9] an overview of the work within COBRA on different MLLD geometries is presented.

So in summary it can be said that integrated MLLDs are able to generate pulse trains with typical average power levels of a few milliWatts, but high power output of 250 mW has been reported. Pulse durations down to about 0.5 ps with peak powers of over 1 W are state-of-the art. Repetition rates are typically about 10 GHz to 40 GHz, but may be anywhere in the range of 1 GHz to over 1 THz.

1.3.2 Pulse chirper

The aim of a pulse chirper, in the definition used in this work, is to increase the coherent optical bandwidth of a pulse train. There are several ways to increase this bandwidth, most of which are making use of optical non-linearities. Short, high peak power pulses traveling through an optical waveguide induce a self-phase modulation (SPM) due to the optical Kerr effect and/or the (partially) associated two-photon absorption (TPA) [43]. However the pulse peak powers that are obtained from MLLDs are not high enough to significantly broaden the spectrum by making use of this effect. More significant broadening can be expected when the pulses propagate through a pumped gain medium, depleting the carriers in the process and experience the associated SPM [44,45].

1.3.3 Pulse shaper

Pulse shapers are able to apply a (chromatic) dispersive profile that is preferably tunable, to an optical pulse train. Highly non-tunable dispersive elements have been realized, e.g. in a coupled waveguide structure [46]. Moreover waveguides, especially near cut-off width, and photonic crystal waveguides at frequencies near the stop-band can show large values for the dispersion, though at a narrow bandwidth of up to around 1 nm [47]. Tunable small-bandwidth dispersion compensation has been achieved using integrated filters [48,49].

However for large-bandwidth applications corresponding to sub-picosecond pulse durations, tunable pulse shapers based on arrayed waveguide grating (AWG) pairs seem most promising. Configurations with phase tuning elements and amplitude modulators have been reported for full control over the optical spectrum [11,50,51], realized in silicon technology. The AWG channel spacings reported have a resolution down to 10 GHz [50]. In InP-based technology a similar configuration has been realized using phase control only [11]. Channel spacings of AWGs realized in this material go down to 50 GHz [52]. An alternative for these high resolution AWGs are echelle gratings in InP [53].

In conclusion it can be said that tunable pulse shapers are a promising candidate for high-bandwidth pulse shaping. As the mode-spacing in MLLDs is in the order of around 40 GHz, the current AWG integration technology is (almost) able to match this value with their channel spacing resolution. This would make individual mode control, both in phase and in amplitude, possible.
1.4 Summary of the work and conclusions

The work started with an investigation of the technologies and principles to generate short optical pulses and how these concepts can be used to realize an integrated source for femtosecond pulse generation using the available fabrication technology present at COBRA. A model specifically tailored to what may be realized using the technology available at COBRA has been set up and is presented in Chapter 3. Limitations of current MLLD designs and techniques have been studied and their origins have been identified. The main results of these simulations were the following:

- Using MLLD configurations with an SOA and SA consisting of ridge waveguide InP/InGaAsP bulk gain material, pulse durations are limited on the lower boundary down to 1 ps. Further pulse shortening is limited by the SPM in the gain material.
- The simulated output pulses have a predominantly linear chirp and with a second order dispersive component at the laser output these pulse durations can be compressed down to 0.3 ps.

The main conclusion is then that either a new gain material is required for the gain medium in a MLLD or components need to be included in or added to the laser to manipulate the coherent bandwidth in the optical signal. The model has been used to develop and simulate new laser configurations.

- Based on the simulations in Chapter 3 two designs have been made for MLLDs with intracavity AWG-based pulse shaping components. Both a Fabry-Pérot type cavity and a ring cavity have been designed and are presented in Chapter 7. Simulations of these cavities show the feasibility of obtaining femtosecond pulses at high repetition rates, i.e. 0.4 ps at 400 GHz. The limitations and practicality of such devices are discussed.
- Using new QD gain material FP-type MLLDs have been designed and realized. Due to the limited gain in this QD material, the cavities are ‘long’, i.e. 4 mm to 9 mm. The designs and first results are presented in Chapter 7. Passive mode-locking and Q-switching are observed and discussed.

In Chapter 4 a new device concept for chirping of an optical pulse is presented, named IRIS. These devices consist of a concatenated sequence of SOAs and SAs. Picosecond pulse propagation through the IRIS devices has been investigated. Depending on the design and operating conditions this device can also fulfill the role of a picosecond pulse amplifier or an optical isolator for picosecond pulse propagation. In summary the results from the simulations are the following:

- Used as a pulse chirper coherent optical bandwidths well over 10 nm were obtained after propagation of a 40 GHz picosecond pulse train through the IRIS device. Moreover the simulated output spectra have a smooth shape, making further pulse processing, e.g. compression, possible.
- As an amplifier for a 40 GHz pulse train the IRIS device can achieve 10 dB of amplification without temporal pulse broadening. Moreover the noise in the form of amplified spontaneous emission (ASE) is reduced with over 6 dB as compared to a conventional amplifier, i.e. SOA, of equivalent length.
Finally the simulations show the possibility for optical isolation of 20 dB to 30 dB against reflections. More specific when the IRIS device is operated at transparency for a 40 GHz picosecond pulse train, the lower power reflections of this pulse train are absorbed in the IRIS device by over 20 dB.

These IRIS devices have been realized and the model presented in Chapter 4 has been fit to the experimentally obtained results. These are presented in Chapter 5. The main conclusions are the following:

- The improved spectral shaping of the IRIS device was confirmed and smooth spectra with a width of over 5 nm were obtained for a picosecond pulse train at 10 GHz.
- Comparing the IRIS device to an SOA of equivalent length for pulse amplification it can be concluded that the achievable pulse energy gain is about 3 dB lower, but with a 4 dB better signal-to-noise ratio. Moreover the IRIS devices show a decreased pulse broadening during the amplification.
- The model for pulse propagation through individual SOA and SA sections agrees quantitatively with the experimental results. Qualitative agreement is obtained for a full IRIS simulation.

Finally an integrated pulse shaping component is realized. It is based on an AWG-pair with an array of phase tuning components in between them to tune the dispersion of the device. The channel spacing used is 200 GHz. A measurement technique has been developed to characterize this device. The design and results are presented in Chapter 6. In summary the following can be stated:

- Pulse reconstruction of the pulse shaper of a 0.3 ps input pulse train at 80 MHz is achieved.
- It is shown that the device can be used to compensate an amount of linear dispersion of up to 0.2 ps/nm.
- Pulse ringing is suppressed from over 50% down to about 15% of the central pulse peak power using flattened AWG passbands.

The fabrication technology that was used in the realization of all these devices is presented in Chapter 2 and the possibilities for integrating all these devices, i.e. MLLD, pulse chirper and pulse shaper, on the same chip is discussed. The feasibility of fabricating all of these devices in the InP/InGaAsP active-passive material system is shown.

In summary, the above three different device types have been designed and realized, i.e. a MLLD, a pulse chirper and a pulse shaper. Their proof-of-principle performance is shown. Two main points have to be noted:

- The theoretical study and experimental characterization of the devices are done using input parameters that are typical for the output of a device further upstream in the circuit as shown in Fig. 1-1.
- The devices have been simulated and fabricated using the same material system, i.e. the InP/InGaAsP active-passive integration platform.
This leads to the main conclusion of this work: the components for a complete platform for ultrafast integrated semiconductor laser technology operating at wavelengths of 1.55 μm are presented and the feasibility of such a platform for pulse generation and shaping is shown.

The chapters 3 to 7 have also been published (or accepted for publication) separately with the following titles:

Chapter 3:

Chapter 4:

Chapter 5:

Chapter 6:

Chapter 7:


Een statisticus waadde vol vertrouwen door een rivier die gemiddeld één meter diep was. Hij verdrong.

G. Bomans
2 Integration Technology

Abstract – In this chapter the technology to fabricate fully integrated active-passive structures is presented in general. The fabrication technologies that were used to realize the devices in this thesis work are presented. Their compatibility with the full active-passive processing scheme is discussed. Two important aspects of the fabrication of active components, namely the contact metallization and the facet coating, are investigated and discussed more in detail.

2.1 Introduction

Large scale integration of optical components on a single optical chip offers very promising perspectives for optical devices with high functional density, small size, increased stability, potentially low cost fabrication and scalability [1,2]. This integration density continues to increase [3]. For monolithic integration on a single chip of light sources and other components working with wavelengths around 1.55 μm, InP/InGaAsP is the material of choice due to the possibility of growing lattice matched layers with different bandgaps, i.e. without strain. The first commercially available large-scale integrated circuits realized in this material system have now appeared on the market [4].

However a bottleneck limiting the scaling of integration density in InP/InGaAsP is the lack of standardization and the large diversity of components available at the moment [5]. In order to progress the implementation and commercialization of this technology a trade-off has to be made between integration and the required standardization on the one hand and the optimized performance and flexibility using separate components on the other hand.

The work on photonic integration at COBRA is aimed at a general fabrication technology which supports a limited number of different components: passive waveguiding structures, semiconductor optical amplifiers (SOAs) and electro-optic phase modulators (PHMs). These components are able to fulfill most of the basic operations required in a photonic integrated circuit (PIC) [6]. As the number of components is being limited, the fabrication technology can be optimized with limited number of constraints. This approach may be used to achieve standardization of design and fabrication of the components and may ultimately lead to a technology platform for InP-based PICs [7]. Using the aforementioned basic components, devices for pulse generation, chirping, amplification and shaping have been designed and fabricated. An integration technology that can combine all of these components on the same chip opens the possibility for a fully integrated short pulse generation and processing platform. In this chapter the technology that can be used to fabricate all of these components on the same chip will be discussed. This technology is named the ‘active-passive integration technology’. In the following ‘active’ refers to components that are able to generate, amplify or absorb (detect) light. In these components
the InGaAsP waveguiding layers include a layer with a bandgap that is equal or smaller than the energy of the manipulated photons, i.e. the energy corresponding to a wavelength of 1.55 μm. The InGaAsP composition of the index-guiding layers in the ‘passive’ components has a bandgap larger than the photons.

In section 2.2 first the semiconductor layer structure will be described that is used for the PIC fabrication. Hereafter the processing scheme that can be used to fabricate active-passive PICs on InP is discussed. This section is concluded with an overview of the technologies that were used in this work to realize the individual pulse generation and processing components. Their compatibility with the active-passive integration technology is discussed. In sections 2.3 and 2.4 two important aspects of the fabrication technology for active components are investigated and discussed more in detail, namely the contact metallization and the facet coating.

2.2 Fabrication technology

2.2.1 Active-passive layerstack

To be able to monolithically integrate active and passive components on the same chip, layerstacks with different-bandgap materials have to be combined on the same wafer. Options to realize this include quantum well intermixing [8], evanescently coupled twin-waveguides [9], selective area growth [10], offset quantum wells [11] or butt-joint coupling [12].

At COBRA the butt-joint integration approach was chosen. In Fig. 2-1 the wafer fabrication process and the designed layerstack are shown. First the active layerstack is grown on an n-doped InP substrate using metal-organic vapor phase epitaxy (MOVPE). This active layerstack is realized by sandwiching a low bandgap InGaAsP layer (Q1.55) between two higher bandgap InGaAsP layers (Q1.25). The active areas are then defined by SiNx masking and the layerstack is etched back down to 50 nm below the active layer (Q1.55). In the first regrowth step the passive Q1.25 layerstack is grown. A common p-doped cladding is grown in the second regrowth. The final layerstack and doping profiles are shown in Fig. 2-1 (b).

The advantage of using butt-joint coupling is the freedom of choice in design, i.e. layer composition and doping levels. In this work we have realized active structures based on two different gain materials, i.e. bulk gain material (IRIS) as presented in Fig. 2-1 and quantum dot material (QD-MLL). In principle these structures can be equally well integrated with passive components, or with each other, using this butt-joint coupling technology with (multiple) regrowths. The passive layerstack is optimized separately for passive waveguiding and phase shifting [13,14,15]. An important trade-off in this optimization has been made between phase shifting performance (requiring higher doping levels) and the passive waveguide losses, which increase with the increased doping.

Disadvantages of butt-joint coupling are the possible losses and reflections at the interfaces. However a characterization of these reflections and losses [16] shows that by careful design there is no detrimental effect of the butt-joint interfaces for the applications as discussed in this work. More specific the reflections at the interfaces can be below -50 dB and the losses per interface below 0.2 dB.
Except for the multi-wavelength MLLD designs most of the work in this thesis either utilizes all-active material or all-passive material, i.e. without any regrowth. However the layerstacks that were used are the same as used in this active-passive material, i.e. they have the layer thicknesses and corresponding doping levels as in Fig. 2-1. This makes that future further integration of the components presented in this work is feasible.

![Fig. 2-1](image)

Fig. 2-1  (a) Schematic overview of the active-passive wafer fabrication using SiN$_x$ (hatched) as a masking material for defining the active blocks (1). After etching back (2) the passive areas are regrown (3). In a second regrowth the common cladding is grown (4). 
(b) The final active-passive layerstack with the design (target) values of the layer thicknesses and doping levels.

### 2.2.2  General active-passive processing scheme

In our technology a limited set of waveguiding structures is used. These are passive waveguides, PHMs and SOAs, as explained above. These waveguides can be either shallowly etched, i.e. with a depth around the start of the Q1.25 film, or deeply, i.e. at least 100 nm through the Q1.25 film. Shallow (or low-contrast) waveguides are mainly used for low-loss interconnects and deep (or high-contrast) waveguides for small bend radii. To avoid issues related to surface passivation of the sidewalls of deep waveguides when electrical fields are applied [13], i.e. in the case of SOAs and PHMs, we limit ourselves in our designs to shallow SOAs and PHMs. Another type of waveguide is created when the conducting p-doped top cladding is etched away. This type is used for electrical isolation purposes as it prevents the (electrical) current flow through the cladding of the waveguides.
We note that other passive structures such as the arrayed waveguide gratings (AWGs) and multi-mode interference couplers (MMIs) used here, have an identical layerstack and processing scheme as the passive waveguides.

In the following an overview is given of the complete active-passive processing scheme that is able to combine the fabrication and achieve the integration of the components presented in this work. This scheme is also depicted in Fig. 2-2. It is illustrated for a shallow SOA, a shallow passive waveguide, a deep passive waveguide, an isolation section (waveguide) and a shallow PHM respectively. The scheme is based on the wafer design presented in the previous section. A total of seven masks are to be used.

The active-passive processing scheme is as follows:

(a) Using a PECVD process 50 nm of SiN\textsubscript{x} is deposited on the wafer. The lithography for the waveguides is optimized for this thickness. The waveguide pattern is defined by optical lithography using positive photoresist. This pattern is then transferred to the SiN\textsubscript{x} layer using a dry etch CHF\textsubscript{3} RIE process. This SiN\textsubscript{x} layer of 50 nm is thick enough not to be etched away during consequent InP RIE etching steps, while it serves as a mask.

(b) The shallow waveguide areas are covered by 100 nm Ti. The pattern is defined by lithography using negative photoresist, Ti evaporation and consecutive lift-off. The Ti serves as a mask to define the difference between the deep and shallow waveguide areas on the chip. Another possibility is to use photoresist instead of Ti as a masking material.

(c) The difference between the etch-depth of shallow and deep waveguides is now etched, using an optimized CH\textsubscript{4}/H\textsubscript{2} RIE process. Differences between the etching speeds of the different layers (i.e. InGaAs, p-InP and Q1.25/Q1.55) have to be taken into account.

(d) After removing the Ti mask wet chemically (using oxalic acid / H\textsubscript{2}O\textsubscript{2}), the complete waveguide pattern is further etched in a second RIE etch step. The etching is stopped well before the final etch depth is reached, in such a way that with the next (two) further RIE etch steps (f,h) the waveguides end up at the required depth.

(e) The isolation sections are then defined by etching away the SiN\textsubscript{x} masking on top, using optical lithography with negative photoresist. A HF solution is used for the SiN\textsubscript{x} etching.

(f) After removing the negative photoresist, the waveguide pattern is further etched in a third RIE etch step. Part of the p-doped cladding of the isolation sections is etched away in the process. Again the final etch depth of this step is such that with the next (and final) RIE etch step the required etch depth is reached.

(g) The waveguides that require a metal contact, i.e. the SOAs and PHMs, are covered with photoresist and the SiN\textsubscript{x} masking is removed from the passive waveguides using an HF solution.

(h) In a fourth and final RIE dry etch step the waveguides are etched to their final dept, i.e. 100 nm into the Q1.25 film for the shallow waveguides and over 100 nm through the film for the deep waveguides. The p-cladding of the isolation sections is now etched down to the Q etch stop layer (Fig. 2-1) and the InGaAs contact layer has been removed from the passive waveguides. After removing the remaining SiN\textsubscript{x} masking, the waveguide topology is now finished.
Polyimide is spun to passivate the waveguide sidewalls and to planarize the surface. Four to six layers of polyimide are used, which are cured at a temperature of up to 300°C in between to render them inert during future further processing.

The polyimide is etched back with a CHF$_3$/O$_2$ barrel etcher process down to around 100 nm – 200 nm above the InGaAs contact layer. Negative photoresist is then used to cover the areas that need to remain covered by the polyimide. The openings in the layer of photoresist give the areas that have to be opened for the contact metallization a headstart in the further etching back of polyimide.

The polyimide is etched back further until the InGaAs contacts on the SOAs and PHMs are open. The negative resist covering the rest of the wafer is (partially) etched away in this process, serving as a sacrificial layer for the offset. Remains are removed with acetone. The goal of this extra masking step (instead of using a self-aligned process [17]) is that crossings can be made between metal contact lines and PHMs, e.g. as used in Chapter 6.

The final metallization pattern is then defined by negative photoresist with a lift-off profile. Hereafter 100 nm to 150 nm of the InGaAs contact layer is etched back wet chemically. Plasma induced (chemically and ballistically) defects in the upper part of this InGaAs layer are etched away. These defects might decrease the doping necessary for low-resistance contacts, as explained in section III. Immediately hereafter (thus having a clean InGaAs surface) a Ti/Pt/Au metal layer of 50nm/75nm/300nm is evaporated.

After lift-off the backside of the wafer is metallized with evaporated Ti/Pt/Au to create the n-contact. The frontside of the chip, with the structures on top, can be protected with a thick layer of photoresist during this process. The resistance between the metal contacts to the InGaAs and n-InP respectively is optimized (minimized) by rapid thermal processing of 30 s at 325°C. The process optimization is explained in section 2.3 in more detail.

Hereafter the thickness of the metallization can be further increased using an Au plating process. To ease the cleaving, polyimide in between the contacts can be etched away using a RIE CHF$_3$ process and using the metallization pattern as a mask. Note that this is not possible when metal contacts only partially cover the PHM or SOA, as is the case for the pulse shaper (Chapter 6). Finally the wafer can be cleaved and possibly be coated at the facets with a high-reflection (HR) or anti-reflection (AR) coating. The quality of the AR coating is discussed in section 2.4.

In practice a four-step RIE dry etch process requires careful analysis of the etching speeds to calculate the intermediate etch depths. These etching speeds depend both on the material and on the layout, i.e. the part of the mask that is open and is being etched and the structures in the immediate vicinity. An accuracy of about 100 nm can be reached, which is not a problem if the correct tolerance margins are taken into account. These are the following:

- Shallow etch depth is the most critical parameter, so the RIE etch time is adjusted to aim for this value (±10 nm). Note that due to the RIE lag this translates to about 150 nm – 200 nm as measured by a step-height analysis, e.g., using the Tencor Surface Profiler.
The deep waveguides have to be etched at least 100 nm through the Q1.25 film, but a larger etch depth is not a problem. In practice it is wise to overestimate the difference between deep and shallow etching in the first RIE etch step by about 100 nm.

The etching of the p-cladding in the isolation sections can be less deep than the Q-etch stop layer, but not deeper as this contributes to increased optical losses and reflections. So again it is wise to underestimate this etch as ending up 100 nm to 200 nm above the Q-etch stop layer is not a problem and might even be advantageous to decrease reflections even further. The design of the length of the isolation section has to be robust against this tolerance margin, i.e. it has to be long enough to give electrical resistance over 100 kΩ [17].

The etch depth of the 300 nm InGaAs top layer is not critical, and can easily be increased to 100 nm – 200 nm deeper.
Fig. 2-2 Overview of the active-passive process scheme. Note that the dimensions are not scaled.

2.2.3 Specific processing used in this thesis

As mentioned above the devices presented in this work, i.e. the IRIS devices, the pulse shaper and the QD-MLLs could be realized in the aforementioned process scheme. However in practice for these individual devices a less complicated scheme is used (IRIS,
MLL), as not all of the waveguiding structures mentioned in Fig. 2-2 are present. The pulse shaper was originally designed for another process scheme and the deviations will be discussed below.

### 2.2.3.1 IRIS processing

An all-active (bulk gain material) wafer is used in the fabrication of the IRIS devices. The processing is done according to the active-passive processing scheme above, with the exception of the contact opening (Fig. 2-2(j,k)); as all of the waveguides had to be contacted, the polyimide was etched back to just below the top of the InGaAs layer all over the wafer surface. The metallization (Fig. 2-2(l-m)) was increased in one realization by plating, as mentioned, but in a second realization by a second Au-evaporation step. Although the waveguides in the IRIS devices are shallow, full deep-shallow processing was used as they were fabricated on the same chip with deeply etched structures [18].

### 2.2.3.2 Pulse shaper processing

An all-passive wafer is used in the fabrication of the pulse shaping devices. As compared with the layerstack shown in Fig. 2-1 the InGaAs contact layer was only 70 nm, as used in previous designs [19]. As the oxalic acid / H$_2$O$_2$ Ti-etchant attacks this InGaAs layer, this may result in additional sidewall roughness. Therefore it was decided to remove this layer wet chemically from the passive waveguide areas in the first step, using the contact layer mask. As a result the PHM waveguides have a slightly decreased effective etch depth, due to the pedestal originating from the InGaAs layer. This layer extends about 5 nm to either side of the PHM and creates an offset for the further etching. This is not a problem, since these PHMs are straight waveguides.

The isolation sections were fabricated using a selective InP wet etch down to the 20 nm Q etch stop layer. This is possible as the isolation sections are large as compared to e.g. the isolation sections in the IRIS devices (i.e. 100 μm as compared to 10 μm to 15 μm) and underetch in the lateral waveguide direction is not a problem. The wet etch time is however quite long, i.e. almost 30 min, due to faceting, as the waveguides are oriented along the (0-11)-direction.

Finally the contact metallization was achieved by evaporation of Ti/Au followed by Au and Ti wet etches respectively. Using a wet etch process as opposed to a lift-off process (Fig. 2-2(l,m)), we can evaporate the Ti/Au under a 45° angle, covering steps that might arise due to non-perfect polyimide planarization. The PHMs do not need optimized contact resistance as they are operated in reverse bias, with correspondingly low currents. This means that this non-optimized Ti/Au metallization can be used and the plating step can be omitted.

### 2.2.3.3 QD MLL processing

An all-active wafer is used in the fabrication of the QD MLLs, containing 5 InAs QD layers in the Q1.25 layer [20] instead of a bulk gain Q1.55 layer. The processing is analogous to the active-passive processing scheme above, with the exception that only a two step RIE process is used, for the definition of the shallow waveguides and the isolation sections. Analogously to the IRIS device fabrication, no contact opening mask was used.
The isolation section was deliberately etched 150 nm to 200 nm above the Q etch-stop layer to minimize possible reflections.

2.3 Contact metallization

The contact resistance at the interface between the metal contacts and the semiconductor material, especially under forward bias, is a critical parameter. This resistance should be low and Ohmic. In an SOA, where current is injected, the p-contact is at the top of the ridge. This ridge width is typically around 2 \( \mu \text{m} \), meaning that this interface between metal and semiconductor is literally a bottleneck for the electrical current and heat will be generated. This heating is detrimental to the performance of the SOA. As the current through the PHMs is orders of magnitude lower than through SOAs (nanoAmpères up to microAmpères as opposed to milliAmpères), the contact resistance is less of an issue for PHMs. For doped substrates, the contact resistance of the n-contacts is less critical, as the whole backside of the wafer can serve as the n-contact.

In this work we use a Ti/Pt/Au metallization layer for both the n- and p-contacts, e.g. as presented by [21]. This will facilitate future processing on semi-insulating substrate, where the n- and p-contacts can then be deposited simultaneously in a single evaporation step [22]. To optimize the interface, i.e. lowering the contact resistance, rapid thermal annealing is applied using a rapid thermal processor (RTP). In this process the wafer is quickly heated up for a short time (typically around 30 s). The process takes place in an N\(_2\)-environment. During the RTP process the oxide layer at the interface is removed as the oxygen is absorbed on the surface of the metal. The RTP process is optimized for minimum overshoot of the chamber temperature by using a two-step ramp up process, as illustrated schematically in Fig. 2-3.

To be able to optimize the annealing process, linear TLM structures (transmission line method, [21]) have been fabricated to measure the contact resistance. A mesa structure with a width of 100 \( \mu \text{m} \) is etched wet chemically. Ti/Pt/Au contacts of 25 nm/75 nm/250 \( \mu \text{m} \) are deposited on top, having a dimension of 100 \( \mu \text{m} \times 100 \mu \text{m} \) and an increasing spacing of 5 \( \mu \text{m} \), 10 \( \mu \text{m} \), 20 \( \mu \text{m} \) and 40 \( \mu \text{m} \) between the pads. The mesa structures and the SI substrate limit current spreading in the transverse directions when measuring the resistance between two pads. This resistance is measured using a four-probe setup and the contact resistance can be determined using the method presented in [23]. Above 40 \( \mu \text{m} \) spacing the linearity between resistance and pad spacing was lost, possibly due to current spreading into the substrate.
A set of wafers was fabricated with a single p-InGaAs or n-InP contact layer grown epitaxially on an SI InP substrate. The doping levels are varied. The details are given in Table 1. The RTP process is kept at a fixed duration of approximately 30 s, i.e. the duration in the process where the temperature in the process chamber is within ±10% of the target temperature (in °C). The number of RTP cycles of 30 s and the maximum RTP temperature are varied to obtain an optimized RTP process.

In Fig. 2-5 the measured contact resistances are shown for the p- and n-contacts. Looking at the p-contacts (Fig. 2-5(a)) a minimum of the resistance can be observed for an RTP temperature between 300°C and 350°C for doping levels over $10^{19}$ cm$^{-3}$. The obtained resistances do not depend on the contact layer thickness (200 nm and 400 nm were used with the MO155 and JDSU15746 samples respectively) and on the Ti thickness (25 nm and 50 nm was used with JDSU15746-1 and -2 respectively). The resistance $\rho$ is expected to depend on the doping level $N$ according to [24]:

$$\rho \propto N^2$$
assuming that tunneling is the dominant mechanism for carrier transport over the contact. Using two or more RTP cycles of 30 s does not further decrease the contact resistance significantly, and will eventually increase the resistance. For reference, the obtained resistance of $\rho=10^{-6} \, \Omega \cdot \text{cm}^2$ results in a heating of 1 mW for an SOA of 500 $\mu$m length and 2 $\mu$m width and using an injection current of 100 mA. This value of the resistance is in agreement with [21]. We have to note that the value of this low resistance is at the limit of the accuracy of the linear TLM measurement method, with measurement error margins going up from about 10% for the higher values of the resistance, i.e. $\rho=10^{-4} \, \Omega \cdot \text{cm}^2$, to 50% for resistance values of $\rho=10^{-6} \, \Omega \cdot \text{cm}^2$.

The measured resistance for the n-contacts is shown in Fig. 2-5 (b). As can be seen an RTP cycle decreases the resistance by about half an order of magnitude at temperatures between 300°C and 400°C, but by about a full order of magnitude at 450°C. However these RTP temperatures are not feasible when the p- and n-contact are to be annealed at the same time. For the MO351 sample, lower resistances are observed as compared to the MO309 samples, which have a nominally two times higher doping level. This discrepancy is possibly due to off-target doping level growth, as indicated by the lower values of $N_{3d}$ for MO309 in the Hall measurements (see footnote in Table 1). The resistance of the n-contact is about $\rho=10^{-4} \, \Omega \cdot \text{cm}^2$ between 300°C and 350°C, i.e. the RTP temperature for optimized p-contacts. This resistance is sufficient for our purpose as the wafer back contact has a relatively large surface and the heat generated can more easily dissipate and is further away from the SOA active region. Some preliminary measurements were performed on NiGeAuTiAu n-contacts, showing that resistances of about $\rho=5 \cdot 10^{-6} \, \Omega \cdot \text{cm}^2$ could be obtained at RTP temperatures of 300°C.

In conclusion an optimized a metallization process has been obtained, i.e. Ti/Pt/Au layer stack of 25 nm/75 nm/250 nm and a RTP annealing process of 30 s at 325°C, that can achieve p-contact resistances of $\rho=10^{-6} \, \Omega \cdot \text{cm}^2$ and n-contact resistances of $\rho=10^{-4} \, \Omega \cdot \text{cm}^2$. The n- and p-contacts can be metallized using the same layerstack and the same RTP process. The RTP process is compatible with the complete active-passive process scheme (Fig. 2-2) as the annealing temperature is below the polyimide curing temperature.

Table 2-1 Wafer data for metallization tests

<table>
<thead>
<tr>
<th>Wafer number</th>
<th>Contact layer</th>
<th>Nominal doping level</th>
<th>Metallisation (Ti/Pt/Au)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MO154</td>
<td>200nm p-InGaAs</td>
<td>$2.7 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>25nm/75nm/250nm</td>
</tr>
<tr>
<td>MO155</td>
<td>200nm p-InGaAs</td>
<td>$1.5 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>25nm/75nm/250nm</td>
</tr>
<tr>
<td>MO157-1</td>
<td>200nm p-InGaAs</td>
<td>$0.3 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>25nm/75nm/250nm</td>
</tr>
<tr>
<td>MO157-2</td>
<td>200nm p-InGaAs</td>
<td>$0.3 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>25nm/75nm/250nm</td>
</tr>
<tr>
<td>JDSU15746-1</td>
<td>400nm p-InGaAs</td>
<td>$(1 - 1.5) \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>25nm/75nm/250nm</td>
</tr>
<tr>
<td>JDSU15746-2</td>
<td>400nm p-InGaAs</td>
<td>$(1 - 1.5) \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>50nm/75nm/250nm</td>
</tr>
<tr>
<td>MO309-1</td>
<td>400nm n-InP</td>
<td>$2.0 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>50nm/75nm/250nm</td>
</tr>
<tr>
<td>MO309-2</td>
<td>400nm n-InP</td>
<td>$2.0 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>50nm/75nm/250nm</td>
</tr>
<tr>
<td>MO351</td>
<td>400nm n-InP</td>
<td>$1.0 \cdot 10^{19} , \text{cm}^{-3}$</td>
<td>50nm/75nm/250nm</td>
</tr>
</tbody>
</table>

*) The Hall measurements at room temperature show $N_{3d}=2.25 \cdot 10^{18} \, \text{cm}^{-3}$ for MO309 and $N_{3d} = 2.85 \cdot 10^{18} \, \text{cm}^{-3}$ for MO351.
Fig. 2-5 Calculated contact resistance for (a) the p-InGaAs contact and (b) the n-InP contact. Values at a temperature of 0°C are obtained with samples without any RTP treatment. The sample codes correspond to the wafer data mentioned in Table 2-1.

2.4 AR coating

To minimize reflections at the cleaved facets of the chips, i.e. at the inputs and outputs, ant-reflection (AR) coating can be applied. This is especially necessary for the IRIS devices, where the reflections at the facets cause feedback into the SOA sections. As a result, lasing might occur above relatively low current levels in the amplifier and the performance of the device is severely decreased. In this section an experimental method is presented to determine the quality of the AR coating, i.e. the residual reflection at the facets. This method is applied to the AR coatings of the foundry that also coated the IRIS devices.

To determine reflections of AR coated facets the Fabry-Perot (FP) loss measurement method [25] is used. In this method polarized light is coupled into an optical waveguide. The waveguide is defined by the power reflectivities at the input and output facets, \( R_{in} \) and \( R_{out} \) respectively, and the optical propagation loss \( \alpha_{wg} (m^{-1}) \). The waveguide will act as an FP-resonator and fringes in the transmission spectrum will appear. The depth (contrast ratio) \( K \) of these fringes depends on the total waveguide loss \( \alpha_{tot} = \alpha_{wg} \cdot L \) and the reflectivities \( R_{in} \) and \( R_{out} \) according to:

\[
\alpha_{tot} = \alpha_{wg} \cdot L = -\ln \left( \frac{1}{\sqrt{R_{in} R_{out}}} \sqrt{K - 1} \right)
\]

\[
K = \frac{P_{\text{max}}}{P_{\text{min}}}
\]

in which \( L \) is the length of the waveguide and \( P_{\text{max}} \) and \( P_{\text{min}} \) are the maxima and minima in the FP spectrum respectively. The approach in calculating the reflectivity of an AR coated facet is then the following:
1. The as-cleaved facet reflectivities $R_{in}=R_{out}$ are calculated using simulation software, e.g. “MIRF”, a tool developed by the ETH Zürich, and the waveguide length $L$ is measured;

2. The propagation losses $\alpha_{wg}$ are determined using the FP method (eq. (2.2));

3. One of the facets is AR coated ($R_{in}\neq R_{out}$) and the FP method is applied again. As the waveguide losses $\alpha_{wg}$ are known, the AR coated facet reflectivity can be calculated.

We have designed a mask (M040528) with sets of waveguides ranging in width from 1.0 $\mu$m up to 4.0 $\mu$m (designed value) and a length of over 10 mm. The waveguides were fabricated on an undoped wafer with a 500 nm Q1.25 film and a 500 nm InP cladding (MO298). Waveguide losses of the 9.5 mm shallow waveguides were determined. To obtain a clean facet for AR coating, the sample was cleaved again (3.0 mm and 6.5 mm) and the fresh facets were coated by a contractor. With these samples the AR coated facet reflectivity was determined and the results are shown in Fig. 2-6. Note that the actual waveguide width on the chip is decreased by about 0.2 $\mu$m as compared to the designed value due to the mask and chip fabrication.

As can be seen in Fig. 2-6 for the 3.0 mm sample the reflection for TE input light is below $10^{-3}$ for waveguide widths up to 2 $\mu$m, increasing up to about $2\cdot10^{-3}$ for the broader waveguides. The reflectivity for TM is slightly larger, i.e. around $4\cdot10^{-3}$. The appearance of the coating on the 6.5 mm sample looked bad (rugged) under the optical microscope, indicating a bad optical quality of the coating. This is confirmed by the measurements, which show a huge spread for the TE measurements all over the range between reflectivities of $10^{-4}$ up to 1. The reason for this is not known. It has to be noted that the wider waveguides can support multiple optical transverse modes (first order starting at 1.2 $\mu$m width and second order around 2.4 $\mu$m), limiting the accuracy of the FP method [26], especially above 2.4 $\mu$m width where the symmetric second order mode is easily excited.

![Fig. 2-6](image_url) Calculated AR coated facet reflectivities for a range of shallow waveguide widths (measured using an SEM) for (a) the sample with 3.0 mm waveguides and (b) the sample with 6.5 mm waveguides. Measurements have been done for both TE (black) and TM (grey) polarized light (only TE for the 6.5 mm sample)


5 MIT microphotonics center industry consortium 2005 communications technology roadmap


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“O denkt men er zo over!”
zei het jongetje
dat de wet van Newton gelezen had
en hij steeg als een leeuwerik
in de dampige najaarshemel
en geen sterveling op aarde
heeft hem ooit nog teruggezien

C. Buddingh’
3 Simulation and design of integrated femtosecond passively mode-locked semiconductor ring lasers including integrated passive pulse shaping components

Abstract—In this paper a model is presented for the simulation of integrated passively mode-locked InP/InGaAsP ring laser systems that include active components such as an amplifier and saturable absorber, and passive components that can be frequency dispersive. These dispersive components can have a complex frequency dependence, such as arrayed waveguide gratings (AWGs). The model is a lumped element model that is used as a design tool for developing integrated femtosecond pulse sources with internal dispersion control. Simulations based on an InP/InGaAsP amplifier and absorber show the possibility of laser designs that are able to generate pulses with pulse durations down to 300 fs in the 1550 nm wavelength range. The designs are based on femtosecond laser systems in bulk and fiber optics that are published in literature. The femtosecond laser sources presented here can be realized using existing InP/InGaAsP active-passive integration technology.

3.1 Introduction

Sources for (sub-)picosecond optical pulses with a wavelength around 1550 nm have applications in optical telecommunications for time domain multiplexing or as a synchronized source for wavelength division multiplexing. They can also function as optical clocks and all optical clock recovery devices within a telecommunication system. For future terabit optical signal processing and telecommunication applications, pulses with a duration well into the femtosecond regime are necessary. E.g. to create a pulse stream at 1 THz pulse durations of 200 fs – 300 fs full width at half maximum (FWHM) and an extinction ratio of over 25 dB are required [1].

The generation of femtosecond pulses using solid state mode-locked laser technology is now well established [2]. Although multi-Gigahertz femtosecond laser sources in the 1550 nm wavelength range are reported (see e.g. [3]) no sources that comply with all the requirements above are currently available [4]. For reasons of stability, compactness and fabrication costs, hybrid or monolithic integration of semiconductor mode-locked lasers seems the most attractive option for such a source. Using monolithic integration these devices can be further integrated on the same chip with other devices for a further reduction of costs and size.

Nowadays monolithic passively mode-locked (PML) semiconductor laser sources are able to produce pulses with durations down to 1 ps – 2 ps having a good extinction ratio, both at wavelengths of 1.55 μm [5,6,7] and of 1.3 μm [8]. Shorter pulses at higher repetition rates can be obtained through harmonic mode-locking [9], though with limited
extinction ratio. The gain medium in all of these devices is the semiconductor optical amplifier (SOA). The minimum of the pulse duration that can be obtained from a laser is limited by the interplay between the self-phase modulation (SPM) in the SOA and the gain dispersion. Femtosecond pulses have been observed to break up while propagating through an SOA due to this interplay [10,11]. This indicates there is a severe restriction in obtaining femtosecond pulses from a mode-locked semiconductor laser.

Pulse durations below 200 fs have been obtained using an SOA in a long extended cavity to form a mode-locked laser. In these configurations bulk and fiber optics are used in the laser cavity to address the detrimental effect of SPM in combination with gain dispersion. To this end the pulses that propagate through the SOA are kept relatively long, with a pulse duration of above a few picoseconds, and their spectral bandwidth is maximized. These pulses can then be compressed using a dispersive element at the output. Azouz et al. have used active mode-locking to create large-bandwidth highly chirped pulses of a few picoseconds, which were compressed below 200 fs at the laser output using second and third order dispersion [12]. Gee et al. have used intra-cavity spectral shaping to generate large bandwidth pulses with hybrid mode-locking by tailoring the gain spectrum. These pulses could then be compressed down to 250 fs [13]. To optimize the linearity of the chirp over the pulse Resan et al. have used a breathing-mode configuration [14], where the pulse is stretched prior to the SOA to minimize the SPM and is recompressed afterwards. This configuration is able to produce pulses with durations as low as 185 fs [15].

In this paper we describe a model we have developed and how we have used it to investigate the possibilities for the design of integrated femtosecond semiconductor lasers (IFSLs) in the InP/InGaAsP active-passive integration scheme [16]. In this integration scheme, active components for a mode-locked laser, a bulk SOA and saturable absorber (SA), can be integrated monolithically with passive components, such as passive waveguides, arrayed waveguide gratings (AWGs), multi-mode interference couplers (MMIs) and phase modulators (PHMs) [17]. The passive components available in the InP/InGaAsP material system can be utilized to shape the laser pulse, both inside the laser cavity and at the laser output. A PML ring laser configuration is most promising for obtaining an IFSL. PML has no need for external (electrical) modulation and Terahertz repetition rates can be obtained. In a ring laser configuration the roundtrip time can be tuned by lithographic means and needs no accurate cleaving of the facets. Another advantage of a ring configuration is that it can be integrated with other components on the same chip.

Since the publication of the theory for mode-locking with a slow saturable absorber by Haus [18] much research in the field of modeling of mode-locking has been done. Avrutin et al. [19] have made a distinction in time-domain mode-locking theories between lumped-element models [20,21] and fully distributed time-domain models [22]. The model we present in this work is based on the lumped-element approach as presented by Koumans and Van Roijen [20]. To be able to correctly describe the propagation of short pulses through the SOA, we have extended their SOA rate equations with the effects of carrier heating (CH), two photon absorption (TPA) and ultrafast nonlinear refraction (UNR) as described by Tang and Shore [23]. Short pulse propagation through an SOA has been extensively investigated experimentally and theoretically, both for picosecond pulses [24] and sub-picosecond pulses [25,26]. The rate equations presented in [23] allow for an efficient and realistic implementation of ultrafast dynamics. We have also developed a new numerical algorithm to switch between pulse descriptions in the time and frequency
domain. As a result we can implement laser cavity dispersion and bandwidth limitation as lumped elements in the frequency domain instead of in the time domain, as was done in [20]. More importantly this allows us to implement passive components with an arbitrary transmission in a straightforward way. With this facility in the model integrated pulse shaping functionality can be added to the PML ring laser model.

This paper is organized as follows. In section 3.2 the model is introduced in detail and the different components of a PML ring laser are described. The equations for simulation of the pulse propagation through these components are given. The numerical algorithm to switch between pulse descriptions in the time domain and in the frequency domain is presented in section 3.3. In section 3.4 a simple PML ring laser, consisting of a single SOA and SA and a passive ring cavity, is simulated for various design and operating parameters. Restrictions and opportunities for obtaining femtosecond pulses are identified. Designs for IFSLs based on these findings are presented in section 3.5. Their output is simulated using the model we developed.

3.2 Theory

The model for the PML ring laser is implemented as a lumped element model, analogous to the work of Koumans and Van Roijen [20]. This means that in the model the laser cavity dispersion and the bandwidth limitation of the active components are treated as separate components of the laser cavity next to the SOA and SA. This is depicted schematically in Fig. 3-1. The lumped element approximation is allowed as the bandwidth limitation and cavity dispersion only have a limited effect on the pulse shaping mechanism in a single roundtrip [20].

![Fig. 3-1 Configuration for a PML ring laser model including bandwidth limitation (BW) and cavity dispersion (D). At the points denoted by ‘\(\omega/t\)’ the pulse description is changed from the time domain to the frequency domain or vice versa. The MMI section couples out 50% of the optical power. Pulse propagation is clockwise.](image)

The pulse in the laser cavity is described in a time frame that is moving along with its complex optical field [24]. The length of this time frame corresponds to the pulse roundtrip time. The operation of the PML ring laser is then simulated by calculating the pulse shaping effects of the different lumped elements on the optical field iteratively, according to the scheme presented in Fig. 3-1. Passive mode-locking is achieved when a stable pulse shape has formed with constant pulse duration. The power amplitude of this pulse can vary in
time, with a super-modulation of the pulse stream over time because of self-pulsations or even Q-switching [27]. Starting conditions for the optical field can be either noise or a trial pulse shape.

The pulse shaping effect of cavity dispersion and bandwidth limitation is best described in the frequency domain. This is particularly true for passive components with a more complicated dispersion and transmission profile, such as AWGs. Laser structures incorporating these components inside the laser cavity are described in section 3.5. To simulate dispersion and bandwidth limitation with filters in the frequency domain, the pulse description in the time domain has to be switched to a description in the frequency domain and back again. The algorithm to achieve this is presented in section 3.3.

In the following subsections the different components of a simple ring laser cavity are described: the SOA, SA, cavity dispersion and bandwidth limitation. The simulations assume a single transverse mode with a single polarization. This condition can be fulfilled in practice by careful design of the laser. The difference between TE and TM gain in the SOA will result in polarized laser operation [28]. Passive components are assumed to be linear and losses can easily be implemented in either the frequency domain or the time domain by decreasing the optical power accordingly. The sequence of the components in the laser cavity has significant effect on the pulse shaping and as a result the characteristics of the output pulse. The model operates unidirectionally. Near unidirectional operation can in principle be achieved by using specific location of the absorber with respect to the amplifier [29]. The approach presented in this paper prevents us from describing colliding pulse mode-locking [22]. Parameters and dynamics presented below are based on the InP/InGaAsP material system for wavelengths around 1.55 μm. It is in this system that we can realize the designed devices.

3.2.1 **Semiconductor Optical Amplifier (SOA)**

The interaction of SPM in the SOA with the gain dispersion prevents the formation of femtosecond pulses in passive mode-locking. Light pulses of several hundred femtoseconds have even been shown to break up when propagating through an SOA, both theoretically [30,31] and experimentally [10,11]. The consequence is that in order to obtain ultra short pulses from a semiconductor laser system the duration of the pulse propagating through the SOA should be in the picosecond regime. This concept has been demonstrated successfully in bulk optics [12,13,14].

In this work we use the model presented by Tang and Shore to describe the propagation of short pulses through an SOA [23]. It includes the effects of carrier depletion, carrier heating (CH), two-photon absorption (TPA), spectral hole-burning (SHB) and ultrafast nonlinear refraction (UNR). Spontaneous emission is not taken into account as it does not play a significant role in the pulse shaping and saturation of the SOA [32]. This model was derived in the adiabatic limit for local carrier density and carrier temperature, which means it is valid for pulse durations longer than the carrier temperature relaxation time, i.e. for pulse durations down to approximately 1 ps. This approach has been validated by Schell et al. [33].

The pulse is described by its power \( P(z,t) \) and phase \( \phi(z,t) \) in a time frame moving along with the pulse [24] and propagation in the z-direction. These relate to the complex
optical field envelope according to \( A(z,t) = \sqrt{P(z,t)} e^{i\phi(z,t)} \). The pulse shaping effect of the SOA is expressed by the following three ordinary differential equations [23]:

\[
\begin{align*}
\frac{\partial G}{\partial t} &= \frac{G_0 - G}{\tau_s} - \frac{1}{E_{sat}} \frac{G - \varepsilon_2 P^2}{1 + \varepsilon_1 P} + \Gamma_2 \beta' \frac{P^2}{2} \\
\frac{\partial P}{\partial z} &= \frac{G - \varepsilon_2 P^2}{1 + \varepsilon_1 P} - 2\Gamma_2 \beta_2 \frac{1}{\sigma} P^2 - \alpha_{int} P \\
\frac{\partial \phi}{\partial z} &= -\frac{1}{2} \left[ \alpha_N G - \alpha_T \frac{\varepsilon_1 G P - \varepsilon_2 P^2}{1 + \varepsilon_1 P} \right] - \Gamma_2 c \frac{\omega_0}{n_2} \frac{1}{\sigma} P
\end{align*}
\] (3.1)

\( G=G(z,t) \) and \( G_0 \) are the linear gain and the small signal gain of the SOA respectively and are defined by:

\[
G = \Gamma a_N \left( N - N_{tr} \right) \quad (3.2)
\]

\[
G_0 = -\Gamma a_N N_{tr} \left( \frac{I \tau_s}{q V N_{tr}} - 1 \right) \quad (3.3)
\]

in which \( N \) and \( N_{tr} \) are the carrier density and the carrier density for transparency respectively, \( a_N \) the differential gain, \( \Gamma \) the carrier lifetime, \( I \) the injection current, \( q \) the electron charge and \( V \) the volume of the active area. In (3.1) \( \varepsilon_1 \) is the nonlinear gain compression due to SHB and CH, \( \varepsilon_2 \) is the gain compression due to TPA, \( \alpha_N \) and \( \alpha_T \) are the carrier density and temperature linewidth enhancement factors respectively, \( \Gamma_2 \) and \( \beta_2 \) are the confinement factors associated with TPA and UNR respectively, \( \beta_2 \) and \( n_2 \) are the TPA and UNR coefficients respectively, \( c \) the light velocity in vacuum, \( \omega_0 \) the pulse central frequency, \( \alpha_{int} \) the SOA waveguide linear loss and \( \sigma = wd/\Gamma \) the mode cross section (with \( w \) and \( d \) the width and thickness of the active region respectively). Furthermore the saturation energy \( E_{sat} \) and \( \beta' \) are defined by:

\[
E_{sat} = \frac{h \omega \sigma}{a_N} \quad (3.4)
\]

\[
\beta' = \frac{a_N \beta_2}{h \omega \sigma^2} \quad (3.5)
\]

The pulse propagation through the SOA is calculated by solving (3.1) by a finite difference method. In the numerical implementation a SOA with a length of 500 \( \mu \)m is divided in 50 sections. The pulse propagation through each section is then calculated, with a time resolution of \( \Delta t=50 \) fs, and the resulting gain \( G \) of that section is stored for the next roundtrip.
3.2.2 Saturable Absorber (SA)

In practice the SA is a reversely biased SOA and therefore has the same layerstack. As a result of the applied field the absorption recovery time is reduced. There is far less literature on the propagation of short optical pulses through an SA than there is on propagation through an SOA. We base our description of the SA section on the model presented by Koumans and Van Roijen [20] and extend it with an absorption compression factor $\varepsilon_{1,SA}$ to describe the CH and SHB, analogous to the SOA description. Furthermore we make the following assumptions. First as compared to (3.1) the effects of TPA and UNR are ignored as the SA section is generally about ten to twenty times as short as the SOA section and these effects do not play a significant role in the pulse shaping. Secondly the phase change due to CH is ignored, in line with the work presented by Schell et al. [33]. As a last point we note that the absorption compression $\varepsilon_{1,SA}$ is at least partially cancelled by the carrier heating due to the applied field over the SA, as pointed out by Uskov et al. [34]. Applying these approximations leads to the following set of equations to describe the SA section in a mode-locking configuration:

$$\frac{\partial Q}{\partial t} = \frac{Q_0 - Q}{\tau_{eff,SA}} - \frac{Q}{E_{sat,SA} + 1 + \varepsilon_{1,SA}P}$$

$$\frac{\partial P}{\partial z} = \frac{Q}{1 + \varepsilon_{1,SA}P}$$

$$\frac{\partial \phi}{\partial z} = -\frac{1}{2} \alpha_{N,SA} Q$$

$$Q_0 = -\Gamma a_{N,SA} N_{tr,SA}$$

(3.6)

in which $Q$ represents the absorption or negative gain, $Q_0$ the small signal absorption, $E_{sat,SA}$ the saturation energy, $\alpha_{N,SA}$ the carrier density linewidth enhancement factor, $a_{N,SA}$ the differential absorption and $N_{tr,SA}$ the absorber carrier density for transparency. The absorption recovery time, which is lower than the value in the SOA due to the applied field, is implemented by an effective carrier lifetime $\tau_{eff,SA}$ with a typical value of 5 ps – 15 ps [35].

Pulse propagation through the SA is calculated by solving (3.6) by a finite difference method, analogous to the calculation for propagation through the SOA. In the numerical implementation a SA with a length ranging from 30 $\mu$m to 70 $\mu$m is divided in 10 sections. The pulse propagation through each section is then calculated, with a time resolution of $\Delta t=50$ fs, and the resulting absorption $Q$ of that section is stored for the next roundtrip.

3.2.3 Frequency filters – bandwidth limitation and cavity dispersion

The time domain rate equations for the SOA (3.1) and SA (3.6) do not take the gain and absorption dispersion into account. These are combined and implemented as an effective system parameter: the bandwidth limitation. The chromatic dispersion of the different passive components in the laser cavity is implemented as a total cavity dispersion.
Both the bandwidth limitation and the cavity dispersion are implemented as frequency filters and are presented below.

The effect of the bandwidth limitation is represented by the Lorentzian filter function \( H_{\text{BW}}(\omega) \) [20]:

\[
H_{\text{BW}}(\omega) = \frac{1}{1 + i \frac{\omega - \omega_p}{\omega_L}}
\]

in which \( \omega_p \) represents the frequency at peak gain and \( \omega_L \) represents the effective system bandwidth of the combined SOA and SA sections (and possible other elements).

The chromatic second order dispersion of passive components in the laser cavity can be expressed by the second order dispersion \( k'' \), which is defined by:

\[
k''(\omega) = \frac{d^2k}{d\omega^2} = \frac{d}{d\omega} \left[ \frac{1}{v_g} \right]
\]

in which \( k \) represents the wave-number and \( v_g \) the group velocity of the optical field. The total effect of different dispersive components on the pulse shaping is implemented in the model using the filter function for the second order dispersion \( H_D(\omega) \):

\[
H_D(\omega) = \exp \left[ -\frac{i}{2} k''_{\text{tot}} (\omega - \omega_0)^2 \right]
\]

in which \( k''_{\text{tot}} \) is the total second order dispersion of the cavity. Its value for passive components can be calculated using the software presented by Leijtens et al. [36]. Unless the waveguides approach a cut-off width, the dispersion is close to the material dispersion, i.e. \( k'' \approx 4-5 \) ps\(^2\)/m for InP/InGaAsP material. This value also holds for MMIs around its broad transmission peak. Therefore the dispersion of an MMI can be obtained by multiplying its length with the material dispersion. Higher order dispersion can be implemented in an analogous way. The filter function (3.10) only describes the wavelength dependence of the refractive index, not of the absorption. This absorption bandwidth is not significant for passive components such as MMIs and waveguides when compared to the bandwidth limitation of the active components defined above, which is typically around 20 nm – 30 nm.

Pulse shaping components based on AWGs can be implemented in the model in a similar way by the application of a complex transmission filter in the frequency domain. In section 3.5 configurations for these pulse shaping components are presented as well as their filters for numerical implementation.
3.3 Algorithm for switching between space and time descriptions

In this section the algorithm to switch between optical field descriptions in the time domain and the frequency domain is presented. The pulse is described in a time frame of length $T$ moving along with the pulse. This length $T$ corresponds to the small signal pulse roundtrip time. In this algorithm the laser output is assumed to be periodical. Consequently the frequency spectrum $A(z,\omega)$ can be obtained by taking a discrete Fourier transform of the complex field envelope $A(z,t)$ at a point in the laser cavity over the roundtrip time $T$. In the obtained spectrum the discrete set of optical frequencies of the laser modes can be identified. Filter functions such as (3.8) and (3.10) can then be applied on the spectrum of the laser modes contained in $A(z,\omega)$. This is the basic concept of our algorithm, but it has to be extended to take into account the actual non-periodicity of the output.

There are three causes for this non-periodicity. First the pulse power can vary per roundtrip due to self-pulsations or even Q-switching [27] and during start-up because of relaxation oscillations. Also weak mode-locking may cause satellite pulses to rise on the expense of the existing pulse, breaking the periodicity [27]. Secondly the combined effect of the SOA and SA causes a change in roundtrip time through reshaping of the pulse. Thirdly the SPM in the active components causes a change in optical path length. These three points and the way they have been dealt with in the model are discussed below.

By taking a discrete Fourier transform over a time frame of a single roundtrip one assumes that the output of the laser is perfectly periodic. The calculated spectrum is therefore an approximation of the real spectrum. In reality the effects of the variation of pulse power per roundtrip spectrally broaden the laser modes. To optimize the validity of the approximation the optical pulse in the laser is set approximately in the centre of the window over which the Fourier transform is taken. In this way no two consecutive pulses are within one window. This approach is valid when the broadening of the laser modes is small compared to the bandwidth of the components in the laser cavity.

![Fig. 3-2](image)

Fig. 3-2 To be able to use the assumption of periodicity, the time window with length $T$ is not allowed to overlap two consecutive pulses (dashed frame). The pulse is kept centered in the window (solid frame) to avoid the overlap.

Secondly the pulse reshaping by the SA and SOA causes a change in the roundtrip time of the optical pulse from the cavity roundtrip time $T$ [18]. This makes that the optical pulse moves through the time frame each roundtrip. If the window overlaps two consecutive pulses, these are not spaced at a time interval $T$. If one applies the Fourier
transform in this situation, an incorrect pulse shape is transformed. This issue can also be resolved by keeping the pulse centered in the window. The pulse centering is implemented by rotating the optical field through the time window by half a period when the pulse energy reaches the edge of the time window. In practice the pulse moves (almost always) to the right of the time window, as the SA cuts off the leading part of the pulse. After rotation the gain $G$ and absorption $Q$ are adjusted accordingly (i.e. relaxation or recovery without carrier depletion by half a period or $0.5 \cdot T$). Note that this is only a valid approach when the pulse energy is concentrated within half a period $T$.

The third point is that due to the SPM in the active components the optical path length changes as the pulse induces a change in the refractive index. The consequence of this is that the mode spectrum shifts. For the pulse description in our model this means that the phase profile of the pulse after propagation through the SOA and SA becomes discontinuous if periodicity of the output is assumed with a period $T$. This is depicted in Fig. 3-3. The step in the phase represents in practice a shift in the mode spectrum. As a discrete Fourier transform is used, a non-discrete shift in the spectrum can by definition not be accounted for by this transform. To be able to use a discrete Fourier transform, the shift in the mode spectrum is applied in the frequency filters in the model in the following way.

\[
A_C(z,t) = A(z,t)e^{i\Delta \omega(z)t}
\]

\[
\phi(z,t) = \phi_c(z,t) + \Delta \omega(z) \cdot t
\]

The discrete Fourier transform $A_C(z,\omega)$ of $A_C(z,t)$ correctly describes the mode spectrum of $A_C(z,t)$. The shift of these modes with respect to the laser modes of the actual field $A(z,t)$ is described by $\Delta \omega(z)$. The change in optical path length and the resulting shift

Fig. 3-3 The simulated temporal phase profile $\phi(z,t)$ (dashed) and intensity profile (solid) of a light pulse after propagation through an SOA using the model and parameters presented in [23]. The input pulse peak power is 0.1 W and the pulse width is 1.6 ps. The SOA has a length of 500 μm and is biased with $I=100$ mA. The step in the phase profile $\phi(z,t)$ represents the change in optical path length due to the SPM of the pulse.

The phase profile $\phi(z,t)$ of the pulse is split into a continuous part $\phi_C(z,t)$ (i.e. lined up at the start and the end of the period $T$) and a linear part $\phi_L(z,t) = \Delta \omega(z) t$ to account for the step in the phase. We now introduce the periodic and continuous complex field envelope $A_C(z,t)$ defined as:

\[
A(z,t) = \sqrt{P(z,t)} e^{i\phi_c(z,t)} e^{i\Delta \omega(z) t} = A_C(z,t) e^{i\Delta \omega(z) t}
\]

The discrete Fourier transform $A_C(z,\omega)$ of $A_C(z,t)$ correctly describes the mode spectrum of $A_C(z,t)$.
of the mode spectrum is now implemented in the filter function \( H(z, \omega) = H_{BW}(z, \omega)H_{D}(z, \omega) \) in the following way:

\[
A(z, \omega) = A_c(z, \omega - \Delta \omega) \\
A_c(z, \omega - \Delta \omega)H(\omega) = A_c(z, \omega)H(z, \omega + \Delta \omega)
\] (3.12)

This means that we can describe the effect of the frequency filters on the mode spectrum correctly by a discrete Fourier transform, where the shift is accounted for analytically by implementing it in the filter functions (3.8) and (3.10). To regain the pulse description in the time domain an inverse discrete Fourier transform is used to obtain the periodic and continuous field \( A_c(z, t) \). Hereafter the phase \( \phi(z, t) \) and amplitude \( P(z, t) \) of the pulse can be obtained by

\[
P(z, t) = |A_c(z, t)|^2 \\
\phi(z, t) = \text{arg}(A_c(z, t)) + \Delta \omega(z) \cdot t
\] (3.13)

Note that the filter functions are only used to describe linear components and the pulse will not experience SPM. This means that the spectrum is not shifted by the filter functions and the inverse discrete Fourier transform can be implemented directly on the spectrum.

### 3.4 Simulation of a mode-locked ring laser

In this section results of mode-locked ring laser simulations are presented. The SOA and SA are integrated with an extended ring laser cavity formed by passive waveguides. The passive components are transparent to the lasing wavelengths around 1.55 μm since they will be realized using an index guiding layer with a bandgap at 1.25 μm [16]. Half of the pulse power is coupled out each roundtrip with an MMI as a 3-dB splitter. The mode spacing of the laser cavity is set at 40 GHz and the pulse roundtrip time \( T \) equals 25 ps. Therefore its fundamental pulse repetition rate in mode-locked operation will be close to 40 GHz. A schematic overview is given in Fig. 3-4. Unless noted otherwise, the values used for the simulation of the SOA and SA are given in Table 3-1. The passive waveguide and MMI sections can be characterized by their loss and dispersion. We use the values \( k''_{\text{tot}} = 0.01 \text{ ps}^2 \) (i.e. a 40 GHz cavity with a dispersion of \( k'' = 4 - 5 \text{ ps}^2/\text{m} \)) and a total passive cavity loss of 3 dB in addition to the 3-dB loss due to outcoupling at the MMI. The system bandwidth is \( \omega_L = 12 \text{ rad/ps} \), which equals approximately 30 nm.

![Fig. 3-4 PML ring laser configuration under study. The SOA and SA sections can be realized in an active layer stack and the waveguide sections and MMI in a passive layerstack. The MMI couples out](image)
50% of the power. The configuration is based on the work presented by Barbarin et al. [7].
By laser design and operation, some laser parameters can be varied. Their effect on the pulse duration is investigated. In this work first the operation parameters $I_{SOA}$ and $\tau_{\text{eff,SA}}$ are varied, which means in practice that the injection current of the SOA and the reverse bias on the SA are tuned [35]. Secondly the effect of the SPM is investigated by choosing a lower value for the SOA $\alpha$-parameters. In this case we choose $\alpha_N, \alpha_T = 2$. Thirdly the effect of changing the SA length on the performance is studied. The SA length $L_{SA}$ is varied from 30 $\mu$m to 70 $\mu$m while the SOA length is kept constant. As a last point the effect of the cavity dispersion $k_{\text{tot}}''$ on the pulse duration is studied. The main results from the simulations are given in Fig. 3-5 and are discussed below.
Fig. 3-5  Simulation of the duration (FWHM) of the pulses produced by the mode-locked ring laser configuration of Fig. 3-4. Unless noted otherwise the parameters are $k''_{\text{tot}} = 0.01 \text{ ps}^2$, $L_{\text{SOA}} = 500 \mu\text{m}$, $L_{\text{SA}} = 50 \mu\text{m}$, $\alpha_N = 5$, $\alpha_T = 3$ and $\tau_{\text{eff,SA}} = 5 \text{ ps}$. In (a) the pulse duration is calculated as a function of the SOA injection current for different absorber recovery times $\tau_{\text{eff,SA}}$ (5 ps, 10 ps and 15 ps). In (b) the same calculation as in (a) is done, using $\alpha_N = 2$ and $\alpha_T = 2$. In (c) the effect of the absorber length $L_{\text{SA}}$ is calculated for the injection currents $I = 90 \text{ mA}$ and $I = 130 \text{ mA}$. In (d) the effect of the total cavity dispersion $k''_{\text{tot}}$ is calculated for three different injection currents.

In all figures, the range over which the data are plotted indicates the regime of stable pulse formation as explained in the text.

In Fig. 3-5(a) the obtained pulse durations are plotted against the injection current for different absorption recovery times. The stability regime of mode-locking for the longer recovery times is limited, i.e. from threshold up to $I_{\text{SOA}} = 80 \text{ mA}$ for $\tau_{\text{eff,SA}} = 15 \text{ ps}$ and up to $I_{\text{SOA}} = 100 \text{ mA}$ for $\tau_{\text{eff,SA}} = 10 \text{ ps}$. At higher injection currents the net gain window responsible for the passive mode-locking becomes larger and can not suppress weak pulses trailing the main pulse. These weak pulses arise as a result of the interaction of SPM with the gain dispersion (expressed by the bandwidth limitation). Decreasing the recovery time to 5 ps shows stable operation up to 200 mA, which is a practical current limit for pumping a 500 $\mu\text{m}$, 2 $\mu\text{m}$ ridge SOA. For injection currents below 70 mA (75 mA for $\tau_{\text{eff,SA}} = 5 \text{ ps}$) no pulse formation is observed. Pulse durations go down to 1.6 ps for the higher injection currents and vary only within 10% over the range of injection currents studied.

These simulations are repeated with a lower value for the SPM parameters. In Fig. 3-5(b) the pulse durations obtained using $\alpha_N$, $\alpha_T = 2$ are given. Compared to the results obtained with $\alpha_N = 5$ and $\alpha_T = 3$, an increase in the stability regime can be observed, going up to $I_{\text{SOA}} = 90 \text{ mA}$ for $\tau_{\text{eff,SA}} = 15 \text{ ps}$ and up to $I_{\text{SOA}} = 170 \text{ mA}$ for $\tau_{\text{eff,SA}} = 10 \text{ ps}$. The simulated pulse durations are well above 2 ps. This leads to the conclusion that SPM increases the mode-locking strength by more effectively broadening the spectrum.
mentioned previously, the interaction of SPM and the resulting broadened spectrum with the gain dispersion causes instabilities. This is the reason for the increased stability regime at lower SPM parameters.

The effect of changing the ratio of the lengths of the SOA and SA on the pulse duration is limited. In Fig. 3-5(c) it can be seen that increasing the SA length decreases the pulse duration with up to 0.2 ps only. Increasing the SA length will decrease the energy of the pulse, making the laser less efficient. I.e. at $I_{SOA} = 130$ mA the average output power decreases from 8 mW using an SA with a length of 40 $\mu$m down to 3 mW for a SA length of 70 $\mu$m.

The cavity dispersion, with a magnitude of $k''_{tot} = 0.01$ ps$^2$ for a 40-GHz cavity, can increase or decrease the pulse duration, depending on the chirp profile of the pulse. In Fig. 3-5(d) the effect of compensating for the positive waveguide dispersion is given, down to a negative total cavity dispersion of $k''_{tot} = -0.005$ ps$^2$. The pulse duration decreases with decreasing cavity dispersion, as a consequence of an upchirp over the pulse. The maximum compression that can be obtained by compensating for the positive waveguide dispersion is approximately 50%, down to 1 ps pulse duration. At total cavity dispersion values lower than $k''_{tot} = -0.005$ ps$^2$ multiple pulses are formed inside the cavity. Practical realization of integrated dispersion compensation is not trivial and will be discussed in the next section.

As mentioned above, the pulse has a linear upchirp over the pulse maximum. A typical chirp profile is depicted in Fig. 3-6(a). A typical output pulse in the simulations shows a total upchirp of 1 THz – 2 THz. The bandwidth of the pulses (10 nm to 20 nm) is sufficient for compression of these pulses down to 300 fs, using a suitable amount of (negative) dispersion. By applying a total second order dispersion of $k''_{tot} = -0.5$ ps$^2$ on the pulses produced at an injection current of $I_{SOA} = 90$ mA pulse durations of 0.7 ps are obtained. At higher injection current the pulse power increases and as a result the magnitude of the SPM and the resulting chirp profile and pulse bandwidth are increased. For high injection currents of 150 mA – 200 mA, pulse durations down to 0.3 ps at $k''_{tot} = -0.2$ ps$^2$ can be obtained. These results are summarized in Fig. 3-6(b) which show the minimum attainable pulse duration and required dispersion compensation as a function of SOA injection current.

![Fig. 3-6 (a) Pulse power (solid) and detuning or chirp (dashed) profile using $I_{SOA} = 130$ mA, $L_{SOA} = 500$ $\mu$m and $L_{SA} = 50$ $\mu$m. (b) Minimum obtained pulse durations (left axis) and the corresponding applied second order dispersion (right axis).](image)

To summarize we have shown the results of the simulation of passive mode-locking in an InP/InGaAsP active-passive ring laser configuration. The model presented in the previous sections 3.2 and 3.3 is able to describe the mode-locking in these structures.
correctly as the pulse durations are longer than 1 ps, which is the lower boundary of the validity of (3.1). Based on the simulation results two conclusions can be drawn. First no femtosecond pulses (i.e. below 500 fs) are formed at the output of the laser. Our results confirm that the interaction of SPM with the gain dispersion prevents the formation of femtosecond pulses. Secondly a strong upchirp over the pulses is observed. This means that the bandwidth and phase behavior of the pulses is such that femtosecond pulses can be obtained through external compression. Based on these observations structures for IFSLs are proposed and investigated in the next section.

3.5 Integrated femtosecond semiconductor laser designs

The two main conclusions from the previous section indicate that in order to obtain an IFSL, the effect of the SPM should be addressed. Therefore integrated pulse shaping components are necessary. These conclusions agree well with successful demonstrations of femtosecond mode-locked semiconductor lasers using bulk optics, where fibers or grating-based pulse compressors are used to compress the pulses at the output of the laser [12,13], or where the SPM is minimized by operating the laser in a ‘breathing mode’ configuration [14].

In this section we propose two designs for IFSLs and present the simulated output. Realization of these designs is feasible using existing device processing technology. The components used in the design are based on the devices presented in [7] and [17]. The InP/InGaAsP active-passive material system allows for integration of those components on the same chip.

3.5.1 Extracavity pulse compression

The simulation results as presented in Fig. 3-6 show that pulses of 300 fs can be obtained by adding a dispersive element or pulse compressor with a total dispersion of $k''_{tot} = -0.2 \text{ ps}^2$ at the output of a PML ring laser. A pulse compressor can be realized in an integrated circuit and added to a PML ring laser using an AWG-pair with tunable delay lines as depicted in Fig. 3-7. This device is based on a similar design presented by Tsuda et al. [37], extended with PHMs that can be tuned between 0 and $2\pi$ radians phase shift. As a result the total dispersion of the compressor can be tuned.

The pulse compressor is simulated with a discrete phase filter as presented in Fig. 3-8. The discrete steps represent the finite channel spacing of the AWG. The parabolic shape of the phase profile is equivalent to a second order dispersion. The non-flat transmission of the AWG is taken into account with an amplitude filter for each channel. Calculations have been made both for Gaussian and flattened transmission. Note that the pulse propagates through two AWGs and the filter has to be applied twice. The dispersion over the spectrum within the channel (the intra-channel dispersion), is not taken into account as this profile is flat over the transmission maximum and the bandwidth within a channel (200 GHz) is small compared to the total pulse bandwidth (over 1 THz). As a result the pulse is less sensitive towards the intra-channel dispersion than towards the dispersion between the different channels, the inter-channel dispersion.
Fig. 3-7 A pulse compressing element based on an AWG-pair is added to the output of the mode-locked ring laser of Fig. 3-4. In the simulations we assume 20 channels or delay lines \((N = 20)\), spaced at 200 GHz.

Fig. 3-8 Phase (a) and amplitude (b) filter to describe the AWG transmission. The Gaussian (solid), flattened (dashed) and flat, square (dotted) transmission for a 200 GHz channel are given (b). The dispersion of the phase filter is \(k''_{\text{tot}} = -0.1 \text{ ps}^2\). 20 channels of 200 GHz are given.

Applying this filter to the simulated output of the PML ring laser shows that pulse compression down to 300 fs is achieved, as can be seen in Fig. 3-9. However due to the non-flat AWG transmission satellite pulses arise. These are spaced at the AWG channel spacing, i.e. at 5 ps for a 200 GHz AWG compressor. Flattening of the AWG transmission or increase of the crosstalk can reduce this effect. A flat, square transmission profile of the AWG, as shown in Fig. 3-8(b), would cancel these satellite pulses. An AWG with 20 channels spaced at 200 GHz and flattened transmission profiles such as depicted in Fig. 3-8 can be realized in InP/InGaAsP with existing processing technologies. A flat square profile however is not realizable. Designs for these pulse compressing devices, both with Gaussian transmission and with flattened transmission, can be found in [38].
3.5.2 Mode-locked ring laser with intra-cavity pulse shaping element

Resan et al. have obtained 185 fs pulses with a laser using a SOA by operating it in a ‘breathing mode’ configuration [15]. By stretching the pulse prior to entering the SOA the SPM in the SOA is minimized. The pulse is recompressed afterwards to be able to saturate the SA. With this configuration the detrimental effect of the interaction between SPM and the gain dispersion is addressed effectively.

A variation on this ‘breathing mode’ concept is presented in Fig. 3-10. In this design the SOAs are placed between two AWGs. The optical pulses between the AWGs have a low bandwidth and are elongated as a result. This means that the carrier number induced chirp (expressed by $\alpha N$) is minimized as the carrier depletion rate is minimized. Also because the pulse peak power is minimized, the SPM due to CH and UNR, expressed by respectively $\alpha T$ and $n_2$, is minimized. The low-bandwidth elongated pulses are recombined after the second AWG. This pulse is shorter and has a much higher peak power compared to the pulses propagating through the SOAs. The compressed pulse can then saturate the SA and is shortened by it, whereby the SA is taking care of the mode-locking. The SOAs can be individually biased, through which the gain spectrum can be actively controlled. This compares to the configuration of Gee et al [13].
For the simulation of the IFSL of Fig. 3-10 a cavity without PHMs and a cavity including PHMs are considered. The structure is simulated analogous to the scheme given in Fig. 3-1. Starting after the MMI section the pulse description is switched to the frequency domain and split over the number of channels with SOAs using the transmission filter of Fig. 3-8 for each channel. The central frequencies of these filters are separated by the channel spacing, e.g. 200 GHz or 400 GHz. Then the descriptions for these small-bandwidth pulses are switched back to the time domain. The propagation of these pulses through the SOA in their respective channel is then calculated using (3.1). If PHMs are used then the phase is adjusted accordingly. These pulse descriptions are then again switched back to the frequency domain and back to the time domain to apply the channel transmission filters for the second AWG. The pulses are then recombined to a (shorter and higher intensity) pulse by adding their complex field envelopes. Hereafter the recombined pulse propagates through the SA using (3.6) and 50% of the power is coupled out at the MMI.

The physical lengths of the channels with PHMs and SOAs are set to identical values. The SOA and SA lengths are $L_{SOA} = 500 \mu m$ and $L_{SA} = 50 \mu m$ respectively. Phase changes resulting from the SPM in the SOA and the PHM cause a difference in the optical path lengths. A 40-GHz free spectral range cavity is set. In the current InP/InGaAsP integration technology this cannot be realized. Electro-optic PHMs we can currently realize typically have a length of 5 mm [38] for practical phase tuning from 0 to $2\pi$ radians. Optical path lengths in the AWGs can be limited to less than 1 mm in InP [39]. As will be seen from the simulation results, fixing the cavity length is not a limitation for the applicability of the model to a realistic device.

First a $6 \times 200$ GHz configuration without PHMs is simulated. The six channels with SOAs are spaced at 200 GHz. The simulations show that a stable periodical output can be obtained for only a small range of SOA injection current values. This range is only a few milli-Ampères. One stable result is plotted in Fig. 3-11, with injection currents in the six SOAs of respectively 50 mA, 70 mA, 140 mA, 140 mA, 70 mA and 50 mA. Pulse durations of 1.6 ps are obtained with a repetition frequency of 200 GHz. Instability in this system is caused by the fact that the pulses in the six channels experience a much reduced but different SPM in the SOA. As a result the pulses in each channel travel a different
optical path length, which leads to a highly dispersive cavity. The SA locking strength is weak as the recovery time is set to 15 ps. Note the relatively flat (about one tenth of Fig. 3-6) chirp profile over the pulse, which is down-chirped as a result of the SA phase dynamics and the much slower SOA phase dynamics. The 200 GHz pulse rate operation is due to the process of mode-selection. The non-flat AWG transmission attenuates the five 40-GHz-spaced modes inside the 200-GHz channel non-uniform, which results in a different net gain for the modes. The available bandwidth for the pulse in the cavity can be increased through increasing the channel spacing or the number of channels. This in principle allows for shorter pulses. However the instability of the system increases due to the higher sensitivity for the cavity dispersion as compared to lower-bandwidth systems. No stable solutions were found for system bandwidths above 1.2 THz (i.e. 6 × 200 GHz).

Fig. 3-11  Simulated output of a 6 × 200 GHz cavity with only SOAs. Pulse power (solid) and chirp (dotted) are plotted in (a). In (b) the sequence of roundtrips from start-up to 1000 roundtrips is shown. Intensity is color coded with white denoting the higher intensity. The absorption recovery time is 15 ps. The stable operation is indicated by the straight lines in (b) (i.e. no pulse break-up) and the constant intensity. Pulse durations obtained are 1.6 ps.

Fig. 3-12 Simulated output from a 6 × 400GHz cavity with SOAs and PHMs. The results are obtained by first assuming an ideal compensation of the SPM in the SOAs by the PHMs per roundtrip until stable mode-locking is obtained. After the 500th roundtrip the PHM settings are fixed. Pulse durations obtained are 450 fs.

A more stable configuration can be made by using PHMs to compensate the difference in optical path length of the channels due to the SPM in the SOAs. The change in optical path length is not known a priori and can vary per roundtrip when the output has not reached a stable periodical state yet. Therefore an adaptive approach is chosen during start-up of the laser, where the differences in optical path length of the channels are set to be
zero. When a stable mode-locked output pulse stream has formed, the SPM is constant and the settings for the PHMs can be fixed. Hereafter the simulation is allowed to run for a few hundred roundtrips more to check the stability with these fixed PHM settings. In this way a 6 × 400 GHz IFSL is simulated with the conditions the same as in the previous configuration and the result is shown in Fig. 3-12. Injection currents through the six SOAs are respectively 85 mA, 120 mA, 140 mA, 140 mA, 120 mA and 85 mA. The corresponding phase shifts in the PHMs are then 1.44, 0.44, 0, 0.03, 0.53 and 1.61 radians. Pulse durations of 400 fs – 450 fs are obtained with a repetition frequency of 400 GHz. These short pulse durations and high repetition rate make such a device suitable for high bit-rate communication. The repetition rate is in this case determined by the AWG channel spacing. The optical field inside the SOA is almost continuous, i.e. almost all the energy of the optical field is in the mode at the transmission peak of the AWG channel. The (six) dominant modes are locked by the SA.

It turns out that a synchronized multi-wavelength pulse source similar to the system presented by Mielke et al. [40] can also be obtained in the same configuration. This can be achieved by decreasing the absorption recovery time from 15 ps to 5 ps and using the settings for the PHMs as found with the simulation method described above. The result for the 6 × 400 GHz cavity is depicted in Fig. 3-13. All the SOAs are injected with 140 mA. As can be seen, the SA super-modulates the mode-locked pulse stream. This means that six pulses, with their center frequencies spaced at 400 GHz are propagating in a synchronized way through the cavity. These six low-bandwidth pulses are 6 ps – 7 ps long and have a repetition rate of 40 GHz, the inverse cavity roundtrip time $T$. The higher saturation energy of the SA leads to mode-locking within each SOA channel separately. These pulses are synchronized by the common SA. This is opposed to the simulation of Fig. 3-12, where one mode per channel is dominant and the field inside each SOA channel is almost continuous.

The state with the 5-ps SA recovery time is self-starting when the PHMs are set as in Fig. 3-12. The decrease of the absorber recovery time by increasing the reverse bias voltage over the SA can be a practical route to the 400 GHz 400 fs mode-locked state (Fig. 3-12). The absorption recovery time can then be increased to a value of 10 ps – 15 ps after a stable output has formed.

---

![Simulated output of the IFSL of Fig. 3-6](image)

Fig. 3-13  Simulated output of the IFSL of Fig. 3-6. The absorption recovery time is decreased from 15 ps to 5 ps. The mode-locking is self-starting, i.e. the PHM settings are fixed from the start. A stable pulse stream is generated, which is supermodulated. In this state the device is a synchronized pulse source for multi-wavelength applications with six pulses with durations of 6 ps – 7 ps spaced at 400 GHz (b). The frequency detuning of the central channel wavelength from the central carrier wavelength ($\lambda = 1550$ nm) is given.
In the simulations above the pulses are allowed to move out of the window as the optical power is spread out over a series of pulses in the roundtrip time window (see Fig. 3-2). This means that the pulse can not be rotated as described in section 3.3 without influencing the SOA and SA recovery. This approach causes an extra source of possible instability at start-up in the model. In real devices ultrafast dynamics in the SA that are not countered by the carrier heating due to the applied field, such as SHB, can increase the mode-locking strength due to sub-picosecond absorption recovery components [35]. These are not taken into account in this work, but can possibly increase the practical feasibility of the proposed device.

In real devices the SOAs and the physical lengths of the channels with the SOAs and PHMs will not be identical. The resulting relative shifts in phase will be added to the changes caused by the difference in SPM in the SOAs. These differences can be compensated by the phase shifts in the PHMs as long as these shifts are well within the total phase shift that can be achieved by the PHM. For example a mask writing resolution of 25 nm makes it possible to limit the error in the designed length to within 5% of a wavelength. To find the optimal PHM settings for mode-locking e.g. a genetic algorithm can be used.

### 3.6 Conclusion

We have presented a flexible model for the simulation of unidirectional passive mode-locking in semiconductor ring lasers made in the InP/InGaAsP active-passive material system. In this model pulse shaping components based on AWGs can be added to the laser cavity and at the laser output. Using this model to simulate PML ring lasers consisting of an SOA, an SA and a passive cavity confirms that the SPM in combination with the gain dispersion is detrimental to the formation of femtosecond pulses. By variation of SA length, SPM parameters, SA recovery time and cavity dispersion pulse durations down to 1 ps were obtained. This showed that different laser configurations were required to obtain femtosecond pulses. The bandwidth and phase behavior of the simulated output of the simple cavity was however suitable to compress the pulses down to 300 fs using a second order dispersive component at the laser output. Based on these results two IFSLs were proposed and their output was simulated.

For the design of an IFSL with extra-cavity pulse compression a pulse compressor based on an AWG-pair with tunable delay lines is proposed. This pulse compressor is shown to be able to compress the simulated output pulses of a PML ring laser down to 300 fs. To suppress the formation of satellite pulses the AWG transmission has to be flattened.

The design for an IFSL with an intra-cavity pulse shaping component is shown to be promising for obtaining short, high repetition rate pulses. Pulse durations of 1.6 ps at 200 GHz have been observed for a design with six channels spaced at 200GHz with SOAs but without PHMs. Pulse durations of 400 fs at 400 GHz are obtained for a design with PHMs and a channel spacing of 400 GHz. The latter design shows no self-starting in the simulation. A synchronized pulse source for multi-wavelength operation is obtained by decreasing the absorption recovery time to 5 ps. This design is able to produce six pulses with frequencies spaced at 400 GHz and with a pulse duration of 6 ps – 7 ps.
The model uses parameters based on the InP/InGaAsP active-passive material system and the designs are based on components that can be integrated on the same chip in this material system. This shows the practical feasibility of realizing IFSLs.


Schrandere opmerking:

“E = mc²”

Ja, Albert Einstein-
Die kende zijn vak

En zijn betoog was heel
Argumentatierijk
(Blijft achterwege hier
Voor het gemak)

Drs. P
4 Monolithic semiconductor waveguide device concept for picosecond pulse amplification, isolation and spectral shaping

Abstract—In this paper a waveguide device concept, named IRIS, is presented. The device consists of a monolithic array of concatenated semiconductor optical amplifiers and saturable absorbers. We have theoretically investigated picosecond pulse transmission through these devices. The parameters used in the simulation are representative for InP/InGaAsP bulk gain material, operating in the 1550 nm region.

Operated as an optical amplifier for picosecond pulses the simulation results show increased pulse peak amplification and decreased temporal broadening of the pulses for the IRIS devices as compared to a semiconductor optical amplifier of equivalent length. Used as a nonlinear element to increase the optical bandwidth of a picosecond pulse, the spectra obtained with IRIS devices show an increased broadening and smoothness as compared to a semiconductor optical amplifier. Finally the feasibility for using the IRIS device as an optical isolator is shown. It is operated in a regime where the device is transparent for a picosecond pulse train, while it is absorbent for lower power reflections.

4.1 Introduction

Trains of picosecond or femtosecond optical pulses with a wavelength around 1550 nm have many applications. Picosecond optical pulse trains can be used in telecommunications for time domain multiplexing (TDM) systems and as synchronous pulse trains in wavelength division multiplexing (WDM) systems [1]. More advanced telecommunication coding technologies like optical code-division multiple-access (O-CDMA) also make use of short optical pulses [2]. Pulse trains also form a coherent optical frequency comb which can be applied in e.g. optical frequency metrology [3] or arbitrary pulse waveform generation [4].

The generation of short optical pulses using solid state mode-locked laser technology [5] and fiber-based sources [6,7] is now well established and short pulse shaping and processing is often used in laboratory environments, using bulk and/or fiber optics [8].

Hybrid or monolithic integration of short pulse generation and processing systems on an optical chip is in principle possible. This offers certain advantages for applications as mentioned above. The inherent stability, the compactness and manufacturability of an optical system on a single chip can allow for widespread application of such laser systems outside the laboratory environment.

The material of choice for such optical chips operating at wavelengths around 1550 nm is InP/InGaAsP. In this material components can be fabricated to generate short optical pulses with mode-locked lasers (MLLs) [9,10,11,12,13]. By combining different
InP/InGaAsP material compositions (e.g. using butt-joint active-passive integration [14]), these pulse sources can be combined monolithically with pulse processing components on a single optical chip [2,15].

In this paper three important issues will be discussed that concern the implementation of short pulse processing circuits on an optical chip. Possible solutions to these issues using a specially designed device that can be integrated are presented. First the on-chip generated pulse train needs to be amplified on the chip, to overcome losses associated with propagation through passive pulse shaping circuitry and the chip to fiber coupling. A semiconductor optical amplifier (SOA) is a commonly used option for amplification, though at the expense of generating noise in the form of amplified spontaneous emission (ASE). Moreover due to saturation effects picosecond pulses tend to broaden [16] and pulse peak amplification is limited.

A second issue in the integration of pulse generation and processing is the limited availability of options for integrated optical isolators. As mentioned above MLLs can be used for pulse generation, but they are sensitive to optical feedback [17,18]. Reflections of pulses from components further downstream the circuit are the cause for this feedback.

A last important issue for some applications of pulse trains as mentioned above is the required coherent optical bandwidth of the light. This required bandwidth may well exceed 1 THz [2,4]. Using monolithic MLLs for pulse generation, the optical bandwidth that can be achieved is limited, e.g. up to 200 GHz for 2 ps pulses [9]. By changing the design or operating conditions the optical spectrum of the laser output pulses can be broadened, leading to non-transform limited pulses [13,19,20].

In this paper we present an integrated device concept, consisting of a concatenated sequence of SOAs and saturable absorbers (SAs), that can be used to address any of these three issues, depending on how it is operated (Fig. 4-1). As the device concept offers possibilities for picosecond pulse amplification, ASE or noise reduction, optical isolation and increased spectral broadening, we have named it IRIS (Integration of Regeneration, Isolation and Spectral shaping) [21].

In the following we will first present a model for the simulation of picosecond pulse propagation through the device in section 4.2. Here the equations for pulse propagation through the SOA and SA sections of the device are given in which the generation of ASE is taken into account. In section 4.3 we use this model to simulate the device to explore the functionalities of picosecond pulse amplification, isolation and spectral broadening respectively. Results that are optimized for the three functions are presented. We use design and simulation parameters that are representative for InP/InGaAsP bulk gain material. In this material IRIS devices can be realized with a fabrication technology compatible with MLLs [13,22], which is an essential condition for further monolithic integration on a single photonic chip.

4.2 Theory of the IRIS device

The IRIS device consists of a concatenated sequence of SOAs and SAs, as shown in Fig. 4-1. In the next two sections rate equation models are presented to simulate picosecond pulse propagation through the SOA and SA sections respectively. In exactly the same way as the absorbers in MLLs, SAs can be created in InP/InGaAsP gain material by reversely biasing an SOA. Using common contacts for the SOAs and SAs respectively (see Fig. 4-1),
control of the device is relatively easy in practice. Current can be injected through the common SOA contact and all the SAs can be biased together using their respective contact.

![Diagram of the IRIS device](image)

Fig. 4-1  Schematic overview of the IRIS device used in the simulations. The input signal \( P(z,t) \) enters from the left side, starting with an SOA and exits from the right side. The total device consists of 10 SOA/SA pairs of 200 \( \mu \)m, making 2 mm length in total. The ratio of the SOA and SA length within the 200 \( \mu \)m section is varied in the simulations.

In this work we focus our simulations on a configuration with ten SOA/SA pairs and with a total length of 2 mm. All the SOAs and SAs each have the same length, so the length of one SOA and SA together is 200 \( \mu \)m. Their length ratio is varied in the simulations. The reasons for this chosen configuration are threefold. First a relatively short SOA limits the gain self-saturation due to ASE [23]. The SAs on the other hand can not be too short as in practice electrical isolation between the SOA and SA sections is needed. This isolation section should preferably be smaller than the SA. Thirdly a total length of 2 mm is still manageable when the device is integrated with other components where chip surface areas of up to 1 cm\(^2\) can be used.

As a main application of the IRIS device is the combination with a MLL, the simulations assume a single transverse mode with a single polarization. Integrated (mode-locked) lasers typically generate polarized light, due to the difference between TE and TM gain in the SOA [24]. Careful design of the integrated circuit maintains the polarization and ensures single transverse mode operation.

As we consider single-pass propagation of (transform limited) picosecond pulses through a 2 mm device, the effects of the gain bandwidth of the SOA and chromatic dispersion can be ignored. Also we do not explicitly take the electrical isolation sections between the SOA and SA into account (see Fig. 4-1). In realistic devices the isolation sections have lengths down to 5 \( \mu \)m – 10 \( \mu \)m [13]. In the model these sections are ignored.

### 4.2.1 SOA Equations

In this work we use the model presented by Tang and Shore to describe the propagation of short pulses through and SOA [25]. It includes the effects of carrier depletion, carrier heating (CH), two-photon absorption (TPA), spectral hole-burning (SHB) and ultrafast nonlinear refraction (UNR). This model was derived in the adiabatic limit for local carrier density and carrier temperature, which means that it is valid for pulse durations longer than the carrier temperature relaxation time, i.e. for pulse durations down to approximately 1 ps. This approach has been validated by Schell et al. [26].
The pulse is described by its power $P(z,t)$ and phase $\varphi(z,t)$, where $z$ is the longitudinal coordinate along the propagation direction and $t$ the time. These expressions relate to the complex optical field envelope according to $A(z,t) = \sqrt{P^+(z,t)}e^{i\varphi(z,t)}$. For SOAs longer than 500 $\mu$m it is necessary to take the carrier depletion due to ASE into account [23]. Part of the spontaneous emission generated inside the SOA will couple into the guided mode and is amplified when it propagates through the SOA. In long SOAs and depending on the injection current, the power of the ASE can be large enough to saturate the SOA near its input and output. As this self-saturation decreases the gain of the SOA, the ASE is included in the model by separate bi-directionally propagating fields $P^\pm_{\text{ASE}}(z,t)$ and $P^\pm(z,t)$. Their phase is ignored. As the ASE is broadband radiation, the effective gain it experiences can differ from the gain experienced by the pulse, which in our case has a small bandwidth of up to 2 nm. Hence we have extended the model of [25] with an ASE source term which adds to the forward and backward propagating fields $P^\pm_{\text{ASE}}(z,t)$ and an effective ASE amplification parameter. This is analogous to the approach in [27,28]. Note that we keep the value of the carrier lifetime $\tau_s$ constant. Furthermore a counter propagating field $P^\pm(z,t)$ is added to the model to be able to test the isolation from reflections. This field has the same wavelength and its gain is described with the same parameter as the pulsed signal $P^+(z,t)$. $P^-(z,t)$ is also assumed to be at least an order of magnitude weaker than $P^+(z,t)$. The signals involved are indicated schematically in Fig. 4-2. The pulse shaping effect of the SOA and the generation of ASE is expressed by the following set of 6 ordinary differential equations:

\[
\begin{align*}
\frac{\partial G}{\partial t} &= \frac{G_0 - G}{\tau} - \frac{(P^+ + P^-)(G - \varepsilon_z P^{+2})}{E_{\text{sat}}} \left( \frac{P^+_{\text{ASE}} + P^-_{\text{ASE}}}{G \cdot a_{N_{\text{ASE}}} / a_N} \right) + \Gamma_2 \beta_2 P^{+2} \\
\frac{\partial \varphi}{\partial z} &= -\frac{1}{2} \left[ \alpha_N G - \alpha_t \frac{\varepsilon_{\text{GP}} + \varepsilon_2 P^{+2}}{1 + \varepsilon_1 P^+} \right] - \left( \Gamma_2 \frac{\alpha_0}{c n_2} \right) \frac{P^+}{\sigma} \\
\frac{\partial P^+}{\partial z} &= G - \varepsilon_z P^{+2} \left( 1 + \frac{1}{1 + \varepsilon_1 P^+} \right) - 2 \Gamma_2 \beta_2 \frac{P^{+2}}{\sigma} - \alpha_{\text{int}} P^+ \\
\frac{\partial P^-}{\partial z} &= GP^- - \alpha_{\text{int}} P^- \\
\frac{\partial P^+_{\text{ASE}}}{\partial z} &= G \cdot a_{N_{\text{ASE}}} \frac{P^+_{\text{ASE}}}{a_N} - \alpha_{\text{int}} P^{+2}_{\text{ASE}} + \beta B h \omega \sigma \left( \frac{G}{\Gamma a_N} + N_v \right)^2 \\
&\text{(2 equations)}
\end{align*}
\]

$G = G(z,t)$ and $G_0$ are the linear gain and the small signal gain of the SOA respectively and are defined by:

\[
G = \Gamma a_N \left( N - N_v \right) \quad (4.2)
\]

\[
G_0 = -\Gamma a_N N_v \left( \frac{I_{\tau_s}}{qV N_v^r} - 1 \right) \quad (4.3)
\]
in which $N$ and $N_tr$ are the carrier density and the carrier density for transparency respectively, $a_N$ the differential gain, $\Gamma$ the linear confinement factor, $\tau$ the carrier lifetime, $I$ the injection current, $q$ the electron charge and $V$ the volume of the active area. In (4.1) $\varepsilon_1$ is the nonlinear gain compression due to SHB and CH, $\varepsilon_2$ is the gain compression due to TPA, $a_N$ and $\alpha_T$ are the carrier density and temperature linewidth enhancement factors respectively, $\Gamma_2$ and $\Gamma'_2$ are the confinement factors associated with TPA and UNR respectively, $\beta_2$ and $n_2$ are the TPA and UNR coefficients respectively, $c$ the light velocity in vacuum, $\omega_0$ the pulse central frequency, $a_{\text{int}}$ the SOA waveguide linear loss and $\sigma = wd/\Gamma$ the mode cross section (with $w$ and $d$ the width and thickness of the active region respectively). Furthermore the saturation energy $E_{\text{sat}}$ and $\beta'_2$ are defined by:

$$E_{\text{sat}} = \frac{\hbar \omega \cdot \sigma}{a_N}$$

$$\beta'_2 = \frac{a_N \beta_2}{\hbar \omega \sigma^2}$$

The effective amplification of the ASE is implemented by a separate differential gain parameter $a_{N,\text{ASE}}$ and the generation by $\beta B$, in which $B$ is the radiative recombination parameter and $\beta$ the fraction of the spontaneous emission that is coupled into the guided mode, i.e. added to the ASE field. In (4.1) we ignore TPA and fast effects like CH and UNR for both low peak power ASE fields $P_{\text{ASE}}^\pm (z, t)$ and reflected signals $P^\pm (z, t)$. This is allowed as the peak powers are about three orders of magnitude lower (see next section). We would like to point out that TPA effects that occur at high power continuous wave field propagation involve additional physical effects and as a result these must be described using different parameters [29]. Also the effective parameters for CH and UNR are not valid for broadband ASE fields.

![Fig. 4-2 Schematic overview of the propagation of the optical fields through the IRIS device and their gain parameters.](Image)

4.2.2 SA equations

To simulate pulse propagation through the SA we use the model presented by Koumans and Van Roijen [30]. We refer to our work in [19] for the assumptions and implementation with respect to picosecond pulse propagation. Furthermore as an approximation we use the same effective differential absorption $a_{N,\text{SA}}$ for both the broadband ASE and the (narrowband) pulse. Unlike the SOA, which is operated around its gain maximum, the SA is operated along the slope of the gain (absorption) curve [31]. This means that broadband ASE generated by the SOA will experience larger absorption than
the pulsed signal $P^*(z,t)$ for the shorter wavelengths and smaller absorption for the longer wavelengths. Hence we assume these absorption values to be of the same order.

Applying these approximations leads to the following set of 6 equations to describe the SA sections in the IRIS device:

\[
\frac{\partial Q}{\partial t} = \frac{Q_0 - Q}{\tau_{SA}} - \frac{Q}{E_{sat,SA}} \left( P^+ + P^- + P^+_{ASE} + P^-_{ASE} \right)
\]

\[
\frac{\partial P^+_{ASE}}{\partial z} = QP^+_{ASE} \quad \text{(4 equations: for $P^+$, $P^-$, $P^+_{ASE}$ and $P^-_{ASE}$)}
\]

\[
\frac{\partial \phi}{\partial z} = -\frac{1}{2} \alpha_{N,SA} Q
\]

\[
Q_0 = -\Gamma a_{N,SA} N_{tr,SA}
\]

in which $Q$ represents the absorption or negative gain, $Q_0$ the small-signal absorption, $E_{sat,SA}$ the saturation energy, $\alpha_{N,SA}$ the carrier density linewidth enhancement factor, $a_{N,SA}$ the differential absorption and $N_{tr,SA}$ the absorber carrier density for transparency. The absorption recovery time is implemented by an effective carrier lifetime $\tau_{eff,SA}$ with a typical value of 5 ps – 15 ps [32]. This is significantly lower than the value in the SOA due to the applied field.

4.2.3 Implementation

Pulse propagation through the IRIS device is calculated by solving the sets of differential equations (4.1) and (4.6) by a finite-difference method on a spatio-temporal grid with a resolution of $5.00 \mu m \times 59.3$ fs. The spatial resolution $\Delta z$ of the device is related to the temporal resolution $\Delta t$ through the group velocity $v_g$ of the light inside the device according to $\Delta z = v_g \cdot \Delta t$.

The values of the parameters we use in our simulations are given in Table 4-1. We use effective ASE generation parameters $\beta_B$ and $a_{N,ASE}$ which we have matched to the ASE output power of our SOAs using (4.1). The values we found agree well with [27,28,33]. Strictly speaking the ASE spectrum will become more narrow while propagating through the SOA, increasing the effective ASE gain $a_{N,ASE}$. In this work we treat this parameter as a constant. The main implication is that the ASE generation in a long SOA (2 mm, used for reference below) is underestimated with respect to the IRIS configurations, which have (ten) shorter SOAs. The differential gain value $a_N$ has been obtained using a method based on [34].

4.3 Applications

In this section we investigate theoretically three possible applications of the IRIS device: picosecond pulse amplification, optical isolation and the addition of spectral bandwidth. These three applications will be addressed respectively below. We use the SOA and SA models described above to simulate the propagation of an optical pulse through a
2 mm long IRIS device. As a reference we will compare the obtained results using the IRIS device with the results of pulse propagation through an equally long SOA. Note that this is the limiting case of an IRIS configuration with SA lengths of zero. Also note that SOA structures can be optimized specifically for the applications discussed. A full and extensive comparison of optimized SOA structures with the IRIS configuration is beyond the scope of this work.

For the input our attention is focused on pulses with a full width at half maximum (FWHM) of 2 ps duration and a peak power of 0.1 W (corresponding to approximately 0.1 pJ pulse energy). We investigate two regimes for the pulse repetition rate, 40 GHz and single pulse transmission, i.e. a repetition rate that is low as compared to the carrier lifetime of 0.3 ns. The reason for choosing these input pulse parameters is twofold. First this pulse duration is representative for the output as generated by MLLs [9,10,12], with powers typically in the range of 0.01 W to 0.1 W [35] and record high peak powers of 1 W [36]. Secondly pulse trains with a duration of 2 ps and a repetition rate of 40 GHz have important applications, for example in telecommunications as sources for 40 Gbit/s systems (both WDM and TDM) and as sources which can be interleaved for 160 Gbit/s applications [1].

Table 4-1 Simulation parameters and their values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SOA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASE generation</td>
<td>β·B</td>
<td>10⁻⁹ m³/s</td>
<td>[27,33]</td>
</tr>
<tr>
<td>Width of active region</td>
<td>w</td>
<td>2.0 µm</td>
<td>[13]</td>
</tr>
<tr>
<td>Depth of active region</td>
<td>d</td>
<td>0.12 µm</td>
<td>[13]</td>
</tr>
<tr>
<td>Linear confinement factor</td>
<td>Γ</td>
<td>0.285</td>
<td>[13]</td>
</tr>
<tr>
<td>Confinement factor for TPA</td>
<td>Γ₂</td>
<td>0.5</td>
<td>[25]</td>
</tr>
<tr>
<td>Confinement factor for UNR</td>
<td>Γ₂'</td>
<td>0.4</td>
<td>[25]</td>
</tr>
<tr>
<td>Differential gain</td>
<td>a_N</td>
<td>3.5·10⁻²⁰ m²</td>
<td>[34]</td>
</tr>
<tr>
<td>Differential gain ASE</td>
<td>a_N,ASE</td>
<td>1.0·10⁻²⁰ m²</td>
<td>fit</td>
</tr>
<tr>
<td>Carrier lifetime</td>
<td>τₙ</td>
<td>0.3 ns</td>
<td>[25]</td>
</tr>
<tr>
<td>Carrier density linewidth</td>
<td>αₙ</td>
<td>5</td>
<td>[25]</td>
</tr>
<tr>
<td>Temperature linewidth enhancement factor</td>
<td>αₜ</td>
<td>3</td>
<td>[25]</td>
</tr>
<tr>
<td>Coefficient for TPA</td>
<td>β₂</td>
<td>37 cm/GW</td>
<td>[25]</td>
</tr>
<tr>
<td>Nonlinear gain refractive index</td>
<td>n₂</td>
<td>-3.5·10⁻¹⁶ m²/W</td>
<td>[25]</td>
</tr>
<tr>
<td>Nonlinear gain compression factor</td>
<td>ε₁</td>
<td>0.2 W⁻¹</td>
<td>[25]</td>
</tr>
<tr>
<td>Nonlinear gain compression</td>
<td>ε₂</td>
<td>200 W⁻² m⁻¹</td>
<td>[25]</td>
</tr>
<tr>
<td>corresponding to TPA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transparency carrier density</td>
<td>N_tr</td>
<td>0.3·10²⁴ m⁻³</td>
<td>[25,34]</td>
</tr>
<tr>
<td>Linear loss</td>
<td>αₙbusy</td>
<td>2.0·10⁻¹⁰ m⁻³</td>
<td>[25,34]</td>
</tr>
<tr>
<td><strong>SA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linewidth enhancement factor</td>
<td>α_SA</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>Differential absorption</td>
<td>aₙ,SA</td>
<td>20·10⁻²⁰ m²</td>
<td>[30]</td>
</tr>
<tr>
<td>Effective carrier lifetime</td>
<td>τ₉_SA</td>
<td>5 ps</td>
<td>[32]</td>
</tr>
<tr>
<td>Transparency carrier density</td>
<td>Nₑ,SA</td>
<td>0.7·10²⁴ m⁻³</td>
<td>[19]</td>
</tr>
</tbody>
</table>
4.3.1 Amplification and ASE suppression

As mentioned above, on-chip amplification of optical pulse trains is commonly achieved using an SOA. There are two main problems when using an SOA for pulse train amplification. First of all, picosecond pulses tend to broaden inside the SOA due to gain saturation [16], severely limiting the pulse peak power amplification. Secondly, in the process of amplification ASE is added to the pulse stream, introducing background signals and noise in the system which can limit the application of the light generated. For example, for TDM applications a 40 dB extinction ratio is mentioned for interleaving four 10 Gbit/s pulse trains [1] and a 30 dB ratio is mentioned for interleaving four 40 Gbit/s up to 160 Gbit/s, where the pulse duration should be around 1.5 ps [37].

A configuration similar to the IRIS configuration has been studied for 2R regeneration purposes, both theoretically [38] and experimentally [39], though not for picosecond pulse amplification. Moreover, previous work suggests that a concatenated SOA/SA structure can limit the pulse broadening, or even compress a picosecond pulse [40]. In the following, we will investigate the amplification and temporal broadening of a picosecond pulse train and the ASE suppression in the IRIS device.

To illustrate the capabilities and advantages of the IRIS device for pulse amplification, simulations have been made for a series of 2 mm long IRIS devices with varying amplifier-absorber length ratios. In Fig. 4-3(a) the simulated peak power of a single picosecond pulse after propagation through these IRIS devices is shown. With respect to the amplification of a single pulse, it can be said that the peak power amplification of the IRIS devices is larger than that of an SOA of equivalent length. This increase is up to two times for the configurations with the longer SAs (17 dB, see Fig. 4-3(a)). The larger peak power amplification can be explained by the limited temporal broadening or even compression of the pulse, down to a duration of 1.2 ps for the longer SAs. These simulated pulse durations are shown in Fig. 4-3(b). As compared to the previous theoretical work on a comparable device configuration for pulse compression [40], we have added the effect of TPA. This adds to the temporal broadening and as a result the effect of pulse compression is limited.

As stated above, for specific applications such as TDM [37], only limited or no pulse broadening is allowed. Comparing SOA and IRIS results in Fig. 4-3(a) and (b) for the case where the output pulse duration is around 2 ps, an even more favorable performance of the IRIS devices is predicted. Whereas the amplification in an SOA is about 4 dB at 150 mA injection current, the amplification for the IRIS devices is from 11 dB up to 17 dB with increasing SA lengths, while still having an output pulse of 2 ps duration (Fig. 4-3(a)). As a drawback, it can be said that an increased injection current is needed, ranging from 250 mA up to 700 mA with increasing SA length. The spectral effects which also need to be considered when amplifying are discussed in the last part of this section.

In Fig. 4-3(c) the energy of the output pulses is plotted as a function of input pulse energy, a so-called transfer function. Due to the difference in saturation levels of the SOAs and SAs, the transfer function is nonlinear, resulting in an S-shaped curve. This indicates possibilities for 2R regeneration [38]. However, we limit ourselves to a comparison of the output ASE power levels when no pulse is present in the IRIS device. This is an important parameter as this ASE can severely influence the further system performance. ASE generation could be a problem for IRIS devices as the SOAs inside are operated at higher injection currents than plain SOA devices. However, the nonlinear transfer functions for the IRIS devices indicate that the generation and build-up of ASE, which has low peak power, can be suppressed inside these devices. Simulation results of the ASE power levels are...
shown in Fig. 4-3(d). These show that even decreased ASE levels are obtained from the IRIS devices. For example extending the example mentioned above, a 2 mm SOA operated at 150 mA produces 2.8 \( \mu \)W ASE when no pulsed input is present, whereas the IRIS device with 100 \( \mu \)m SAs produces only 0.58 \( \mu \)W ASE at 700 mA, 7 dB less.

In conclusion it can be said that for picosecond pulse amplification, the investigated IRIS device simulations show an improved performance over a conventional SOA of equivalent length. Assuming no temporal broadening is allowed, an SOA can only achieve an amplification of 4 dB at 150 mA injection current. Operating an IRIS device with 100 \( \mu \)m SAs at 700 mA increases the amplification to 17 dB, while decreasing the ASE generated when no pulse is present with 7 dB.

Fig. 4-3  Simulation results of a single pulse transmission for a series of configurations of an IRIS device (as indicated by the single SOA and SA lengths respectively). The sech\(^2\)-shaped input pulse has a duration of 2.0 ps and a peak power of 0.1 W. Simulated transmission results through a 2 mm SOA are included for comparison. (a) Output pulse peak power. (b) Output pulse duration. (c) Output pulse energy vs. input pulse energy, using an injection current of 400 mA. (d) Forward propagating ASE power level without pulsed input.

Many practical applications require high-repetition rate pulse trains, e.g. 40 GHz and higher for state of the art TDM applications [1], having relatively short pulse durations of about 2 ps. These high repetition rates and corresponding pulse durations are also typically generated by integrated MLLs, owing to their relatively short cavity length [9,10,11,12]. For high pulse repetition rates with a corresponding periodicity significantly below the SOA recovery time \( \tau_s \), the effective gain of the SOA sections decreases as they can not recover fully in between two consecutive pulses. In our model we use a constant carrier
lifetime of 0.3 ns (Table 4-1). This is long as compared to the 25-ps periodicity of pulses in a 40-GHz pulse stream.

Fig. 4-4(a) shows the simulated peak power of a train of pulses at a repetition rate of 40 GHz after propagation through an IRIS device. The input signal is a constant train of pulses with a duration of 2 ps FWHM and a peak power of 0.1 W. This corresponds to an average power of less than 10 mW, which is the power level that can be expected from integrated MLLs. Due to the partial recovery of the SOA sections of the IRIS devices in between the pulses the gain in these sections is significantly lower as compared to the single pulse case mentioned above. The SA sections of the device however recover fully in between two pulses, with an absorption recovery time of \( \tau_{SA} = 5 \text{ ps} \) (Table 4-1). As a result the net gain of the IRIS devices is lower for a 40 GHz pulse train as compared to the single pulse transmission (see Fig. 4-3(a)).

On the other hand, the temporal pulse broadening is severely limited and even significant pulse compression is shown by the simulation results. In Fig. 4-4(b) the output pulse durations are shown. It has to be noted that the rate equation model used in this work has a limited validity, down to picosecond pulse durations [25]. As a result the significant pulse compression in the IRIS devices with longer SAs (60 \( \mu \text{m} – 100 \mu \text{m} \)) can not be fully trusted, but is shown for reference. Concerning these IRIS devices we limit ourselves to the qualitative conclusion that significant pulse compression (over 50%) can be achieved using the IRIS device, as was previously mentioned in [40].

Comparing the IRIS devices with shorter SAs (20 \( \mu \text{m} \) and 40 \( \mu \text{m} \)) with an SOA of 2 mm length at the 10 dB peak gain level, shows that higher injection currents for the IRIS devices are needed (900 mA – 1000 mA as compared to 800 mA for an SOA). On the other hand, there is no pulse broadening (for the 20 \( \mu \text{m} \) SAs) and even compression down to 1.0 ps (40-\( \mu \text{m} \) SAs), whereas the 2.0 ps input pulses broaden inside the 2 mm SOA to 3.1 ps.

In Fig. 4-3(d) it is shown that ASE output levels for IRIS devices are significantly lower than for an SOA. In Fig. 4-4(c) we present the ratio of the peak pulse output power to the forward propagating ASE output power. The time averaged (over one period of 25 ps) ASE power is used in the calculation. This indicates the signal to background or noise ratio (SNR) at the output. Again limiting the comparison with the SOA to the IRIS devices with the shorter SAs, simulations show that an increased SNR can be obtained. A maximum of over 8 dB increase in SNR with respect to an SOA is obtained for the IRIS device with 40 \( \mu \text{m} \) SAs at an injection current of 1.6 A, while the increase is over 6 dB at the 10 dB gain level at 1.0 A injection current. This ASE level is 60 dB below the pulse peak power, which is 20 dB – 30 dB below the requirements as mentioned above [1,37]. We therefore conclude that the ASE from an IRIS device will not lead to a significant contribution to the noise in the system.

It should be noted that the forward ASE field generated by an IRIS device are highly time dependent, with a peak intensity around the signal pulse position. In Fig. 4-4(d) the temporal pulse shapes are shown along with the corresponding ASE fields. The IRIS devices with the shorter SAs are compared with an SOA at the points of maximum simulated SNR (see Fig. 4-4(c)). The peak intensity of these fast ASE signals is quickly reduced. The ASE has a wide bandwidth compared to the spectral width of the pulses and as a result the ASE pulses are far more sensitive to dispersion and their peak intensity will decrease rapidly further downstream in a circuit or fiber. Also the use of bandwidth filters in a system will decrease these ASE pulses.
In conclusion it can be stated that simulations show that the IRIS devices with the 20 μm and 40 μm SAs have an improved performance over a plain SOA with respect to the amplification of a 40 GHz pulse train. Amplification of 10 dB is achieved at higher injection currents (900 mA – 1000 mA as opposed to 800 mA for an SOA), while limiting the temporal broadening of the pulses. In this case ASE generation by the IRIS devices is suppressed by over 6 dB as compared to the SOA. The generated ASE power is 60 dB below the output pulse peak power. This means that the generated ASE will not degrade system performance for future high-speed TDM applications.

Moreover the simulations indicate that IRIS devices with longer SAs can be efficient pulse compressors, with compression down to the sub-picosecond pulse regime. However this compression can not be quantified due to the limited validity of our model in this regime.

As a last remark on the 40 GHz picosecond pulse train amplification we note that we have focused our simulations on a constant pulse train, as generated by MLLs. As a result there are no pattern effects. Using the IRIS device as a full 2R regenerator, would require a more elaborate analysis, such as mentioned in [38]. This is beyond the scope of this paper.

Fig. 4-4 Simulation results for a series of IRIS device configurations of a 40 GHz pulse train transmission (as indicated by the single SOA and SA lengths respectively). The input pulses have a duration of 2 ps and a peak power of 0.1 W. (a) Output peak power. (b) Output pulse duration. (c) Output pulse train signal to noise ratio as defined by dividing the output pulse peak power by the average generated forward propagating ASE power. (d) Temporal output pulse shapes (solid) and corresponding forward propagating ASE fields (dashed) at maximum SNR (see (c)) for one period of the 40 GHz signal.
4.3.2 Optical isolation

All lasers, and particularly MLLs, are sensitive to optical feedback, typically down to levels of -50 dB [17,18]. This feedback typically originates from reflections of the laser output from other components in the circuit or system. Also noise generated by other active components in the system can cause instabilities in the laser. Integrated optical isolators are necessary to prevent this feedback from entering the laser in an integrated circuit.

Currently commercially available isolators are bulk optical components, that are not suitable for integration. Attempts to obtain integrated optical isolators are based on the magneto-optic Kerr effect [41] or electrical traveling waves [42] to break the symmetry between the forward and backward propagation direction. However this is a general purpose isolation. In many practical applications of MLLs, the forward traveling signal will be the output pulse train generated by the MLL. As mentioned above, this pulse peak power is relatively high, typically around 0.1 W. With pulse reflection levels lower than 1% and a power level of backward propagating noise far below the pulse peak powers of 0.1 W, there is already a break of symmetry in such a system.

As mentioned above, due to the difference in saturation energies of the SOA and SA, an SOA/SA pair has a non-linear transfer function for picosecond pulse propagation [38]. As a result in IRIS devices the gain for high power signals can be higher than that for low power signals, as can be seen in Fig. 4-3(c). A single SOA/SA pair can work as an optical gate. It can be ‘opened’ by the high peak power pulse but not by low power signals, such as the reflections of the pulses traveling in the backward direction. This can be used to create an optical isolator for short pulses. The gate function is increased when the pulse train is first amplified (i.e. first encounters an SOA) while the backward propagating low power reflections are first absorbed (i.e. first encounters the SA).

Obviously when a pulse ‘opens’ the SOA/SA pair, a reflection of a previous pulse arriving at the same time at the SOA/SA pair but from the opposite direction, will also pass through. The IRIS device has multiple cascaded SOA/SA pairs or gates. This configuration makes it possible that isolation always takes place, irrespective of timing. There are two important design rules to ensure this isolation. First the spacing between two SAs, should not be of the same length as the distance between two pulses in the pulse train (or an integer number of these pulse distances). Secondly the absorption recovery time of the SA should be short with respect to the interval time between two consecutive pulses and with respect to the time the signal needs to fully propagate through the device. In our case we use a value of the recovery time of $\tau_{SA} = 5 \text{ ps}$ which is low as compared to the time between two pulses in a 40 GHz pulse stream of 25 ps and the 24 ps time needed to travel through the 2 mm device. A short SA recovery time increases the chances that the backward propagating signal will encounter an SA with a recovered absorption. This then increases the absorption of the feedback, resulting in an increased isolation.

The IRIS configurations considered in this work, i.e. 10 SOA/SA pairs with a length of 200 $\mu$m obey the design rules mentioned above if we consider a forward propagating pulse train at 40 GHz repetition rate. To simulate the isolation properties, the transmission of a backward propagating probe signal is calculated (see Fig. 4-2). For the probe signal, a CW optical field is used. While propagating through the IRIS device, this field will be modulated by the pulsed forward propagating signal, i.e. by cross-gain/absorption modulation. The peak transmission of this probe field at the output will then give a value for the minimum isolation that can be obtained. The probe signal is assumed to be at the same wavelength as the pulsed signal and its gain is determined by the same parameter $a_N$.
as the forward going signal. Since we are considering the specific application to isolate a MLL from feedback, this is a valid assumption. Noise generated further downstream the circuit by other components is incoherent and is less likely to cause instabilities in the MLL. The power of the CW probe signal is set to 0.1 mW. This power level is representative for the peak power of reflections that can occur (0.1% of the peak power of the pulses). The fact that the average power of the probe is an order of magnitude higher than that of the reflected pulses which occur in reality is not a problem for the accuracy of the model since these low power reflected signals have only a very small influence on the energy balance in the IRIS devices.

In Fig. 4-5(a) the calculated gain ratio between the forward propagating pulse train and the backward propagating probe signal is shown. The maximum gain of the probe signal is used in the calculation, i.e. the peak power of the transmitted probe signal. In a 2 mm SOA, the gain of the pulse train is lower than the gain of the probe signal, resulting in a ratio below 1. The reason is that the effects of TPA, CH and gain saturation are more significant for the pulse train, which has higher (peak) power than the probe signal. The IRIS devices however show a gain ratio above 1, indicating possible isolation. The increase in gain ratio with increasing injection current is caused by the saturation of the SAs by the pulse train. The following decrease is then the result of the TPA, CH and saturation effects in the SOAs, just like for a 2 mm SOA.

To be able to operate the IRIS device as an optical isolator, it should be transparent for the pulse train, while absorbing the probe signal. In Fig. 4-5(b) the probe absorption is plotted for the different IRIS configurations at the injection current where the device is transparent, i.e. the gain equals 0 dB for the pulse train. For example 10 dB isolation against the CW probe signal can be achieved using an IRIS device with 40 μm SAs and using an injection current of 700 mA. The isolation increases with increasing SA length, up to 45 dB isolation at 1.6 A injection current for the devices with 100 μm SAs. The 60 dB gain ratio at 2 A injection current for this device indicates the possibility for further device optimization with respect to the application as an optical isolator. These isolation values are comparable with the work in [41], where also an electrically pumped optical waveguide structure is used. Moreover the low backward propagating ASE output levels of less than 22 μW make that it is possible to increase the total length of the IRIS devices for increased isolation.

As mentioned above, the absorption recovery time is crucial for the isolation. It determines the time that an SOA/SA pair is ‘open’ for the backward propagating signal. In Fig. 4-5(c) the effect of the gain ratio and the corresponding isolation is shown for 5 ps, 10 ps and 15 ps recovery time τ_SA, for an IRIS device with 60 μm SAs. The gain ratio drops by over two orders of magnitude when the recovery time is increased from 5 ps up to 15 ps, as expected. This shows the importance of a fast SA recovery.

In conclusion it can be said that we have theoretically shown that the IRIS configuration can work well as an integrated optical isolator for picosecond pulse propagation. Simulations show that an isolation of 20 dB to 30 dB can be obtained using 2 mm long IRIS devices with 60 μm or longer SAs at injection currents of 1.0 A to 1.3 A. Assuming reflection levels of 0.1% to 1% (-30 dB to -20 dB) this isolation then reduces the feedback to -50 dB. This level of feedback does not influence a laser, which makes the IRIS device very promising as an integrated optical isolator in combination with a MLL.
Fig. 4-5 Simulations of the isolation, using a 2 ps forward propagating pulse train with peak power of 0.1 W at 40 GHz and a backward propagating CW signal of 0.1 mW. (a) The gain ratio defined as the gain of the forward propagating pulse train divided by the gain of the backward propagating signal for a series of IRIS devices. (b) Isolation defined as the absorption (gain) of the backward propagating signal at transparency for the pulse train. The backward propagating ASE power is also given. (c) The gain ratio plotted for three values of the absorption recovery time $\tau_{SA}$ for an IRIS configuration with 60 $\mu$m SAs.

### 4.3.3 Spectral shaping

Pulsed lasers with a coherent broad optical spectrum are attractive sources for use in arbitrary waveform generators [4, 43], dense wavelength division multiplexing systems [44, 45], optical code-division multiple-access (O-CDMA) systems [2] and frequency comb generation [3]. Such systems can be realized on a single photonic integrated circuit when MLLs are used as the pulsed source. Nowadays monolithic MLLs are able to produce pulses with a typical bandwidth of the optical spectrum of 1 nm – 2 nm [9]. By changing the design or operating conditions the spectrum can be broadened, leading to non-transform limited pulses [13, 19, 20].

To increase the optical bandwidth of picosecond pulses further, amplification and highly non-linear fibers are often used. In a photonic integrated circuit an SOA is an option. However the broadening that can be achieved is limited and the noise in the system output is increased. In this section we compare the performance of the IRIS devices with an SOA with respect to the spectral shaping of a picosecond pulse train. For applications as mentioned above two features of the optical spectrum are important. First the bandwidth needs to be large enough for the application. For example when AWGs are used for further pulse processing, the minimum channel spacings of 10 GHz for silicon-based AWGs [4] or
50 GHz for InP-based AWGs [46] are a restriction. Bandwidths of over 5 nm are needed to be able to use at least ten channels in a high resolution InP-based AWG for e.g. O-CDMA applications. For further pulse compression, down to a few hundred femtoseconds, bandwidths of over 10 nm are necessary [43,47].

Secondly to prevent excessive spectral power equalization of the spectrum afterwards, the spectrum needs to be smooth, i.e. with little modulation in the spectral power. When the spectrum is not smooth, channels may drop out in e.g. WDM applications or further pulse compression is limited as satellite pulses or pedestals may appear.

The calculated spectra of a single 2.0 ps pulse after propagation through different IRIS devices and a 2 mm SOA are shown in Fig. 4-6(a). It can be seen that as a general trend by increasing the injection current the spectra first broaden and then compress afterwards. This broadening and consecutive compression occurs at a higher value of the injection current for increasing length of the SAs (the SOA being the limit of zero length SA). This can be understood by referring to the equations (4.1), where the self-phase modulation (SPM) responsible for the spectral broadening is attributed to the effects of carrier depletion, SHB, CH and UNR. Also temporal changes in the pulse shape, mainly due to gain saturation, cause a change in the spectrum. As the spectra show a red-shift and broadening towards the longer wavelengths with increasing injection current, it can be concluded that the effects of carrier depletion are most important in the SPM. Increasing the SA length in the IRIS devices, decreases the output pulse energy and consequently maximum carrier depletion occurs at a higher injection current. The injection current where the spectral broadening starts corresponds to the current values at which the SAs saturate and the energy of the pulse can increase (Fig. 4-3(a)).

There are two main reasons for the increased broadening with increasing SA length. First the pulse temporal broadening is limited and pulse peak power is higher (Fig. 4-3(a,b)). As a result the carrier depletion takes place in a shorter time, consequently increasing the SPM. The compression of the spectrum at higher injection currents can be attributed to the gain saturation, which temporally broadens the pulse and decreases this SPM.

Secondly, because of the absorption of the SAs, the pulse energy is lowered. As a result gain saturation and the detrimental pulse broadening, takes place at a higher injection current. In these cases, the carrier reservoir that can be depleted is larger, leading to an increased SPM. As a last point it has to be mentioned that the carrier depletion due to ASE is more limited in the IRIS devices with increasing SA length.

The obtained spectral width well exceeds 10 nm for the IRIS devices with SA lengths of 40 μm and longer Fig. 4-6(b), whereas the obtained width for an SOA is only 4.1 nm. This makes the amount of bandwidth that can be obtained suitable for applications as mentioned above. Moreover, the shape of the spectrum shows less intensity modulation over the range of wavelengths (Fig. 4-7). For applications that require the bandwidth to be sliced over different low-bandwidth channels, e.g. for WDM and O-CDMA, a smooth spectrum requires less power equalization, either by absorption or amplification of the respective channels. Also, a smooth spectrum allows for maximum pulse compression without the rise of satellite pulses.
Fig. 4-6 Optical output spectra for a 2 mm SOA and a series of IRIS devices with different SOA/SA lengths ratios and a single 2.0 ps, 0.1 W input pulse. (a) Output spectra as a function of injection currents. The normalized spectral power is coded in greyscale from black up to white with increasing power. In (b) the calculated FWHM of the output spectra is given as a function of the injection current.
Fig. 4-7  Optical output spectra for the same conditions as in Fig. 4-6. The simulated spectra presented here have been selected for their combination of large broadening and smoothness.

In Fig. 4-8 the calculated spectra of a 40 GHz, 2.0 ps pulse train after propagation through the IRIS devices and a 2 mm SOA are shown. The effects of spectral broadening are less pronounced as compared to the single pulse transmission case, as the SOAs in the IRIS device are not able to fully recover in between the passage of two consecutive pulses. The pulse repetition rate is 25 ps as compared to the SOA recovery time of $\tau_s = 300$ ps. The result of this decreased gain is twofold. First comparing Fig. 4-8 with Fig. 4-6 it can be seen that the broadening of the spectrum occurs at higher injection current. Secondly, for the IRIS devices with the longer SAs (60 $\mu$m to 100 $\mu$m), the broadening is to the blue side of the spectrum, indicating an increase in contribution to the SPM due to the SA relative to that of the SOA. The IRIS devices with the shorter SAs (20 $\mu$m and 40 $\mu$m) show a spectral broadening of over 10 nm at an injection current of 1.4 A and 2.0 A respectively, whereas the broadening obtained with the SOA is limited at 5.3 nm at an injection current of 1.0 A. Also comparing the SOA with the IRIS devices containing SAs of 20 $\mu$m and 40 $\mu$m in Fig. 4-8(a) it can be seen that the modulation depth in the power spectrum decreases with increasing SA length, making the spectrum more suitable for applications as mentioned above.

Concluding it can be stated that also at 40 GHz pulse trains the IRIS device can achieve the necessary spectral broadening. At 2.0 A injection current the device with 40 $\mu$m SAs achieves a broadening of 10 nm, while having a smooth spectrum (Fig. 4-8).

Three remarks have to be made on these results. First of all, in our model the gain bandwidth is assumed to be infinite. This approach works well for pulses with small optical bandwidths, i.e. a few nanometers, but in practice the gain bandwidth will limit the spectral broadening of over 20 nm – 30 nm, as observed in the simulations of the IRIS devices with the longer SAs. Secondly nonlinear effects like SHB and CH will also depend on the bandwidth of the pulses. For example one can assume that the effects of SHB will decrease when the optical bandwidth increases while keeping the pulse energy constant. However the simulations indicate that the effects of SHB and CH on the spectral shaping are not significant as compared to the effects of carrier depletion.

As a last point we have to notice that the value of the linewidth enhancement factor $\alpha_N$ is kept constant for different wavelengths. Again this is a valid assumption when the optical bandwidth of the optical pulse does not become too large. For a more extensive revision of the wavelength dependence of $\alpha_N$ we refer to [48].
Fig. 4-8  Optical output spectra for a 2 mm SOA and a series of IRIS devices with different SOA/SA lengths ratios and a 40 GHz, 2.0 ps input pulse train. The input peak power is 0.1 W. (a) Spectra for different injection currents are given. The normalized spectral power is coded in greyscale from black up to white with increasing power. In (b) the calculated FWHM of the output spectra is given as a function of the injection current.
4.4 Conclusion

In this work we have presented a device concept, named IRIS. We have theoretically investigated picosecond pulse transmission through these devices, using a time-distributed model using rate equations. Depending on the design and operating conditions this device can fulfill the role of a picosecond pulse amplifier, an optical isolator for picosecond pulse operation or a spectral shaper, being able to smoothly broaden the spectrum of a picosecond pulse train.

As an amplifier for single pulse transmission, the obtained pulse peak amplification using a 2 mm long IRIS device is up to 17 dB (for an SA length of 100 μm) at 700 mA injection current. An SOA of equivalent length can only achieve a pulse peak amplification of 4 dB at 150 mA, assuming no pulse broadening is allowed. Despite the higher injection currents needed, the generated ASE is about 7 dB lower for the IRIS device.

For 40 GHz, 2.0 ps pulse train amplification, the IRIS devices with the shorter SAs (20 μm and 40 μm) show limited or no temporal pulse broadening at 10 dB amplification, where these pulses broaden up to 3.1 ps in an SOA. Although a slightly higher injection current is needed for the IRIS devices than for the SOA (i.e. 900 mA – 1000 mA and 800 mA respectively), the ASE output is over 6 dB lower. These simulation results indicate that the IRIS device is a better option for picosecond pulse amplification than a conventional SOA.

When the SAs in the IRIS devices can recover in between two consecutive pulses in a pulse train, the device can work as an optical isolator against (lower power) reflections of the pulses on components further downstream the circuit. The simulations show that an isolation of 20 dB to 30 dB can be obtained using 2 mm long IRIS devices with longer SAs at injection currents of 1.0 A to 1.3 A. In integrated circuits, where the main source of feedback into lasers is reflections of about 0.1% to 1%, this ensures an attenuated feedback of below -50 dB. This level of feedback does not influence for example a MLL and as such the IRIS device is a practical solution for an integrated optical isolator for picosecond pulse operation.

With respect to the spectral shaping of picosecond pulses the IRIS device shows superior performance over an SOA. Both for single picosecond pulse and for 40 GHz pulse train transmission, the spectral broadening of a 2 mm long SOA is limited up to 4.1 nm and 5.3 nm respectively, with a large modulation in the power spectrum. The obtained bandwidth with the IRIS devices is significantly larger, and over 10 nm optical bandwidth with a smoother shape of the spectrum at 40 GHz pulse train transmission can be obtained with the IRIS devices with 20 μm and 40 μm SAs. The required injection currents are 1.4 A and 2.0 A respectively. For single pulse transmission the obtained bandwidth with the IRIS devices is strongly increased, going up well over 30 nm for the devices with the longer SAs (60 μm to 100 μm) and with increased smoothness of the shape of the spectrum. For both reasons, i.e. amount of added bandwidth and shape of the obtained spectrum the IRIS device is a better option than an SOA.

Concluding we can say that for picosecond pulse operation the IRIS configuration shows better performance than an SOA of equivalent length, addressing the functions of amplifier and spectral shaper. Moreover it can perform as an optical isolator. As the fabrication process of the IRIS devices can be compatible to both MLLs and further pulse processing components, it is a practical and feasible candidate for integration on an optical
chip and can possibly enable the monolithic integration of picosecond pulse processing systems on a single chip.


21 M.J.R. Heck and E.A.J.M. Bente, patent pending


Ik hield een prisma in de hand
En wierp een schijnsel op den wand,
Dat, schoon het zonlicht, doorgaans wit,
Uit zijnen aard geen kleur bezit,
Zoo velerhande kleuren droeg,
Dat ik mijzelve, peinzend, vroeg,
Hoe toch dit klaar, doorschijnend glas,
Dat zelve volkomen kleurloos was,
Al deze kleuren scheppen kon
En halen uit het licht der zon.

Het licht, dat door dit prisma viel,
Werd mij het beeld van mijne ziel,
Die eveneens een prisma vond,
Waardoor zij hare stralen vond,
Een glas, waarmee ik heb gespeeld,
En dat haar wezen dus verdeeld
En dus gekleurd heeft en getint,
Dat zij maar nauw zichzelf hervindt
In 't spel van dezen regenboog,
Die zoo veelkleurig is voor 't oog.

Edoch, omdat het klare glas
Der kunst volkomen kleurloos was,
Vermoed ik, dat haar eigen aard
Dit kleurenspectrum heeft gebaard,
Dat steeds in 't klaar en nuchter wit
Van mijne ziel verborgen zit.

J.E. van der Waals
Characterization of a monolithic concatenated SOA/SA waveguide device for picosecond pulse amplification and shaping

Abstract—In this paper a monolithic waveguide device, named IRIS, is presented. The device consists of an array of concatenated semiconductor optical amplifiers and saturable absorbers. We have fabricated the devices in InP/InGaAsP bulk gain material and we have experimentally investigated picosecond pulse transmission through these devices.

Operated as an optical amplifier the IRIS devices show a decreased temporal pulse broadening and decreased ASE noise generation as compared to a semiconductor optical amplifier of equivalent length. Used as a nonlinear element to increase the optical bandwidth of a picosecond pulse train, the spectra obtained with IRIS devices show an increased broadening and smoothness as compared to a semiconductor optical amplifier.

We have set up a theoretical model to describe spectral and temporal pulse shaping by the IRIS device. Agreement between the simulations and the experiments is obtained.

5.1 Introduction

Trains of short optical pulses with a wavelength around 1550 nm have many applications. Picosecond optical pulse trains can be used in telecommunications for time domain multiplexing (TDM) systems and as synchronized multiwavelength pulse trains in wavelength division multiplexing (WDM) systems [1]. More advanced telecommunication coding technologies such as optical code-division multiple-access (O-CDMA), also make use of short optical pulses [2]. Other applications are found when the pulse train is used as a coherent optical frequency comb, e.g. in optical frequency metrology [3]. Such an optical frequency comb can also be used for arbitrary waveform generation [4].

Hybrid or monolithic integration of short pulse generation and processing systems on an optical chip offers advantages over bulk and fiber optics systems for applications as mentioned above. An optical chip is more stable and compact and can in principle be mass-produced thus reducing fabrication costs and opening up new application areas of short pulse laser technology. These features are for example essential for reliable and cost effective implementation in future O-CDMA systems [2].

The material of choice for such optical chips operating in the 1.55 \( \mu \)m wavelength region is InP/InGaAsP. In this material system semiconductor mode-locked lasers can be fabricated to generate a train of short optical pulses \([5,6,7,8,9]\). Semiconductor optical amplifiers (SOAs) are commonly used for on-chip pulse amplification, though at the expense of adding noise to the signal in the form of amplified spontaneous emission (ASE). In [10] we proposed the use of a concatenated array of SOAs and saturable absorbers (SAs), named IRIS (Integration of Regeneration, Isolation and Spectral shaping), for further
on-chip pulse train amplification and spectral shaping of these pulses. The interplay between the SOAs and SAs limits the temporal broadening of the pulses in the amplification process. Moreover the fast recovery of the SAs makes them act as gates, closing after the pulse passage and suppressing the generation of ASE. Simulations of such devices using parameters representative for InP/InGaAsP bulk gain material showed the theoretical feasibility to achieve significantly improved performance when compared to a single SOA. Depending on the operation conditions of the device, an increase in pulse peak power amplification and/or an increase of the spectral broadening can be achieved.

In this work we report on the fabrication and characterization of these IRIS devices focusing on the amplification of a train of picosecond optical pulses and the related temporal and spectral shaping of these pulses. As we foresee a main application of the IRIS device in the combination with a semiconductor mode-locked laser, the input pulse parameters are chosen to be representative for the output pulses of these lasers. As a reference we will compare the results obtained with the IRIS devices with those obtained with an SOA of the same length. Note that SOA structures can be optimized specifically for the applications discussed. A full and extensive comparison of optimized SOA structures with the IRIS devices is beyond the scope of this work. We have used the model as presented in [10] with a minor modification to analyze the results. We have fitted a limited number of parameters in the model to reproduce the data obtained from the fabricated devices. In this way we have obtained a design tool for future improvements.

In section 5.2 we present the fabrication technology, structure and basic design considerations of the IRIS devices realized. Three issues need to be addressed in order to be able to describe and interpret the characterization results from the IRIS device with the model described in [10]. The first issue is that an accurate characterization of the optical pulses at the input of the device is required. The second and third issues are the verification of the model and the determination of the parameters for a separate SOA and SA. These three points are at the centre of section 5.3. In section 5.4 the characterization of the IRIS devices is presented and conclusions with respect to the temporal and spectral shaping of the picosecond pulse stream are made. The paper concludes with considerations for optimized performance of IRIS configurations.

5.2 IRIS device fabrication

The IRIS devices consist of a series of equal pairs of one SOA section and one SA section, as schematically depicted in Fig. 5-1(a). Such devices have been realized using InP/InGaAsP bulk gain material, operating at wavelengths in the region of 1.55 μm. The active layer consists of a 120 nm thick bulk InGaAsP layer with a bandgap corresponding to λ = 1.59 μm between two 190 nm thick λ = 1.25 μm InGaAsP layers. This structure is covered by a 1500 nm thick p-InP cladding layer with gradually increasing doping levels and with a 200 nm p-InGaAs contacting layer.

The devices have a total length of 2 mm. Configurations with 5, 10 and 20 SOA/SA pairs and varying length ratio between the SOA and SA have been designed and realized. The sequence of SOAs and SAs is fabricated by etching a shallow ridge waveguide of 2 μm width 100 nm into the InGaAsP layer. To create electrical isolation between the SOAs and SAs, the most highly doped part of the p-cladding layers is etched away. The isolation section between the SOA and SA has a length of 10 μm (used in devices with the shorter
SAs, i.e. up to 10 \( \mu \text{m} \) to 15 \( \mu \text{m} \) (with the longer SAs). The waveguide and isolation sections are etched using an optimized CH\(_4\)/H\(_2\) two-step RIE dry etch process.

The structures are planarized and passivated using polyimide. Two Ti/Pt/Au metal pads alternately contact the waveguide sections to create two common contacts for the SOAs and SAs respectively (Fig. 5-1(b)). The backside of the n-InP substrate is metallized to create a common ground contact. Amplification and absorption are realized by a forward or reverse electrical bias of the diode respectively. To suppress lasing, the waveguide is oriented at the Brewster angle for the fundamental mode with the facets which have also been antireflection (AR) coated. The metal contacts are smaller and thinner towards the input and output to ease cleaving of the devices. The fabrication technology of the IRIS device is fully compatible with the technology to fabricate semiconductor mode-locked lasers as presented in [8,9]. This allows for future further integration of the lasers with the IRIS device.

In this work we focus our analysis on IRIS devices with 20 sections. SOAs of 2 mm length have been processed on the same chip. These devices also have angled AR-coated facets and are used for two purposes. The first is the comparison of the performance of an SOA of comparable length and geometry with the IRIS devices. The second is to test the SOA model and extract model parameters.

Fig. 5-1  (a) Schematic overview of an IRIS configuration with 20 sections used in the simulations and measurements. An input pulse (denoted by \( P(z,t) \)) enters from the left side, starting with an SOA, and exiting from the right-hand side. The ratio of the SOA and SA length within the 100 \( \mu \text{m} \) section (only 7 out of 20 shown) is varied. Common contacts are used for applying the injection current \( I \) and the reverse bias \( V \). (b) Photograph of the realized devices, showing different configurations.
5.3 Characterization of the SOA and SA: extraction of model parameters

To gain insight in pulse temporal and spectral shaping inside the IRIS devices and to obtain a design tool for future device optimization, a model has been set up to describe picosecond pulse propagation through the fabricated IRIS devices. This rate equation model that simulates picosecond pulse propagation through the SOA and SA sections is presented in [10]. In this section we will first describe the characterization setup and investigate the input pulses that are being used. Then we will present the minor modification to the equations as presented in [10] followed by the experimental data and fitting of the parameters used in the model for the SOA and SA sections individually. This model is then used to simulate complete IRIS configurations, as presented in section 5.4. The SOA model presented in this section is the first systematic temporal and spectral study of Gigahertz picosecond pulse propagation that compares a theoretical model with experimentally obtained values.

5.3.1 Setup and input pulse train characterization

Short optical pulses tend to broaden as they propagate through dispersive media, such as optical fibers. In standard single mode fiber (SMF) pulses with a wavelength of around 1.55 \( \mu \text{m} \) broaden in time at a rate of 16 fs to 20 fs per nanometer of optical bandwidth and per meter of fiber (e.g. Corning SMF-28e Photonic Fiber). Of course the temporal broadening depends on its initial chirp profile. To be able to fully characterize the IRIS devices, and the SOAs and SAs individually, the temporal pulse power profile and phase profile of the input pulse train has to be accurately known.

A Pritel mode-locked fiber laser (MLL) is used to generate a 10 GHz picosecond pulse train. The power and polarization of the pulses are controlled. Our devices are not packaged and lensed fibertips are used for incoupling and outcoupling. Needle probes are used for biasing the contacts. The chip is held at 18 °C using a thermo-electric cooler. Pulsed injection current is used to prevent chip heating. In our setup (Fig. 5-2) we make use of an autocorrelator and a 700 GHz optical sampling oscilloscope for temporal pulse power profile characterization. The optical power spectrum is obtained by an optical spectrum analyzer (OSA). The MLL and optical sampling oscilloscope were located in another lab nearby. The optical signals were transported between the two labs through a total of 15 m standard SMF and 80 m of dispersion shifted fiber. This meant that from the MLL to the chip up to a total second order dispersion of 0.34 ps\(^2\) is added onto the pulses. Pulse duration measurements taken with the sampling oscilloscope show a pulse duration of 2.1 ps at the MLL output and 1.8 ps after traveling the 15 m twice (i.e. through the setup, excluding the IRIS device). An autocorrelation measurement at the device input shows a convoluted 2.2 ps pulse duration. Using the algorithm mentioned in [11], the temporal phase profile of the pulse is calculated out of the power spectrum and the temporal pulse profile. The result is presented in Fig. 5-3.

In order to have a have a practical realistic input pulse in the simulations, the parameters in the expressions in (5.1) have been fitted to the measured pulse power and phase values. A Gaussian temporal power profile and a Kerr-like phase profile are used:

\[ \text{....} \]
\[ A(t) = \sqrt{P(t)} \exp(-i\phi(t)) \]
\[ P(t) = P_{\text{max}} \exp\left(-\left(\frac{t}{\Delta t}\right)^2\right) \]
\[ \phi(t) = \phi_{\text{max}} \exp\left(-\left(\frac{t}{\Delta t}\right)^2\right) \]  
(5.1)

With \( \Delta t = 1.25 \) ps and \( \phi_{\text{max}} = 1.0 \), the obtained temporal power and phase profile, as well as the optical spectrum, compare well to the measured values, i.e. the pulse duration is 2.1 ps at the MLL output, 2.2 ps width of the autocorrelation after 15 m SMF (corresponding to a 1.4 ps pulse at the device input) and 1.6 ps pulse duration after 30 m SMF (see Fig. 5-3). The chirp profile of the measured pulse is slightly larger than that of the fitted pulse chirp profile (-0.09 THz/ps vs. -0.05 THz/ps at the pulse center). The relatively large difference originates from the fact that the pulse is close to transform limited, i.e. the chirp is small, and the pulse durations differ by about 0.2 ps. The parameterization matches the experimentally obtained pulse duration at the device input to within \( \pm 0.1 \) ps and the spectral power to within 3% over the FWHM bandwidth.

Fig. 5-2  Schematic overview of the setup used to characterize the SOA and IRIS devices. MLL: 10 GHz mode-locked fiber laser, Att/PM: attenuator/power meter, PC: polarization controller, TEC: thermo-electric cooler, PM: power meter, OSA: optical spectrum analyzer, AC: autocorrelator, Osc: 700 GHz optical sampling oscilloscope. All equipment is fiber pigtailed or has fiber input or output connectors. A pulsed injection current source (\( I_{\text{inj}} \)) and voltage source (\(-V_{\text{bias}}\)) are used to bias the SOAs and SAs respectively.
Fig. 5-3  (a) Measured pulse power profile and extracted chirp profile (using [11]) after traveling back and forth through the setup (30 m SMF). (b) The pulse shape and chirp used as input for the simulations at: the MLL output (black), at the chip facet after 15 m SMF (dark grey) and back to the oscilloscope after 30 m SMF (light grey, to be compared with (a)). (c) Comparison of the spectrum used in the simulations (shifted towards the carrier wavelength) with the measured spectrum.

5.3.2  SOA characterization

Picosecond pulse propagation through an SOA can be described using rate equations. We use the rate equations presented by us [10], which are based on those presented by Tang and Shore [12] and have been extended with equations for the ASE field to describe gain depletion through ASE analogous to e.g. the treatment in [13,14]. Based on the observations presented here we have extended these equations presented in [10] with an extra gain compression and loss term due to free-carrier absorption (FCA) in the active area. This term is often ignored [12] or taken into account into the carrier heating terms [15,16] and linear loss terms. We have rewritten the nonlinear gain $g$ analogous to [12], but without neglecting the FCA in the following way:

$$g = \frac{g_1 - \varepsilon_3 NP - \varepsilon_2 P^2}{1 + \varepsilon_1 P}$$

$$g_1 = a_N \left( N - N_{tr} \right)$$  \hspace{1cm} (5.2)
in which $g_\text{l}$ is the linear gain, $N$ the carrier density in the 120 nm active layer, $N_\text{tr}$ the carrier density needed for transparency, $\alpha_N$ the differential gain and $\epsilon_1$, $\epsilon_2$ and $\epsilon_3$ the nonlinear gain compression factors corresponding to carrier heating (CH), two-photon absorption (TPA) and FCA respectively. The total linear loss term is then:

$$\alpha_\text{tot}(N) = \alpha_\text{int} + \sigma_{\text{FCA}} \cdot N$$ (5.3)

in which $\sigma_{\text{FCA}}$ is the FCA coefficient and $\alpha_\text{int}$ the other passive losses, including FCA in the cladding. For the full set of propagation equations, we refer to [10].

As the application of this set of equations to InP/InGaAsP SOAs has been extensively studied and reported upon in literature, we will try to use the widely used values of the parameters as much as possible in fitting the equations to our experiments. The main aim of the application of the model here is not to perfectly fit our experimental results, but to gain insight in pulse temporal and spectral shaping inside the devices.

The SOAs that were included on the same chip have the same waveguide width and the same total waveguide length of 2.0 mm as the IRIS devices. The SOAs have only one contact to the ridge and no isolation sections. The pulse propagation in these amplifiers has been studied experimentally. We now present these results and compare them to the results obtained from the model presented above. The results will also be used to compare the SOA performance with that of the IRIS devices. The values of the parameters used in the model were optimized to fit the model to the measurement results, but within ranges of experimentally obtained values, as given in the references in Table 5-1. The optimized values are presented in Table 5-1. The experimentally obtained data are compared to the simulated data with respect to the temporal pulse amplification and pulse shaping, the ASE generation and the corresponding signal-to-noise ratio (SNR) and the spectral shaping. Pulsed injection current, with pulses of 300 ns and at a 1% duty cycle, is used to operate the SOA to minimize the detrimental effects of heating the device. This is especially necessary as our devices are not packaged and heat removal is only through a 0.35 mm thick InP wafer. The current source is limited to a maximum of the injection current of 700 mA in our setup. Assuming coupling losses of around 5 dB from the lensed fiber to the SOA, the estimated average power into the SOA was 2 mW. This corresponds to a pulse peak power of 0.1 W at 10 GHz ($P_{\text{max}} = 0.1$ W in (5.1)). All SOA measurements presented here were performed at this input power level.

5.3.2.1 Gain and ASE level

The total optical output power from the SOA consists of the power in the pulse train and ASE power. To obtain the power in the pulse train, the recorded optical spectrum is integrated over the bandwidth of the pulses. Integration over the remaining part of the spectrum yields the ASE power. An SNR can be defined as the ratio between the power of the pulse train and the ASE. The total power in the spectrum is calibrated with a power meter. In Fig. 5-4(a) the measured values of the optical output power levels from the SOA for the pulses, ASE and total as a function of injection current are presented. The device reaches unity gain at 70 mA. The output power then first increases linearly with current up to 200 mA which shows the saturation of the SOA by the input signal. Above 200 mA the output increases more slowly which indicates that gain compression sets in. Simultaneously the ASE output power level goes up due to the increase in gain at other wavelengths.
originating from carriers which are not depleted by the pulse amplification. The same features are reproduced in the simulation results as presented in Fig. 5-4(b). There the gain saturation sets in at about 100 mA and the gain compression and related increase in ASE power level at 300 mA. The SNR values agree well, peaking at 90 and 70 around 150 mA for the experimental and simulated values respectively.

The simulated total output power increases linearly with increasing injection current, starting from 100 mA up to 1 A. The reason is the linear dependency of the number of injected carriers into the active region on the injection current in the model [10]. Combining this with a heavily saturated state of the SOA, i.e. almost all the carriers are converted to photons, gives the linear output power. In the experimental results a deviation from the straight line can be observed. Possible reasons include heating of the device at higher injection currents, a reduction in injection efficiency of the carriers into the relevant active area with increasing current [17], a non-linear dependency of the gain on the carrier density, or an increase in free carrier absorption in the cladding. Higher order carrier density dependent carrier recombination, such as Auger recombination ($N^3$-dependency) and radiative recombination ($N^2$-dependency) can not account for this difference, assuming reasonable values for the parameters, e.g. as mentioned in [13,14]. So including these effects in the effective carrier lifetime $\tau_s$ is a correct approximation.

From the comparison between the signal and ASE power level measurements from the SOA and the model results we can conclude that the model qualitatively and quantitatively agrees with the experimental results considering the picosecond pulse gain and ASE generation for injection currents up to 400 mA. However at the higher injection currents the gain is overestimated by the model, for reasons mentioned above. We have to note that the estimation of the coupling efficiency between a lensed fiber tip and the waveguide has a limited accuracy of up to 1 dB.

5.3.2.2 Spectral shaping

The next issue is to study the spectral shaping of a pulse train propagating through the SOA. This is determined by its non-linear temporal shaping, i.e. due to the effects of gain saturation and TPA, and by the self-phase modulation (SPM) due to carrier depletion,
carrier heating (CH), spectral hole-burning (SHB) and other ultrafast non-linear refraction effects (UNR) like the optical Kerr-effect. The gain and gain compression terms are fixed by fitting them to the output power levels above, so in this section the SPM parameters only are fitted, i.e. $\alpha_N$, $\alpha_T$ and $n_2$.

In Fig. 5-5 the experimentally obtained (Fig. 5-5(a)) and the simulated optical spectra (Fig. 5-5(b)) of the 10 GHz pulse train as a function of injection current are shown. The input pulse spectrum, with an initial full width at half maximum (FWHM) of 1.6 nm, broadens and shifts towards the longer wavelengths with increasing injection current. After a certain value of the injection current, the shifting stops and the shape of the spectrum remains more or less the same. This value is around 300 mA for the experimental spectra and 400 mA for the simulated spectra. These values correspond to the point where the gain compression limits further pulse amplification, as can be seen in Fig. 5-4. The maximum red shift obtained experimentally is approximately 3 nm and in the simulations it is 4 nm. This is because the fit of the SPM parameters is optimized for the spectra obtained for injection currents up to 400 mA. Also a modulation in the spectrum around the input pulse carrier frequency is visible, both in the experimentally obtained and in the simulated spectra. The mainly red-shift of the spectrum indicates that the SPM due to carrier depletion is the dominant effect.

Also the power of the input pulse train has been varied, while operating the SOA at a constant injection current of 350 mA. In Fig. 5-5(a) it can be seen that the spectral broadening for low input-power pulse trains (up till -7 dBm average power) is limited. In this case the pulse train does not saturate the SOA and the effect of SPM due to carrier depletion is limited. Significant modulation in the experimentally obtained spectra occurs at around -3 dBm input power. The shape and position of this spectrum compare well with those of the simulated one at 0 dBm input power. This difference in input power has to be compared to the limited accuracy in determining the input power of the pulses in the SOA of up to 1 dB. Also the measured and simulated spectra compare qualitatively well to those presented in [18].

Concluding the discussion on the SOA optical output spectra, we can say that the model qualitatively reproduces the experimentally obtained spectra for a range of injection currents (50 mA up to 700 mA) and for a range of input pulse powers, ranging from -13 dBm up till 7 dBm. These input power values are representative for the output that can be expected from a semiconductor mode-locked laser [5,6,7,8,9].
Fig. 5-5  Experimental (a) and simulated (b) pulse spectra obtained after propagation of a picosecond pulse train through an SOA for varying total injection currents. The input pulse parameters are as mentioned in Fig. 5-4. Experimental (c) and simulated pulse spectra for varying (average) input powers. The injection current is 350 mA. In (b) and (d) the input pulse central wavelength is chosen to match the experimental plots.

5.3.2.3  Temporal pulse shaping

Using an optical sampling oscilloscope with a resolution of 700 GHz, temporal pulse profiles can be obtained for pulses (in a pulse train) with a duration down to approximately 1 ps. In Fig. 5-6(a) the measured temporal pulse profiles are given for the pulse train after traveling through the SOA. As mentioned, in between the sample and the oscilloscope there is a total length of 15 m of SMF, which contributes to an estimated total dispersion of 0.34 ps$^2$. This needs to be added to the SOA model output in order to make a proper comparison. It can be seen in Fig. 5-6(a) that by increasing the injection current, the pulse is partially compressed, starting from 2.1 ps at 70 mA down to 1.3 ps at 350 mA. Also a significant pedestal is formed, with a width of about 5 ps. The simulations presented in Fig. 5-6(b,c) show that this pulse shaping is due to the dispersion in the 15 m SMF, thus demonstrating that the pedestal is not due to the amplification of initial trailing and leading side pulses, e.g. as observed by [18]. Both the partial pulse compression and pedestal formation as observed in the experiments are reproduced in the simulated pulse shapes.
Moreover the model gives the temporal pulse profile at the SOA facet, thus without applying any dispersion. As can be seen the pulses broaden in time due to the gain saturation, which corresponds with the red-shift as observed before. We could not measure these pulse shapes directly, due to the use of (dispersive) fiber coupling the light to the oscilloscope. So the model proves to be a useful tool to obtain the pulse shape at the facet, which is especially relevant for further on-chip pulse processing.

As an overall conclusion on the SOA results we can say that we have set up a model that describes 10 GHz picosecond pulse propagation through an InP/InGaAsP SOA. Using well known rate equations and widely used values of the parameters therein, the simulated pulse power, shape and spectrum agree with the experimentally obtained ones, both quantitatively and qualitatively. This model can now be used to describe the SOA sections in the IRIS device, both to understand the obtained results and to possibly further optimize the IRIS design. Moreover the model can calculate the actual pulse shape at the output of the chip, which is not possible to measure using our fiber-pigtailed equipment.

![Fig. 5-6](image)

**Fig. 5-6** Temporal pulse profiles obtained with (a) a 700 GHz optical sampling oscilloscope for injection currents of 70 mA up to 350 mA and after propagation through a 2 mm SOA and approximately 15 m of SMF. In (b) and (c) the simulated pulse profiles are given at the SOA output facet (c) and after applying a total dispersion of 0.34 ps² (b). The input pulse parameters are as mentioned in Fig. 5-4. The experimental curves have been shifted to overlap in time; absolute position measurement is not possible.
5.3.3 SA characterization

To describe picosecond pulse propagation through an SA we use the rate equations presented in [10,19,20] and the assumptions mentioned therein. The dependency of the small signal modal absorption on the wavelength is expressed according to [21]:

\[
Q_0 = \Gamma g_0 = \Gamma q_{00} \sqrt{\lambda_g(V) - \lambda} = \lambda_g + V \cdot \Delta \lambda
\]  

(5.4)

where \( \Gamma \) is the confinement factor (assumed identical to the SOA), \( \lambda \) the signal wavelength, \( \lambda_g \) the wavelength corresponding to the bandgap and \( V \) the reverse bias voltage. \( \Delta \lambda, \lambda_{g0} \) and \( q_{00} \) are fitting parameters. This expression includes phenomenologically the effects of the parabolic shape of the density of states, assuming almost empty bands [21], a bandgap shift that depends linearly on the applied bias voltage due to the interplay between the Burstein-Moss or bandfilling effect and the Franz-Keldysh or band renormalization effect [22]. Effects around the bandgap, e.g. an Urbach-tail, are not taken into account in this expression.

As the 2 mm SOAs and IRIS devices offer no direct possibility for isolating measurements on SA characteristics, SAs fabricated on a different wafer, but with the same layerstack [23], are used for experimental characterization. These SAs have been fabricated using a butt-joint active-passive regrowth step, allowing for the characterization of very short SAs (i.e. below the lengths that can be obtained by cleaving the device). Using a 2 ps pulse train at 80 MHz, the linear absorption of SAs with a length of 30 \( \mu \)m, 60 \( \mu \)m and 90 \( \mu \)m has been measured. In Fig. 5-7 the values obtained are given for a range of pulse wavelengths (1530 nm to 1570 nm) and for a range of reverse bias voltages (0 V down to -6 V). As can be seen, the absorption increases for decreasing wavelength and with increasing bias voltage Fig. 5-7(a). Fitting the expression (5.4) to the experimental data shows that this expression is well able to describe the linear absorption. As mentioned above, near the bandgap the description becomes less accurate. With the fitting parameter values we have a quantitative description of the absorption of an SA. For the wavelength range used in our work, the modal absorption ranges from about 50 cm\(^{-1}\) for low voltages near the bandgap, and up to 500 cm\(^{-1}\) for higher voltages (-6 V) at shorter wavelengths. For the modeling of the IRIS devices we will use values of the modal absorption within this range to compare these results to the experimental data. As the studied SA material is from a different wafer, absolute bandgap values and the corresponding wavelength dependency of the absorption may differ by approximately 10 nm from the SAs in the IRIS device.

Another important parameter to describe the effect of an SA is its saturation energy. In Fig. 5-7(b) the total SA transmission is given as a function of the input pulse energy. As can be seen for the lower input pulse energies the transmission is constant and decreasing with increasing reverse bias voltage. This is the regime of linear absorption. Increasing the input pulse energy up to about 0.3 pJ (the limit of our setup), increases the pulse transmission, indicating SA saturation.

Using the rate equations [19] and the parameters as mentioned in Table 5-1 pulse transmission through the SA is simulated as a function of the input pulse energy. To account for the reverse bias voltage the transparency carrier density \( N_t \) is varied, according to [24]. As can be seen in Fig. 5-7, assuming such a relationship, the voltage dependency of
the absorption is described well using a carrier density of $0.05 \cdot 10^{24} \text{m}^{-3}$ matching at 0 V. It can be observed in Fig. 5-7(c) that the transparency carrier density scales approximately linearly with the voltage. The model overestimates the saturation energy by about a factor of 2. These values resemble reported values, which are typically in the range of 0.1 pJ up to 1 pJ [21,25]. A possible explanation for the deviation is the omission of the gain (absorption) compression. Quantification of this effect is however complicated [26] and beyond the scope of this work.

Fig. 5-7 (a) Experimental (dots) and simulated (lines) linear modal absorption for the SA for reverse bias voltages of 0 V (black), -2 V, -4 V down to -6 V (light grey). Values of $q_{00} = 209 \text{nm}^{0.5}$, $\lambda_{\text{g0}} = 1558 \text{nm}$ and $\Delta \lambda = -4.74 \text{nmV}^{-1}$ are used in the simulations.

(b) Experimental (dots) total absorption for a 90 μm SA for reverse bias voltages of 0 V (black) down to -6 V (light grey) as a function of pulse input energy at a wavelength of 1560 nm. Simulations for different values of the transparency carrier density ($N_t = 0$ up to $N_t = 0.3 (\times 10^{24} \text{m}^{-3})$) have been done (lines).

(c) Corresponding matching of the 90 μm SA transmission dependency on $N_t$ and $V$ for the small-signal absorption. All these experiments and simulations have been done using 2 ps pulses with a repetition rate of 80 MHz (experiment) or single pulse transmission (simulation), and variable pulse energy. In the simulations a sweep-out time of 10 ps is assumed.

The last parameter that is dependent on the reverse bias voltage is the SA carrier lifetime or sweep-out time $\tau_{SA}$. Typical values range from 40 ps down to 5 ps, decreasing with increasing voltage [27]. As the time between the pulses in abovementioned experiments is long as compared to these values, this parameter has no effect on picosecond
pulse transmission. However this SA carrier lifetime and the recovery of the absorption do influence the ASE build-up in the IRIS device. In the simulations a value of 10 ps is used.

As a summary of this section we have, with the characterization of the SA structures that are similar to those used in the IRIS devices, obtained a description that can quantitatively reproduce the experimentally obtained results. In combination with the model to describe pulse propagation through an SOA we now have a complete set of simulation tools to simulate picosecond pulse propagation through an IRIS device.

Table 5-1 Simulation parameters and their values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASE generation</td>
<td>$\beta$</td>
<td>$10^{18}$ m/s</td>
<td>fit, [13,28,14]</td>
</tr>
<tr>
<td>Width of active region</td>
<td>$w$</td>
<td>2.0 $\mu$m</td>
<td>[9]</td>
</tr>
<tr>
<td>Depth of active region</td>
<td>$d$</td>
<td>0.12 $\mu$m</td>
<td>[9]</td>
</tr>
<tr>
<td>Linear confinement factor</td>
<td>$\Gamma$</td>
<td>0.285</td>
<td>[9]</td>
</tr>
<tr>
<td>Confinement factor for TPA</td>
<td>$\Gamma_2$</td>
<td>0.5</td>
<td>[12]</td>
</tr>
<tr>
<td>Confinement factor for UNR</td>
<td>$\Gamma_2'$</td>
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<td>[12]</td>
</tr>
<tr>
<td>Differential gain</td>
<td>$\delta N$</td>
<td>$3.5 \cdot 10^{20}$ m$^2$</td>
<td>fit, [29]</td>
</tr>
<tr>
<td>Differential gain ASE</td>
<td>$\delta N_{ASE}$</td>
<td>$2.5 \cdot 10^{20}$ m$^2$</td>
<td>fit, [14]</td>
</tr>
<tr>
<td>Carrier lifetime</td>
<td>$\tau_c$</td>
<td>0.5 ns</td>
<td>fit, [12]</td>
</tr>
<tr>
<td>Carrier density linewidth</td>
<td>$\alpha_N$</td>
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<td>fit, [12]</td>
</tr>
<tr>
<td>Enhancement factor</td>
<td>$\alpha_T$</td>
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<td>fit</td>
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<tr>
<td>Temperature linewidth enhancement factor</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient for TPA</td>
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<td>[12]</td>
</tr>
<tr>
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<td>[12]</td>
</tr>
<tr>
<td>Nonlinear gain compression factor</td>
<td>$\epsilon_1$</td>
<td>0.2 W$^{-1}$</td>
<td>[12] *)</td>
</tr>
<tr>
<td>Nonlinear gain compression</td>
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<td>200 W$^{-2}$m$^{-1}$</td>
<td>[12]</td>
</tr>
<tr>
<td>Corresponding to TPA</td>
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<td></td>
</tr>
<tr>
<td>Nonlinear gain compression</td>
<td>$\epsilon_3$</td>
<td>$5 \cdot 10^{9}$ W$^{-1}$ $\mu$m$^{-3}$</td>
<td>fit, *)</td>
</tr>
<tr>
<td>Corresponding to FCA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCA coefficient</td>
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<td>fit, [30]</td>
</tr>
<tr>
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<td>fit, [12,29]</td>
</tr>
<tr>
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<td>fit, [12,29]</td>
</tr>
<tr>
<td>SA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linewidth enhancement factor</td>
<td>$\alpha_{SA}$</td>
<td>1</td>
<td>[31]</td>
</tr>
<tr>
<td>Differential absorption</td>
<td>$\delta_{N,SA}$</td>
<td>$40 \cdot 10^{20}$ m$^2$</td>
<td>fit, [20]</td>
</tr>
<tr>
<td>Effective carrier lifetime</td>
<td>$\tau_{SA}$</td>
<td>10 ps</td>
<td>[27]</td>
</tr>
<tr>
<td>Transparency carrier density</td>
<td>$N_{T,SA}$</td>
<td>$(0-0.6) \cdot 10^{24}$ m$^{-3}$</td>
<td>fit</td>
</tr>
</tbody>
</table>

*) As the effect of $\epsilon_1$ and $\epsilon_3$ is closely related, the value of $\epsilon_1$ is fixed at the value in [12] and the value of $\epsilon_3$ is fitted to the experimental data.

5.4 IRIS characterization

In this section we describe the experimental results obtained using 2 mm IRIS devices with configurations as shown in Fig. 5-1. In the following picosecond pulse propagation through these devices is measured with respect to the spectral and temporal shaping of the pulses using the setup as pictured in Fig. 5-2. The model and parameters for the SOA and SA from section 5.3 are then used to investigate the experimentally obtained results. Also the results obtained with the 2 mm SOA as mentioned above are used as a reference, for the IRIS applications as an amplifier and spectral shaper. After some general aspects
concerning the devices and measurements, the spectral shaping properties are discussed, then the amplification of picosecond pulses and ASE issues are dealt with, after which the shaping of the temporal profile of the amplified pulses is discussed.

For the experimental characterization we mainly focus on the IRIS devices with 20 sections for which we have obtained the most complete dataset including both time and frequency domain measurements. The SOA lengths within this set of devices are 60 μm down to 40 μm and the corresponding SA lengths are 10 μm up to 20 μm. The isolation sections between SOA and SA are 10 μm up to 15 μm respectively. In the following the IRIS configurations will be denoted by their respective SOA and SA lengths, e.g. a 60 μm/10 μm configuration.

Simulations of the configurations are done using the designed SOA length, but for the SA length they include the isolation sections. This creates an effective SA in the simulations to simulate an isolation-SA-isolation section in the realized IRIS devices. In practice an isolation section is not biased, so it will act as an absorber. The field applied to the neighboring SA can penetrate into the isolation sections, effectively increasing the absorption in the isolation sections. As this effect is hard to quantify, we use this approach of a single effective SA in the simulations. The SOA sections have a common contact and uniform injection current is expected. Operating conditions of the IRIS SOA sections are identified by the total injection current, which is assumed to be uniformly divided over the 20 SOA sections. Please note that injection current density is different for different IRIS configurations at the same total injection current. The reverse bias voltage over the SA is simulated by scaling the transparency carrier density \( N_{tr} \) up to about 0.6·10^{24} m^{-3}, where a voltage of -1 V corresponds approximately with a density of 0.05·10^{24} m^{-3} to 0.1·10^{24} m^{-3} (based on the SA characterization above (Fig. 5-7(c)) and the results obtained presented below).

5.4.1 IRIS spectral shaping

In Fig. 5-8(a) the measured spectra of the picosecond pulse train (Fig. 5-3) after transmission through IRIS devices as a function of injection current for a set of four SOA-SA length ratios (including SOA only) are shown. Much like the spectra obtained with an SOA of equivalent length, the spectra broaden with increasing injection current towards the longer wavelengths. This occurs up to a value of 400 mA, for the 10 μm SAs, or 550 mA for the 20 μm SAs. With a further increase of the injection current the broadening of the spectra remains unchanged.

Analogously to the SOA this can be explained by the saturation of the gain, up to 400 mA (550 mA) and consequent gain compression, above 400 mA (550 mA). As the SAs lower the optical power of the transmitted pulse train, the gain compression takes place at a higher value of the injection current.

In Fig. 5-8(b) the simulated pulse spectra of a 60 μm/40 μm IRIS model configuration are shown for different values of the SA transparency carrier density. Note that the effective SA length is used in the model configurations as compared to the experimental devices, which are denoted with the SA length excluding isolation sections. From a comparison of these simulated spectra with the experimentally obtained spectra in Fig. 5-8(a) for the 60 μm/10 μm and 50 μm/10 μm devices, good agreement is seen for values of the transparency carrier density of 0 to 0.1·10^{24} m^{-3}. As the SA bias voltage in the experiments was -1 V this is in agreement with the results as given in Fig. 5-7(c).
The simulations in Fig. 5-8(b) indicate that a broader and smoother spectrum can be obtained by increasing the SA bias voltage (i.e. the corresponding value of $N_{tr}$). More specific an increase in the red-shift can be observed of up to 8 nm for $N_{tr} = 0.3 \cdot 10^{24} \text{m}^{-3}$. A larger shift is expected for higher values of the transparency carrier density. These results would however occur at values of the injection current of over 1 A, which is beyond the scope of our analysis. Also, at lower values of the injection current and increasing with $N_{tr}$, an increase in blue-shift can be observed and a smooth shape of the spectrum. Such spectra thus are generated at the operating points where the SAs saturate and compress the pulses while the SOA saturation is limited. As a result the temporal broadening and the red-shift is also minimized. For a more extensive review of this subject we refer to the section below on temporal pulse shaping.

Experimentally the largest spectral broadening has been observed with the 50 $\mu$m/10 $\mu$m devices. In Fig. 5-8(c) we have plotted the measured spectra for a 50 $\mu$m/10 $\mu$m device at a constant injection current of 700 mA. The SA bias voltages are decreased from -1 V down to -10 V. As can be seen the spectrum measured at FWHM broadens to over 5 nm at voltages below -3 V. Moreover the whole range of this bandwidth has a modulation depth of less than 3 dB, making the full bandwidth usable for applications such as pulse compression. Comparing these spectra to the simulated spectra in Fig. 5-8(d) shows that the model correctly describes the spectral broadening quantitatively. A broadening of 5 nm is observed and a broadening between 4.0 nm and 5.5 nm is simulated. For the smoothening of the spectral shape there is qualitative agreement between measurements and model results. The shift of the simulated spectra towards the longer wavelengths (for the lower values of $N_{tr}$) can be explained by the overestimation of the spectral shift in the model as discussed in section 5.3 for the SOA model. There is no significant influence of the SA recovery time in the model on the simulated spectra in the range of 5 ps up to 50 ps [27]. This can be explained by the fact that the pulse period of 100 ps is far above this range and the SA can fully recover between two pulses. On the other hand the SA recovery time of over 5 ps is well beyond the pulse duration of 1 ps to 2 ps, meaning that only limited SA recovery takes place during the pulse propagation.

So concluding it can be said that the IRIS configuration shows improved spectral shaping of picosecond pulses as compared to an SOA of equivalent length. Spectral widths of over 5 nm can be obtained with a smooth shape. The useful bandwidth from the SOA stays limited to about 2 nm. This makes the spectrum suitable for use in the target applications mentioned [2,32,33]. Moreover the spectra obtained with our obtained model show a quantitative agreement with the experimentally obtained spectra, making it a useful design tool. A further increase in bandwidth can be obtained at the higher injection currents, i.e. around and beyond 1 A, as can be seen in Fig. 5-8(b). Another working point indicated by the simulations is where the output spectra are most blue-shifted. However the total gain in these points is much below 0 dB from which we conclude that these operating points are unpractical.
Fig. 5-8  (a) Experimentally obtained pulse spectra after transmission through an SOA and IRIS devices with 60 μm/10 μm, 50 μm/10 μm and 40 μm/20 μm configurations respectively. The injection current through the SOAs is varied and $V_{SA} = -1$ V. The spectra are normalized and the linear intensity scale is grey scale coded from black (0) to white (1). No spectra were recorded for the lower injection currents, hence the offset. (b) Simulated pulse spectra after transmission through a 60 μm/40 μm IRIS configuration for varying injection currents. Plots for different values of the transparency carrier density $N_{tr} (\times 10^{24} \text{ m}^{-3})$ are given. (c) Experimentally obtained pulse spectra after transmission through a 50 μm/10 μm IRIS configuration for an injection current of 700 mA. The SA bias voltage is swept from -1 V down to -10 V. (d) Comparison of simulated spectra for a 60 μm/40 μm configuration at an injection current of 700 mA and with varying values of $N_{tr} (\times 10^{24} \text{ m}^{-3})$.

In both the experiments and the simulations the input pulse parameters are as mentioned in Fig. 5-4. The input pulse central wavelength is set to 1560 nm in the plots of the simulations to match the experimental plots.
SOAs typically add a significant amount of noise to the signal being amplified because of the ASE generated. This is especially the case when no or low-power signal is present or when the signal has a low repetition rate and as a consequence the gain is not depleted by the signal but by the ASE. High gain may be required for on-chip signal amplification. As mentioned in [34, 35] a concatenated array of SOAs and SAs can have an S-shaped transmission curve, where lower and higher input power signals experience a lower gain than medium power signals. This feature can be used for 2R regeneration [34, 35]. In this paper we restrict ourselves to an experimental investigation of the gain and ASE generation and its suppression in the SAs in the IRIS devices when used for amplifying a 10 GHz picosecond pulse train. We will compare the results with those from an SOA.

In Fig. 5-9 the S-shaped transmission is visualized by plotting the picosecond pulse train gain for two IRIS configurations with 10 SOA/SA pairs as a function of input power. Fig. 5-9(a) presents the measurement results from a 150 µm/10 µm device with $V_{SA} = -1$ V and Fig. 5-9(b) presents results from a 110 µm/30 µm device with $V_{SA} = -3$ V. The gain presented is defined as the total recorded output power minus the ASE floor, divided by the picosecond pulse input power. As can be seen the gain for the IRIS devices peaks at a specific input power $P_{g_{max}}$. $P_{g_{max}}$ decreases with increasing injection currents for a specific device. The contrast in gain at low(er) input power levels and at $P_{g_{max}}$ shows the possibility of ASE suppression while still amplifying the picosecond pulse train. Comparing the IRIS device with the shorter SAs (and $V_{SA} = -1$ V) in Fig. 5-9(a) with the one with the longer SAs (and $V_{SA} = -3$ V) in Fig. 5-9(b), it can be seen that the gain contrast is largest (13 dB) for the 110 µm/30 µm device. The gain contrast for the 150 µm/10 µm device is 7 dB only. However the total device gain for the 110 µm/30 µm device is about 5 dB lower than that of the 150 µm/10 µm device. Thus depending on the application a trade-off has to be made between the signal gain and the contrast between the peak gain and the lower power gain.

To optimize the balance between ASE suppression and total gain, the observed device gain and ASE generation is presented in more detail in Fig. 5-10. The recorded optical spectra of the device output can be used to separate the power in the pulse train from the
generated ASE. As can be seen in Fig. 5-10(a) for high injection currents (in this case $I = 700 \text{ mA}$) the ASE generation is suppressed by 10 dB with respect to the SOA output near the picosecond pulse wavelength. The power in the pulse train is however only 3 dB to 5 dB lower compared to the SOA. The same effect can be observed when the reverse bias over the SA is increased (Fig. 5-10(b)).

![Output pulse spectra obtained at an injection current of 700 mA, for IRIS configurations of 60 μm/10 μm, 50 μm/10 μm and 40 μm/20 μm and with $V_{SA} = -1 \text{ V}$. The SOA spectrum is given for reference.](image)

![Output pulse spectra at 700 mA for different reverse bias voltages for a 50 μm/10 μm configuration.](image)

![Output pulse power (solid) and SNR (dotted) for different configurations as a function of injection current and (d) the SNR plotted versus the output pulse power.](image)

Fig. 5-10  (a) Output pulse spectra obtained at an injection current of 700 mA, for IRIS configurations of 60 μm/10 μm, 50 μm/10 μm and 40 μm/20 μm and with $V_{SA} = -1 \text{ V}$. The SOA spectrum is given for reference.

(b) Output pulse spectra at 700 mA for different reverse bias voltages for a 50 μm/10 μm configuration.

(c) Output pulse power (solid) and SNR (dotted) for different configurations as a function of injection current and (d) the SNR plotted versus the output pulse power.

By integrating the power in the spectrum over the pulse train bandwidth and the ASE bandwidth separately, the ratio of power in both fields can be determined. In this paper we define this ratio by the signal-to-noise ratio (SNR). In Fig. 5-10(c) the calculated pulse gain and the corresponding SNR are plotted. As expected the gain for the reference SOA shows a sharp increase at lower injection current values as compared to the IRIS configurations (i.e. 70 mA as compared 120 mA up to 200 mA for increasing SA length). The reason is the increased power (i.e. increased gain) that is necessary to saturate the SAs. The gain that can be obtained using an SOA is however only 3 dB more than that can be obtained with an IRIS device. The SNR curves, the IRIS devices show a superior performance over the SOA for the higher injection currents. To make a good comparison between the IRIS device and
an SOA with respect to picosecond pulse amplification and the SNR, the gain of the devices is plotted against the SNR in Fig. 5-10(d). As can be seen the SOA can achieve higher gain values, but at very low SNR values. For the lower values for the gain, the IRIS devices show an increased performance with SNR values of up to 4 dB better than an SOA.

In Fig. 5-11 the ASE output is shown when no input pulse train is present. As can be seen in the SOA the amplification of the generated spontaneous emission causes the output power to rise quickly, to over 1 mW at 150 mA injection current. The amplification of the SOAs in the IRIS devices is counterbalanced by the attenuation of the SAs, leading to a heavily decreased ASE power, i.e. about three orders of magnitude lower at the IRIS output facets. The difference between the ASE at the IRIS output and the (counter propagating) ASE emitting from the input side is explained by the fact that the IRIS configuration studied starts with an SOA at the input and ends with an SA at the output. We note that the ASE power at the output side can be decreased further when the small SOA sections at the output in the devices discussed here are omitted. This is more easily realized in an active-passive integration scheme, where no cleaving through the IRIS device is necessary.

The ASE suppression is only working up to the level where the total ASE power starts to saturate the SAs. This effect of SA saturation can be observed when looking closer to the ASE output from a 60 μm/10 μm configuration. Starting from around 300 mA an increase in ASE power is observed at the output facet.

Concluding it can be said that the IRIS devices perform better than an SOA of the same length with respect to picosecond pulse amplification. The SNR can be improved by about 4 dB and the ASE generation when no signal is present by over 30 dB. However maximum gain levels that can be achieved are higher for an SOA by up to 4 dB. Note that in this section we consider the pulse energy gain. The effects of pulse shaping and the corresponding effect on the pulse peak gain are discussed in the next section.

![Fig. 5-11 L(I-curves for the 2 mm SOA and IRIS configurations with 60 μm/10 μm, 50 μm/10 μm and 40 μm/20 μm configurations at $V_{SA} = -1$ V. The solid curves represent the fiber coupled ASE at the output facet and the dotted curves the counter-propagating ASE at the input facet.](image)
5.4.3 IRIS time domain pulse shaping

In the application for amplification of picosecond pulses we now want to compare the performance of the IRIS devices to an SOA with respect to pulse shaping in the time domain. We specifically paid attention to the peak power amplification that could be obtained. The temporal pulse shaping in the IRIS devices has been studied analogously to the method applied to the SOA presented in Fig. 5-6 using the 700 GHz optical sampling oscilloscope (Fig. 5-2). As the spectra obtained with the IRIS devices can be smoother than those obtained with the SOA, this can indicate an increased linearity of the chirp. This would make the output pulses more suitable for further compression using only second order dispersion, e.g. as present in SMF. In our setup the temporal output pulse shapes were measured after propagation through 15 m of SMF, with a total dispersion of 0.34 ps². This corresponds to a pulse broadening (or compression) value of approximately 0.3 ps per nanometer optical band-width, assuming linear chirp profiles. Given the optical bandwidths as mentioned in Fig. 5-8, this value of the dispersion will clearly lead to either pulse compression or broadening in our setup, depending on the sign of the chirp of the pulses.

In Fig. 5-12(a) the experimentally obtained temporal profiles of pulses amplified by 20 SOA/SA pairs, 50 µm/10 µm and 40 µm/20 µm IRIS devices are shown. As can be seen the pulses are compressed down to 1.1 ps, which is at the limit of the 700 GHz oscilloscope bandwidth. Comparing these shapes to the pulse shapes obtained with an SOA (Fig. 5-6(a)), a clear reduction of the pulse pedestal can be observed, especially for the 40 µm/20 µm configuration. Decreasing the SA voltage down to -3 V reduces the pedestal even slightly more. The model is then used to simulate the pulse shape directly at the IRIS output and after 15 m of SMF. The results are shown in Fig. 5-12(b). By comparing the simulated pulse shapes after 15 m of SMF with the experimentally obtained ones, we can state that there is qualitative agreement. A value of \( N_{tr} = 0.1 \cdot 10^{24} \text{ m}^{-3} \), which relates to an SA voltage of between -1 V and -2 V, clearly reduces the pulse pedestal, just as observed in the experimental results. The simulated pulse shapes at the IRIS facet show that this decrease is a result of the limited temporal broadening due to the SA absorption. Moreover the simulation results show the possibility of obtaining pedestal free sub-picosecond pulses. Directly at the IRIS facet a pulse duration of 0.6 ps is simulated for a 60 µm/40 µm device at \( N_{tr} = 0.5 \cdot 10^{24} \text{ m}^{-3} \) (a high reverse bias voltage). This is the relevant pulse duration when the IRIS device is integrated with further pulse processing components on the same chip. After 15 m of SMF a minimum value of 0.8 ps is simulated at \( N_{tr} = 0.3 \cdot 10^{24} \text{ m}^{-3} \). It has to be noted that the model used in the simulations has a limited validity to temporal pulse shapes down to around 1 ps. We note that the simulated pulse shapes obtained at \( N_{tr} = 0.6 \cdot 10^{24} \text{ m}^{-3} \) are low-power due to the increased absorption in the SAs and the SAs are driven into saturation less deeply. As a result the SOAs and SAs operate in a more linear regime and temporal pulse compression is decreased.

So concluding it can be said that in picosecond pulse amplification, the IRIS device shows an increased linearity of the chirp at the output facet compared to an SOA. Consequently in combination with a second order dispersive element, the IRIS device shows better performance for compressing picosecond pulses. As such it is a promising candidate for further integration with mode-locked semiconductor lasers, which typically generate picosecond pulses and are often fiber coupled. The simulations show that increased compression is possible down to 0.6 ps, but this is beyond the resolution of our measurement equipment. It has to be noted that due to the relatively low peak power and the pulsed injection current it was not possible to obtain autocorrelator traces for reference.
Fig. 5-12  (a) Normalized temporal pulse profiles after propagation through 15 m of SMF, obtained with a 700 GHz optical sampling oscilloscope. Pulse profiles obtained with IRIS configurations of 40 µm/20 µm and 50 µm/10 µm are shown. These experimental curves have been shifted to overlap in time; absolute position measurement is not possible. (b) Simulated pulse shapes for a 60 µm/40 µm configuration at the output and (c) after propagation through 15 m of SMF at an injection current of 500 mA. Traces are given for a range of SA transparency carrier densities $N_{tr} \times 10^{24} m^{-3}$.

5.5 Conclusion

In this work we have presented a new device, named IRIS, which consists of a concatenated array of SOAs and SAs. We have experimentally and theoretically investigated picosecond pulse transmission through these devices. To this end we have first set up models to describe pulse propagation through a single SOA or SA section. These were validated experimentally to be able to describe picosecond pulse shaping, both temporally and spectrally, and ASE generation quantitatively. These models were then combined to simulate complete IRIS configurations. Depending on the design and operating conditions, the IRIS device can fulfill the role of a picosecond pulse amplifier, a temporal pulse shaper or a spectral shaper. Different device configurations have been realized.

As a spectral shaper the IRIS device shows improved spectral shaping of picosecond pulses as compared to an SOA of equivalent length. Spectral widths of over 5 nm can be
obtained with a smooth shape. This makes the spectrum suitable for use in target applications where integrated AWGs are used [2,32,33]. The 5 nm bandwidth makes it possible to use over ten channels in high resolution InP AWGs.

With respect to the amplification of a picosecond pulse train it can be concluded that the achievable pulse energy gain is about 3 dB lower for the IRIS devices than for an SOA of equivalent length. The SNR for an IRIS device is up to 4 dB better. Moreover the experiments and the simulations demonstrate a decreased pulse broadening for the IRIS devices and even the possibility for pulse compression, from 1.4 ps down to 1.1 ps experimentally and 0.6 ps in the simulations. An increased linearity of the pulse chirp for the IRIS devices also suppresses the formation of a pulse pedestal. The absence of a pedestal makes the IRIS device more suitable for application in future high bit-rate OTDM networks. As a last important feature it has to be mentioned that the ASE generation when no input light is present is heavily suppressed in the IRIS devices as compared to SOAs, with suppression of up to 30 dB. As a drawback one has to mention that the IRIS devices generally operate at higher injection currents than SOAs of comparable size because of the inclusion of the SA sections.

The quantitative agreement of the model with the SOA and SA experiments and the qualitative agreement for full IRIS simulation give us a tool to identify design and operating issues and to optimize the IRIS design.

Concluding we can say that for picosecond pulse amplification and spectral shaping the IRIS configuration shows better performance than an SOA of equivalent length. As the fabrication process of the realized IRIS devices is compatible to the process to fabricate semiconductor mode-locked lasers, it is a promising option to integrate the two devices in order to either boost the pulse power or to increase the spectral bandwidth. Using active-passive integration further pulse processing components, e.g. AWG based, can be monolithically integrated.

References


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Als je de tijd na de donder vermenigvuldigt met de snelheid heb je de afstand. Dus als je de afstand deelt door de snelheid weet je precies hoe snel je geteld hebt.

H. Finkers
6 Design, fabrication and characterization of an InP-based tunable integrated optical pulse shaper

Abstract – In this paper a tunable integrated semiconductor optical pulse shaper is presented. The device consists of a pair of arrayed waveguide gratings with an array of electro-optical phase modulators in between. It has been fabricated in InP/InGaAsP material for operation at wavelengths around 1.55 μm. Multimode inputs to the waveguide gratings are used to flatten their optical passband. We have used a new short pulse characterization technique to fully characterize pulse shaping by the device, i.e. both the power and the phase profile. A fourfold decrease in pulse ringing was observed for the devices with flattened passbands. Moreover these devices showed a 25% increase in pulse peak power. The possibilities for using the device as a dispersion (pre-) compensator have been investigated. Pulse reconstruction could be obtained for dispersion values of up to 0.2 ps/nm. The fabrication technology of the pulse shaper is compatible with the fabrication of integrated mode-locked lasers, which makes further integration of complete arbitrary pulse generators possible.

6.1 Introduction

Spectral phase control of short optical pulses with wavelengths around 1550 nm has many applications. In telecommunications it can be used for dispersion (pre-) compensation in ultrafast time domain multiplexing systems [1] and arbitrary waveform generation [2,3], e.g. to create rectangular pulses to define switching windows. More advanced telecommunication coding technologies such as optical code-division multiple-access (O-CDMA), also make use of spectral phase control [4,5]. Other important applications can be found in bio-imaging, using second harmonic pulses for multiple photon excitation [6,7].

Control of the spectral phase of short optical pulses is commonly achieved using liquid crystal spatial light modulators (SLMs) or acousto-optic modulators [8]. However these are bulk optical components and have to be aligned carefully. A relatively compact, robust and flexible setup utilising these components is presented in [9]. Hacker et al. have presented a micromirror SLM for pulse shaping [10].

For reasons of stability, compactness, cost and potential scalability, integration of pulse shapers on an optical chip is attractive. Silica based planar lightwave circuits have been extensively studied for phase control. These circuits typically make use of arrayed-waveguide gratings (AWGs) to access the frequency domain of the signal, where a phase or amplitude filter can be applied. Configurations with external phase filters have been reported in [1,5]. Integration of phase and amplitude modulators on the same chip makes it possible to increase the stability and tunability. Configurations with double-pass AWGs [11] and AWG pairs [3,12] have been reported, with AWG channel spacings down to 10 GHz [11].
Further integration can be achieved when the optical source and the pulse shaper are combined on the same optical chip [4,13]. Sources for generating light at wavelengths around 1.55 μm are commonly realized in the InP/InGaAsP material system. Mode-locked lasers to generate picosecond optical pulse trains have been extensively studied [14,15]. Methods to increase the optical bandwidth of these pulse trains for purposes as mentioned above have been studied by us [16]. Realization of an InP based pulse shaper makes it possible to integrate the source and the shaper monolithically on the same chip, using an active-passive integration scheme [4,17]. The fabrication process of passive components in InP however is less mature than their silica based counterparts and current state of the art InP based AWGs have a channel spacing down to 50 GHz [18]. Integrated electro-optical phase modulators however can achieve switching speeds of less than 10 ns [19], opening up new possible applications for ultrafast pulse shaping, such as in-vivo imaging.

In this work we present a 4 THz bandwidth InP-based integrated pulse shaper, consisting of an AWG pair and electro-optical phase modulators. In section 6.2 the design and fabrication are discussed. Special attention is paid to the suppression of ringing of the signal due to the non-flat AWG channel transmission [13]. In section 6.3 we introduce a relatively new interferometric measurement method and apply it for the first time to an integrated optical circuit to characterize the optical signal both in power and in phase. The full characterization of the pulse shaper is presented in section 6.4. The optical transmission and the electrical and electro-optical characterization of the phase modulators are described. The pulse shaping capabilities of the pulse shaper are shown and its application as a dispersion compensator is studied. In section 6.5 we conclude and discuss the feasibility of integrating a complete pulse generator and shaper on a single optical chip.

### 6.2 Design and fabrication

In bulk optics, grating or prism pairs can be used to spatially disperse the optical frequency spectrum of an optically coherent (broadband) source, e.g. a train of short optical pulses. Pulse shaping can then be achieved by parallel phase and/or amplitude modulation of the spectral components in the frequency domain [8]. In an integrated equivalent of these bulk pulse shaping configurations, an AWG can be used to spectrally decompose the signal. An array of phase modulators (PHMs) and/or amplitude modulators (e.g. electro-absorption modulators or optical amplifiers) can be integrated to modulate these spectral components. A second AWG is then used to recombine the spectral components. A schematic overview using only PHMs is given in Fig. 6-1, where the pulse shaper is used to compress a chirped optical pulse.
In this work we have designed a pulse shaper with two separate AWGs, i.e. a configuration analogous to [4,3,12]. Unlike reflective style AWG pulse shapers [1,5,11], where the AWG input is also the output, there is no need for optical circulators. This is essential, as there are no integrated equivalents of optical isolators or circulators presently, which would prohibit further integration with a source. A drawback of using two AWGs is that their transmission spectra have to be aligned, which can be a problem due to non-uniformities over the wafer surface, either due to growth or etching. These issues can be overcome by either placing the AWGs close together, i.e. minimizing the non-uniformities, or placing them far apart, so that the transmission spectra of the AWGs can be tuned individually by separate temperature controls. We have opted for possible individual temperature tuning. Moreover by using multiple outputs for the pulse shaper, a large misalignment of both AWGs can be compensated in discrete steps by shifting to adjacent output waveguides, as mentioned in [4].

The AWG pair is designed to have 20 channels with a 200 GHz spacing and a center frequency around 1550 nm. The free spectral range is 4 THz, i.e. equal to 20 × 200 GHz. The total bandwidth of 4 THz is chosen for possible pulse compression down to about 300 fs, as mentioned in [20]. A channel spacing of 200 GHz limits the size of the AWGs to about 1.5 mm × 1.5 mm and the number of channels to 20. To minimize ringing, i.e. the appearance of satellite pulses at 5 ps time spacing (i.e. the inverse of 200 GHz), due to the non-flat AWG channel transmission, we have added waveguides with MMI couplers for flat-top transmission [21]. In Fig. 6-2 the design and realization of our 20 × 200 GHz pulse shaper are shown. The AWGs are designed as described in [22].

The array of phase modulators is designed for optimal phase shifting for the transverse electric (TE) mode since integrated InP-based laser sources tend to generate TE-polarized light [23]. The highest phase shifting efficiency for the TE polarization is achieved when the direction of the phase modulator waveguide is parallel to the [0-11] crystal direction. In this direction the Pockels effect and the carrier effects both provide a positive refractive index change. For our structure the Pockels effect increases the phase shifting efficiency by about 50% as compared to using carrier effects only [24]. The PHMs have a length of 5 mm and are designed to work under reverse bias. A simulation tool based on the work in [24] predicts a TE phase shifting efficiency of 2π radians at -5 V at this length. We note that the length can be decreased by allowing for higher voltages and a significantly more than
linear increase in current. The PHMs can be individually biased by applying voltages to the contact pads.

Fig. 6-2  (a) Schematic overview of the AWG-based pulse shaper configuration with both Gaussian and flat-top transmission in/outputs. (b) Picture of the realized device. The close-up of the mask designs show the MMI in/outputs (1) and the metal contacts to the 20 PHMs (2). (c) Schematic cross-sections of the high-contrast (Deep), low-contrast (Shallow) and phase modulating (PHM) waveguides.

The epitaxial layer thicknesses and doping levels were chosen to be compatible with possible future active-passive integration [17] using a low-pressure metal organic vapor
phase epitaxy (MOVPE) process. The pulse shaper is then fabricated by first defining the waveguides and AWGs by optical lithography. The structure is etched using an optimized two-step CH\textsubscript{4}/H\textsubscript{2} reactive ion etching (RIE) process as mentioned in [22], to create both high-contrast and low-contrast waveguides (Fig. 6-2(c)). Electrical isolation sections at the ends of the PHMs are created by etching away the highly-doped p-cladding wet chemically. Polyimide is used for planarization of the surface and for passivation of the PHMs. A layer of titanium-gold (Ti/Au) is then evaporated and a pattern is etched wet chemically to create the electrical contacts to the PHMs. We note that the operation of the pulse shaper is tolerant for small changes in the optical path lengths of the channels. Differences in physical length between the channels of up to 40\,\mu m still allow for pulse reconstruction with a pulse peak power of over 95% of the pulse peak power that is obtained using identical channel lengths [20].

6.3 Measurement setup

Passive optical circuits inherently introduce loss as they lack the possibility for on-chip optical amplification. Also the optical input power that can be used is limited due to two-photon absorption in the optical waveguides. As a result the output powers from passive optical chips tend to be low, i.e. far below the milliwatt regime. Such power levels are generally too low for direct application of pulse characterization techniques, like autocorrelation and FROG [25]. These techniques can be used when the output from the chip is first amplified, e.g. using an erbium-doped fiber amplifier (EDFA). However dispersion and gain nonlinearities can distort the pulse shape. A pulse characterization technique using spectrograms, as proposed in [26], has a high sensitivity but a limited temporal resolution down to about 1\,ps.

In this work we use a relatively new technique for ultrashort pulse characterization, named SIMBA (Spectral Interferometry using Minimum-phase Based Algorithm [27,28]), and apply it for the first time to the characterization of an integrated optical circuit. With this technique it is possible to completely characterize a short optical pulse, i.e. both the power and the phase profile. The setup used in this work is shown in Fig. 6-3. In this setup the 80 MHz, 200 fs pulses from the MLL are split between the arm with the chip and a reference arm of approximately the same length. A delay line is used to delay the pulses propagating through the chip by about 100\,ps with respect to the pulses in the reference arm. The interference spectrum of both pulses is then recorded with a high-resolution spectrum analyzer with a resolution of 20 MHz, recording 20,000 points per spectrum (APEX AP2041A). The delay between the pulses of 100\,ps results in fringes in the interference spectrum of about 10 GHz width. This means that there are multiple fringes in the 200-GHz AWG-channel-width and the fringes are resolved accurately with the 20 MHz resolution and about 20 sampling points. Using an iterative Fourier algorithm on the spectrum, the pulse shape at the output of the chip can then be calculated, assuming the combination of both pulses is a (close to) minimum-phase function [27]. This is realized by keeping the reference pulses short (i.e. close to transform limited) and by tuning their power to exceed the power of the pulses propagating through the chip by about 20\,dB.

To test the SIMBA measurement technique for our purposes we first applied it to a chip with a semiconductor optical amplifier (SOA) fabricated by us [29]. The reason is that the pulses propagating through the chip are amplified by the SOA and the power level at the output of the chip allows us to apply other measurement techniques, such as a cross-
correlation. We used a 1.2 nm bandwidth filter to limit the input pulse duration in the SOA to a minimum duration of about 2 ps. In Fig. 6-4 the pulse shape calculated by the SIMBA technique is shown. Using the same setup a cross-correlation is made between the picosecond pulse at the SOA output and the 200 fs pulse in the reference arm. This cross-correlation is also shown in Fig. 6-4 and the shape agrees well with the result obtained with SIMBA. From these results we conclude that we can apply the SIMBA measurement method to characterize short pulse propagation through our chip.

A problem with our setup is that the interferometer is not stable during the time the OSA needs to record a spectrum as wide as that required to characterize the pulse compressor. As a result the calculated phase of the pulses drifts away as the interference pattern shifts. To solve this we have implemented an averaging algorithm, where the phase difference between adjacent pulse compressor transmission channels is averaged over 10 recorded OSA traces. This is allowed as the phase change due to the instability of the interferometer is small between two channels. More specific this (random) phase change is far smaller than ±π radians between two adjacent (i.e. separated by 200 GHz) channels. Another option would be to stabilize the setup using a feedback to the optical delay line. However this was not implemented.

The purpose of the EDFA after the MLL is to partially amplify the optical spectrum, increasing the spectral peak power with over 9 dB and narrowing the spectral bandwidth from over 30 nm down to about 12 nm, thereby increasing the pulse duration and correspondingly reducing the two-photon absorption. This bandwidth narrowing occurs due to the limited overlap of the EDFA gain spectrum with the MLL output spectrum. The spectrum before and after partial EDFA amplification is shown in Fig. 6-5(a). The increase in spectral peak power was necessary to overcome the noise floor of the high resolution OSA. No self-phase modulation and corresponding chirping of the pulses takes place in the EDFA. The optical spectrum of the pulses is compared to the spectrum obtained with time-broadened (using a length of SMF) pulses to verify this. After propagation through the EDFA the pulses are predominantly linearly chirped due to the dispersion of the optical fiber inside the EDFA. Using different lengths of dispersion compensating fiber (DCF) and monitoring the pulse duration on an autocorrelator, this linear chirp can be quantified, as can be seen in Fig. 6-5(b). The chirp is about 0.32 ps/nm, equivalent to a compensation length of 3.2 m of DCF. All the autocorrelator traces were pedestal free, also indicating a linear chirp profile. The minimum in the plot of Fig. 6-5(b) corresponds to a time-bandwidth product of 0.5, close to transform limited. This linear chirp profile on the input pulse is eliminated in the pulse reconstruction by the SIMBA technique and has to be added to the calculated pulse shape to obtain the actual pulse shape at the output of the device. The dispersion of the reference arm is below 4 fs/nm.

The on-chip average optical input power is about 1 mW – 2 mW. Two separate thermo-electric coolers (TECs) control the temperature of the two halves of the chuck the chip is mounted on. As a result the passbands of the AWGs on both halves of the chip can then be temperature tuned separately. Needle probes can be used to bias a single PHM and a 20-pins multi-contact wedge can be used to bias all 20 channels individually at the same time.
Fig. 6-3  Schematic overview of the SIMBA measurement setup. MLL: 80 MHz mode-locked fiber laser, VOA: variable optical attenuator, PC: polarization controller, ODL: optical delay line, TE: polarization filter, TEC: thermo-electric cooler, OSA: optical spectrum analyzer, PM: power meter, DUT: device under test, 50/50: 3-dB fiber coupler. All fiber pigtailed components use dispersion shifted fiber.

Fig. 6-4  Comparison of the temporal pulse profiles after propagation through an SOA obtained with an autocorrelation (dotted) and with the SIMBA method (solid).

Fig. 6-5  (a) Spectrum of the optical pulses entering the pulse shaper before (grey) and after EDFA amplification and spectral narrowing (black). (b) Measured pulse durations at the 3-dB fiber coupler at the output in Fig. 6-3 when different lengths of DCF are used after the EDFA. Durations are obtained from an autocorrelation using a deconvolution factor of 1.5 (diamonds). The dotted lines are fit to the measured data, assuming linear pulse chirp.
6.4 Characterization

In this section first the results on the static characterization of the pulse shaper, both electrically and optically are presented. Then, the characterization results obtained by studying pulse shaping effects that have been recorded using the SIMBA technique. As a last point, the specific application of the pulse shaper as a dispersion compensator is investigated.

6.4.1 Static characterization

Using the ASE emission of an EDFA the optical transmission through the pulse shaper is characterized. In Fig. 6-6 transmission spectra of the device are shown. First the on-chip losses are determined by subtracting the transmission spectrum of a straight waveguide from the transmission spectrum of the pulse shaper, to cancel out fiber to chip coupling losses. As mentioned above the transmission is sensitive towards the alignment of the two passbands of the AWGs in the device with respect to each other. The on-chip transmission is optimized by keeping one side of the chip, i.e. one of the AWGs, at 20 °C and varying the temperature of the other AWG. In Fig. 6-6(a) it can be seen that a temperature difference of 6 °C, i.e. a temperature of 14 °C for the other AWG, results in an optimum peak transmission of -19 dB. With previously published AWG losses around 4 dB [22] and passive waveguide propagation losses of about 2 dB/cm for our doped layerstack, this means that the losses of the pulse shaper are about 7 dB higher than expected. This can mainly be attributed to increased sidewall roughness in the (shallow) waveguides as compared to the work in [22]. Losses of these waveguides were determined to be (3.8 ± 0.5) dB/cm using a Fabry-Pérot based loss measurement technique [30].

Due to the passing of the light through two AWGs the crosstalk levels are down to -30 dB. The addition of MMIs at the inputs and outputs of the AWGs as mentioned in Fig. 6-2 will flatten the AWG passbands. This can be seen in our measurement results in Fig. 6-6(b), where the channels with Gaussian transmission are compared to those with the flattened transmission. The 3-dB-bandwidth of the passband for the flat-top AWG pair channels is increased from 0.3 nm to 0.8 nm. The peak transmission is however reduced by about 4 dB to 5 dB.

![Fig. 6-6](image)

Fig. 6-6 (a) On-chip losses for a pulse shaper with AWGs with Gaussian passbands. One AWG is kept at a temperature of 20 °C whereas the other AWG is temperature tuned between 14 °C and 24 °C. (b) Comparison of the transmission of a pulse shaper with Gaussian AWGs (black) with flat-top AWGs (grey). The AWG temperature difference is 4 °C in both cases.
For the electrical characterization of the PHMs we have measured the dark current through the 5 mm PHMs under reverse bias. This current is below 4 nA at -5 V and less than 20 nA at -10 V, indicating good surface passivation by the polyimide [31]. The electro-optical characterization, using test PHM structures on the same chip, shows a phase shifting of $2\pi$ radians for a 5 mm PHM at reverse bias voltages between -5 V and -6 V, depending on the position of the PHM on the wafer surface, i.e. depending on the distance of the PHM to the center of the wafer. This difference is ascribed to a gradient in the doping and/or layer profile over the wafer surface. For the PHMs in the pulse shaper described in this work the $2\pi$ radian shift value is -6 V. Note that the PHMs were designed for switching $2\pi$ radians at -5 V, so there is close agreement with the design [24]. Optical losses induced by the field over the PHM are negligible, i.e. less than 0.1 dB per PHM when the voltage is decreased from 0 V down to -10 V.

In summary we can say that the optical losses of the pulse shaper are about 7 dB higher than what was expected. The passband broadening due to the flat-top AWG inputs and which is required to improve performance with respect to pulse ringing, is clearly observed. The electrical and electro-optical behavior of the PHMs are close to the design values, with a $2\pi$ phase shifting voltage of -6 V and dark currents below 20 nA at -10 V bias voltage.

### 6.4.2 Pulse shaping characterization

Using the SIMBA measurement technique as described in section 6.3, we will first present the measured power and phase spectra of a pulse train after propagation through the pulse shaper. Then these results are translated to the time domain and pulse shaping, in particular pulse compression is investigated using optimized PHM voltage settings for the pulse shaper.

In Fig. 6-7 the output pulse spectrum of the pulse shaper with Gaussian AWG passbands is presented. The pulse train with the spectrum as presented in Fig. 6-5 is used as the input. Only the phase data of the spectral components with the highest power, i.e. with power over approximately -15 dB of the peak power at $\lambda = 1565$ nm, are shown. The phase of the spectrum is quantified at 0 V, -2 V and -4 V bias on the PHMs. Using multiple sets of measurements, the error margin achieved in the phase over the central ten, high power channels is less than ±0.25 radians. The error margin is less than ±0.5 radians for the lower power outer channels. Possible reasons for the limited accuracy are the instability of the SIMBA interferometric setup, as explained above, or phase instabilities in the wings of the spectrum of the MLL generated input pulses. When the PHMs are biased at -2 V and -4 V the SIMBA measurement clearly shows the phase shift in the channels of about $2\pi$ radians for -6 V.

So concluding we can say that the SIMBA technique is able to characterize the phase of the spectrum at the output. The PHMs in the pulse shaper channels work at their designed values. This complete characterization of the spectrum makes it possible to calculate the pulse shapes at the output.
Fig. 6-7 Measured phase of the spectral components of the transmitted pulse spectrum using Gaussian AWG channels. The PHMs in the channels are separately biased at -2 V (dark grey) and -4 V (light grey) and compared to the unbiased case (black). The transmitted spectrum is also shown.

Using the results given in Fig. 6-7, the PHM settings can be calculated to minimize the duration of the output pulses. In Fig. 6-8(a) the pulse shape with minimized duration derived from the SIMBA measurements when the Gaussian AWG channels are used is shown. As can be seen, severe ringing in the form of satellite pulses takes place. These satellite pulses are spaced at 5 ps, corresponding to the 200 GHz AWG channel spacing. Their peak power is between 50% and 60% of the central pulse peak power. In Fig. 6-8(b) it can be seen that when flat-top AWG inputs are used this ringing is significantly suppressed to about 12% to 16% of the central pulse peak power. Moreover the central pulse peak power is increased by about 25% as compared to pulse shaping using Gaussian AWGs. For both cases the pulse duration is about 0.3 ps at FWHM.

As mentioned above the spectral phase can only be measured with a limited accuracy in our SIMBA measurement setup. The effect of this limited accuracy on the uncertainty in the pulse shape was investigated. Taking the data used for the result presented in Fig. 6-8(b), the pulse shape was calculated assuming a random phase error per channel of ±0.25 and ±0.5 radians respectively. The variation in the output pulse peak power is within 3% for a phase error of ±0.25 radians and within 11% for ±0.5 radians. These numbers quantify the accuracy of our pulse characterization setup.
6.4.3 Dispersion compensation of the pulse shaper

One main application of a pulse shaper is dispersion (pre-)compensation [1]. For example by adding a linear chirp profile to the pulses, second order dispersion as imposed by optical fibers can be compensated. In the following we will calculate this dispersion compensation using the phase tuning results as presented in Fig. 6-7, using the same input pulse. The effect of second order dispersion on a pulse can be expressed by the filter function $H(\lambda)$, according to:

$$H(\lambda) = \exp\left(i\pi cD\frac{(\lambda - \lambda_0)^2}{\lambda_0^2}\right)$$  \hspace{1cm} (6.1)

in which $c$ is the speed of light in vacuum and $D$ the total second order dispersion (in units of ps/nm). Tuning the phase shifting in the PHMs in the pulse shaper with such a parabolic profile imposes a linear chirp on the pulse. In Fig. 6-9(a) output pulse shapes and chirp profiles for different values of the total dispersion $D$ are plotted, using flat-top AWG inputs. Positive and negative linear chirp profiles over the pulse are obtained for dispersion values up to 0.5 ps/nm, but the pulse shape becomes heavily distorted. For a dispersion of 1.0 ps/nm the chirp profile can not be recognized as being linear (Fig. 6-9(a)).

The possibilities for using the pulse shaper as a dispersion (pre-)compensator are investigated by applying the continuous filter (6.1) to the pulses obtained in Fig. 6-9(a). In this way the effect of a second order dispersive medium, such as optical fiber, is simulated. For the continuous filter a total dispersion $D$ of equal magnitude but of opposite sign as used for the pulse shaper dispersion is used. In Fig. 6-9(b) the resulting pulse peak power and the pulse duration is plotted. As can be seen, the pulse peak power can be reconstructed to within 95% of the input pulse peak power for dispersion values of $D = \pm0.2$ ps/nm, which is the equivalent of about 10 m of SMF. The parabolic phase shape due to the second order dispersion within the 0.8 nm bandwidth AWG channel, cannot be compensated by the pulse shaper. This is the cause of the decreased performance for higher values of the dispersion compensation in Fig. 6-9(b). With the decrease of the peak power, the pulse duration increases, as can also be seen in Fig. 6-9(b).
Concluding we can say that our pulse shaper can perform dispersion compensation for dispersion values of up to about 0.2 ps/nm. This makes the device suitable for use in e.g. bio-imaging systems, where the total value of the dispersion is limited but where tuning and delivering of the pulse peak power is essential [6,7].

### Conclusion

In this work we have presented an integrated optical pulse shaper, fabricated in the InP/InGaAsP material system and working for pulses with wavelengths around 1.55 μm. The device consists of an AWG pair with an array of PHMs between them to tune the dispersion of the device MMI inputs have been added to the AWG to flatten the optical passbands in order to reduce pulse ringing.

We have used a new measurement technique, called SIMBA, and applied it for the first time to characterize short pulse propagation through an optical chip. The technique was verified by comparing the results of pulse propagation through an SOA measured by the SIMBA technique and by a cross-correlation. The accuracy of measuring the phase of the spectrum was quantified to be sufficient, i.e. within ±0.25 radians. Using this technique the pulse shaper was characterized and the pulse shaping by the pulse shaper was investigated for pulses at 80 MHz and with a duration of 0.3 ps. Our flat-top AWG inputs strongly reduce the pulse ringing as compared to AWGs with Gaussian inputs by a factor of four, i.e. from 50% - 60% down to 12% - 16% and are well able to reconstruct the short pulses, i.e. the output pulses have a duration of 0.3 ps. The application of the pulse shaper as a dispersion compensator was investigated. The pulse shaper is well suited to compensate dispersion values of up to 0.2 ps/nm, i.e. the equivalent of about 10 m of SMF, with pulse peak power reconstruction of over 95%.

The fabrication of the pulse shaper is compatible with the fabrication of integrated mode-locked lasers. This makes it possible to make a fully integrated arbitrary pulse generator for wavelengths around 1.55 μm. Moreover as integrated modelocked lasers typically have repetition rates of up to 40 GHz, this combination offers the possibility to avoid pulse ringing by matching the pulse repetition rate with the AWG channel spacing in the pulse shaper.
Fig. 6-9  (a) Calculated pulse shapes with corresponding chirp profiles for different parabolic phase profiles in the pulse shaper PHM settings. Total dispersion values of -0.1 ps/nm up to 1.0 ps/nm are shown.

(b) Plot of the calculated peak power and pulse duration after propagation through a second order dispersive element and the pulse shaper. The phase settings in the pulse shaper are set to compensate this dispersion. The value of the total (compensated) dispersion is given along the horizontal axis. It indicates the possibilities for use of the device for dispersion (pre-)compensation. Peak powers have been normalized with respect to the input pulse peak power.


Een feit dat u, hoop ik, meer boeit dan ontstelt:
Het is wat u hoort als een trein langs u snelt
Of iets van de brandweer dat rusteloos belt –
Een feit dat uw denken beheerst

De toon is zeg sol, en ineens wordt het do
In tekst uitgedrukt gaat dat ongeveer zo:
iiiiiiIIIIIIOOOOOOoooooo...
Dus duidelijk lager dan eerst

Dat is wel opvallend maar geenszins suspect
Wij insiders spreken van dopplereffect
En wat dat mag wezen verneemt u direct
Ik zet het voor u op een rij

Er is een geluidsbron (bijvoorbeeld een Daf)
Geluidsgolven komen van daar op u af
Normaal doen ze dat al in stevige draf
Maar nu komt de bron dichterbij

De golven, dynamisch en logisch te moe
Begeven zich dus extra snel naar u toe
Daardoor – deze waarheid is groot als een koe –
Verneemt u een hogere toon

Uw oren (in feite is dat het geval)
Ontvangen een opgehoogd trillingsgetal
En denken naïef: O, we weten het al
Dat ding speelt een sol, heel gewoon

Maar u en ik weten: de bron speelt een mi
Hij nadert steeds meer... dan passeert hij, en zie!
Plots meldt zich een andere anomalie:
De toon die u hoort, stort omlaag

Het trillingsgetal: is verminderd, nietwaar?
De bron van ’t geluid distantiert zich, vandaar –
Dus trager bereikt het u: do. Zonnelaar?
Dit was het dan weer voor vandaag

Drs. P
Observation of Q-switching and mode-locking in two-section InAs-InP (100) quantum dot lasers around 1.55 \( \mu \)m

Abstract – First observation of passive mode-locking in two-section quantum-dot lasers operating at wavelengths around 1.55 \( \mu \)m is reported. Pulse generation at 4.6 GHz from a 9 mm long device is verified by background-free autocorrelation, RF-spectra and real-time oscilloscope traces. The output pulses are stretched in time and heavily up-chirped with a value of 20 ps/nm, contrary to what is normally observed in passively mode-locked semiconductor lasers. The complete output spectrum is shown to be coherent over 10 nm. From a 7 mm long device Q-switching is observed over a large operating regime. The lasers have been realized using a fabrication technology that is compatible with further photonic integration. This makes the laser a promising candidate for e.g. a mode-comb generator in a complex photonic chip.

7.1 Introduction

Active and passive mode-locking of laser diodes is a well-established technique for generating picosecond pulses at wavelengths around 1.55 \( \mu \)m [1,2,3]. These wavelengths are of primary interest for telecommunication applications. The material of choice for fabricating these mode-locked laser diodes (MLLDs) is InP/InGaAsP, using either bulk or quantum well gain sections [3]. Recently passive mode-locking has also been observed in quantum-dot based lasers [4].

Quantum dot (QD) gain material is promising for applications in MLLDs due to the broad gain spectrum, low spontaneous emission levels and a low threshold current density [5,6]. In principle this allows for the generation of ultrashort, transform limited pulses. Sub-picosecond pulse generation down to 0.4 ps pulse duration has been achieved with InAs-GaAs QD material operating at wavelengths around 1.3 \( \mu \)m [5,7]. Sub-picosecond pulse amplifiers [8] and MLLDs have been realized with this material demonstrating average output powers of 45 mW, with pulse peak powers over 1 W [7]. Recently lasing has been reported in Fabry-Pérot type ridge waveguide InAs-InP (100) QD structures operating in the 1.55 \( \mu \)m wavelength region [9]. It was demonstrated that similarly to the InAs-GaAs QD material, this material does not suffer from ridge side-wall surface recombination. As a result it is possible to make high-contrast ridge waveguides, reducing the size of the devices and increasing the possible integration density [6].

In this work the results obtained with monolithic two-section QD lasers operating at wavelengths around 1.55 \( \mu \)m are presented. First the device design and fabrication are presented in section 7.2. Hereafter the experimental results are presented and discussed for
the laser configurations showing Q-switching (section 7.3) and passive mode-locking (PML, section 7.4). The conclusions are summarized in section 7.5.

7.2 Design and fabrication

The QD laser structure is grown on n-type (100) InP substrates by metal-organic vapor-phase epitaxy (MOVPE), as presented in [6,9]. The QD wavelength is tuned into the 1.55 μm region through insertion of ultrathin GaAs interlayers. In the active region five InAs QD layers are stacked, separated by 40-nm InGaAsP layers with a bandgap corresponding to a wavelength of 1.25 μm (Q1.25). The QDs have a diameter of approximately 50 nm and a height of 4 nm – 7 nm. The QD layers are placed in the center of a Q1.25 InGaAsP optical waveguiding core layer which is in total 500 nm thick. The bottom cladding of this laser structure is a 500-nm thick n-InP buffer and the top cladding is a 1.5-μm p-InP with a compositionally graded 300-nm p-InGaAs(P) top contact layer. Note that this layerstack is compatible with the butt-joint active-passive integration process as mentioned in [10,11] for possible further integration.

Two-section FP-type laser devices have been designed and realized with total lengths of 4 mm up to 9 mm and section ratios of 3% up to 30%, as shown in Fig. 7-1. The ridge waveguides have a width of 2 μm and are etched 100 nm into the InGaAsP Q1.25 layer. To create electrical isolation between the two sections, the most highly doped part of the p-cladding layer is etched away. The waveguide and isolation sections are etched using an optimized CH₄/H₂ two-step reactive-ion dry etch process. The structures are planarized and passivated using polyimide. Two evaporated Ti/Pt/Au metal pads contact the two sections to create two contacts. Au-plating is used to increase the Au-thickness to over 1 μm to ensure uniform injection current and to increase dissipation of the generated heat. The backside of the n-InP substrate is metallized to create a common ground contact for the two sections. The structures are cleaved to create the mirrors for the FP cavity.

The two-section devices are operated by forward biasing the longer gain section, creating a semiconductor optical amplifier (SOA) and by reversely biasing the shorter gain section, creating a saturable absorber (SA). The devices are mounted on a copper chuck, p-side up. In this work we focus our analysis on two devices, i.e. a device with a length of 7 mm and an SA section of 5% of the total length and a device with a length of 9 mm, with an SA section of 3%. In the following these devices are used to investigate Q-switching and mode-locking respectively.

Fig. 7-1 Photograph of the realized devices, showing different configurations. The SOA (gain) and SA (saturable absorption) sections are indicated.
7.3 Q-switching

Q-switching of the laser by low-frequency (self-)modulation of the cavity losses, is a commonly found operating regime in two-section lasers, e.g. [12]. However in QD-based laser diodes, Q-switching is thought to be suppressed or even absent due to the fast recovery of the saturable gain [13,14].

Using the setup depicted in Fig. 7-2 a laser with a total length of 7 mm and an SA with a length of 5% of the total cavity (SA length equals 350 μm) is studied. Anti-reflection coated lensed fibers are used to couple light out of the laser and optical isolators are used to prevent feedback from reflections into the laser cavity. The copper chuck below the laser is kept at a fixed temperature of 10 °C. Needle probes are used to bias the two sections of the laser respectively.

In Fig. 7-3 the fiber-coupled output power is plotted as a function of the injection current. As can be seen, there is a step-like curve around the lasing threshold. This is because the SA saturates as a result of the increased optical power, resulting in a reduced optical loss. The lasing threshold current increases from around 700 mA for an SA voltage of 0 V, up to 775 mA with the bias voltage decreased to -3 V. These lasing thresholds are relatively large as compared to bulk or quantum-well lasers. The reason is the low modal gain of the QD lasers [9]. The reverse bias current is also recorded and it is observed to scale approximately with the intensity of the optical output. Moreover, sudden changes in optical power levels are observed when increasing the injection current, indicating dynamics in the optical field.

To study these dynamics the RF-spectrum of the laser is recorded, using a 50-GHz bandwidth electrical spectrum analyzer (ESA) with a 50-GHz photodiode. A reverse bias of -3 V is applied. The RF-spectra for frequencies up to 5 GHz are plotted in Fig. 7-4(a). Three regimes of Q-switching can be identified, with RF-peak spacings of approximately 32.5 MHz, 153 MHz and 390 MHz with increasing injection current. The increase in the oscillation frequency with increasing injection current is in agreements with the observation in [14]. Q-switching has been verified by recording the optical output with a 6-GHz bandwidth oscilloscope and a 45-GHz photodiode. The traces are shown in Fig. 7-4(b) and are obtained with values for the injection current corresponding to the three regimes of Q-switching in Fig. 7-4(a). The pulse repetition rates corresponding to the RF-peak spacing are 31 ns, 6.5 ns and 2.6 ns respectively for increasing injection current. These repetition rates are in agreement with the oscilloscope traces in Fig. 7-4(b). The pulses are characterized by a steep (leading) peak, with a duration of 0.6 ps – 0.8 ps and a risetime of 0.3 ps. The pulses at 32.5 MHz and 153 MHz, i.e. at the lower injection currents, also have a significant trailing part, due to the relatively low gain just above threshold. Concluding we can say that passive Q-switching in QD-lasers has been shown.

A point to note is that the ESA spectra around 840 mA show no Q-switching, having an RF-peak around the cavity roundtrip time (outside the plot in Fig. 7-4(a)). This indicates a very small regime of possible mode-locking at this SA voltage value for this 7 mm device. Mode-locking in these two-section devices will be discussed in the next section for a 9 mm device. This regime around 840 mA corresponds to the peak in the LI-curve of the SA voltage of -3 V in Fig. 7-3.
Fig. 7-2  Schematic overview of the setup used to characterize the QD lasers. PM: power meter, Iso: optical isolator, TE cooler: thermo-electric cooler, SOA: optional booster amplifier, ESA: electrical spectrum analyzer including a 50-GHz photodiode, OSA: optical spectrum analyzer, Osc: 6-GHz real time oscilloscope including 45-GHz photodiode, PC: polarization controller, AC: autocorrelator. All equipment is fiber pigtailed or has fiber input or output connectors. A current source (I) and voltage source (-V) are used to bias the SOA and SA respectively.

Fig. 7-3  $LI$-curves for different SA bias voltages (solid). The fiber coupled optical power is plotted. The SA bias current is also shown (dotted). The total device length is 7 mm and the SA length is 5%.
7.4 Passive mode-locking

With the same setup as presented in Fig. 7-2 passive mode-locking in the QD-lasers is studied for a device with a total length of 9 mm and a 270 μm (3%) SA section length. In Fig. 7-5 the $LI$-curves are given, showing threshold current values of 660 mA up to 690 mA for SA bias voltages of 0 V down to -4 V. Comparing these curves with the ones obtained for the 7 mm device in Fig. 7-3 it can be observed that threshold currents are lower for the 9 mm device and output power levels are of the same order. Moreover the step-like behavior around threshold is less pronounced owing to the shorter SA length.
The RF-spectra obtained for this laser show clear peaks at the cavity roundtrip-frequency of 4.6 GHz, corresponding to the 9-mm cavity. In Fig. 7-6 the RF-spectrum at an injection current of 900 mA and an SA bias voltage of -1 V is shown. The first RF-peak at the fundamental frequency is 43 dB over the noise floor. Also the width of this peak is narrow, i.e. 0.57 MHz at -20 dB, as can be seen in Fig. 7-6(b). Moreover, the lower-frequency signal intensity around the DC-component in the spectrum is very low, i.e. in the order of the noise floor up to 5 GHz. Concluding it can be said that this RF-spectrum indicates clear and stable mode-locking [15].

The optical spectrum corresponding to this operating point is given in Fig. 7-7. Using an OSA with a 0.16 pm resolution, the mode-structure can clearly be distinguished, with a mode-spacing of 36 pm corresponding to the roundtrip frequency (Fig. 7-7(b)). The spectrum seems to be broad, as can be expected from QD-lasers [6], but with a modulation on top (Fig. 7-7(a)), which is unlike what is to be expected from a typical mode-locked spectrum in quantum-well or bulk gain lasers. However no clear pulse traces were obtained with the autocorrelator, using the setup as pictured in Fig. 7-2. Traces obtained with a 6-GHz bandwidth 10 Gs/s real-time oscilloscope showed a small modulation at 4.6 GHz, though with a strong DC-offset. More specific, the modulation depth was only 15% of the total signal power.
To investigate the fact that the RF-spectrum shows a clear indication of mode-locking whereas there appears to be no significant pulse shaping, a tunable optical bandpass filter of 1.2 nm bandwidth is placed after the QD-laser output. A reduction of the DC component in the RF-spectrum, i.e. representing the average power, is observed (this DC component is not shown in Fig. 7-6), while the RF-peaks at the fundamental frequency and their higher harmonics remain strong. Clear pulse shapes can now be observed with the autocorrelator, as can be seen in Fig. 7-8. With the filter set around 1534 nm, the widths (FWHM) of the traces ranges from 9 ps up to 16 ps when increasing the injection current from 850 mA to 1.0 A. Assuming a deconvolution factor of 1.5 these values correspond to pulse durations of 6 ps to 11 ps. The traces are background-free, as they should be. Moreover the 6-GHz oscilloscope shows traces with a modulation depth down to the 0-Volt-level, i.e. background-free, as shown in the paragraphs below.
Fig. 7-8  Autocorrelator traces (second harmonic power given) obtained with a 9 mm device with 3% SA length and with a 1.2 nm optical bandwidth filter. Injection current is varied from 750 mA up to 1 A and SA bias voltage is -1 V. A booster SOA is used for amplification.

By tuning the 1.2 nm bandpass filter over the full spectrum of the laser (about 10 nm as can be seen in Fig. 7-7), clearly defined picosecond pulses are observed at all wavelengths. Thus the laser is mode-locked over this range. To investigate the timing between these separate spectral components of the output pulse, the setup of Fig. 7-9 is used. In here the output pulses of the laser are split using a 3-dB coupler and they are separately filtered using two optical bandpass filters (with bandwidths of 1.2 nm and 2.0 nm respectively). Both filtered output pulses are then recorded with the 6-GHz oscilloscope. One of the bandpass filters (with 2.0 nm bandwidth) is kept at a fixed position and is used to trigger the signal, i.e. it serves as a reference. The other bandpass filter (with 1.2 nm bandwidth) is tuned and the output is recorded by the oscilloscope with the reference signal as a trigger. A typical oscilloscope trace is shown in Fig. 7-9(b).

Using these oscilloscope traces the relative delay of the pulse trains resulting after filtering is then determined. In Fig. 7-10 the optical spectra and resulting delays are plotted for different settings of the tunable bandpass filter. As can be seen the difference between the minimum and maximum delay is almost 0.2 ns, i.e. almost equal to the cavity roundtrip time of 216 ps. This leads to the conclusion that the output pulse of the QD-laser is very elongated, i.e. well over 100 ps duration, and is heavily up-chirped, with a chirp value of about 20 ps/nm. The chirp profile is predominantly linear over the pulse center as can be seen in Fig. 7-10(b). The full-bandwidth pulse duration of over 100 ps agrees with the 6 ps – 11 ps duration for the filtered pulse, assuming the same time-bandwidth product (due to the linear chirp). Note that the full bandwidth is coherent, effectively creating a mode-comb.

The RF-peak at the fundamental frequency in the filtered laser output is stable, i.e. its value is stable within ±50 kHz when the optical bandpass filter is tuned. This is demonstrated by measurement of the RF-spectra around this peak as a function of filter wavelength. A 0.22-nm wide tunable optical bandpass filter is used. The result is presented in Fig. 7-10(c), where the RF-spectra are shown over a 1.9 MHz frequency range. Tuning
the position of the bandpass filter changes the intensity of the peak, much like the spectrum in Fig. 7-7(a), but not its position. However we have observed an increase in the pedestal around both the RF-peak and the DC-peak when the bandpass filter is included as compared to the case without a filter. This suggests that energy exchange between different spectral components of the pulse takes place to some degree at lower frequencies, i.e. in the MHz-range. Investigation of this effect is beyond the scope of this work.

This result is strikingly different from what is commonly observed in mode-locked lasers based on bulk or quantum-well gain material, or even on QD gain material operating at wavelengths around 1.3 μm, where shorter pulses with a lower time-bandwidth product are commonly obtained. The origin of the observed dynamics of the lasers presented here is not understood yet, however this will be investigated further by us. Most probably the laser behavior is related to the not well-known dynamics governed by the energy level structure and spectral inhomogeneous aspects in the 1.55 μm QD gain material. For example as compared to the 1.3 μm QD gain material our material has a relatively low carrier confinement in the dots and a relatively small energy separation between the ground and excited state due to the larger dot size.

Fig. 7-9  (a) Schematic of the setup used to investigate the timing of the spectral components of the pulse. The two photodiodes (PDs) are connected to two channels of the oscilloscope (Osc). (b) A typical example of the oscilloscope traces. The ‘signal’ is obtained with the 1.2 nm filter and the ‘ref.’ with the 2.0 nm filter. The ‘ref.’ has a vertical offset for easy comparison.
Fig. 7-10  (a). Resulting optical spectra by tuning the 1.2 nm optical bandpass filter. (b) Relative delay of the different pulse trains corresponding to the spectra in (a). (c) RF-spectra obtained after filtering the laser output with a 0.22-nm optical bandpass filter. Injection current is 1.0 A and SA bias voltage is -1 V. The spectra are color-coded in dB scale. The electrical bandwidth used to obtain the spectra is 50 kHz.

7.5 Conclusion

In this work mode-locking in two-section QD-lasers operating at wavelengths around 1.55 μm has been demonstrated for the first time. It has been verified by background-free autocorrelator signals, RF-analyzer signals and real-time oscilloscope traces. The output pulses are heavily upchirped, with a value of 20 ps/nm. Pulse durations well over 100 ps are obtained for a repetition rate of 4.6 GHz. Mode-locking is very stable as indicated by the RF-peak power of 43 dB over the noise floor and a peak width of 0.57 MHz at -20 dB. The
full optical bandwidth of the output is coherent. Moreover large regimes of Q-switching are observed in similar but slightly shorter devices and having a longer SA section with a higher bias voltage. As a result the saturation energy of the SA increases, leading to a decreased (or vanishing) regime of mode-locking.

These results indicate that the dynamics in our two-section InAs/InP (100) QD-lasers operating at 1.55 μm are significantly different from their bulk and quantum-well counterparts and also from those published for 1.3 μm InAs/GaAs QD-lasers.

Lasing thresholds in these devices are relatively high as compared to lasers based on bulk or quantum-well gain material and output power levels are relatively low because of the lower modal gain of the QD lasers. This can in principle be improved by increasing the carrier confinement into the QDs by e.g. operation at a lower temperature or by decreasing the bandgap of the InGaAsP core layer. In the latter case the compatibility for possible further integration using an active-passive integration scheme [10,11] is compromised. Another more suitable option from point of view of integration, is to increase the number of QD-layers.

These devices have been realized with a fabrication technology that is compatible with further photonic integration. As such these devices can perform the function of e.g. a mode-comb generator in a complex photonic chip, and applications like an integrated arbitrary pulse generator or spectral domain encoder become possible.


Summary

This thesis presents a platform for ultrafast integrated semiconductor laser technology operating at wavelengths of 1.55 μm. This platform is based upon three components, namely a pulsed laser source, a pulse shaper and a novel device, named IRIS. The functionalities of optical pulse generation, pulse amplification, optical isolation and spectral and temporal pulse shaping can be addressed by these components. The components have all been realized in the InP/InGaAsP semiconductor material, using ridge waveguide structures. The materials and processing technologies that were used to fabricate these components are compatible with each other. This allows for further monolithic integration of these components into a single laser system in the future. For example a combination of these components on a single chip can bring about a complete monolithic arbitrary pulse shaper.

In this work first the technologies and principles to generate short optical pulses and how these concepts can be used to realize an integrated laser source for femtosecond pulses were investigated. A model specifically tailored to the available technology at COBRA has been set up and applied to different laser configurations. Its main conclusion is that using InP/InGaAsP bulk gain material in the laser and without any dispersion management, the output pulse durations are limited to about 1 ps. Shorter pulses down to 0.3 ps can be obtained by connecting dispersive components to the laser output.

Secondly the three components, namely the laser source, pulse shaper and IRIS device, were investigated individually. Fabry-Pérot type passively mode-locked lasers using novel quantum dot gain material were fabricated and tested. Pulse generation at 4.6 GHz from a 9-mm long device was observed and verified. This is the first report of passive mode-locking in quantum dot lasers operating at 1.55 μm. The output pulses are very elongated, i.e. over 100-ps duration, and heavily upchirped, with a value of 20 ps/nm. The observed mode-locking regime is unlike what is commonly observed in lasers with quantum well or bulk gain material, or even quantum dot lasers operating at 1.3 μm.

The IRIS device is a new device concept, which consists of a concatenated sequence of optical amplifiers and saturable absorbers. Depending on the operating conditions, it can amplify and/or add bandwidth to a picosecond optical pulse, or it can perform the function of an optical isolator. Simulations show that the IRIS device can be used as a chirper, i.e. to add coherent optical bandwidth. In the propagation of a 40-GHz picosecond pulse train through the device, total spectral widths well over 10 nm with a smooth shape are predicted. Experimentally a 5-nm bandwidth was obtained for a 10-GHz pulse train. The broad and smooth spectrum makes further pulse compression and shaping possible.

Measurements on the amplification of a picosecond pulse train show that the IRIS device can achieve a 4 dB better signal-to-noise ratio as compared to a conventional optical amplifier of equivalent length, while the achievable pulse energy is about 3 dB lower. Also the temporal pulse broadening due to gain saturation is decreased in the IRIS device. The
simulations show that even pulse compression down to 0.6 ps is possible, though this could not be confirmed experimentally.

As a last functionality the IRIS device can be used as an optical isolator. Simulations show that when a picosecond pulse train propagates through the device at transparency, counter-propagating, lower power pulses originating from reflections are attenuated by 20 dB – 30 dB, in which case the device effectively operates an optical isolator.

The third component realized in this work is a temporal pulse shaper. It is based on a pair of arrayed-waveguide gratings with an array of phase tuning components in between them to tune the dispersion of the device. The channel spacing used is 200 GHz. A measurement technique has been developed to characterize this device. With this technique it has been shown that the pulse shaper can recompress 0.3 ps pulses at 80 MHz that have been broadened after propagation through a dispersive medium. A total linear dispersion of up to 0.2 ps/nm can be compensated by the pulse shaper. Pulse ringing is suppressed from over 50% down to about 15% of the central pulse peak power by using a flattened channel transmission of the arrayed waveguide gratings.

With the integrated technology presented in this work compact, stable and small footprint pulse sources including additional pulse processing components can be realized. The potential scalability and low cost make this technology a very attractive and promising option for large-scale implementation of ultrafast photonics in the fields of e.g. telecommunication, biomedical imaging and spectroscopy, sensing and metrology.
List of publications

International journals


Patent


International conferences


Non-refereed and national conferences


Verder niets... er zijn alleen nog een paar dingen
die ik houd omdat geen mens er iets aan heeft,
dat zijn mijn goede jeugdherinneringen,
die neem je mee zolang je verder leeft.

B. de Groot
Men zegt wel eens: “Promoveren doe je niet alleen”. Dat is niet helemaal waar, want voor een groot deel sta je er echt alleen voor, en dat is eigenlijk ook wel het mooie ervan. Echter, om die taak goed aan te kunnen, vol te kunnen houden en bovenal leuk te blijven vinden, zijn er velen die mij hierbij geholpen hebben.

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“Indien ik eens uit een vergrootglas mocht drinken
Hoe groot zou ik dan kunnen worden, papa?”
De vraag van de jongen mag achterlijk klinken
Correctie: Martijnje was heus bij de pinken
Wel vijf jaar oud slechts, dus gaat u maar na

De vader verklaarde, didactisch bevlogen
“Geenszins! Een vergrootglas, daar drinkt men niet uit
Uw groei ligt ook stellig niet in zijn vermogen
En als het vergroot is, is ‘t alleen in uw ogen”
“Hoe gaat zulks precies in zijn werk?” vroeg de guit

“Dat glas is een kijkglas, waardoor ge kunt kijken
En daar het glas bol is ontstaat het visioen
Dat letters of torretjes groter gaan lijken
Het komt doordat lichtstralen af moeten wijken”
En hier moest Martijnje het dan maar mee doen

Drs. P
Curriculum vitae

Martijn Jan Resie Heck was born in Nijmegen, the Netherlands, in 1976. In 1995 he obtained his VWO “gymnasiumstroom” diploma from the SG Augustinianum in Eindhoven. He received the M.Sc. degree in applied physics from the Technische Universiteit Eindhoven in 2002. He did his Master thesis work at ASM Lithography on the characterization of processed optical alignment marks on semiconductor wafers using an atomic force microscope. Also during his studies, in 2000, he had an internship in the International School of Photonics, CUSAT, Kochi, India.

From 2003 to 2007 he has been working toward the Ph.D. degree in the Opto-Electronic Devices group of the COBRA Research Institute, where he was involved in research on integrated ultrafast semiconductor technology.

Presently he is working on a commercial feasibility study on biomedical applications of integrated ultrafast optics, with the aid of a Valorisation Grant of the Dutch government.