Design and Performance of Optically Pumped Semiconductor Disk Lasers with Wide Tuning Ranges

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Chalmers University of Technology
Göteborg, Sweden, 2010
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Abstract
In this work I present a strategy for providing the possibility to select the wavelength, or color, of a semiconductor laser over a very large range, by cleverly designing the vital part of the laser: the gain element of a so called optically pumped semiconductor disk laser.

Optically pumped semiconductor disk lasers (OP-SDLs) are a relatively new class of lasers showing great promise for future applications. The advantages include the wavelength versatility that is common for all semiconductor lasers, but also adds the ability to deliver multi-Watt output powers into a nearly diffraction-limited beam, and a free-space cavity for the easy insertion of various optical elements. These properties have generated great interest in the OP-SDL for use in life science, metrology, entertainment applications, forensics, and many other fields. Recently, efforts have also been made to extend the tuning range for use in spectroscopic applications such as intra-cavity laser absorption spectroscopy.

The work underlying this thesis has focused on the design of the gain element of an OP-SDL and how to obtain a wide tuning range while keeping the output power at a high level. The strategy has been to balance the effects of the spectral dependencies of material gain, subcavity resonance, and spatial overlap of quantum wells and optical field. Experimental evaluations show that the strategy has been successful and a relative tuning range of 4.3% with a maximum output power of 2.6 W was obtained.

Furthermore, a new measurement technique for the full characterization of a laser beam has been developed. This technique is well suited for the high-intensity beam from an OP-SDL.

Keywords: Semiconductor laser, optically pumped semiconductor disk laser, vertical-external-cavity surface-emitting laser, design, high power, tuning range, beam characterization
List of papers

This thesis is based on the following appended papers:


[III] C. Borgentun, J. Bengtsson, and A. Larsson, "Full characterization of a high-power semiconductor disk laser beam with simultaneous capture of optimally sized focus and farfield, and phase retrieval in a branched optical system." In manuscript.
Acknowledgement

Thank you all.

Especially to those of you who have in some way or other helped in the making of this thesis, and there are many more of you than one might believe. I will try to mention some of you here even though I am fully aware that the list will not be complete.

I am in immense debt to my supervisor Jürgen for pedagogically pointing out my many obvious mistakes, and to Prof. Anders for giving me permission to board this journey in the first place. A warm hug goes to my room-mate Yuspin for his undying patience regarding my singing and drumming in the office. All the wonderful people in the optoelectronics group (The Adolf, Black Petter, Rambo etc) have to be thanked for enjoyable distractions during and after working hours. Although in my view way too seldom, the Fellowship of the Fiber has also provided good times. I would like to thank the city of Brussels for providing an inspiring environment for thesis-writing without too many distractions except the odd laser conference, geocache, and irritated volcano. Gröter and Deckar’n (Yes, let’s go for a landala- mändag!) each deserves a lorry of love for helping me survive the first years of Chalmers.

Naturally, I cannot even begin to thank Hannah for her understanding and love during these difficult times, and as always: Praise be to God!

This work was financially supported by the Vetenskapsrådet, and hence, by a lot of Swedes. I would also like to acknowledge IQE Europe Ltd. in Cardiff, UK for supplying the epitaxial material.

Carl Borgentun

Göteborg
May 2010
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<tr>
<td>AR</td>
<td>Antireflectance</td>
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<tr>
<td>BPP</td>
<td>Beam parameter product</td>
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<tr>
<td>BRF</td>
<td>Birefringent filter</td>
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<tr>
<td>CCD</td>
<td>Charged-coupled device</td>
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<tr>
<td>COD</td>
<td>Catastrophic optical damage</td>
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<tr>
<td>DBR</td>
<td>Distributed Bragg reflector</td>
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<tr>
<td>ICLAS</td>
<td>Intra-cavity laser absorption spectroscopy</td>
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<tr>
<td>MBE</td>
<td>Molecular beam epitaxy</td>
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<td>MOCVD</td>
<td>Metal-organic chemical vapor deposition</td>
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<td>MOVPE</td>
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<td>OP-SDL</td>
<td>Optically pumped semiconductor disk laser</td>
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<td>QW</td>
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<td>RPG</td>
<td>Resonant periodic gain</td>
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<td>TEC</td>
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<td>TMM</td>
<td>Transfer matrix model</td>
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1 Introduction

Since its birth 50 years ago [1, 2], the laser has become an important technology for modern society and the applications are numerous, ranging from medicine to telecom [3–7]. The majority of modern semiconductor lasers are either edge-emitting lasers or vertical-cavity surface-emitting lasers (VCSELs). The edge-emitting lasers can emit beams of high output powers but the beams are highly elliptical and require sophisticated external optics for satisfactory use in many applications [8]. A beam from a VCSEL on the other hand, can be close to diffraction-limited enabling easy and efficient coupling into optical fibers but the single-mode VCSELs are limited to output powers in the milli-Watt range. Optically pumped semiconductor disk lasers (OP-SDLs), or vertical-external-cavity surface-emitting lasers (VECSELs) as they are also referred to, can combine the high output power of the edge-emitting devices with the superior beam quality of the VCSELs [9–14]. Another advantage of the OP-SDL is its free-space cavity, which allows for the insertion of various optical elements, such as non-linear crystals for frequency doubling [15], semiconductor saturable absorber mirrors (SESAMs) for mode-locking [16] or wavelength-selective elements for wavelength tuning [17], i.e. for a precise change of the wavelength, or color, of the light from the laser.

![Schematic view of an OP-SDL.](image_url)

Although a widely tunable OP-SDL would be highly useful for applications such as intra-cavity laser absorption spectroscopy (ICLAS) [18, 19], research in extending the tuning range has not until recently been given major attention. Pioneering
efforts were made by Garnache et al., who applied a design principle balancing the wavelength dependent effects of sub-cavity resonance and material gain maximum [20]. There has also been research on employing a multi-chip setup, which has produced record-high output powers though the tuning range in those experiments was limited [21]. A recently developed OP-SDL used a set of heterogeneous quantum wells (QWs) resulting in a very wide tuning range but low output power [22].

The work underlying this thesis has investigated whether the tuning range of an OP-SDL could be extended by cleverly designing the gain element. Besides a wide tuning range, the output power was to be kept at a high level as constant as possible throughout a large part of the tuning range. The balancing principle of Garnache et al. was used but the design was extended to include a much longer sub-cavity with 12 homogeneous QWs. In this way most of the pump light will be absorbed and more optical gain will be provided. Also, part of the structure was parametrically optimized to even more accurately control the broadband properties.

This thesis begins with a brief introduction to the theory of lasers in chapter 2. The remainder of the thesis follows the timeline of the work behind it: Chapter 3 explains the strategies used in the design of a broadband OP-SDL gain element, followed by the fabrication of such a gain element, described in chapter 4. Chapter 5 presents the performance of the gain element in an OP-SDL setup, and finally, chapter 6 describes a new measurement technique to characterize the output laser beam.
2 Elements of laser theory

In this chapter I will briefly explain some important concepts that are essential for understanding the laser described in this thesis. Generally, a laser consists of two parts: an amplifying medium and a cavity. Firstly, in section 2.1 I will summarize how a medium can be amplifying through photon interaction with matter, followed by some fundamentals of laser cavities in section 2.2. Finally, I will focus on different methods of tuning OP-SDLs in section 2.3.

2.1 Amplification

Amplification of light involves transitions between energy levels. In theory only two energy levels are required: an upper and a lower laser energy level. A system, such as an atom or a molecule, is somehow excited from the lower to the upper level and can then relax back to the lower level while emitting a photon. The efficiency can however be radically increased by the use of one or two additional energy levels: an upper and/or a lower pump energy level, see figure 2.1. This facilitates the creation of population inversion, which is necessary for lasing and means that the population of the upper laser level is larger than that of the lower laser level. The transition from the upper pump level to the upper laser level as well as the transition from the lower laser level to the lower pump level should therefore have a short lifetime so that the upper laser level always is as filled as possible and the lower laser level always is as empty as possible.

In a semiconductor the distinct energy levels of the atoms are split into energy bands. The lower energy band is called the valence band and the higher the conduction band. When an electron is excited to the conduction band, a vacancy in the valence band is created. This vacancy is called a hole and can in fact be seen as another species of charge carrier, just like the electrons but with different diffusion velocity, (sign of) charge, and mass.

The excited system in most semiconductor lasers is a region where there is a non-equilibrium excess of electrons and holes. There are mainly two methods to create such a non-equilibrium: by electrical or optical pumping. By electrical pumping, a current is injected into the p-n junction region of the semiconductor laser creating a population of electrons in the conduction band and a population of holes in the valence band. In an optically pumped laser the non-equilibrium is created through absorption of incident light from a pump source, which is often another laser.

With a certain possibility an incident photon will trigger the excited system to
2. Elements of laser theory

![Figure 2.1: The energy levels of generic two-, three-, and four-level laser systems. The upper laser level is by convention denoted 2, and the lower laser level 1. The upper pumping level is denoted 3 and the lower pumping level 0, if they differ from the laser levels. The transitions between levels 3-2 and 1-0 are generally non-radiative, i.e. no photon is emitted in the process.](image)

relax to the lower laser level, releasing another photon at the same time. This process is called stimulated emission and the essential point is that the emitted photon is an exact copy of the incident photon regarding phase, polarization, wavelength, and propagation direction. The excited system can, with another well-defined possibility, instead relax without the help of an incident photon, but the emission is in that case spontaneous, i.e. the phase, polarization, and propagation direction are random.

The wavelength of the emitted photon is governed by the energy difference by the excited state and the lower state, which means that the wavelengths of spontaneous and stimulated emission can be equal. In fact, the seed that initiates the stimulated emission in a laser is a spontaneously emitted photon, which, by chance, has a combination of wavelength, polarization, and propagation direction that is supported by the laser cavity, see section 2.2.

Most semiconductor lasers include a thin layer sandwiched between materials with a higher bandgap energy. When the width of the sandwiched layer is decreased quantum effects become important and the energy levels in it become quantized. The sandwiched layer is called a quantum well (QW) and the surrounding material is called barriers, see figure 2.2. By adjusting the width and the depth of the QW, the energy levels can be engineered to allow the emission of a photon of an almost arbitrary wavelength.

2.2 Cavity

A cavity, or resonator, usually consists of two or more mirrors of some sort. The mirrors can be standard dielectric, as the out-coupling mirror of an OP-SDL, or semiconductor reflectors, as the distributed Bragg reflector (DBR) in an OP-SDL gain element, or some other reflective surface or structure. In an edge-emitting laser, for example, the mirrors are simply the facets of the cleaved semiconductor chip; the difference in refractive index of air and semiconductor is so large that a considerable part (∼ 32%) of the power of the incident field is reflected. The standard free-space cavity laser consists of a linear cavity with two mirrors opposite each other, as for the OP-SDLs considered in this work, but others have used OP-SDLs whose cavities
2.2. Cavity

are folded one, two, or even more times, and where light can be coupled out through one or many of the mirrors.

In a free-space cavity, where there is no waveguiding effect, the shapes of the cavity mirrors are important for the optical stability of the cavity. Consider, for example, a linear cavity with two planar mirrors. Since the laser field makes so many round-trips in the cavity, even the slightest misalignment of one of the mirrors, or the propagation direction of the field, will eventually cause the field to escape the cavity by simply walking off the mirrors. This cavity is said to be unstable. Stable cavities need at least one non-planar mirror, and often spherical mirrors are used. The external cavity of a linear OP-SDL is a plano-spherical cavity with one planar mirror, i.e. the gain element itself, and one spherical dielectric mirror. As long as the length of this cavity is shorter than the radius of curvature of the spherical mirror, the cavity is stable [23].

The cavity determines many of the properties of the emitted laser light. This comes from the fact that a cavity only supports lasing under certain circumstances: during a round-trip in the cavity the field has to repeat itself with respect to its phase and amplitude. The amplitude condition is often referred to as the lasing condition and in words states that after one round-trip in the cavity the gain should compensate for the losses from the cavity so that the intensity of the field is the same as before the round-trip. The lasing condition for a standard OP-SDL with one out-coupling mirror with reflectance $R_{OC}$, a gain element with an effective reflectance $R_{GE} > 1$, distributed scattering losses $\alpha_s$, and cavity length $L_c$ is:

$$1 = \exp(-\alpha_s 2L_c) \cdot R_{OC} \cdot R_{GE} \quad (2.1)$$

The phase condition simply states that the phase of the optical field after one round-trip should be the same, ensuring that the field is not interfering destructively with itself. This means that the phase change, $\Delta \phi$, after one round-trip must be an integer multiple of $2\pi$, i.e.

$$\Delta \phi = k_0 n 2L_c = q 2\pi \quad \text{where } q \in \mathbb{N}$$

$$\Rightarrow L_c = \frac{q \lambda_0}{2n} \quad (2.2)$$

Figure 2.2: Schematic showing the constituting parts of a generic active region in a semiconductor laser.
where \( k_0 = \frac{2\pi}{\lambda_0} \) is the wavenumber, \( \lambda_0 \) is the wavelength, and \( n \) is the refractive index of the material filling the cavity. In words, the cavity supports only those wavelengths for which the cavity length is an integer number of half wavelengths in the material. These wavelengths are called the *longitudinal modes* of the cavity and are separated in frequency by \( \nu_F = \frac{c_0}{2\pi n L_c} \). Depending on the properties of the gain medium and of the cavity, a laser can lase in one single mode or in many longitudinal modes simultaneously. The mode(s) that will lase are determined by the gain spectrum and the possible modes, see figure 2.3.

A laser cavity also supports modes with different transverse field distributions. The simplest one is called the *fundamental mode*, which often is the only desired one. Which of these *transverse modes* of an OP-SDL that are actually lasing is to a great extent controlled by the overlap of the pump spot, i.e. the area on the gain element illuminated by the pump laser, and the cavity field. Therefore it is common to match the sizes of the pump spot and the fundamental mode on the gain element, which will then likely result in a highly single-mode optical field in the fundamental mode. If the pump spot size is decreased, the cavity can no longer support any lasing. If the pump spot size is increased, higher transverse modes with larger mode sizes will compete for the existing gain and in many cases win over the fundamental mode. This results in an output beam of lesser quality but often of higher output power. The diameter of the cavity field at the gain element, \( 2\omega_0 \), is in a linear OP-SDL controlled by the length of the external cavity:

\[
2\omega_0 = 2\sqrt{\frac{\lambda_0 L_c}{\pi}} \cdot \sqrt{\frac{\varrho}{L_c} - 1}
\]  

(2.3)

where \( \varrho \) is the radius of curvature of the spherical external mirror.
2.3 Tuning of OP-SDLs

The possibility to adjust the lasing wavelength, i.e. to tune the wavelength, is important in many applications [24, 25]. It is quite evident from equation 2.2 that a change in $L_c$, $n$, or $q$ will also change $\lambda_0$. For example, the length of the cavity can be changed by adjusting the position of a cavity mirror [26,27] or by including a gradient in the waveguide [28]. The refractive index of the waveguide can be changed electrically [29]. Longitudinal mode selection can be realized through an external dispersive element such as a grating [30] or an intra-cavity etalon [31]. Since the bandgap energy and the refractive index are temperature dependent, fine-tuning of the lasing wavelength can be achieved by deliberately adjusting the temperature [32, 33]. In this work I have used another principle of tuning, a birefringent filter (BRF), to select a certain wavelength by increasing the losses for other wavelengths.

![Figure 2.4: Schematic view of an OP-SDL with a wavelength-selective element (i.e. the rotatable birefringent filter) inserted in the external cavity.](image)

2.3.1 Birefringent tuning filter

A BRF is simply a thin plate of a birefringent material, e.g. crystalline quartz. In birefringent media the refractive index is anisotropic and differs ever so slightly along two perpendicular axes in the crystal: the ordinary and the extraordinary. An incident optical field is decomposed into a mode along each optical axis, propagating as if the medium was isotropic. Due to the refractive index difference a phase retardation is introduced between the modes [34,35]. This causes a change in polarization of the total field when the two components are recombined after the propagation, but for some certain wavelengths the retardation is a multiple of $\pi$ and the polarization is unaltered. If the BRF is sufficiently thin, within the wavelength range with positive gain in the gain element, there is only one wavelength for which this is fulfilled, see figure 2.5.

The plot in the figure further assumes that the BRF is inserted at the Brewster angle, and that the field is obeying the polarization condition for zero reflection (the
2. Elements of laser theory

Figure 2.5: Tuning with a BRF. For each rotation angle, the wavelengths are plotted, for which the polarization after propagation through a 1 mm thick BRF is unaltered, which is the condition for negligible reflection loss at the Brewster angle.

Brewster effect). For all other polarizations there will be reflection losses. Thus, if inserted at the Brewster angle, the BRF makes the polarization of the optical field linear in the plane of incidence of the BRF. Further, the wavelength will be set to the one fulfilling the repetition condition indicated in the figure, since this field will obey the Brewster condition for zero reflection also when exiting the BRF, and thus ideally experiencing zero total reflection loss.

The refractive index of the extraordinary mode, \( n[\theta] \), depends on the angle between the polarization plane of the incident field and the crystal optical axis, \( \theta \). Thus, the wavelength, for which the polarization is unaltered and is consequently not filtered by the Brewster surfaces, can be tuned by rotating the BRF.
3 Design of gain element

In this chapter I will describe how the epitaxial layer structure of the gain element of a tunable OP-SDL can be optimized to obtain a desired set of properties. The layer structure usually consists of two main parts: the active region and the DBR, see figure 3.1. The active region mainly contains layers that absorb the field of the pump laser, but also thin layers working as QWs, which can provide optical gain through stimulated emission. The DBR is one of the cavity mirrors - the other being the external out-coupling mirror - and is composed of $\lambda/4$ thick layers of alternating high and low refractive index. The field will reflect at the layer interfaces due to multiple constructive interference, provided that the wavelength is close to the design wavelength.

As a component in the external cavity the gain element is equivalent to a mirror with gain, i.e. its reflectance is larger than unity for some wavelengths. Naturally, if one wants a widely tunable OP-SDL, the reflectance of the gain element needs to be larger than unity for a wide wavelength interval. If the output power should vary slowly in this interval as the wavelength is tuned at a constant pump intensity, it is further reasonable to assume that the spectral reflectance of the gain element should be flat and smooth without significant peaks.

To enable the design of a gain element so that the spectral reflectance can be prescribed, I have first developed a model for the optical gain of the QWs, which is presented in section 3.1. To simulate the propagation of the optical field within the gain element I used a transfer matrix model (TMM) described in section 3.2. In section 3.3 I show the optimization process of the gain element to find a structure design that provides a high, wide, and flat reflectance spectrum.

Figure 3.1: Schematic showing the many layers of a generic gain element and its two main parts: the active region and the DBR. Here I also show the window structure for reasons that will become obvious in section 3.3.
3. Design of gain element

3.1 Gain model

Optical gain, which we denote by $g$, is often described by the relative increase, or decay, per unit length of the intensity of a plane wave propagating in a medium. In modeling of optical fields it is customary to instead use an imaginary part, $n''$, of the refractive index to account for optical gain. Using $n = n' + i n''$ for the refractive index, the intensity of a propagating plane wave can thus be written in two ways:

$$
\begin{align*}
I & \propto \exp (g \cdot d) \\
I & \propto \left| \exp \left( i \frac{2\pi}{\lambda_0} (n' + i n'') \cdot d \right) \right|^2 = \exp \left( -\frac{4\pi}{\lambda_0} n'' \cdot d \right)
\end{align*}
$$

(3.1)

where $d$ is the propagated distance. Thus, by identification, $n'' = -\frac{2\pi}{\lambda_0} \cdot g$, so that a negative imaginary part of the refractive index signifies positive gain, i.e. amplification or an increase in amplitude. Gain can also be negative, which means an absorption of the field, or a decrease in amplitude, and this is signified by a positive imaginary part of the refractive index.

To calculate the amount of gain from the stimulated emission of a QW, I developed a model, numerically realized in MATLAB, in which a value for $g$ is obtained. This value will later be converted into $n''$ in the optical model, see section 3.2.

Even for high gain values, the real part of the refractive index is much larger than the magnitude of the imaginary part of the refractive index, and is supposed to be not significantly affected by the changes in gain. The real part of the refractive index has been modeled using the model by Afromowitz [37] for Al(1-x)Ga(x)As and GaAs(x)P(1-x), and the model by Adachi [38] for In(x)Ga(1-x)As.

3.1.1 Gain calculation details

First, we want to calculate the bandgap energy (see figure 3.3) in the QW. We need this to determine the energy levels in the conduction and valence energy bands. The energy of the bandgap of a ternary material, such as In(x)Ga(1-x)As, is modeled by a first or second degree polynomial with the composition parameter, $x$, as the variable. The polynomial is fitted to experimental values, especially to those of the binary extremes, in this example InAs and GaAs, which can be more precisely measured. The fitted polynomial coefficients can be found in table 3.1 along with other material parameters used in this section.

However, the crystalline patterns of the atoms, i.e. the lattices, in the GaAs pump barriers and the InGaAs QWs do not match exactly, since the volume of the unit cell of InGaAs is slightly larger than that of the GaAs unit cell. The atoms of the QW still adapt to the crystal lattice of the barriers but the InGaAs atoms are compressed in the plane of the substrate more than what is natural, a condition known as strain. Strain is not always compressive but can also be tensile, if the atoms of the thinner layer are more closely spaced, i.e. has a smaller lattice constant, than the surrounding layers. The strain is accumulated for every strained atomic layer and a strain energy is built up. When the strain energy reaches a critical value, the lattice bonds can no longer manage to keep the lattice together and the lattice relaxes to its natural lattice constant by introducing a defect in the lattice, see figure 3.2. The defects reduce performance for most optical devices since they provide the charge...
3.1. Gain model

carriers with a way to recombine nonradiatively, but as long as the critical value is not reached, the defect density can be kept low: under such circumstances strain can even be beneficial for the performance of some lasers [39,40]. Strain can be partly compensated for by introducing layers with the other kind of strain. In this work we used \( \sim 30 \text{ nm} \) thick tensile strained GaAs\((x)P(1-x) \) layers with about 7\% P to compensate for the 6 nm thick compressively strained In\((20\%)Ga(80\%)As \) QWs.

Since strain changes the bandgap energy we have to take this into account. This is done by equation 3.2, which can be found in Coldren [41], as is the case for all equations in this chapter unless otherwise stated.

\[
E_g = E_g^{\text{strained}} = E_g^{\text{unstrained}} + \left( \frac{2}{3} \right) \frac{dE_g}{dP} \left( C_{11} + 2C_{12} \right) \left( 1 - \frac{C_{12}}{C_{11}} \right) + Sb \left( 1 + 2 \frac{C_{12}}{C_{11}} \right) \cdot \varepsilon \tag{3.2}
\]

To calculate the barrier height for the electrons and holes, respectively, we need to model how the total difference in bandgap between the QWs and the barrier is distributed on the conduction and valence bands. We assumed that the fraction of the difference in bandgap energy between the QWs and the barriers that is in the conduction band is \( \Delta E_c = 0.7 \) and in the valence band \( \Delta E_v = 0.3 \), which is a common assumption supported by measurements.

When the QW depth for electrons and holes has been determined, the energy levels of the electrons and the holes are next in line. Since the QW is geometrically quite different in different directions, the energy levels are also anisotropic. The energy levels in the plane of the QW, \( E_{1,2} \), follow the equations for bulk material and are calculated with equation 3.3, where \( m_r \) is the reduced effective mass. The energy levels perpendicular to the QW plane, \( E_{en} \) for electrons and \( E_{hn} \) for holes, are quantized with quantum number \( n \) and are determined by numerically solving
3. Design of gain element

![Energy diagram of a typical quantum well and its surrounding barriers. The QW energy levels in the conduction band are denoted $e_0$ and $e_1$. The valence band energy levels are $hh_0$ and $hh_1$ for the heavy holes and $lh_0$ for the light holes.](image)

Figure 3.3: Energy diagram of a typical quantum well and its surrounding barriers. The QW energy levels in the conduction band are denoted $e_0$ and $e_1$. The valence band energy levels are $hh_0$ and $hh_1$ for the heavy holes and $lh_0$ for the light holes.

equation 3.4. See figure 3.3 for a schematic over the energy levels involved.

$$E^h_1 = 0 - (E_{21} - E_g) \cdot \frac{m_{xy}}{m_h}$$ (3.3a)

$$E^e_2 = E_g + (E_{21} - E_g) \cdot \frac{m_{xy}}{m_e}$$ (3.3b)

$$m_r = \frac{m_e m_h}{m_e + m_h}$$

$$0 = \tan \left( \sqrt{\frac{m_{e,h} L_z^2}{2 \hbar^2} E_{en,hn}^2} \right) - \sqrt{\frac{m_{e,h}^2}{m_{e,h}^2} \Delta E_{c,v} - E_{en,hn}}$$ for even $n$ (3.4a)

$$0 = \cot \left( \sqrt{\frac{m_{e,h} L_z^2}{2 \hbar^2} E_{en,hn}^2} \right) + \sqrt{\frac{m_{e,h}^2}{m_{e,h}^2} \Delta E_{c,v} - E_{en,hn}}$$ for odd $n$ (3.4b)

There are in fact two type of holes: light and heavy. They have different masses, hence their names, and thus have different energy levels in the valence band. This lifting of the valence band degeneracy is not always included, but it has been in this work. Some of the following equations therefore have to be calculated separately for the heavy and the light holes, and the contributions to the gain are finally added in equation 3.11.

The probability of an optical transition between two energy levels is proportional to the transition matrix element, $M_T$. There are a few different models for the spectral dependence of the matrix element and the one I have chosen leads to the mathematical expression shown in equation 3.5 [42]. $M_T$ is different for heavy and
light holes because the perpendicular energy levels, $E_{hn}$, and the in-plane energy levels, $E_1$, are different.

$$M_3^2 = 1.33 m_0 E_g \frac{3}{4} \left( 1 + \frac{E_g + E_{en} + E_{hn}}{E_g + E_1 + E_2} \right)$$ \hspace{1cm} (3.5)$$

The density of states is a function describing how the availability of electron or hole states varies with transition energy. The reduced density of states, $\rho$, is a function that combines the separate density of states functions of the electrons and the holes into a function describing the availability of electron-hole pairs. The expression can be found in equation 3.6, which gives different results for heavy and light holes because of different reduced effective masses and valence band energy levels. The function $H$ is the heaviside function, which is a step function with a value of zero for negative arguments and of one for positive.

$$\rho = \frac{m_{xy}^z}{\pi \hbar^2 L_z} \sum_n H \left[ E_{21} - (E_g + E_{en} + E_{hn}) \right]$$ \hspace{1cm} (3.6)$$

The energy level where an electron state is equally probable to be filled as to be empty is called the Fermi energy level. When the material is not in thermal equilibrium, which occurs as soon as there are excess charge carriers, the Fermi energy level is split into two separate so called quasi-fermi energy levels: one for the conduction band, $E_{fc}$, and one for the valence band, $E_{fv}$. It is thus assumed that there is a local thermal equilibrium in each band. The filling of the states is described by the Fermi factors, $f_1$ and $f_2$ for holes and electrons, respectively. Equation 3.7a has to be used for heavy and light holes separately, since the in-plane energy levels, $E_1$, are different, as seen in equation 3.3.

$$f_1 = \frac{1}{1 + \exp \left( \frac{E_1 - E_{fc}}{k_B T} \right)}$$ \hspace{1cm} (3.7a)$$

$$f_2 = \frac{1}{1 + \exp \left( \frac{E_2 - E_{fc}}{k_B T} \right)}$$ \hspace{1cm} (3.7b)$$

We are now ready to write an expression for the gain of the transition between state 2 in the conduction band and state 1 in the valence band.

$$g_{21} = \frac{\pi q^2 h}{\epsilon_0 c m_0^2 n} \cdot M_T^2 \cdot \frac{f_2 - f_1}{E_{21}}$$ \hspace{1cm} (3.8)$$

However, we are still not finished. Due to energy uncertainty of short-lived states, gain for a certain transition energy receives contributions from electron-hole pairs with slightly different transition energies in a process called lineshape broadening. Often this lineshape is modeled with a Lorentzian lineshape function, as in equation 3.9, and the broadening as a convolution with the unbroadened gain spectrum,
3. Design of gain element

as stated in equation 3.10.

\[ LS \left[ E - E_{21} \right] = \frac{\hbar/ (\pi \tau)}{(\hbar/\tau)^2 + (E - E_{21})^2} \] (3.9)

\[ g^{LS} \left[ E \right] = \int g_{21} \left[ E_{21} \right] \otimes LS \left[ E - E_{21} \right] dE_{21} \] (3.10)

The total gain is now found by adding the contributions from the heavy and the light holes.

\[ g_{\text{tot}} = g^{LS}_{\text{heavy}} + g^{LS}_{\text{light}} \] (3.11)

There are some refinements to this model that can have significant effects. For instance, when too many charge carriers are located close together, like in a highly populated QW, the Coulomb interaction between them will start to screen out the atomic potential of the lattice. This process is not fully understood but has been shown to shrink the bandgap and therefore it is sometimes referred to as bandgap shrinkage or bandgap renormalization. The magnitude of the shrinkage depends on the population in the QW and to a first approximation the effect on the gain spectrum is a rigid shift in wavelength of the entire spectrum. The population-dependent wavelength shift is approximately given by

\[ \Delta \lambda = \frac{C_{\text{shrink}}}{hc} \cdot N_{QW}^{1/3} \cdot \lambda^2 \] (3.12)

where \( N_{QW} \) is the excess carrier density per volume in the QW.

The gain spectra for some various excess charge carrier populations are shown in figure 3.4. To show the obvious redshift at higher carrier concentrations due to bandgap shrinkage, figure 3.5 compares the gain spectra close to the gain peak with and without inclusion of the effect of Coulomb interaction.

3.2 Optical model

Having determined the real and imaginary parts of the refractive index of each layer we are ready to simulate the propagation of an incident optical field in the gain element. A simple model for the propagation of a field with amplitude \( A_{\text{right}} \) a distance \( d \) in a homogeneous medium can be described with equation 3.13, see also figure 3.6(a).

\[ B_{\text{right}} = A_{\text{right}} \cdot \exp (i k d) \] (3.13)

At the interface between two media of different refractive indices, the field will be partly reflected and partly transmitted. The fields propagating right and left in the layer structure will couple to each other through the reflections at the interfaces, according to equation 3.14, see also figure 3.6(b).

\[
\begin{align*}
A_{\text{left}} &= T B_{\text{left}} + R A_{\text{right}} \\
B_{\text{right}} &= T A_{\text{right}} + R B_{\text{left}}
\end{align*}
\] (3.14)
3.2. Optical model

Figure 3.4: Gain spectra for a 6 nm In(20%)Ga(80%)As QW for different excess carrier populations.

Figure 3.5: A close-up of the peak of the gain spectra in figure 3.4 to show the effect of Coulomb interaction. Solid lines and dashed lines are calculated with and without including the effect, respectively.
### Table 3.1: Material parameters used in the gain calculations.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Expression</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstrained lattice constant for</td>
<td>( a_0^{ln} = (5.6533 + 0.405 x) \cdot 10^{10} )</td>
<td>[44]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unstrained lattice constant for</td>
<td>( a_0^{Al} = (5.6533 + 0.0078 y) \cdot 10^{10} )</td>
<td>[45]</td>
</tr>
<tr>
<td>Al(y)Ga(1-y)As, [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lattice mismatch parameter, [-]</td>
<td>( \varepsilon = \frac{a_0^{Al} - a_0^{ln}}{a_0^{ln}} )</td>
<td>[41]</td>
</tr>
<tr>
<td>Unstrained bandgap in</td>
<td>( E_g^{ln} = (1.424 - 1.615 x + 0.555 x^2) \cdot q )</td>
<td>[46]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [J]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unstrained bandgap in</td>
<td>( E_g^{Al} = (1.424 + 1.247 y) \cdot q )</td>
<td>[45]</td>
</tr>
<tr>
<td>Al(y)Ga(1-y)As, [J]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear deformation potential for</td>
<td>( Sb = (-1.7 - 0.1 x) \cdot q )</td>
<td>[41]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [J]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure dependence of the band</td>
<td>( \frac{dE_g}{dq} = (1.17 - 0.13 x) \cdot q \cdot 10^{-10} )</td>
<td>[41]</td>
</tr>
<tr>
<td>gap for In(x)Ga(1-x)As, [J m^2/N]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic stiffness coefficient for</td>
<td>( C_{11} = (11.88 - 3.551 x) \cdot 10^{10} )</td>
<td>[44,45]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [N/m^2]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic stiffness coefficient for</td>
<td>( C_{12} = (5.38 - 0.854 x) \cdot 10^{10} )</td>
<td>[44,45]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [N/m^2]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron effective mass in the z-dim for</td>
<td>( m_e^{In} = (0.0665 - 0.0435 x) \cdot m_0 )</td>
<td>[41]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy hole effective mass in the z-dim for</td>
<td>( m_h^{In} = (0.34 + 0.06 x) \cdot m_0 )</td>
<td>[41]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light hole effective mass in the z-dim for</td>
<td>( m_{lh}^{In} = (0.094 - 0.067 x) \cdot m_0 )</td>
<td>[41]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron effective mass in the z-dim for</td>
<td>( m_e^{Al} = (0.0665 + 0.0835 y) \cdot m_0 )</td>
<td>[45]</td>
</tr>
<tr>
<td>Al(y)Ga(1-y)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy hole effective mass in the z-dim for</td>
<td>( m_h^{Al} = (0.34 + 0.42 y) \cdot m_0 )</td>
<td>[41,45]</td>
</tr>
<tr>
<td>Al(y)Ga(1-y)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light hole effective mass in the z-dim for</td>
<td>( m_{lh}^{Al} = (0.094 + 0.043 y) \cdot m_0 )</td>
<td>[45]</td>
</tr>
<tr>
<td>Al(y)Ga(1-y)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron effective mass in the xy-plane for</td>
<td>( m_e^{xy} = 0.071 m_0 )</td>
<td>[43]</td>
</tr>
<tr>
<td>In(x)Ga(1-x)As, [kg]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luttinger band parameter 1 for Ga, [-]</td>
<td>( g_1^{Ga} = 6.98 )</td>
<td>[44]</td>
</tr>
<tr>
<td>Luttinger band parameter 2 for Ga, [-]</td>
<td>( g_2^{Ga} = 2.06 )</td>
<td>[44]</td>
</tr>
<tr>
<td>Luttinger band parameter 1 for In, [-]</td>
<td>( g_1^{In} = 20.0 )</td>
<td>[44]</td>
</tr>
<tr>
<td>Luttinger band parameter 2 for In, [-]</td>
<td>( g_2^{In} = 8.5 )</td>
<td>[44]</td>
</tr>
<tr>
<td>Luttinger band parameter 1 for In(x)Ga(1-x)As, [-]</td>
<td>( g_1 = (1 - x) g_1^{Ga} + x g_1^{In} )</td>
<td></td>
</tr>
<tr>
<td>Luttinger band parameter 2 for In(x)Ga(1-x)As, [-]</td>
<td>( g_2 = (1 - x) g_2^{Ga} + x g_2^{In} )</td>
<td></td>
</tr>
<tr>
<td>Heavy hole effective mass in the xy-plane for In(x)Ga(1-x)As, [kg]</td>
<td>( m_{lh}^{xy} = \frac{1}{g_1 g_2} m_0 )</td>
<td>[47]</td>
</tr>
<tr>
<td>Light hole effective mass in the xy-plane for In(x)Ga(1-x)As, [kg]</td>
<td>( m_{lh}^{xy} = \frac{1}{g_1 g_2} m_0 )</td>
<td>[47]</td>
</tr>
<tr>
<td>Reduced effective mass, [kg]</td>
<td>( m_r = \frac{m_e m_h}{m_e + m_h} )</td>
<td>-</td>
</tr>
<tr>
<td>Intra-band scattering time, [s]</td>
<td>( \tau = 100 \cdot 10^{-15} )</td>
<td>[41]</td>
</tr>
<tr>
<td>Shrinkage constant, (( L_z ) is the QW thickness), [J m]</td>
<td>( C_{shrink} = 32 \cdot 10^{-3} \cdot q \cdot \left( \frac{10^{16}}{L_z} \right)^{-1/3} )</td>
<td>[41]</td>
</tr>
</tbody>
</table>
3.2. Optical model

(a) Propagation of an optical field in a homogeneous medium.

(b) Reflection and transmission of an optical field at the interface between two media with different refractive indices.

Figure 3.6: The two cases occurring for the propagation of an optical field through a multilayered structure.

The magnitudes of reflection and transmission are described by equation 3.15, assuming that absorption only takes place in the media and not at the interfaces.

\[
R = \frac{n_A - n_B}{n_A + n_B} \quad (3.15a)
\]

\[
T = \frac{2 n_A}{n_A + n_B} \quad (3.15b)
\]

Because of the coupling between the right and left propagating fields, it is convenient to describe the propagation with matrices. The field amplitudes of the right and left propagating fields are then put in column vectors, and are for propagation in a homogeneous medium related by the matrix shown in equation 3.16. To describe the reflection and transmission at an interface the matrix in equation 3.17 is used.

\[
\begin{bmatrix}
A_{right} \\
A_{left}
\end{bmatrix} = \begin{bmatrix}
\exp(-i k_0 d n) & 0 \\
0 & \exp(+i k_0 d n)
\end{bmatrix}
\begin{bmatrix}
B_{right} \\
B_{left}
\end{bmatrix} \quad (3.16)
\]

\[
\begin{bmatrix}
A_{right} \\
A_{left}
\end{bmatrix} = \frac{1}{2 n_A} \begin{bmatrix}
2 n_A & n_A + n_B & n_A - n_B \\
2 n_A & n_A - n_B & n_A + n_B
\end{bmatrix}
\begin{bmatrix}
B_{right} \\
B_{left}
\end{bmatrix} \quad (3.17)
\]

The two types of matrices shown in equations 3.16 and 3.17 are called elementary transfer matrices and we find that the total transfer matrix for an optical system is simply the matrix product of the respective elementary transfer matrices of the separate parts of the system. This is called the transfer matrix model (TMM).

\[
\begin{bmatrix}
A_{right} \\
A_{left}
\end{bmatrix} = M_1 M_2 M_3 \begin{bmatrix}
B_{right} \\
B_{left}
\end{bmatrix} = M \begin{bmatrix}
B_{right} \\
B_{left}
\end{bmatrix} = \begin{bmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{bmatrix} \begin{bmatrix}
B_{right} \\
B_{left}
\end{bmatrix} \quad (3.18)
\]

We are interested in the reflectance of the structure, which is the square of the ratio between the reflected and the incident fields:

\[
R = \left| \frac{A_{left}}{A_{right}} \right|^2 \quad (3.19)
\]
3. Design of gain element

An essential assumption is that no light is incident from the backside of the gain element, i.e., $B_{left} = 0$. Using this assumption together with equations 3.18 and 3.19 we can find an expression for the reflectance.

$$\begin{align*}
A_{right} &= M_{11} B_{right} + M_{12} B_{left} \\
A_{left} &= M_{21} B_{right} + M_{22} B_{left}
\end{align*}$$

$$\Rightarrow B_{right} = A_{right} M_{11} = A_{left} M_{21} \Leftrightarrow R = \frac{|A_{left}|^2}{|A_{right}|^2} = \frac{|M_{21}|^2}{|M_{11}|^2} \quad (3.20)$$

Since the wave vector, $k_0 = \frac{2\pi}{\lambda_0}$, and the refractive indices are wavelength dependent, the reflectance has to be calculated for each wavelength separately.

We are also interested in the field variations within the gain element, since we want to position our QWs at positions of high field intensity for the center wavelength. Due to the high refractive index step at the interface to air, the gain element will form a distinct subcavity between that interface and the DBR, and the field will form standing waves with nodes and antinodes. The subcavity will be resonant for certain wavelengths leading to an increase in field intensity, which we will use to balance the effects of material gain and the walk-off of the antinodes from the QW positions.

Thus, we have found a way to calculate the gain element reflectance for a certain wavelength by calculating the optical gain and including it in the imaginary part of the refractive index, and using the TMM to simulate the field propagation in the layer structure. Now it is time to put our model to use!

3.3 Optimization

I wanted to optimize the structure of the gain element parameters so that the reflectance spectrum of the gain element made the best fit to a target reflectance spectrum, shown in figure 3.8. This target was a top-hat function with a lower level of 1.00, which is the approximate reflectance of the DBR stopband, and an upper
level of 1.03, which is the reflectance required to overcome the estimated cavity losses. The width of the upper level was set to ±20 nm from the center design wavelength, i.e. between 960 and 1000 nm.

The conventional design of an OP-SDL gain element not intended for tuning is to position the QWs at consecutive antinodes of the standing wave of the optical field at the design wavelength. The thickness of the window layer or the top pump-absorbing barrier is then adjusted so that the structure is resonant for the design wavelength, i.e. so that the field has an antinode at the interface to air; this also ensures that the amplitude of the standing wave is maximized. This design is commonly known as a resonant periodic gain (RPG) design. The subcavity field and the reflectance for such a design are presented in figures 3.9 and 3.10. Note that the positions of the QWs and the antinodes are aligned and that there is a field antinode at the interface to air. The reflectance spectrum shows a distinct peak for the design wavelength which should come as no surprise as everything in the OP-SDL design is adjusted to benefit this particular wavelength.

However, this is far from our target reflectance spectrum so we have to do something to produce a better target fit. For instance, we could make the structure antiresonant at the center wavelength, i.e. adjusting the total structure thickness so that a field node is at the air interface. This is easily done by increasing for example the top barrier layer thickness by $\lambda/4 \approx 69.5$ nm for GaAs and $\lambda = 980$ nm. The resulting subcavity field and the reflectance for this design are presented in figures 3.11 and 3.12. Note that the positions of the QWs and the antinodes are still matched but that there now is a field node at the air interface and that the standing wave now has a lower amplitude. There is no longer a large peak in the reflectance spectrum but one small peak (at 1000 nm) and one dip (at 950 nm) that is even below unity reflectance, i.e. the structure no longer provides gain for this wavelength.

One reason for the low reflectance is the large thickness of the subcavity. The pump light is absorbed exponentially which makes the carrier densities in the bottom QWs so low that the gain is in fact negative, i.e. the QWs absorb light instead of
3. Design of gain element

Figure 3.9: The calculated intensity of the optical field inside the subcavity for a conventional RPG design (A). Also shown is the refractive index profile (B). The QWs are marked with vertical dotted black lines.

Figure 3.10: Simulated unsaturated reflectance spectrum for a conventional RPG design (A). Also shown is the target reflectance spectrum (B), as shown in figure 3.8.

amplify it. To counter this the QWs can be positioned in pairs at each antinode making the required subcavity length shorter. Further, the populations of the QWs can be equalized by introducing high-bandgap diffusion barriers [48]. These hinder diffusion of charge carriers so that separate absorption volumes can be constructed, within which all absorbed charge carriers will eventually populate the only QW pair in that volume. The thickness of the absorption volumes increases with depth to compensate for the exponential decay of pump light intensity, so that all QWs are equally or at least more equally populated.

Postulating that the number of QWs should be 12 (dictated partly by material growth issues) and, as mentioned, that the QWs should be positioned in pairs at the field antinodes of the center design wavelength, that they should be equally populated, and that the structure should be antiresonant for the center wavelength, the parameters of the layer structure are in fact to a large extent already given.
3.3. Optimization

Figure 3.11: The calculated intensity of the optical field inside the subcavity for an antiresonant design (A). Also shown is the refractive index profile (B). The QWs are marked with vertical dotted black lines. Note the much lower field intensity for this structure than for the conventional, RPG design.

Figure 3.12: Simulated unsaturated reflectance spectrum for an antiresonant design (A). Also shown is the simulated reflectance spectrum for the conventional RPG design (B), as shown in figure 3.10.

Subcavity field and the reflectance for this design are presented in figures 3.13 and 3.14. As in the previous example of a likewise antiresonant subcavity, the positions of the QWs are aligned with the antinodes and there is a field node at the air interface, but the QWs are now positioned in pairs and there are low-index diffusion barriers to ensure equalized QW populations. Note how the absorption volumes grow larger towards the bottom of the structure in order to excite an equal amount of charge carriers in all volumes. The reflectance spectrum is now much more symmetric and fairly flat, but it is still quite low. This can however be remedied by means of an antireflectance (AR) structure.

An AR structure is similar to a DBR in that it is a stack of \( \lambda/4 \) thick layers with alternating high and low refractive indices. The difference is that the AR structure also includes a \( \lambda/2 \) thick layer, which makes the partially reflected fields
3. Design of gain element

Figure 3.13: The calculated intensity of the optical field inside the subcavity for an antiresonant 2QW design (A). Also shown is the refractive index profile (B). The QWs are marked with vertical dotted black lines.

Figure 3.14: Simulated unsaturated reflectance spectrum for an antiresonant 2QW design (A). Also shown is the simulated reflectance spectrum for the antiresonant 1QW design (B), as shown in figure 3.12.

interfere destructively lowering the total reflectance. The AR structure has three free parameters: the number of layer pairs, the difference in refractive index, and the center wavelength.

The number of layer pairs in the AR structure controls both the width and the height of the reflectance spectrum, but as is evident from figure 3.15 they cannot be controlled separately. Either the width is large but the height low or the height is high and the width is small. The optimum lies, as so often is the case, somewhere in between.

The difference in refractive index is in my case controlled by the aluminum content of the high index layers, since these are Al(x)Ga(1-x)As layers and the low index layers are pure AlAs layers. Therefore, a decrease in aluminum content leads to an increase in refractive index difference which leads to a more pronounced effect of the AR structure. This is illustrated in figure 3.16.
3.3. Optimization

Figure 3.15: Simulated reflectance spectra from the AR structure optimization process when varying the number of layer pairs: A) 4.5 pairs, B) 3.5 pairs, C) 2.5 pairs, D) 1.5 pairs, and E) without AR structure. The high index layers contain 20% aluminum and the center wavelength is 968 nm for all cases. Option C was later chosen for the optimized device.

Figure 3.16: Simulated reflectance spectra from the AR structure optimization process when varying the composition of the high index layers: A) 10% aluminum, B) 20% aluminum, C) 40% aluminum, D) 60% aluminum, and E) 80% aluminum. The number of layer pairs is 2.5 and the center wavelength is 968 nm for all cases. Option B was later chosen for the optimized device.

Figure 3.17: Simulated reflectance spectra from the AR structure optimization process when varying the center wavelength of the AR structure: A) 995 nm, B) 985 nm, C) 975 nm, D) 968 nm, E) 960 nm. The high index layers contain 20% aluminum and the number of layer pairs is 2.5 for all cases. Option D was later chosen for the optimized device.
3. Design of gain element

The center wavelength of the AR structure controls the thicknesses of the layers, since they should be $\lambda/4$ thick for this wavelength. The center wavelength adjusts the spectral position of the reflectance minimum of the AR structure and is important for the symmetry of the reflectance spectrum, which is shown in figure 3.17.

I initiated the process of optimizing the AR structure parameters by investigating the three effects of the parameters as described above. I constrained the parameter space to the following limits:

**Number of pairs** was between 0 and 4.5, *i.e.* up to nine layers were considered.

**Aluminum content** was varied between 10% and 80%.

**Center wavelength** was varied between 960 and 1000 nm.

For each combination of parameters a multitude of reflectance spectra were simulated with different total structure thicknesses, realized by varying the thickness of a spacing layer between the AR structure and the active region, to find the correct thickness that provided antiresonance for 980 nm, the center design wavelength. The reflectance spectra for different combinations of the three AR parameters were compared using a combination of two quality measures: the width of the wavelength range for which the reflectance was larger than the high target level, *i.e.* 1.03, and the variance of the reflectance in that wavelength range. The wavelength range should be as large as possible to maximize the tunability and the variance as low as possible to enable low power variations. I considered the width of the wavelength range to be more important than a low variance, since variations in output power are unavoidable anyway and the tuning range is more important for many potential applications. During the entire optimization I made sure that the QWs were equally or close to equally populated, assuming a certain pump intensity and negligible saturation.

I also made simulations for a different type of AR structure with the $\lambda/2$ layer embedded with $\lambda/4$ layers on both sides, but this had only detrimental effects on the reflectance spectrum.

Finally, I found that 2.5 pairs of Al(20%)Ga(80%)As/AlAs layers with thicknesses corresponding to a center wavelength of $\lambda = 968$ nm was a combination that provided a sufficiently high reflectance for the widest possible wavelength range while still keeping the variance low. This AR structure was calculated to have a reflectance larger than 1.03 for a 34 nm wavelength range for an incident pump intensity of $9.1 \cdot 10^7$ W/m$^2$. The reflectance spectrum is shown in figure 3.19 together with the target reflectance spectrum. The intensity of the subcavity field is show in figure 3.18 for two wavelengths: the antiresonant wavelength (980 nm) and one of the resonant wavelengths (960 nm).

### 3.4 Threshold simulations

Due to the difficulty in realizing an experiment directly measuring the spectral reflectance of the pumped gain element to validate the optimized design, I simulated the spectral behavior of the threshold pump intensity. The simulations results were achieved by simulating many reflectance spectra for various incident pump intensities and interpolating for each wavelength to find the pump intensity needed to
3.4. Threshold simulations

Figure 3.18: The calculated intensity of the optical field inside the sub-cavity for the optimized broadband design for the antiresonant wavelength (A) and for a resonant wavelength (B). Also shown is the refractive index profile (C). The QWs are marked with vertical dotted black lines.

Figure 3.19: Simulated reflectance spectrum for the optimized device, and the target reflectance spectrum.
3. Design of gain element

overcome the losses of the cavity. The cavity losses were assumed to come only from the out-coupling mirror and from reflections from the surfaces of the BRF. The loss from the out-coupling mirror is known since the reflectance is given in the data sheet and the losses from the BRF were estimated by measuring the power reflected out of the cavity, see figure 3.20 and equation 3.21.

\[
\begin{align*}
P_{out} &= (1 - R_{OC}) \cdot P_{cav} \\
P_{BRF} &= R_{BRF} \cdot P_{cav}
\end{align*}
\Rightarrow R_{BRF} = \frac{P_{BRF}}{P_{cav}} = \frac{P_{BRF}}{P_{out}} (1 - R_{OC})
\]

(3.21)

The reflectances of the out-coupling mirrors used were \(R_{OC} = 97\%\) and \(R_{OC} = 99\%\), and the estimated reflectance of the BRF surfaces was \(R_{BRF} = 0.1\%\). In similarity with equation 2.1 the lasing condition for this cavity can be written, as in equation 3.22, and value for the required reflectance of the gain element was \(R_{GE} = 1.012\) and \(R_{GE} = 1.033\) for 99% and 97% out-coupling reflectance, respectively, assuming that there were no scattering losses, \(\alpha = 0 \text{ m}^{-1}\).

\[
1 = R_{GE} \cdot e^{\alpha 2L_c} \cdot R_{OC} \cdot (1 - R_{BRF})^2
\Leftrightarrow R_{GE} = \frac{1}{e^{\alpha 2L_c} \cdot R_{OC} \cdot (1 - R_{BRF})^2}
\]

(3.22)
4 Fabrication of gain element

The gain element of an OP-SDL is a highly complex structure of more than 100 very thin layers. Since the thickness as well as the elemental composition of each layer can be chosen freely, the degrees of freedom are numerous and the possibilities almost endless. Depending on the design, a layer can for instance be a QW or one of the many layers of a DBR.

The thickness of a layer usually lies within 5 to 200 nm, or about 50 to 2000 atomic layers, and the technique for building these microstructures is called epitaxy\textsuperscript{a}.

4.1 Epitaxial growth of wafer

It is important to have accurate control not only of the thicknesses of the layers, but also of the compositions of the constituent elements of each layer. A reliable method for this is epitaxial growth. There are nowadays mainly two variants of epitaxial growth: molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD)\textsuperscript{b}. The principle of both variants is to let a controlled flux of atomic gas be incident on a crystalline substrate, which is a flat disk typically $\sim$5-8 cm (2 or 3 inches) in diameter but only 0.3-0.5 mm thin. The atoms in the gas will condense on the substrate and will continue the crystalline pattern of the substrate, \textit{i.e.} the lattice. The growth of the structure is linked to the gas flux and can be controlled to within a single atomic layer.

The structures used in this thesis were grown by MOCVD.

4.2 From wafer to gain element

The result of the epitaxial growth, a substrate covered with the thin layer structure, is called a wafer, which has to be further processed before it can be used. The processing takes place in a clean-room, where the environment is closely controlled regarding particle density, temperature, and humidity.

The normal way of epitaxial growth is to start to grow the structure with the DBR towards the substrate and end with an anti-oxidation layer at the top. In such a case the wafer can be directly used in a laboratory setup after cleaving and mounting.

\textsuperscript{a}from Greek: \textit{epi taxis} meaning "order upon"

\textsuperscript{b}this variant is also referred to as metal-organic vapor phase epitaxy (MOVPE)
4. Fabrication of gain element

However, it is sometimes preferred to epitaxially grow the structure in reverse order. The reason for this is that the substrate is not a good thermal conductor and the heat extraction efficiency can be greatly improved by removing the substrate. To do this, the structure is grown starting with the anti-oxidation layer and ending with the DBR. The wafer is then turned upside down and the DBR is soldered directly to a heatsink and the substrate is subsequently removed. This technique is called flip-chip and has been used to produce the gain elements described in this thesis.

The remainder of this section will explain the process steps involved in producing a ready-to-use gain element from an unprocessed flip-chip wafer.

4.2.1 Wafer cleaving

Because the diameter of the wafer is so large compared to the thickness it breaks easily. Therefore the wafer is separated into smaller, more manageable pieces by cleaving. Due to the crystalline structure, the wafer tends to break along one of the crystal directions in a perfectly straight line. It is therefore convenient to split the wafer by simply scratching its surface along a crystal direction and apply a slight downwards pressure. The ~2 mm scratch is preferably made with a diamond needle at one of the wafer edges. The wafer is then sandwiched between two clean-room tissues with the scratch down before applying the slight pressure with some blunt object.

Cleaving the wafer to the final chip, a piece of about 3 mm × 3 mm, is done stepwise producing successively smaller pieces. As an example, the first cleaving step should produce pieces with dimensions about 18 mm × 15 mm, which is a suitable size for the following metallization process.

4.2.2 Metallization of DBR side

To decrease the risk of breaking or losing the processed gain element, the chip will be soldered onto a carrier or submount. The soldering surface needs to be wet to provide good bonding with the solder, but semiconductor surfaces do not wet well. Therefore the surface that is to be soldered needs to be coated with wettable metals, i.e. metallized.

Unfortunately, no single metal can be found that is wettable as well as easily fastened to semiconductor surfaces. For instance, gold wets well, but is not easily attached to semiconductors. Titanium, on the other hand, readily adheres to semiconductor surfaces but neither wets well nor produces a mechanically strong interface with gold. The solution is to use both of these metals but also to include an intermediate layer of platinum, which provides strong mechanical connections with both gold and titanium.

The metallization process in fact resembles the epitaxial growth of the MBE in some ways. High-purity lumps of metal are heated by high-energy electrons and the flux of metallic gas is guided onto the samples. In the Lesker Spectra apparatus used in the work of this thesis, the samples are mounted with clamps. These effectively hinder the gaseous metal from reaching the shadowed parts of the samples, which thus remain unmetallized. As metallization is performed after the first cleaving step,
the size of the samples is $18 \text{ mm} \times 15 \text{ mm}$ and a circa $3 \text{ mm}$ wide strip can be used for the clamps, leaving a square $15 \text{ mm} \times 15 \text{ mm}$ surface of the metallized sample. Recommended metallization thicknesses are:

- 100 nm Ti, as the first layer on the semiconductor,
- 200 nm Pt, as the intermediate layer, and
- 4000 nm Au, as the wetting layer.

The evaporation rates are about 2 Å/s for Ti, 1 Å/s for Pt, and 4 Å/s for Au. Allowing time for cooling and preparing the vacuum chamber, the metallization of a sample requires in total about one hour with the Lesker Spector.

The process steps following the metallization require that the chip has its final size, so the $15 \text{ mm} \times 15 \text{ mm}$ metallized piece is cleaved into $3 \text{ mm} \times 3 \text{ mm}$ chips.

### 4.2.3 Soldering

Heat extraction is important for the laser performance, so the material of the submount should have good thermal properties, such as copper or even better diamond. It is also essential to ensure that the connection between the metallized semiconductor chip and the submount has a low thermal resistance. A polished submount and a soft solder will reduce the amount of trapped, thermally insulating air. The softness of the solder will also reduce the mechanical strain due to the possible difference in thermal expansion coefficients of the submount and the gain element. A good solder combination is In(80%)Pb(15%)Ag(5%). If the submount is made of copper or diamond, the surface needs to be wetted and can be metallized or gold-plated or alternatively flux can be used. Preferably the solder is applied onto the submount by metallization in order to provide a thin and flat layer.

It is vital to stop the surfaces from oxidizing in the soldering process. Therefore it is recommended that it takes place in a controlled atmosphere, e.g., in a flow of inert gases. The submount is heated to the melting point of the solder (circa 149 °C for the InPbAg solder) and the chip is pressed onto the melted surface, after which the temperature can be lowered and the pressure released.

### 4.2.4 Mechanical etching

After the chip has been fastened to a submount, it is time to remove the substrate part of the chip. To shorten the process time, most of the substrate can be removed by mechanically etching it away in a process called *lapping* or *abrasive machining*. The idea is to grind down the substrate surface with a slurry of a very fine powder, for instance consisting of silicon carbide or boron carbide.

At the MC2 clean-room at Chalmers, the grain size of the used powder is about $22 \mu\text{m}$ and the powder concentration of the slurry is about 25-50 volume-%. The powder is mixed with water on a glass plate, on which a large metal cylinder has been placed. The submount is temporarily glued to a smaller metal cylinder using a low temperature wax, which melts already at $\sim 70 \degree\text{C}$. The small cylinder is very tenderly placed with the chip down in a hole in the larger cylinder. Using gentle hands and tiny vertical forces the whole structure is moved across the glass plate
4. Fabrication of gain element

in figures of eight and the substrate is ground at a rate of about 5-10 μm/figure of eight. Much care must be taken in order to not crack the chip. It is recommended to not lap the substrate to less than ~150 μm thickness, since the ultra-thin chip easily breaks.

Note that it is also possible to skip this process step altogether and just perform wet etching, if high yield is more important than short process time, since it is not unusual to crack the chip.

![Diagram](image.png)

Figure 4.1: The chip in the first fabrication steps: Epitaxial growth, metallization, soldering, and lapping.

4.2.5 Wet etching

The remaining part of the substrate has to be removed by means of wet chemical etching in order to ensure an optimally flat surface. In this process step, the chip is completely submerged in various solutions of acids. The solutions contain one oxidizing component that oxidizes surfaces and one component that removes oxide-rich surface layers. These two chemical agents will thus in effect dissolve the substrate layer by layer. To protect the chip structure from lateral etch, the sides of the chip should be protected with e.g. photoresist. A durable photoresist is AZ1512, which can be applied by means of a clean-room cotton tip. After application, the photoresist should be hardened on a hotplate at 120 °C for 2 minutes. For more accurate control of the thickness, photoresist can be applied using a resist spinner, in which case AZ4562 is a good choice. This photoresist will be spread to a 6.2 μm thick coating when spun at 4000 revolutions/min. After spinning, the photoresist should be hardened on a hotplate at 110 °C for 4 minutes.

Fortunately, different wet etching agents etch different materials at different rates, which enables the etching process to be selective [49]. For instance, a solution of 1:19 NH₄OH:H₂O₂ etches GaAs surfaces at about 3.5 μm/min but etches AlₓGa(1-x)As surfaces very lightly, as long as the aluminum content is larger than x ≥ 30% [50,51]. Thus, the chip structure can be protected by including carefully chosen etch stop layers next to the substrate in the epitaxial growth.

Häring et al. [16] recommends the use of three etch stop layers: 300 nm Al(85%)Ga(15%)As next to the substrate, an intermediate layer of 20 nm GaAs, and 70 nm AlAs as the final layer to be removed. A good combination of solutions to use for the removal of the substrate and these etch stop layers is:
4.2. From wafer to gain element

- **Coarse substrate removal:** If the mechanical etching process step was not performed, most of the substrate can be wet etched by a 1:10 (20:200 ml) NH$_4$OH:H$_2$O$_2$ solution, which will etch the GaAs substrate at a rate of about 5 μm/min or 600 μm/120 min [50, 51]. The thickness of the remaining chip should occasionally be monitored e.g. by removing the chip from the etch solution and measuring with a microscope or a surface profiler. The etching should stop when the thickness is about 50-100 μm.

- **Fine substrate removal:** 1:19 (15:285 ml) NH$_4$OH:H$_2$O$_2$ to remove the remaining GaAs substrate at a rate of about 3.5 μm/min [50,51], and leave a flat surface. This solution will only lightly etch the AlGaAs etch stop layer. The surface appearance will change from the dull or darkly reflecting substrate to the reddish surface of the AlGaAs layer.

- **AlGaAs removal:** 5% (50 ml) HF for ~10 s to etch the AlGaAs layer at a rate of about 2 μm/min. This solution will not etch the GaAs etch stop layer. During etching, the color of the surface will quickly alternate through the colors of the rainbow and finally end up at the light gray and mirror-like surface of the GaAs layer [52,53].

- **GaAs removal:** 1:19 (15:285 ml) NH$_4$OH:H$_2$O$_2$ for ~30 s to etch the GaAs layer at a rate of about 3.5 μm/min [50,51]. This solution will not etch the AlAs etch stop layer, which will appear reddish.

- **AlAs removal:** 2.5% (100 ml) HF for ~20 s to etch the AlAs layer at a rate of about 1 μm/min [52,53]. This solution will not etch the GaAs anti-oxidation layer, which is the first layer of the gain element structure and which will look light gray and mirror-like.

![Diagram of the etching process](image)

Figure 4.2: The four steps of the wet etching process resulting in a chip with only the layers left that are needed for the chip to serve as a gain element in an OP-SDL setup.

In the etching, it is important to ensure that the chip is always surrounded by fresh etch solution, which can be accomplished by stirring the solution lightly with a magnetic stirrer and having a large solution volume. This is particularly important if the mechanical etching process step was not performed since the amount of material to remove is so large. The chip should be generously sprayed with deionized water.
when switching between the etch solutions, to not contaminate the solutions with residual agents from other solutions.

4.2.6 Cleaning of the chip and submount

Lastly, the photoresist is removed and the chip surface cleaned, for instance using this combination of solvents:

- acetone at 50 °C for ~5 minutes, to dissolve the photoresist,
- methanol for ~30 seconds, followed by
- isopropanol for ~2 minutes, to remove any residual contamination from the chip surface.

The submount is now ready to be attached to the cooling block, and the chip is ready to be optically pumped and serve as the gain element in the external cavity of an OP-SDL.
5 Experimental evaluation

To see how well the designed broadband gain element would perform, I conducted several experiments, of which a selection is presented in this chapter. First, I will in some detail describe the different parts of the experimental setup in the laboratory in section 5.1. Then I will present experimental results in section 5.2. Particularly important are the measurements in section 5.2.1, in which the design is experimentally validated through measurements of the threshold pump intensity for different wavelengths. I also performed high-power tuning experiments, which are shown in section 5.2.2, and measurements of the output power of the OP-SDL under different conditions in section 5.2.3.

5.1 Lab setup

A schematic of the laboratory setup can be seen in figure 5.1.

![Figure 5.1: Schematic view of the laboratory setup during measurements.](image)

5.1.1 OP-SDL cavity

The ready-to-use gain element should already be mounted on a submount according to chapter 4. When used in an OP-SDL setup, the submount should in turn be mounted on a heatsink for cooling. While the submount can be made of e.g. cheap
copper or expensive diamond, the heatsink is too big to be made of anything more expensive than copper; in our case the size of the heatsink was 40 mm × 40 mm × 10 mm. The actual mounting can be done by screws if the submount has holes, or clamps if not. Since it is vital to have an unobstructed heat flow from the gain element, I used a soft foil of thermally conducting indium between the submount and the heatsink to fill any insulating pockets of trapped air. I used a special type of indium foil with patented microstructures, which was kindly donated by Ellsworth Adhesives\textsuperscript{a}.

At the other end of the linear OP-SDL cavity, an out-coupling mirror was used to extract useful laser light. I used plano-concave mirrors\textsuperscript{b} with reflectances of either $R_{OC} = 97\%$ or $R_{OC} = 99\%$ of the concave surface and a diameter of 10 mm. The radius of curvature of the concave side was 100 mm and the mirror was mounted on a translator at a variable distance of 80 – 95 mm from the gain element.

### 5.1.2 Cooling

The temperature of the active region in an OP-SDL gain element can increase by 50 – 200 °C during high-power operation and since many material and structural properties, with bandgap energy and layer thicknesses being the most important, are temperature dependent, this of course has an effect on the performance. Therefore a lot of effort is devoted to removing the heat from the active region and many different techniques are used. An intra-cavity heatspreader is a thin (\sim 300 \mu m) sheet of a material with a very high thermal conductivity, often diamond or SiC, that is bonded to the gain element surface most commonly through liquid capillary bonding. This convenient and non-permanent bond method uses the capillary force of a thin film of a liquid (\textit{e.g.} methanol) that is sandwiched between two smooth surfaces with a slight pressure. As the liquid evaporates the surfaces are pulled closer until they reach atomic contact, and the gap between the surfaces can be as small as 15 Å \cite{54}. For a successful capillary bonding, it is important to remove all foreign particles between the smooth surfaces to ensure that the trapped pockets of air are as small and as few as possible. Though simple and efficient, the intra-cavity heatspreader is not optimal for continuously tunable OP-SDLs since the heatspreader works as an etalon and the lasing wavelength will thus hop between the resonance wavelengths of the etalon. A wedged etalon with non-parallel surfaces and AR coating can however decrease this detrimental effect. Another method of heat extraction is the flip-chip design, which is used in this work and is further described in section 4.2.

To extract heat through the layers of the DBR, a heatsink at the far end of the DBR is needed with a temperature that is lower than that of the active region. Since the heat extraction is more effective the larger the temperature difference, I cooled the heatsink using a thermoelectric cooler (TEC)\textsuperscript{c}, which is a device that uses the Peltier effect to transfer heat from one side of it to the other. The cool side of the TEC was permanently bonded to the heatsink using heat-conductive epoxy glue\textsuperscript{d} and to increase the heat extraction capacity further, an even larger copper heatsink was required.

\textsuperscript{a} Model: SMA-TIM Heat-spring
\textsuperscript{b} wzw optic AG, model: S-SET-980NM
\textsuperscript{c} Elfa, model: Supercool, 75-661-77
\textsuperscript{d} Microjoining, model: Epotek H20E
5.1. Lab setup

(a) Pump spot before focus.  
(b) Pump spot at focus.  
(c) Pump spot after focus.

Figure 5.2: The shape of the pump spot at focus and slightly out of focus.

bonded in the same way on the hot side of the TEC. The heat was thus transferred from the heatsink with the gain element to the other heatsink, which was in its turn cooled with a double-loop liquid system. The inner loop of the system was closed and used coolant fluid that was cooled via another TEC by the open outer loop using running cold water from the tap.

The TEC between the copper heatsinks was controlled by a commercial temperature controller\(^5\) and the TEC in the liquid system was set at maximum cooling power. The entire cooling system allowed me to control the temperature of the smaller heatsink from \(-20 \degree C\) to \(+30 \degree C\) almost regardless of incident pump power.

5.1.3 Pump laser

The pump laser was a diode laser\(^1\) with a wavelength of 808 nm, which is the most common pump laser wavelength for pumping GaAs absorption barriers. The absorption coefficient of GaAs at this wavelength is about \(1.3 \cdot 10^6 \text{ m}^{-1}\) [55]. The output light from the laser diode was fed via an SMA connector plug into a high-power multi-mode optical fiber\(^2\) with core and cladding diameters of 100 and 140 \(\mu\text{m}\), respectively. The other end of the fiber was connected to a lens package\(^3\), consisting of a collimating and a focusing lens with focal lengths of 150 mm and 120 mm, respectively. The maximum output power of the pump laser was 16.7 W as measured after the pump lens package.

The lens package produces a focus of the pump light in free space after \(\sim 10\) cm propagation. The shape of the pump spot before, in, and after focus are shown in figure 5.2. It is clear that the pump spot is Gaussian only in the focus, perhaps because of the multimode nature of the pump light. Mostly the pump spot was operated slightly out of focus to obtain a desired size of the pump beam on the gain element.

\(^{\text{e}}\)Thorlabs, model: TED350
\(^{\text{f}}\)LIMO GmbH, model: LIMO35-F100-DL808
\(^{\text{g}}\)LIMO GmbH, model: LIMO-SMA905-F100-1.5
\(^{\text{h}}\)US Laser Corp., model: N3303-6 and N3304-5
5. Experimental evaluation

5.1.4 CCD camera

A CCD camera\textsuperscript{1} was used in combination with a camera objective to image the gain element. I could then measure the diameter of the pump spot on the chip by means of a video analyzer system\textsuperscript{j}.

For the capture of intensity profiles a CCD detector array\textsuperscript{k} was used, with a pixel size of 4.4 $\mu$m and a detector surface size of 1600 $\times$ 1200 pixels. This CCD was connected via FireWire to a standard computer with an image capturing software from Spiricon. The camera was equipped with various neutral density optical filters to attenuate the laser intensity.

5.1.5 Spectrometer

For general wavelength measurements I used a fiber spectrometer\textsuperscript{l} with a cosine-correcting lens, which makes it possible to collect light from many incidence angles. A reflecting filter with 79\% transmissivity was used as a beam-splitter to extract part of the output laser light and guide it into the cosine-corrector through a variable attenuating filter plate. The resolution of this spectrometer was 0.3 nm.

5.1.6 Power measurement

The output power was measured with a thermal surface absorber measurement head\textsuperscript{m} connected to a power meter\textsuperscript{n}. This setup had a $\pm$3\% measurement error according to the data sheets.

5.1.7 Birefringent filter

As a wavelength-selective element I used a birefringent filter (BRF)\textsuperscript{o}, in this case a 1.0 mm thick crystalline quartz plate, with a free spectral range of $\sim$80 nm. It was mounted on a goniometer providing a way to rotate the BRF around an axis normal to its surface. Theoretical details on the tuning process can be found in section 2.3.1.

5.2 Measurements

In this section I will first describe how the setup was aligned and then describe the performed measurements.

To begin, the optical axis of the external cavity should be aligned. This was done by guiding the output light from a standard 632 nm He-Ne laser directly onto the gain element so that the laser light was reflected back to a well defined point, \textit{e.g.} the He-Ne laser output aperture, \textit{i.e.} so that the light retraces its path. I did this

\textsuperscript{1}Hamamatsu, model: C3057
\textsuperscript{2}Colorado Video Inc., model: Video Analyzer 321
\textsuperscript{j}Spiricon, model: Scorpion
\textsuperscript{k}Avantes, model: AvaSpec3648-UA-25-AF
\textsuperscript{m}Thorlabs, model: S314A
\textsuperscript{n}Thorlabs, model: PM300E
\textsuperscript{o}VLOC Inc., model: BF25.4-2T
either by adjusting the angle of the gain element using tuning screws on the heatsink, or by adjusting the angle of the incident laser light. The out-coupling mirror was then moved into place and its angle adjusted so that the reflected laser light from the planar side also hit the He-Ne laser output aperture. The surfaces of the gain element and the out-coupling mirror were after this parallel to each other and perpendicular to the optical axis.

Next, I adjusted the pump spot to the size I wanted to use for the experiment by changing the distance between the gain element and the lens package of the pump laser. The size of the pump spot was measured using the image on the CCD. With the video analyzer system I could determine the distance between the points where the intensity had dropped to $e^{-2}$ of its peak value, which I used as an approximate measure for the pump beam diameter. Since the image was magnified by the camera objective, the measured beam diameter had to be converted to the physical beam diameter by moving the gain element a certain distance using a well-calibrated translator and measuring the distance moved on the CCD image. By adjusting the distance between the lens package and the gain element, I could continuously change the size of pump spot until it reached the desired value. I commonly used pump spots with diameters between $180 \mu m$ and $350 \mu m$. The precision of the measurement of the pump spot diameter was 1% as determined by comparing repeated measurements.

The CCD image was also used to align the out-coupling mirror in the transverse directions. Then, low power light from the pump laser generated spontaneous emission from the QWs in the gain element. The emission produced two images on the CCD: one direct image and one that is twice reflected, first in the out-coupling mirror and then on the gain element or the submount. The out-coupling mirror could thus be aligned by moving the out-coupling mirror so that the twice reflected image was overlayed with the direct image. The pump power was then increased above the expected threshold of the OP-SDL. Due to a slight non-parallelism between the out-coupling mirror and the gain element, lasing still did not always commence. Nevertheless, the position of the out-coupling mirror provided a good starting point for a quickly performed systematic movement of the out-coupling mirror until lasing was initiated.

As mentioned in section 2.2 good overlap between pump spot and cavity field is important to suppress higher order transverse modes of the output beam. Therefore the cavity length should be adjusted so that the size of the fundamental mode, as determined by equation 2.3, is approximately equal to the size of the pump spot. In practice it turns out that for a high-power beam of good quality, the size of the pump spot should be somewhat larger than the fundamental mode, by a factor of 1.2-1.4.

The BRF was inserted into the cavity and aligned in the Brewster angle to the cavity optical axis by means of the He-Ne laser mentioned previously. A polarizer was used to linearly polarize the He-Ne laser in the same plane as the OP-SDL, i.e. the horizontal plane, and the angle between the BRF surface normal and the cavity optical axis was changed until the reflections from the surfaces were minimized.

During some experiments I experienced problems with catastrophic optical damage (COD) that occurred for high pump intensities and, for reasons not entirely understood, more often for short wavelengths. Probably it has to do with insufficient cooling of the active region, which is more severe at wavelengths for which the
output from the OP-SDL is low, since then photon cooling is not effective in lowering the temperature. This photon cooling is clearly illustrated in the plot of the temperature of the heatsink in figure 5.3, in which the temperature increases rapidly at the edges of the power spectrum, where the output power of the OP-SDL is decreasing. This particular measurement was performed using an old cooling system, which could only partially compensate for this effect.

5.2.1 Threshold

To validate the design concepts used in chapter 3, one would ideally measure the same quantity that was optimized, i.e. the spectral reflectance of the gain element under pump excitation. This would however be a challenging measurement requiring a tunable laser with accurately controlled intensity to probe the reflectance for each wavelength. Instead I performed measurements of the threshold pump intensity versus wavelength. This kind of measurement is not commonly performed, or at least not reported, but is in fact very informative and straight-forward to implement. The measurements were performed by tuning the BRF to a certain wavelength and increasing the pump power until the OP-SDL began to lase. The corresponding simulation results were achieved by the method described in section 3.4.

Results from the threshold measurements with comparisons between measurements and simulations for a conventional and a broadband design can be seen in figure 5.4. It is clear from the much wider low threshold regime of the broadband design that it indeed shows promise of a wider tuning range, and the good agreement with the experimental results shows that the used models are adequate.

For the broadband element the simulated and measured curves have a different
5.2. Measurements

(a) Threshold pump intensity for an OP-SDL with the broadband gain element.

(b) Threshold pump intensity for an OP-SDL with a conventional RPG gain element.

Figure 5.4: Measurements and simulations of threshold pump intensity for an OP-SDL with the optimized broadband gain element and with a conventionally designed gain element.

sign of the weak slope in the central wavelength region. One possible explanation for this is an over-estimation of the effect of Coulomb interaction on the gain spectra, see section 3.1.1. An over-estimation would redshift the spectra too much, and this would lead to an over-estimation of the material gain at longer wavelengths so that the calculated threshold pump intensity would be too low. Figure 5.5 is identical with figure 5.4, only that in the calculation the Coulomb interaction-induced redshift has been reduced by 10%, which is not unrealistic considering the high uncertainty in the model parameter describing this effect. As can be seen the degree of agreement is significantly increased.

Figure 5.6 shows the effect of heatsink temperature on the pump threshold; the entire spectrum is blueshifted with increasing temperature, which is consistent with the fact that both material gain and resonance wavelength redshift with increasing temperature, although at different rates: as a rule of thumb with $\sim 0.35$ nm/K for material gain and $\sim 0.08$ nm/K for resonance wavelength.

5.2.2 High-power tuning

We were also interested in whether the broadband properties, that were so obvious in the threshold measurements, would prevail even when the gain element was pumped high above threshold. This is evidently of great practical interest, and three of the most prominent published results for OP-SDLs are gathered in table 5.1.

Two typical power spectra for the broadband design are shown in figure 5.7, with tuning ranges ranging of 28 (43) nm and maximum output powers of 2.8 (2.6) W. The tuning ranges for the conventional design was 17 (27) nm with maximum output powers of 3.1 (1.9) W, for two different out-coupling reflectances. Figure 5.8 shows a comparison between the conventional and the broadband design for two different out-coupling reflectances.

That the broadband properties prevail under high pumping is obvious but the output power from the widely tunable gain element does not have the desired top-hat
5. Experimental evaluation

Figure 5.5: Measurements and simulations for an OP-SDL with the optimized broadband gain element. The simulations in this figure were based on gain that was calculated with the Coulomb interaction shrinkage constant, $C_{\text{shrink}}$, reduced by 10% as compared to the simulations in figure 5.4(a). As can be seen, the agreement between measurement and simulation is improved.

(a) Threshold pump intensity for an OP-SDL with the broadband gain element.

(b) Threshold pump intensity for an OP-SDL with a conventional RPG gain element.

Figure 5.6: Threshold pump intensity dependence on temperature.
5.2. Measurements

Figure 5.7: Measured power spectra of the OP-SDL with the broadband gain element pumped with two high pump powers. The tuning range for 16.7 W incident pump power was 43 nm and for 11.0 W it was 42 nm.

Figure 5.8: A comparison between the power spectrum for an OP-SDL with the optimized broadband gain element and a conventionally (RPG) designed gain element. When the broadband gain element is used in the OP-SDL cavity, the tuning range increases significantly. The tuning range is also wider for a higher out-coupling reflectance.
5. Experimental evaluation

(a) Reflection loss for an OP-SDL with the broadband gain element for two different out-coupling reflectances.

(b) Reflection loss for an OP-SDL with a conventional RPG gain element for two different out-coupling reflectances.

Figure 5.9: A comparison between the reflection losses from the BRF for an OP-SDL using the optimized broadband gain element and using a conventionally (RPG) designed gain element. The reflection loss was calculated using equation 3.21.

shape that was used for the target reflectance spectrum in the design, see figure 3.8. The reason for this is most likely that I have designed the gain element reflectance only at threshold, and did not consider effects that become dominant at high powers, such as gain saturation and temperature increase.

The odd twin-peak appearance of the spectra for the conventional design, which is especially notable for the lower out-coupling reflectance, seems to be somehow associated with a change in the polarization of the cavity field, since the reflection loss from the BRF is increasing in the central region, see figure 5.9(b). For comparison, the reflection loss from the BRF for the broadband design are shown in figure 5.9(a), and it is apparent that this design does not suffer from the same effect.

Table 5.1: Table listing three prominent published results for high-power tuning of OP-SDLs.

<table>
<thead>
<tr>
<th>$\Delta \lambda$</th>
<th>$P_{\text{max}}$ [W]</th>
<th>$\lambda_{\text{center}}$ [nm]</th>
<th>Strategy</th>
<th>Reference</th>
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<tbody>
<tr>
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<td>8.0</td>
<td>980</td>
<td>2-chip</td>
<td>[21]</td>
</tr>
<tr>
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<td>2.6</td>
<td>980</td>
<td>Anti-resonant + AR</td>
<td>[56]</td>
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<td>1970</td>
<td>Heterogeneous QW</td>
<td>[22]</td>
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</table>
5.2. Measurements

A commonly measured quantity of a laser is its power characteristics, i.e. the relation between the incident pump power and the output power of the laser. In my case it was difficult to measure the pump power, since space was too cramped for a direct measurement of the pump beam power to be made. Therefore I had previously measured the output power of the pump laser for different injection currents when the gain element was removed and space was less limiting. Thus it was sufficient to note the pump current when measuring the OP-SDL output power and then look up the corresponding pump power when organizing the data.

Figure 5.10 shows a selection of plots of output power versus incident pump power for the broadband design. The figure shows a plot for the free-running OP-SDL, i.e. without the BRF in the cavity, as well as three plots when the OP-SDL was tuned to three different wavelengths: $\lambda_1 = 979$ nm, $\lambda_2 = 996$ nm, and $\lambda_3 = 1004.68$ nm. These wavelength were chosen since they represent the wavelength for maximum output power in the power spectrum in figure 5.7 ($\lambda_2$) and the wavelengths for an output power of 1.5 W ($\lambda_{1,3}$). As is quite evident the threshold pump power increased for increasing wavelength, from 2.4 W for $\lambda_1$ to 9.8 W for $\lambda_3$. This can also be seen in figure 5.4, where $\lambda_1$ can be found in the regime of low threshold whereas $\lambda_2$ and $\lambda_3$ are found at the edge or outside of this regime.

There is a difference in slope efficiency of the power-power plots for the three wavelengths. When the pump power increases, the temperature of the gain element increases as well and the emission spectrum is redshifted, which is disadvantageous for short wavelengths and beneficial for long wavelengths. Thus, the slope efficiency is increased with increasing wavelength, from $\sim10\%$ for $\lambda_1$ to $\sim20\%$ for $\lambda_3$.

The setup for this measurement was a 300 $\mu$m diameter pump spot and a cavity.
5. Experimental evaluation

length of $L_c = 84.9$ mm, which corresponds to a fundamental mode diameter on
the gain element of $210 \ \mu$m. The out-coupling reflectance was $R_{OC} = 99\%$ and the
temperature of the heatsink $\sim -8^\circ\text{C}$. 
In many applications, a laser beam of high quality is of utmost importance. The standard way to quantify the quality of a beam is the $M^2$ value, which is a measure of how similar the beam is to the ideal shape of a Gaussian beam. More specifically, the $M^2$ value is the ratio of the beam parameter product (BPP) of the measured beam to that of a Gaussian beam at the same wavelength, where the beam parameter product is the beam waist diameter, $2\omega_0$, multiplied with the divergence full-angle, $2\theta$, [57]:

$$M^2 = \frac{BPP_{\text{real beam}}}{BPP_{\text{Gaussian}}} = \frac{2\omega_0 2\theta}{4\lambda_0/\pi}$$  

(6.1)

Common techniques for measuring $2\omega_0$ and $2\theta$ are either to monitor the power drop as a knife-edge cuts into the beam, or to capture cross-section intensity profiles by a scanning detector. Both techniques involve measurements at two or more positions along the optical axis, since determining the beam parameter product requires accurate measurements of the near-field, for $2\omega_0$, as well as of the far-field, for $2\theta$ [58]. Thus measurements are in general made at different times, which for pulsed or spontaneously fluctuating laser output fails to produce a reliable measure of the $M^2$ value.

In this chapter we describe a new technique for fully characterizing the beam and, based on this, determining its $M^2$ value. The full characterization means that rather than extracting a single figure of merit we determine the entire optical field distribution - amplitude and phase - in a beam cross-section. This technique relies on a single instantaneous measurement and thus removes the uncertainty inherent in having to connect measurements spread out in time. The principle of the method is laid out in section 6.1, the setup and the alignment thereof are described in section 6.2, and the simulations are briefly explained in section 6.3.

### 6.1 Method principle

For many lasers it is difficult or even impossible to directly measure the intensity profile of the near-field, i.e. the waist, of the laser beam, since the physical location of the waist often is inside or at the edge of the cavity. Furthermore, the high intensities of the narrow near-field require very high attenuation to prevent saturation in the measurement device. The concept of this measurement technique is to simultaneously
image the near- and far-field on a single CCD camera array using the weak reflections from the flat as well as the curved surface of a plano-convex lens. When the lens is inserted into the laser beam with a slight tilt, it is possible for the two reflections to be captured at two different positions on the CCD detector surface. The reflection from the curved surface of the lens will create an image of the near-field on the CCD, if the distances between the beam waist, the lens, and the CCD are carefully chosen. The field reflected from the flat surface will continue to propagate and should be allowed to reach the far-field regime before the CCD camera.

When the cross-section intensity profiles have been captured, the optical phase distribution of the beam can be retrieved by the Gerchberg-Saxton algorithm [59], after which the beam is fully characterized. The $M^2$ value is then easily calculated by numerically simulating the insertion of a thin lens into the beam using a simple beam propagation method and making virtual beam cuts to find the beam waist and divergence.

The small detector surface of many CCD cameras sets a boundary condition for the distances between the beam waist, the lens, and the camera, since both the near- and the far-field images must fit within the surface without overlap, and should preferably be equally large to provide the phase retrieval with as much information as possible. A further requirement is that the flat surface reflection should propagate a distance longer than the Rayleigh range to ensure that the intensity profile truly is the far-field. It can be shown numerically that all these requirements can be fulfilled simultaneously.

### 6.2 Setup

In the experiment used to examine this technique, a beam from an OP-SDL was used. The near-field of this type of laser is not possible to measure directly, since the beam waist is located inside the laser cavity, at the planar gain element. Therefore the intensity profile can only be measured by producing an image of the near-field, e.g. with the use of a lens, as in this method. As shown in figure 6.1, an ordinary double-convex lens was used to create an auxiliary beam waist outside the cavity, and this beam waist was then imaged onto the CCD array by the reflection from the curved surface of the plano-convex lens. Moreover, the lens was coated with an anti-reflection coating at the laser wavelength to further attenuate the intensity falling on the CCD detector surface. The CCD detector used in the setup was of the latter type described in section 5.1.4.

From numerical calculations, approximate positions of the components in the setup are obtained, but an experimental fine-tuning is required. Since many laser beams, especially the beams from OP-SDLs and VCSELs, are of high quality, close to Hermite-Gaussian beams, their intensity profiles in the near- and far-field are quite similar and it can therefore be difficult to visually ascertain that the setup is producing the actual near- and far-field. A trick to solve this dilemma is to deliberately make the laser lase in a higher order mode, e.g. the TEM$_{10}$ mode. If part of the beam is blocked by a knife-edge in, say, the far-field, the near- and far-field would behave radically different and would thus be easily distinguished from each other. Figure 6.3 shows a time-lapse as a knife-edge is cutting into the beam close to
6.2. Setup

Figure 6.1: Schematic view of the setup. The designated distances produce diameters of the near- and far-field of $\sim 2$ mm on the CCD.

Figure 6.2: Close-up of the unfolded setup for the reflections from the flat and curved surfaces, respectively.
6. Full characterization of the laser beam

Figure 6.3: Time-lapse of a knife-edge cutting into the far-field of a TEM$_{10}$ beam from an OP-SDL. The reflection from the flat surface (top, right) gives an intensity distribution on the CCD that has a one-to-one correspondence with the knife-edge plane, indicating that this is also the far-field. The reflection from the curved surface (bottom, left) is behaving quite differently, proving that this is the near-field.

the double-convex lens. By adjusting the position of the double-convex lens as the knife-edge is fully blocking one of the lobes, a symmetry point for the appearance of the reflection from the curved surface can be found, indicating that the near-field is imaged. Once the setup is fixed the near- and far-field of the laser beam can be captured; figure 6.4 shows two captured intensity distributions of a sample beam.

6.3 Numerical phase retrieval

The intensity distributions of the near- and far-field were used as input to the Gerchberg-Saxton (GS) phase-retrieval algorithm. The outline of one iteration of the algorithm is shown in figure 6.5. It consists of the following operations (numbers corresponding to those in the figure):

1) The numerically calculated far-field intensity distribution is replaced by the measured, whereas the phase distribution is retained. This operation is called a projection and is done to iteratively force the numerical intensity results to be closer to the measured intensity distribution. Compared to the original GS algorithm, the projection operation used here has been modified to improve convergence.

2) The optical field is numerically propagated back to a plane immediately before the plano-convex lens. The new two-step method [60] was used to enable a
6.3. Numerical phase retrieval

Figure 6.4: Two simultaneously captured intensity distributions of the near-field (top, left) and the far-field (bottom, right) of a sample laser beam. The beam was intentionally made to lase on a higher order mode.

convenient choice of the sampling distance.

3) The optical field is multiplied with a phase modulating function to simulate the reflection in the curved surface of the plano-convex lens.

2) Propagation forward to the detector plane.

5) A GS projection of the measured near-field intensity distribution onto the calculated.

2) Propagation back to the lens plane.

4) Inversion of the lens function, to simulate the reflection from the planar surface.

2) Propagation to the detector plane to calculate the far-field.

Figure 6.6 shows an example of the retrieved phase distribution in the far-field of a nearly fundamental-mode field after convergence of the GS algorithm (~100 iterations).
6. Full characterization of the laser beam

Figure 6.5: Flow chart over the Gerchberg-Saxton algorithm.

Figure 6.6: Optical phase distribution for a sample beam as retrieved by the modified Gerchberg-Saxton algorithm after convergence.
References


