Mapping of local temperatures on laser diode mirrors using reflection modulation

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Professor: Prof. dr. G.A. Acket

The Department of Electrical Engineering of the Eindhoven University of Technology is not responsible for the contents of graduation reports.
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Abstract

Local heating at the mirror facets of semiconductor laser diodes puts a limit on laser output power either through output power saturation or mirror degradation processes. Knowledge of the local mirror temperatures is highly useful for optimizing protective dielectric coatings and coating techniques. This report describes the development of an experimental setup for measuring local mirror temperatures using reflection modulation. Reflection modulation is shown to offer numerous advantages over alternative techniques such as Raman spectroscopy and photoluminescence techniques. It makes use of extremely small reflection changes of the semiconductor material due to heating. The temperature change is related to reflection changes according to \( \Delta T = C \cdot \Delta R/R \), where \( \Delta R \) is approximately four orders of magnitude smaller than \( R \). Knowing the physical constant \( C \) allows the recording of \( R \) and \( \Delta R \) in order to calculate the facet temperature rise \( \Delta T \). A measurement of this constant is performed for several semiconductor materials.

The construction of the setup requires careful design of a microscope with large magnification, a positioning and aligning unit for the laser diode and a sensitive detection circuit. The major part of this report describes the optical and electrical components of the setup. A small part deals with the calibration of the physical constant \( C \) and considers what will happen if a coated laser facet is to be measured with this technique. A great diversity of experiments can be performed using the reflection modulation technique including the recording of temperature vs current, temperature vs time, reflection vs time and temperature maps. The setup is capable of measuring temperatures within 2°C accuracy and with a spatial resolution of 0.5\( \mu \)m, providing a powerful technique for the characterization of laser diode mirror temperatures.
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Chapter 1

Introduction

Semiconductor lasers have been applied over many years, and today they are of growing importance in many applications. Typical applications are optical data storage, bar-code scanners, fiber-optic communications and laser printers. In the course of developing laser diodes from III-V compounds semiconductors and mixed crystals thereof, high reliability and long lifetime have always been of great importance. Extensive empirical and theoretical research on laser degradation has led to great progress in revealing and understanding basic degradation modes. This deeper knowledge of degradation processes, accompanied by essential improvements in laser design and fabrication technologies, has dramatically improved the laser performance and reliability of laser diodes. However, as system demands continue to increase optical output power from a decreasing area, the stress on materials, in particular at the laser mirrors, poses a great challenge on reliability. Local heating at the mirror surfaces is one route that limits the maximum obtainable output power. A better understanding of the local mirror temperatures of operating laser diodes is highly useful for optimizing protective dielectric coatings. Previously, local mirror temperatures have been measured by micro-Raman spectroscopy using the Stokes/anti-Stokes phonon line intensity ratio [1, 2, 3, 4] and by the photoluminescence technique, making use of the temperature dependence of the energy gap of any semiconductor material [5]. This report describes an alternative, method [6] of laser mirror characterization, called reflection modulation.

Reflection modulation techniques make use of changes in refractive index of laser diode mirrors as they are operated. Because the refractive index depends on the temperature, the facet temperature can be calculated by measuring the reflectivity of the laser diode facet. Therefore knowing the relationship between the temperature and the refractive index, \( \frac{dn}{dT} \) for a specific wavelength is necessary. Once we know \( \frac{dn}{dT} \) we can calculate the temperature change \( \Delta T \) due to switching of the laser diode, according to

\[
\Delta T = C \cdot \frac{\Delta R}{R}
\]  \hspace{1cm} (1.1)
where $\Delta R$ is the reflectivity change of the laser diode facet as the laser is pulse operated, and $R$ is the mirror reflectivity when the laser diode is switched off. Hence a continuous recording of $\Delta R$ and $R$ allows us to determine the temperature of the laser diode facet.

$$R = \frac{(n + 1)^2 + k^2}{(n - 1)^2 + k^2}$$  \hspace{1cm} (1.2)

$$\frac{dR}{dT} = \frac{dR}{dn} \cdot \frac{dn}{dT}$$  \hspace{1cm} (1.3)

After some calculations 1.3 becomes

$$\frac{dR}{dT} = \frac{4(n - 1)}{(n + 1)^2} \cdot \frac{dn}{dT}$$  \hspace{1cm} (1.4)

Typically, $n=4.39$ for GaAs at 488nm $[11]$ and $\frac{dn}{dT} \approx 10^{-3}/K$, so that

$$\frac{dR}{dT} = 8 \cdot 10^{-4} \cdot \frac{dn}{dT} \approx 10^{-6}$$  \hspace{1cm} (1.5)

and hence $\frac{\Delta R}{R} \approx 4 \cdot 10^{-3}/K$, using $R \approx 0.4$ for GaAs at 488nm (1.2).

Reflection modulation, from now on denoted as RM, offers numerous advantages:

- it’s a relatively fast method of mirror characterization compared to the alternative techniques.
- it allows continuous recording of the temperature increase $\Delta T$ as a function of the optical power output $P$.
- it allows the characterization of the mirror facet of mounted laser devices.
- it represents a very sensitive and local probe for observing the temporal development of degradation processes.
- it allows the recording of a temperature map with high spatial resolution of the hot mirror region in active layers.

This report describes the building of an experimental setup for RM measurements. Chapter 2 gives a short introduction to laser degradation processes. In chapter 3 the experimental setup is discussed in detail, paying attention to the optical components. Chapter 4 describes the electrical part of the setup, discussing the photo diode pre-amplifiers and the use of lock-in amplifiers. In chapter 5 the final setup is characterized in terms of sensitivity and reproducibility. The first experimental results are discussed in chapter 6, whereas the end conclusion about this graduation project is drawn in chapter 7.
Chapter 2

Laser degradation

Laser degradation puts a limit on optical output power of diode lasers. One of the critical parameters of laser diodes is their operating temperature, especially when a high output power is required. Heat generation is mainly due to nonradiative recombination processes and carriers generated by absorption of laser photons. Below threshold, joule effect can also be an important heating mechanism. Facet heating is due to excessive nonradiative recombination centers near the semiconductor-air interface. Due to the band bending at the laser diode facets the laser light absorption is enhanced and non-radiative recombination of generated carriers at the mirror facet leads to local heating. The laser light absorption is enhanced further because of the decreased energy gap due to an increased temperature, and hence a positive feedback loop according to figure 2.1 is created. At a certain temperature, this positive feedback loop causes thermal runaway, finally ending up in melting of the active layer area and hence catastrophic optical mirror damage occurs. The dark area created by COMD appears to be highly nonradiative and

Figure 2.1: Positive feedback loop of laser light absorption causing thermal runaway and finally melting of the laser facet.
hence a considerable temperature rise can be expected (see figure 2.2). In addition to catastrophic optical mirror damage, also slow degradation processes due to absorption of laser photons and facet heating, can contribute to degradation of laser life time.

Figure 2.2: S.E.M. picture of molten laser facet.

A very common way to increase the laser diode optical power output without decreasing its lifetime is to apply a protective dielectric coating on the mirror facet. In addition to protection against oxidation the coating is used for lowering the front mirror reflectivity while the rear mirror facet is coated to a high reflectivity, in order to increase the optical output power of the front mirror. Another important assumed function of dielectric coatings is the passivation of the laser diode mirror. In the process of optimization of dielectric coatings many different coatings have been applied and characterized by the laser diodes life time. There is still a lot of research going on to optimize both the coating and the coating process. As there are many different types of coatings still to be explored, it is important to provide for a fast way of characterization. RM techniques offer the ability to a fast characterization of the laser diode facet.
Chapter 3

The design of the optical setup

3.1 Introduction

Figure 3.1 schematically illustrates the scheme of the final experimental setup. The laser diode device is mounted on a high precision (5 nm resolution) \(x, y, z\)-translation stage (MELLES GRIOT) for positioning and aligning. A rotation facility for the laser diode is provided to align the laser diode parallel to a scan direction. For visual inspection, and adjustment the laser diode facet is illuminated with white light, coupled via the beamsplitters IBS2, PB5S21 and through the objective lens onto the laser diode facet (section 3.2.1). Beamsplitter IBS2 is only used for illumination of the laser diode facet for inspection with the microscope, and is removed during a actual measurement. The illuminated region and the reflected probe laser spot are observed with a colour video camera (see section 3.2). The laser diode is square-pulse modulated with a low repetition frequency \(f_2 = 280Hz\) and a duty cycle of 50\%, ensuring the reflection response is maximum during excitation and turned off between the pulses. A cw Ar\(^+\) laser beam (Spectra Physics model 161C-010, \(\lambda=488\text{ nm}\)) is used for probing the mirror facet. The reason for using a rather small wavelength for probing is because:

1. The absorption length (~ 80nm) of the probe laser must be kept to a minimum to make sure that only the mirror surface temperature is measured.

2. The diffraction limited spot size must be as small as possible.

3. Optical separation of the probe laser wavelength and the semiconductor laser wavelength is made easier.

A spatial filter is provided to eliminate high frequency spatial intensity variations. A 16mm and 100mm lens beam expander ensures that the aperture of the objective lens is entirely filled by the incident probe beam. For focussing the beam passes through
3.1. Introduction

Figure 3.1: Schematic diagram of the experimental setup.
3.1. Introduction

Figure 3.2: Picture of the final reflection modulation optical setup.
3.1. Introduction

an objective lens (125x) with a high numerical aperture of N.A.=0.8 to obtain a spot diameter of 0.5 $\mu$m (see section 3.2.3). The power incident on the laser diode facet is less than 0.25mW to reduce probe beam induced heating of the laser facet. Once the laser diode is positioned properly, IBS2 is removed and the laser beam impinges under normal incidence on the hot nearfield spot of the operating laser diode. Due to reflection

changes at the facet, caused by heating of the laser diode mirror, the reflected beam is amplitude modulated with frequency $f_2$ (figure 3.3) and reaches via PB$^2$S$^2$1 and LWP3 filter stack 3, where the 488 nm light is separated from the laser diode light. Special designed dielectric Fabry-Perot filters (section 3.5.2) make sure that only the 488 nm component reaches the detector. Because we’re dealing with a very small optical signal of approximate 25 $\mu$W for $R$ and 10 nW for $\Delta R$ , we have chosen to make use of the more light efficient dielectric Fabry-Perot filters instead of using a monochromator. Finally a silicon photodiode (B, type EG&G UV-444BQ) is used for detection and the signal is measured by lock-in amplifiers (EG&G 5208) tuned to frequency $f_1$ to detect $R$ and to frequency $f_2$ to detect $\Delta R$. The reason why we’re using photo diodes instead of a photomultiplier tube is because of the rather large recovery times of photomultipliers if they saturate. The output signal of the lock-in amplifier measuring $R$ is connected to the ratio input of the lock-in amplifier that measures $\Delta R$. This makes the output of the latter lock-in amplifier proportional to $\Delta R/R$. While measuring $\Delta R/R$ photodiode A monitors the laser diode output power. The entire setup, including laser diode power

![Figure 3.3: Illustration of the optical signals representing R and $\Delta R$. The R signal; is mechanically chopped with frequency $f_1$ whereas the $\Delta R$ signal is related to laser pulse frequency $f_2$.](image-url)
supply, translation stage, and the lock-in amplifiers is controlled by a personal computer
that can automatically perform the recording of a temperature map of the laser diode
mirror. Besides the recording of a temperature map the computer also automatically
performs \( L-I \) and \( T-I \) recordings. In the following sections several optical components
will be considered in more detail.

3.2 The microscope

Building an experimental setup as described in the previous section demands for a careful
design of each individual part and carefully fitting into the system. An important part

![Diagram of the microscope]

Figure 3.4: Schematic diagram of the microscope.

of the setup is the microscope through which the probe laser beam is focussed onto the
laser diode mirror. The microscope is being used for:

1. inspection of the laser diode mirror,
2. positioning and aligning the laser diode active region parallel to the scan direction,
3. focussing the probe laser beam into a very small spot.

To serve all of the above mentioned goals, the microscope must provide for proper
illumination, magnification and spatial resolving power.

3.2.1 Illumination

Proper illumination of the object plane is one of the most important issues in building a
microscope, because image formation is based on reflection or transmission of incident
3.2. The microscope

Figure 3.5: Köhler's method of illumination.

light onto the object. Hence intensity and spatial coherence of the light source determines the quality of the image. As we can see from figure 3.4 both the incident as the reflected light passes through the objective lens, which means that the light, that is reflected through beamsplitter 1, carries the image information. The resolving power of the microscope is determined by both the numerical aperture of the objective lens as well as the degree of spatial coherence of the illumination. A very common method of illumination due to Köhler is illustrated in figure 3.5. The collector lens collects the light from the light source and forms an image of the source in the focal plane of the condensor, which now contains the condensor diaphragm. The rays from each source point then emerge from the condensor as a parallel beam. This arrangement has the advantage that the irregularities in the brightness distribution on the source do not cause irregularities in the intensity of the field illumination. The aperture stop that is in front of the focal plane of the condensor determines the aperture of the illumination and hence the resolving power and the contrast of the image. The field stop diaphragm determines the area of illumination in the object plane.

3.2.2 Magnifying power

The magnifying power $M$ of the microscope consist of a magnification by the objective lens and a second magnification by the so called eyepiece. In figure 3.4 the eyepiece consists of two lenses of focal distances of 80mm and 30mm respectively. In contrast to the regular microscope the eyepiece does not focus at infinity in order to achieve an easy focus by the human eye, but it does focus onto the CCD-plane of the camera. The first 80mm lens forms an image in its focal plane, because of the parallel incident light. This image is projected onto the camera by the second 30mm lens. The magnification introduced by these two lenses is determined by the ratio $m_e = \frac{b}{v}$. As $v = 112.8 - 80 = 32.8$mm and $b = 351$mm while $\frac{1}{v} + \frac{1}{b} = \frac{1}{30}$, $m_e = 10.7$, the magnifying power of the eyepiece. The overall magnifying power is given by $M = \Gamma \cdot m_e$ and depends on the objective lens being used. The available objective lenses and their specifications are listed in table 3.1.
3.2. The microscope

<table>
<thead>
<tr>
<th>Type</th>
<th>N.A.</th>
<th>Working Distance (mm)</th>
<th>Transmission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 NPLAN ∞/0</td>
<td>0.22</td>
<td>11</td>
<td>93</td>
</tr>
<tr>
<td>25 PLAN ∞/0</td>
<td>0.40</td>
<td>-</td>
<td>89</td>
</tr>
<tr>
<td>50 PLAN ∞/0</td>
<td>0.60</td>
<td>6.8</td>
<td>87</td>
</tr>
<tr>
<td>125 PLAN ∞/0</td>
<td>0.80</td>
<td>1.96</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 3.1: Objective lens specifications.

The largest possible magnifying power $M$ equals $10.7 \cdot 125 \approx 1340 \times$. While monitoring the laser diode on a color TV monitor, an additional magnification of approximately ten times is introduced. This means that the final image can be monitored at 13,400 times the object size, which means that 1μm object size is displayed as 1.3 cm on the monitor. Note that the spatial resolving power is limited by the N.A. of the objective lens while the eyepiece and the auxiliary magnification by the monitor do not contribute to this. In the next section the spatial resolution of the microscope will be calculated. Also the minimum possible spot size is calculated, using the numerical apertures listed in table 3.1.

3.2.3 Resolving power

In order to achieve as high spatial resolution as possible while scanning the laser diode mirror, the probe spot should be as small as possible. The minimum spot size is determined by the N.A. of the objective lens. Figure 3.6b shows the beam waist $w_0$ that is diffraction limited according to equation 3.1 [7], where the numerical aperture of the lens is defined in equation 3.2, using $D$ at $1/e^2$ intensity. Using equation 3.2 the Gaussian spot diameter is diffraction limited to 0.5μm. The definition of the size of a Gaussian is somewhat arbitrary, because the Gaussian beam has no obvious boundaries to give it a characteristic dimension such as the diameter of a circular aperture. Many definitions for the beam radius are being used, such as the half maximum and the $1/e$ intensity. The beam radius used in this report, also called the beam waist $w_0$, is the radius at which the intensity has decreased to $1/e^2$ of its value on the axis (see figure 3.6a).

$$2w_0 = 0.82 \frac{\lambda}{N.A.}$$

(3.1)

$$N.A. = n \sin(\alpha)$$

(3.2)

The spot size has been measured using a ccd camera, a monitor, a video line selector.
3.2. The microscope

![Gaussian intensity distribution](image1)

Figure 3.6: a. The Gaussian intensity distribution. b. Illustration of the beam waist.

and a sampling oscilloscope as illustrated in figure 3.7. The Gamma correction of the camera must be disabled while monitoring the selected video line on the oscilloscope. If this is not done, the intensity to voltage conversion of the camera is not linear, hence finding the $1/e^2$ intensity is difficult. The time between the two $1/e^2$ points of the intensity signal is proportional to the beam waist. Calibration is performed using a ridge wave guide laser with a well known ridge width, measured with a scanning electron microscope. The width of the ridge being 3.42 $\mu$m at $1/e^2$ intensity corresponds with 15.5 $\mu$s on the time axis of the oscilloscope. The spot size, focussed through the 125 $\times$ objective lens corresponded to approximately 2.1 $\mu$s, hence the spot diameter ($1/e^2$) is $\frac{2.1}{15.5} \cdot 3.42 \approx 0.5 \mu$m.

This value is by chance exactly equal to the theoretical value of the spot size. Of course a certain error is introduced because of the focus mismatch that occurs when focussing

![Experimental setup for measuring the probe spot size](image2)

Figure 3.7: Experimental setup for measuring the probe spot size.
of the probe spot has to be performed manually.

### 3.3 Probe beam induced heating

In this section we will calculate the probe laser-induced temperature rise at the laser diode facet. The temperature \( T \) at the center of a Gaussian heat source with an \( e^{-1} \) radius of \( \rho_0 = \omega_0 \cdot \frac{1}{\sqrt{2}} = 3.5 \mu m \) on the surface of half infinite medium switched on at \( t=0 \) and with a pulse time \( t_0 \) is given [8] by

\[
T(\rho = 0, t) = \begin{cases} 
\frac{\alpha P}{\pi^{3/2} K \rho_0} \cdot \arctan \left( \frac{4 D t}{\rho_0^2} \right) & 0 \leq t < t_0 \\
\frac{\alpha P}{\pi^{3/2} K \rho_0} \cdot \arctan \left( \rho_0 \cdot \frac{\sqrt{4 D t - \sqrt{D(t-t_0)}}}{2 \sqrt{D(t-t_0)+\frac{\rho_0^2}{4}}} \right) & t > t_0
\end{cases}
\]  

\[ K_{GaAs}(T) = 5.5 \times 10^4 T^{-1.25} \text{ W/mK} \]  

\[ D_{GaAs}(T) = 0.03 T^{-1.25} \text{ m}^2/\text{s} \]

where \( K \) and \( D \) are the thermal conductivity and thermal diffusivity of the medium given [9] by equations 3.4 and 3.5. Because equation 3.3 is only valid provided that \( D \) and \( K \) are temperature independent quantities, we take \( D_{GaAs}(T = 300K) = 2.4 \cdot 10^{-5} \text{ m}^2/\text{s} \) and \( K_{GaAs}(T = 300K) = 44.1 \text{ W/mK} \). \( P \) is the absorbed light power incident on the laser diode facet. In order to determine the absorption coefficient we need to know the reflection and the transmission coefficients first. The transmission can be calculated using equations 3.6 through 3.8 [10]. The penetration depth \( z_0 \) in the GaAs material according to 3.6 through 3.8 is approximately 80nm, using \( k(\lambda = 488 \text{nm}) = 0.476 \) [11]. Note that the absorption coefficient \( \alpha \) in equation 3.6 through 3.8 is not equal to the absorption coefficient in equation 3.3.

\[
\alpha_{GaAs} = - \frac{1}{P} \frac{dP}{dz} = 4\pi \frac{k}{\lambda} \]  

\[ P = e^{-\alpha z} \]  

\[ z_0 = \frac{1}{\alpha} \]

The reflection coefficient for GaAs can be calculated by equation 1.2 using \( n = 4.392 \) and \( k = 0.476 \) [11] for \( \lambda = 488 \text{nm} \) and amounts to 39.6%. Hence the absorption is
3.4. Using polarization to increase light power for detection

60.4%. For pulse times beyond \( \tau = \rho_0^2/4D \approx 13\mu s \), and because the 488nm light is pulsed at 3.2kHz, the temperature rise can be considered stationary.

\[
T(\rho = 0, t \to \infty) = \frac{\alpha P}{\pi^{3/2} K \rho_0} \cdot \frac{\pi}{2}
\]

and hence the temperature rise induced by the scanning laser beam is approximately 1.8°C if the probe power is 0.25mW. If the incident probe power is increased to a few milliwatt the local temperature rise causes the laser diode facet to oxidate rapidly. Figure 3.8 illustrates such a probe laser induced local facet oxidation. Knowing the size of the top of the ridge, being approximately 2.5 \( \mu m \) the oxidated area provides some supplementary information about the probe spot size.

Figure 3.8: S.E.M. Picture of local probe laser induced facet oxidation.

3.4 Using polarization to increase light power for detection

Because of the very small signal corresponding to \( \frac{\Delta R}{R} \), optical signal loss in lenses, beamsplitters and filters must be kept to a minimum. Using anti reflection coatings on lenses and high transmission filters for 488 nm (see section 3.4) reduces signal loss in the
3.4. Using polarization to increase light power for detection

Polarization can be used to increase light power for detection of respective components. Beamsplitters cannot be designed having up to 100% transmission and a 100% reflection, as \( (T)ransmission + (R)eflection + (A)bsorption = 1 \).

\[
\begin{array}{cccc}
\lambda (\text{nm}) & \text{Reflection S} (%) & \text{Transmission P} (%) & \text{Elliptical} (%) \\
488 & 95 & 80 & 90 \\
670 & 62 & 78 & 42 \\
780 & 70 & 75 & 47 \\
\end{array}
\]

Table 3.2: Measured reflection and transmission of \( \text{PB}^2\text{S}^2\text{I} \) for \( \lambda = 488 \text{nm}, 670 \text{nm} \) and \( 780 \text{nm} \).

This means that \( \text{PB}^2\text{S}^2\text{I} \) in our setup (see figure 3.1) will be lossy for at least a 50%. This unacceptable signal loss caused by beamsplitter 1 can be omitted by making use of the polarization of the 488nm light. The probe laser beam is S polarized and rotated 90 degrees to P polarization by a half lambda plate. \( \text{PB}^2\text{S}^2\text{I} \) is now designed to have 95% transmission for P polarized light at \( \lambda = 488 \text{nm} \) and 5% reflection. The 5% reflected part provides a reference signal for monitoring the probe laser output. After passing through \( \text{PB}^2\text{S}^2\text{I} \) the probe laser beam passes through a quarter lambda plate that rotates the polarization over 45 degrees. The probe beam is now reflected by the laser diode mirror and again its polarization vector is rotated over 45 degrees by the quarter lambda plate and becomes S polarized. While the transmission of \( \text{PB}^2\text{S}^2\text{I} \) is 95% for the P component, the reflection for S polarized light is designed to be as close to 100% as
3.4. Using polarization to increase light power for detection

Possible. In addition, the beamsplitter has to reflect sufficient light ranging from 600 up to 1100nm to monitor the laser diode output power $P$. Note that the polarization of the laser diode output is elliptical after passing through the quarter lambda plate. Figure 3.9 shows the measured response of the PB$^2$S$^2$1 beamsplitter. The transmission and reflection coefficients are listed in table 3.2. Note that the laser diode light is polarized as well which might cause problems in calibrating the laser diode light output. But the laser diode light is turned into either circularly or elliptically polarized light by the quarter wavelength plate. Hence the transmission coefficient of beamsplitter PB$^2$S$^2$1 is almost independent of the polarization of the laser diode. Experimental data proves that that the detected laser diode output power does not change significantly if the laser diode ($\lambda = 780\text{nm}$) is rotated over 90 degrees. The second polarizing beamsplitter provides a long wave pass filter of which the response is plotted in figure 3.10. Notice that the reflection coefficient for S-polarized 488 nm light is nearly 100%, while only 3% of the 670nm and 0.05% of the 780nm laser diode light is reflected.

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>Reflection S (%)</th>
<th>Reflection Elliptical(%)</th>
<th>Transmission Elliptical (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>488</td>
<td>98</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>670</td>
<td>1</td>
<td>3</td>
<td>96</td>
</tr>
<tr>
<td>780</td>
<td>0.1</td>
<td>0.05</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 3.3: Measured reflection and transmission of LWP3 for $\lambda=488\text{nm}$, 670nm and 780nm.
3.5 Filters

3.5.1 Spatial filtering

In section 3.2.3 we already calculated the minimum obtainable spot size as it passes through a 125× objective lens with high numeric aperture. Besides the small spot size, the quality of the spot determines the resolution of our measurements as well. The laser beam picks up intensity variations from scattering by optical defects and particles in the air (see figure 3.11). Those intensity variations are known as spatial noise. High spatial frequencies can be blocked by a pinhole, whereas low spatial frequencies can be blocked by a circular aperture stop. In our case we want to block the high spatial frequencies due to scattering from dust particles and imperfections in lenses and other optical components. We will now calculate the recommended pinhole diameter and F-number of the focussing lens.

If the incident laser beam radius is \(a\) and the focal distance of the lens is \(F\), then the pinhole diameter \(D\) is given by equation 3.10. In practice a pinhole diameter of 1.5× the calculated diameter is recommended. In our setup of figure 3.1 \(F = 16\text{mm}\) and \(a = 0.62\text{mm}\), hence \(D = 12.6\mu\text{m}\). In practice we use a pinhole of 20\(\mu\text{m}\) diameter. Note that the numerical aperture of the focussing lens equals \(\frac{a}{2F}\) making use of \(\sin(\alpha) = \alpha\) for large angles. The fraction of power passed by a pinhole of diameter \(D\) is given by equation 3.11, that is in our case almost 100%.

\[
P(D) = 1 - e^{-\frac{1}{2A}(\frac{a}{D})^2}
\]

As we can see from figure 3.11, the beam diameter is expanded as it passes through the second lens. The expansion ratio is equal to the ratio of the focal lengths of the respective lenses if the focal planes of the 16mm and 80mm lens coincide. Expanding
3.5. Filters

the beam is necessary in order to fill the aperture of the objective lens, and hence using its full numeric aperture. The smallest aperture is approximately 7mm (i.e. the 125× objective lens), and hence the beam has to be at least $\frac{5}{1.2} \approx 6$ times expanded in order to fill the aperture. Even a little overfilling of the aperture is achieved by using a 100mm lens, resulting in a beam diameter of $\frac{100}{16} \cdot 1.2 = 7.5$mm.

3.5.2 Wavelength filtering

The experimental setup shows several filters and even a stack of filters to block unwanted wavelengths. The most important one is filter stack 3 (see figure 3.1) which needs to separate the 488nm light from the laser diode light. Therefore we would like to design a bandpass filter that passes only 488nm and blocks all other wavelengths. The $\Delta R$ signal which is approximately 10nW, is much smaller than the laser diode output power which might easily be as much as 25mW. Only $47\% \times 0.05\% \times 25\mu W \approx 6\mu W$ of 780nm light and $42\% \times 3\% \times 25\mu W \approx 250\mu W$ of 670nm light reaches the filter stack due to the transmission and reflection characteristics of PB$^2$S$^2$1 and LWP3, and can be considered as noise. When measuring 780nm lasers, the noise(780nm light) signal exceeds the $\Delta R$ signal by about a factor $10^3$. When measuring 670nm laser, the noise(670nm) signal exceeds the $\Delta R$ signal by about a factor $10^5$. The transmission of filter stack 3 is 49% for $\lambda=488$nm whereas the transmission for $\lambda=670$nm and $\lambda=780$nm is approximately 0.005%. Hence the rejection factor is $10^4$, resulting in an optical signal to noise ratio of 10dB when measuring 780nm diode lasers and a signal to noise ratio of -10dB when measuring 670nm lasers. This means that measuring 670nm laser diodes requires a better filter stack than the one we’re using now. Filter 2 blocks only 488nm for detection of the

![Figure 3.12: Measured transmission of filter stack 3.](image-url)
3.5. Filters

Laser diode output and filter 1 blocks the laser diode light preventing the laser diode light being fed back into the Ar⁺ laser that is operated in light stabilization mode. Filter 4 is added in order to obtain equal intensities of both the probe laser light and the laser diode output on the CCD camera, whereas filter 5 passes only the 488nm light for detection of a reference signal.
Chapter 4

Description of the electrical setup

4.1 Photodetector and pre-amplifier choice

Because we want to detect very weak optical signals, remember that $\Delta R$ corresponds to 8 nW if the resolution is 1 °C, then extra attention has to be paid to the detection part. The choice of the photo detector is based on the demand of a high response at 488 nm combined with a large detector area because of the sensitivity to mechanical vibrations when using high magnification. We have chosen a EG&G UV-444BQ UV-enhanced silicon photodiode with a large photosensitive surface diameter of 11.4mm and a response at 900nm of 0.6A/W. From figure 4.1 we read the response around $\lambda=488\text{nm}$ being approximately 0.3A/W.

![Figure 4.1: Response of the UV-444BQ photodiode.](image)

Because we want to keep the noise to a minimum a transimpedance pre-amplifier with
4.1. Photodetector and pre-amplifier choice

High gain is mounted close to the detector. Figure 4.2 shows the electrical scheme of the pre-amplifier. The most important part is the Burr Brown OPA128LM operational amplifier which has an input bias current of less than 75fA. The photodiode is reverse biased to increase gain while operating in the avalanche zone of the i-V curve.

![Electrical scheme of the transimpedance pre-amplifier](image)

**Figure 4.2: Electrical scheme of the transimpedance pre-amplifier**

The 100kΩ load marked with an asterisk in figure 4.2 determines the gain of the pre-amplifier. Using a 100kΩ resistor results in a gain of $10^5$V/A. Photodiode A and B are connected to a pre-amplifier with $10^4$V/A gain, whereas photodiode C is equipped with a $10^3$V/A pre-amplifier. The amplifier noise is negligible, being less than $100nV/\sqrt{Hz}$ for output frequency’s higher than 100 Hz. The dc component in the output signal is eliminated by using ac (capacitor C2) coupling in the amplifier.

![Amplitude response of the transimpedance pre-amplifier](image)

**Figure 4.3: Amplitude response of the transimpedance pre-amplifier**

The amplitude response is plotted in figure 4.3. Note that it is linear from 0 μW up to
4.2 Synchronous detection

30 $\mu$W. The phase response is flat for frequency's less than the cut off frequency of the differentiating circuit, given by $R_1$ en $C_1$ according to equation 4.1. In case the gain is $10^4$ V/A the cutoff frequency is 720 kHz, which means that high frequency noise is eliminated by the differentiating circuit.

$$f_c = \frac{1}{2\pi R_1 C_1}$$ (4.1)

At the end of this section about photodetector choice and pre-amplifier design we can draw the conclusion that the chosen photodetector connected to the pre-amplifier circuit shown in figure 4.2 satisfies our claims for high gain and a flat phase response.

4.2 Synchronous detection

The title of this section refers to the use of lock-in amplifiers in the detection circuit. The reason for using lock-in amplifiers is because of the increased sensitivity and dynamic reserve. Phase sensitive detection reduces the detection bandwidth and hence the noise in the detection bandwidth is remarkably reduced. The second reason is to eliminate the influence of ambient light by chopping or pulsating the detection signal. Figure 4.4 shows the electrical circuit. The reflection signal $R$ is detected synchronous to the chopper frequency of 3.2kHz by lock-in amplifier 1, whereas the reflection variations $\Delta R$ due to heating of the laser diode facet are detected synchronous to the laser pulse drive current at 280 Hz and 50% duty cycle by lock-in amplifier 2. The output of lock-in amplifier 1 is connected to an auxiliary input of lock-in amplifier 2 that divides it's output by the incoming signal. The output of the second lock-in amplifier is thus linear to $\Delta R/R$ and mismatched by a factor that is equal to the difference of the input sensitivity's of the lock-in amplifiers. In the current setup, the first lock-in amplifier is continuously operating in the 100mV range and the second lock-in amplifier is operating in the 10mV range. Except for the range mismatch, the ratio has to be multiplied by two because the $\Delta R$ signal is carried by a 50% duty cycle pulse of 3.2 kHz and hence only half of the signal is measured by lock-in amplifier 2. Lock-in amplifiers 3 and 4 are used to measure the reference signal for the $\text{Ar}^+$ laser and the laser diode output power respectively.

Another part of the setup shown in figure 4.4 is the laser drive source. For lack of a pulse current source to drive the laser diode, the current drive is replaced by a voltage drive provided by a pulse generator. The maximum current that can be drawn from the pulse generator is restricted to 200 mA, whereas ramping the voltage across the laser diode results in a non-linear current ramp because of the $I - V$-curve of the laser. Measurements are performed by ramping the voltage and reading the current across a 39$\Omega$ resistor. It is obvious that this combination of the pulse generator and a multimeter should be replaced by an adequate laser diode pulse current drive source that can be
connected to a personal computer via a GPIB bus. This would also increase the speed of the $\Delta T - i, L - i$ and $i - V$ measurements.

The Laser diode is mounted on a Melles Griot nanometer translation block which enables precise positioning of the laser diode within 5nm. The laser diode can be rotated as well in order to align the stripe parallel to the translation directions. The contact socket is suited for both SOT and TO5 packages and it's temperature can be set using Peltier heating.

### 4.3 PC Control

The complexity and great diversity of the measurements that can be performed using the reflection modulation setup demands for automatic data acquisition, storage and processing. The different types of measurements provided for are:

- $\Delta T - i, L - i, V - i$ and $L - \Delta T$
- $R - t, L - t$ and $\Delta T - t$
- Temperature maps
4.3. PC Control

For every type of measurement a Labview program is written that automatically performs the measurement. The communication between the apparatus and the PC is performed via the GPIB (General Purpose Interface Bus) bus. The current settings of all the GPIB addresses are listed in table 4.1. An example of the print output of the program that

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Type</th>
<th>GPIB address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lock-in amplifier 1</td>
<td>EG&amp;G 5209</td>
<td>28</td>
</tr>
<tr>
<td>Lock-in amplifier 2</td>
<td>EG&amp;G 5209</td>
<td>29</td>
</tr>
<tr>
<td>Lock-in amplifier 3</td>
<td>EG&amp;G 5209</td>
<td>18</td>
</tr>
<tr>
<td>Lock-in amplifier 4</td>
<td>EG&amp;G 5209</td>
<td>5</td>
</tr>
<tr>
<td>Nano Controller</td>
<td>Melles Griot</td>
<td>12</td>
</tr>
<tr>
<td>Pulse Generator</td>
<td>Philips PM5781</td>
<td>1</td>
</tr>
<tr>
<td>Multimeter</td>
<td>Philips PM2535</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.1: Apparatus and their GPIB addresses

performs the $\Delta T - i$, $L - i$, $V - i$ and $L - \Delta T$ measurements is shown in appendix A. The data from the temperature measurements is further processed with MATLAB, High-Performance Numeric Computation and Visualization Software, into a colourmap. An example of a temperature map is displayed in appendix B.

At present, the current software is being re-written and re-organized into a robust user program.
Chapter 5

Characterization of the setup

In this section the experimental setup for measuring mirror temperatures of semiconductor laser diodes will be characterized in terms of sensitivity and reproducibility of the results.

5.1 Resolution

We've already seen that it is possible to measure very local temperatures of laser diode mirrors, once we know the physical constant C of the semiconductor material that provides a relationship between the reflection coefficient and the temperature (see chapter 6 for further details on determining the physical constant C). And since we are dealing with very small optical signals that are easily disturbed by mechanical vibrations, the detected signal is rather noisy. In chapter 4 we already saw how to deal with noise using sensitive photocurrent amplifiers and synchronous detection. The final setup is capable of $\Delta T$ detection within approximately 2°K accuracy.

5.2 Reproducibility

The reproducibility of the results depends mainly on two settings:

- The focus of the probe spot (see section 6.3)
- The position of the probe spot

Since the probe spot is manually positioned using the camera view of the near field pattern of the laser diode output below threshold, it not possible to position the spot
5.3. Sensitivity to focus and probe power

5.3.1 Sensitivity to the focus

In order to determine the sensitivity to the focus setting of the probe spot, we measured several $\Delta T - i$ curves using different focus settings each time. The result is plotted in figure 5.1 where the normalized temperature at 50mA is plotted against the focus error.

![Figure 5.1: Normalized temperature error as a function of the focus error of the probe spot](image)

The error between the measured depth of focus and the calculated value is mainly due to a curve fit mismatch applied to the five measured data points in figure 5.1. The measured temperature dependence on the focus error is probably caused by the change of the probe spot size at the facet which causes the probed area to increase for both positive as negative focus error. Manually adjusting the focus using the camera picture results in a maximum focus error of 50nm which does not affect the temperature measurement according to figure 5.1.
5.3. Sensitivity to focus and probe power

5.3.2 Sensitivity to the probe power

In section 3.3 we showed that 250μWatt of probe power incident on the laser diode facet causes approximately 1.8°C heating in the center of the gaussian spot with a diameter of 0.5μm. We can only decrease this temperature rise by reducing the probe laser intensity (see equation 3.9), which also causes a proportional decrease of the ΔR signal. If the ΔR signal becomes too small detector and amplifier noise start playing a major role. To determine the minimum probe power required ΔR and R were measured at different probe power incident on the laser diode facet. Theoretically the ratio of ΔR and R does not depend on the probe power, but according to figure 5.2 the ratio increases as the probe power is less than 100μWatt. This is because of a system offset due to background illumination incident on the detector.

Figure 5.2: \( \frac{\Delta R}{R} = f(\text{probe power}) \)
Chapter 6

Introduction to coating performance measurements

This chapter gives an introduction to reflection modulation measurements. The calibration of the physical constant C is performed for several semiconductor materials and its sensitivity to a possible coating mismatch is explained. Finally some experimental results are illustrated, showing the possibilities of the RM technique.

6.1 Calibration of the physical constant C

Before we are able to present some results about temperature rise at the laser facet we need to know the exact value of the physical constant C that relates $\Delta T$ to $\Delta R/R$. Determining C is performed according to the method shown in figure 6.1. A substrate of bulk semiconductor material is mounted on a Peltier element. The temperature is

![Figure 6.1: Setup for calibration of the physical constant C.](image-url)
6.2 Coating choice

changed between 20°C and 80°C while the reflection coefficient is measured for wave­
lengths ranging from 450nm to 550nm. The constant can be calculated using the reflection change due to a 60°C temperature change and the reflection coefficient at 20°C.

Using our MOVPE facility we prepared special samples for this purpose and table 6.1 gives the measured value of C for several semiconductor materials. Figure 6.2 illustrates that the relationship between ΔT and ΔR/R is linear and that the constant for GaAs is 4·10³ [12], in agreement with the experimental data in table 6.1. Table 6.1 shows a

<table>
<thead>
<tr>
<th>Material</th>
<th>Constant C (·10³) at λ=488nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>4</td>
</tr>
<tr>
<td>InP</td>
<td>10</td>
</tr>
<tr>
<td>Al₀.₇Ga₀.₃As</td>
<td>7</td>
</tr>
<tr>
<td>Al₀.₃₅Ga₀.₅In₀.₁₅P</td>
<td>-6</td>
</tr>
</tbody>
</table>

Table 6.1: Measured physical constant C for different types of semiconductor material.

rather large difference between the constant for GaAs and the constant for Al₀.₇Ga₀.₃As. If we want to measure a temperature map of the laser diode facet, we are scanning both GaAs (active layer) and AlGaAs (cladding layers), and hence we need to be aware of the different constants for both materials. For some lasers such as buried ridge waveguide lasers (BRIDGE-lasers), in which the active layer is surrounded by many different types of semiconductor material, it is very difficult to record a temperature map. One can consider recording a temperature map using an average constant. In that case it's still possible to compare different lasers of the same type, whereas no information about absolute temperature is obtained.

6.2 Coating choice

As mentioned in chapter 1 we want to use the RM technology for optimizing dielectric coatings and different coat processes. If we want to compare a coated laser to a uncoated laser we need to make sure that both mirror loads are the same. This can be achieved by applying a coating that is transparent for the semiconductor laser wavelength, i.e. m·0.5λ for 780nm. Except for transparency at the semiconductor wavelength the coating must be transparent at 488nm. This can be approximated by coating 1.5λ at 502nm. The reflectivity of the coated laser facet is illustrated in figure 6.3. Again we determined the constant C for a Al₂O₃ coated sample of Al₀.₇Ga₀.₃As. The results are plotted in figure 6.4. The fact that the 0.5λ wavelength is 479nm instead of 488nm does not affect the insight obtained from this measurement. Notice that the constant for the coated material
6.2. Coating choice

Figure 6.2: $n(T), k(T)$ and $R(T)$ according to [12] for GaAs at $\lambda=488\text{nm}$.

is equal to the constant of the uncoated material at the $0.5\lambda$ wavelength. Notice also that within a few nanometers from the centre wavelength the constant differs considerably from the constant of the uncoated material. At lower wavelengths the constant is much higher whereas at higher wavelengths the constant decreases slightly. The results of this experiment show that it is very important to coat exactly a $0.5\lambda$ at 488nm. If the coating has to be exact $1.5\lambda$ at 488nm then the $0.5\lambda$ wavelength is no longer 780nm. This means that the mirror reflectivity changes and hence the mirror load changes too. If we want to compare coated lasers to uncoated lasers, we need to compensate for the different mirror loads.

Figure 6.3: Reflectivity of a $1.5\lambda\backslash_{502\text{nm}}$ Al$_2$O$_3$ coated sample of Al$_{0.7}$Ga$_{0.3}$As.
6.2. Coating choice

6.2.1 Compensation for equal mirror loads

In this section we will derive an expression that gives the output power compensation in order to keep the internal mirror load for two different coated lasers equal. The laser gain condition is given by equation 6.1 (see figure 6.5).

\[ R_1 R_2 e^{2(g-\alpha)L} = 1 \]  

Figure 6.4: Measured influence of a coating to the constant C.

Figure 6.5: Wave amplitudes inside a laser cavity.

Because both mirror reflectivities of an uncoated laser are equal, we have to make sure that the front and rear mirror of the coated laser are equal as well, which means that
6.3. Experimental results

\( R_1 = R_2 = R \). Using figure 6.5, equations 6.2 and 6.3 can be derived.

\[
P_{in2} = R_2 e^{(g-a)L} + e^{(g-a)L} \quad (6.2)
\]

\[
P_{out2} = (1 - R_2) e^{(g-a)L} \quad (6.3)
\]

The ratio between \( P_{in2} \) and \( P_{out2} \) now follows from previous equations.

\[
\frac{P_{in2}}{P_{out2}} = \frac{1 + R_2}{1 - R_2} = \frac{1 + R}{1 - R} \quad (6.4)
\]

Keeping both mirror loads equal for both the coated and the uncoated laser is implied in equation 6.5. Finally equation 6.6 gives an expression that gives the output power of the coated laser that is required to keep the mirror load equal to the mirror load of the uncoated laser. It is derived using equation 6.4 for both uncoated \((R)\) and coated \((R_c)\) laser facets and next equating \( P_{in,uncoated} \) with \( P_{in,coated} \).

\[
P_{in,uncoated} = P_{in,coated} \quad (6.5)
\]

\[
P_{out,coated} = P_{out,uncoated} \cdot \frac{(1 - R_c)(1 + R)}{(1 + R_c)(1 - R)} \quad (6.6)
\]

Using \( R_{GaAs} = 33\% \) [11] at \( \lambda = 780\text{nm} \), the output power compensation required to equalize mirror loads between coated and uncoated lasers according to equation 6.6 is illustrated in figure 6.6.

![Figure 6.6: Output power compensation required for equalization of mirror loads between coated and uncoated laser facets.](image)

Using \( R_{GaAs} = 33\% \) [11] at \( \lambda = 780\text{nm} \), the output power compensation required to equalize mirror loads between coated and uncoated lasers according to equation 6.6 is illustrated in figure 6.6.

6.3 Experimental results

The first measurements investigate different types of coatings and sputter processes of which the performance is known from earlier lifetime experiments. The first RM
measurements disagree with the results for life time experimental results and proved the importance of the coating transparency at 488nm, as ioned in the previous sections. Because the applied coating at the current mounted laser devices does not meet this condition, a comparison between facet temperatures of coated lasers is not possible unless we compensate for this coating mismatch.

![Graph](image)

Figure 6.7: Measurement of the COMD level of an uncoated laser

More reliable results are shown in figures 6.7 and 6.8 where the COMD level is determined and the temperature increase in time is measured respectively. Notice the sudden temperature increase that is known as thermal runaway. The absolute temperatures after thermal runaway are not realistic, because the reflectivity of the mirror facet decreases rapidly due to melting of the mirror, and hence the ratio $\frac{\Delta R}{R}$ increases. The recorded graph tells us something about the COMD level that can be expressed in either output power $L$ or temperature $\Delta T$. Notice also that the $\Delta T - i$ curve also exists of a slope below threshold and a slope above threshold, equal to the $L - i$ curve (see also appendix A). The lower slope can be thought of as joule heating, whereas the high slope is a superposition of joule heating and heating due to excess nonradiative facet recombination. If the lower slope does indeed represent joule heating, is still doubted, because the thermal resistance calculated from the $\Delta T - i$ curve ($\approx 120^\circ$K/W for epi-up mounted lasers) is much higher than the specified thermal resistance ($\approx 54^\circ$K/W for epi-up mounted lasers and $28^\circ$K/W for epi-down mounted lasers). A possible explanation for this disagreement is the mismatch of the constant C because the probe beam does not impinge under normal incidence and hence the coating does no longer meet the transparency condition. Figure 6.8 shows an increase of the temperature slope above threshold with time of a SiO$_2$ coated 780nm ridge waveguide laser. The drive current is 80mA and the temperature is 50°C. Other experiments, concerning uncoated lasers investigate the heat spreading at the mirror facet. Figure 6.9 shows four temperature maps of the same laser, operated at 30, 40, 60 and 80 mA respectively. Notice that the hot spot area is very small and that the temperature decreases within a few $\mu$m. It would
6.3. Experimental results

![Graph](image)

Figure 6.8: Temperature slope increase with time of a SiO$_2$ coated 780nm ridge waveguide laser operated at 80mA and $T=50^\circ$C.

be interesting to investigate if there is any difference in heat transfer at the facet between epi-up and epi-down mounted lasers. Also the thermal properties of a coating will probably affect the heat conduction at the facet. In order to compare the performance of different coatings, using the present data, we have to compensate for the mismatch of the physical constant $C$ due to a mismatch of the applied coating at 488nm. In section 6.1 we already illustrated the sensitivity of the constant $C$ to the position of the $1.5\lambda$ wavelength. A comparison between different coatings and uncoated lasers can be made if we presume the lower slope representing the thermal resistance and next calculating $\frac{dT}{di}$ above threshold by equating $\frac{dT}{di}$ below threshold to the specified thermal resistance. Because the thermal resistance is equal for all lasers a fair comparison between different coatings can be made. The results are given in table 6.2.

<table>
<thead>
<tr>
<th></th>
<th>Uncoated</th>
<th>Al$_2$O$_3$ magnetron</th>
<th>Al$_2$O$_3$ diode</th>
<th>SiO$_2$ magnetron</th>
<th>Si$_3$N$_4$ magnetron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dT}{di}$</td>
<td>0.08</td>
<td>0.07</td>
<td>0.19</td>
<td>0.1</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 6.2: Measured facet temperatures of different coated lasers when equating the thermal resistance to 54°K/W for all lasers.
Figure 6.9: Temperature map of an uncoated laser facet for $i=30$, 40, 60 and 80mA respectively
Chapter 7

Conclusions

Reconsidering the goals of this graduation project, the following conclusions can be drawn concerning the experimental setup for reflection modulation measurements:

- A relative simple and powerful technique for laser mirror temperature characterization is provided.
- The setup is capable of automatic recording of:
  1. $\Delta T - i$ curves.
  2. $L - i$ curves.
  3. $i - V$ curves.
  4. Temperature maps.
  5. $\Delta T - t$ curves.
  6. $R - t$ curves.
  7. $L - t$ curves.
- The temperature resolution is approximately $2^\circ C$.
- The Spatial resolution, when recording temperature maps, is $0.5 \mu m$.

The first measurement results with different coated lasers are in contrast with previous lifetime results. This has lead to the insight that the transparancy for 488nm is of major importance when comparing different types of coatings. If the coating does not satisfy this condition, it will show in the temperature slope below threshold and hence a compensation for the physical constant $C$ can be calculated.
Chapter 8

Recommendations

A great diversity of experiments, using reflection modulation can be thought of. Investigation of different coatings and sputter techniques are of primary interest, whilst the cleaving process and the soldering do certainly affect the facet heating behaviour as well. The amount of damaging to the laser facet prior to coating plays a major role in laser diode facet degradation. This could be confirmed by well considered experimental measurements, such as the recording of the facet temperature as a function of intentional damaging of the facet by sputter etching or by other means. Also the facet temperature of (N)on (A)bsorbing (M)irror lasers could confirm the importance of laser degradation due to excess non radiative recombination processes. Coating properties such as density and stress between the coating and the laser diode facet, will affect laser degradation processes as well. The recording of the facet temperature will provide more insight into degradation due to stress and density. Finally the investigation of coatings with different heat conduction is recommended. Because the hot spot area of conventional coated lasers is very local, a temperature decrease is expected if better heat conduction is provided. This will show in a temperature map of the facet. Maybe cooling of the facet could be obtained by creating a ridgy coating, surrounding the hot area.
References


Appendix A

Program output example
Reflectance Modulation Data

L-i-V curve

\[ \Delta T (K) \]

\[ L (mW) \]

\[ i (mA) \]

\[ V (Volt) \]

\[ \Delta T-i \] curve

file: 94100504.asc
uncoated laser EXAMPLE
T = 25

Reflection
31.97

i threshold
34.36 mA

low slope
0.26 K/mA

high slope
1.11 K/mA

\[ dT/dL \]
2.29 K/mW
Appendix B

Temperature map example

Figure B.1: Example of a temperature map of an uncoated laser facet at $i=80\text{mA}$ and $L \approx 25\text{ mW}$