



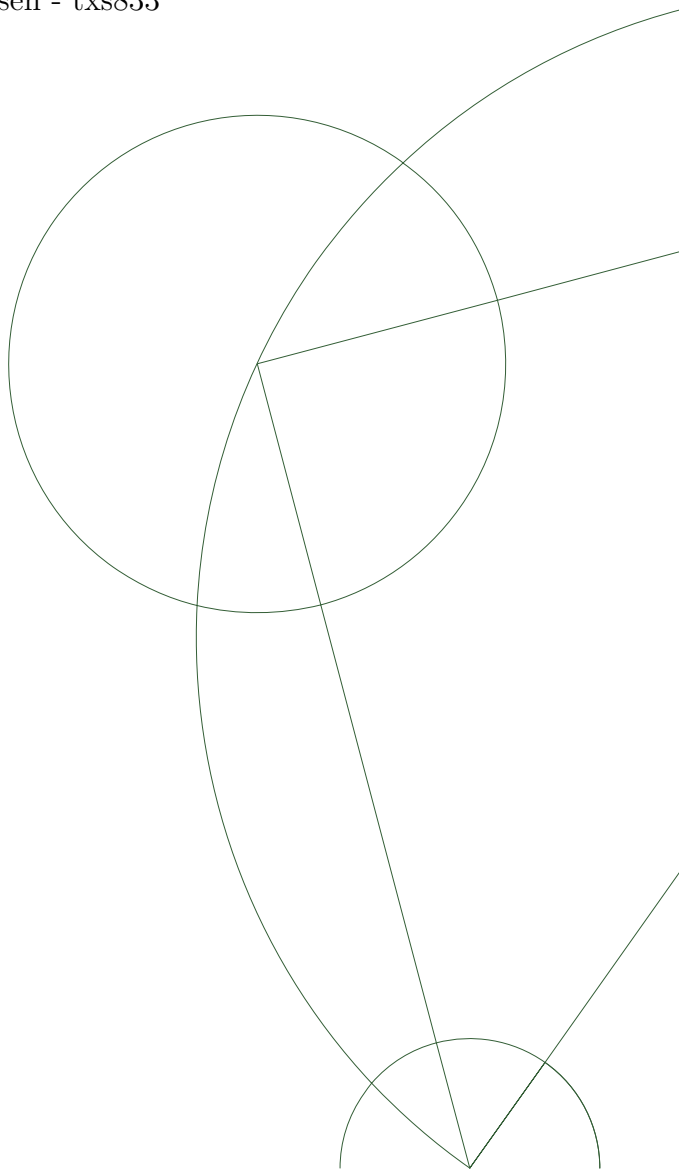
Bachelor project
Constructing an Extended Cavity Diode Laser for
Iodine spectrometry

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Submitted: June 11, 2014



Abstract

This report will focus on the construction of an Extended Cavity Diode Laser with the final goal of producing 514.67 nm light through fiber amplification and frequency doubling. The light is to be used to probe a 514.67 nm transition in the Iodine molecule, but this application is not in the scope of this project.

The amplification will be done by two Ytterbium doped optical fibers, optically pumped at 966 nm. A second harmonic generating crystal, which has previously been used to generate 517 nm, will be used for frequency doubling the light. Therefore an ECDL with a wide tuning range will be built in order to make it possible to investigate the capabilities and limitations of the crystal.

A Littman-Metcalf ECDL has been built with a tuning range between 1070 nm and 986 nm, well beyond the two target wavelengths (1029.5 nm and 1034 nm). The output power, gain threshold, polarization, frequency stability and beam profile for the ECDL have been characterized and the results are shown.

It is concluded that the ECDL cannot be amplified in the Ytterbium fiber, in the current setup, due to the divergence of the beam being too large. A new setup involving two cylindrical telescopes is suggested and roughly outlined. Further improvements of the ECDL, by enclosing it in a box, are also suggested to increase frequency stability.

Acknowledgements

I would like to thank a few people without whom this project would never have taken flight.

First of all I want to thank my supervisors Jan Thomsen and Bjarke Christensen for guiding me in the right direction and shedding light in times of darkness.

I also want to thank them, together with Martin Henriksen and Stefan Alaric, for their endless patience and understanding while I was learning how not to bump the mirrors.

Thirdly I would like to thank the the people who have had to sit through rough drafts and unfinished chapters. Besides my supervisors, a special thanks goes to Christoffer Østfeldt, Anine Borger and JoΦel Wiis. Without their effort this would be a terrible read.

Lastly I would like to thank all them who have helped me keep up the spirit when the days got blue.

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1 Introduction

What do dollar bills, cesium atoms, and a platinum rod, hidden away in a vault in France, have in common? They each hold a value we, as human beings, have agreed upon. We call these standards, be it either for currency, time, or length. And even though the dollar bill does not quite fit in, and the platinum rod has long since been replaced by more accurate measurements, they are all part of how we have measured and standardized our world. Standardization binds the world together, ensuring that numbers and figures can be communicated from person to person, even across language and cultural barriers. It could have prevented Christopher Columbus from miscalculating the circumference of the Earth, because he mistook Arabic miles for Roman miles [1].

Today the meter is linked to the definition of a second which is defined by the frequency of a particular energy level transition in a cesium atom. But cesium is not the only frequency standard, it has been chosen from a wide range of primary standards. A primary standard is a transition, whose frequency have been measured to an extreme precision, and which has been thoroughly investigated, mapping out all uncertainties. Even though the uncertainties are accounted for and their influence well understood, there is still room for improvement. Scientists struggle with improving the methods and breaking the limitations of each standard.

The primary standard I am interested in is the 514.67 nm transition in the iodine molecule (I_2) [2]. It is defined at -5 ± 1 °C, but a higher fractional stability might be obtainable below -5 °C. Iodine tends to condensate at lower temperatures which decreases the density of the molecules, making it hard achieve absorption.

A solution could be to increase the beam size, effectively probing more atoms at once. The experiments involved in defining this frequency standard typically uses a beam diameter of 3 mm. If one could build a cavity which increases the beam width, the 514.67 nm transition might be probed at a temperature lower than -5 °C, maybe leading to a higher stability and precision.

The goal of this project is to create a laser at 514.67 nm (582.5 THz). This will be done by combining a fiber amplified laser with a frequency doubling, Second Harmonic Generation (SHG) crystal.

I will reuse part of a ten year old setup which was once used to create 579 THz (517 nm) light. The setup consists of two Ytterbium doped amplifiers and an SHG crystal. It is unsure if the crystal is capable of creating 582.5 THz light by SHG, so I will construct and incorporate my own Extended Cavity Diode Laser (ECDL) with an output of 291.3 THz (1029.15 nm), but with a tuning range between 278 THz (1080 nm) and 306 THz (980 nm). With this I can determine the efficiency of the crystal at 1029.15 nm compared to 1034 nm. Building the ECDL is both a practical and economical benefit.

This report will contain the following:

First I will sketch up the relevant laser theory needed to understand the principles of the ECDL and the fiber amplifier. Then I will outline how I build my own ECDL and characterize the output. I will show measurements of the gain threshold, the polarization, the beam profile and the stability of the laser. Finally I will explain

how the fiber amplifier works and how the ECDL is coupled into the fiber amplifier, including why the ECDL could not be coupled. Due to time constraints and difficulties in the fiber coupling, I have not been able to obtain light at 582.5 THz, therefore I will not describe in detail how SHG works or display results of frequency doubled light.

In the conclusion I will summarize my results and suggest a future course for the setup.

2 General Laser Theory

In this section I will introduce the fundamental concepts behind lasing: Stimulated absorption, stimulated emission and spontaneous emission, and the corresponding rate equations. I will also briefly explain the multi level lasing and introduce the concepts of gain, gain threshold and modeclamping. As the focus of this project is the experimental implementation, this section will focus on giving a physical understanding and not on derivations. Unless otherwise noted all formulas are from Milonni & Eberly [3].

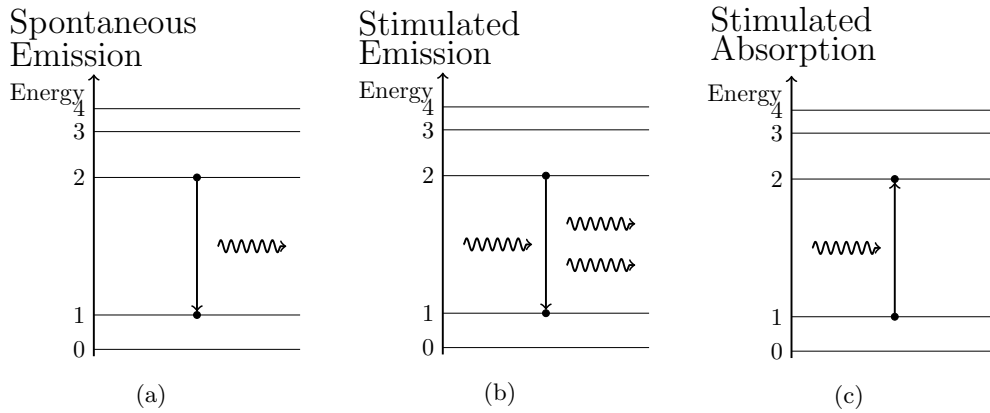


Figure 1: The three main interactions between light and matter. The horizontal lines represent the energy levels of the atom (or molecule), the dots represent electrons and the squiggly arrows represent photons.

Laser is an acronym for Light Amplified by Stimulated Emission of Radiation and as the name indicates, exploit an effect called stimulated emission.

Stimulated emission is one of the three main interactions between atoms or molecules and light, the other two being stimulated absorption and spontaneous emission. I will henceforth only use the word atom, but the theory holds for molecules as well.

As known from quantum mechanics, an atom has discrete energy levels. This is often conceptualized with electron orbitals, where orbitals farther from the core correspond to higher energy levels. The three interactions all affect the energy levels and allow the electrons to jump, not only up and down but sometimes over multiple energy levels. The interactions are divided into two different processes: Emission and absorption.

Emission, which is divided into spontaneous and stimulated emission, is when an atom emits a photon and loses energy. Due to the conservation of energy and the quantization of the energy levels, the photon energy $E = h\nu$ must be close to the energy difference between the ground state (level 1) and the excited state (level 2).

Spontaneous emission, as illustrated on figure 1a, happens all the time. The atom decays spontaneously from the excited state to the ground state and emits a photon with the corresponding energy in a random direction. The time between two spontaneous emissions depends on the stability of the energy level.

The stimulated emission on figure 1b happens when an energy level is perturbed by a photon, and therefore decays and emits an identical photon, this time in the same

direction and phase as the perturbing photon.

Absorption, which is illustrated in figure 1c, is when an atom absorbs a photon and gains the energy. As with the emission, the photon energy must be close to the energy difference between the ground state and the excited state. It is called stimulated absorption because the increase in energy is stimulated by an incoming photon.

A laser is basically built by sending a beam of photons with a well defined energy through a collection of atoms called the gain medium. If stimulated emission happens the total amount of identical photons in the beam will increase, while the opposite is true for absorption. The spontaneous emission process will happen with and without incoming photons, but the emitted photons will not necessarily be identical to the incoming ones, neither in frequency nor phase, and only a fraction of them will be emitted in the same direction as the incoming. It is possible for these spontaneous photons to stimulate emission themselves, but as the emission will be different from the incoming photons we call it Amplified Spontaneous Emission (ASE).

2.1 Emission and Absorption Rates

For stimulated emission to be the dominating effect we need to look at the rates of which the three aforementioned processes happen. When Einstein first introduced the concept of stimulated emission in 1916 [4] he labeled the rates:

$$\begin{aligned} A_{21} & \text{ For spontaneous emission from level 2 to 1} \\ B_{21} & \text{ For stimulated emission from level 2 to 1} \\ B_{12} & \text{ For stimulated absorption from level 1 to 2} \end{aligned} \tag{1}$$

furthermore it turns out that the stimulated emission rate and stimulated absorption rates are identical:

$$B_{21} = B_{12},$$

under the assumption that we are looking at the interaction between one photon and one atom. In the gain medium we will have millions of atoms, so the rates will all be proportional to the amount of atoms available for each process. As spontaneous and stimulated emission requires excited atoms, the rates will be:

$$\begin{aligned} A_{21}N_2, \\ B_{21}N_2, \end{aligned} \tag{2}$$

whereas the stimulated emission requires atoms in the ground state:

$$B_{12}N_1, \tag{3}$$

where N_1 and N_2 designate the population of atoms in the ground state and the excited state respectively.

Each time one of the three processes happen it is followed by a change in population. Therefore the rates are usually collected in the so called rate equations:

$$\begin{aligned} \frac{dN_2}{dt} &= B_{12}N_1 - B_{21}N_2 - A_{21}N_2 \\ \frac{dN_1}{dt} &= B_{21}N_2 - B_{12}N_1 + A_{21}N_2. \end{aligned} \tag{4}$$

From this it can be seen, that as long as N_2 is larger than N_1 emission processes will be dominant. This is called population inversion because it inverts the thermal equilibrium ($N_1 > N_2$). For stimulated emission to dominate over spontaneous emission the excited state must be a stable level. This will make A_{21} much smaller than B_{21} .

For a continuous lasing operation the rate equations need to be in steady state ($\frac{dN_2}{dt} = \frac{dN_1}{dt} = 0$) so a pumping mechanism P must be included which maintains the population inversion:

$$\begin{aligned}\frac{dN_2}{dt} &= B_{12}(N_1 - N_2) - A_{21}N_2 + PN_1, \\ \frac{dN_1}{dt} &= -B_{12}(N_1 - N_2) + A_{21}N_2 - PN_1,\end{aligned}\tag{5}$$

The highest possible population inversion that can be achieved with a two level laser system is $N_2 = N_1$. To circumvent this a 3-level or 4-level laser system is commonly used, these are depicted in figure 2a and 2b. The rate equation theory can without effort be expanded to include multiple levels (see Milonni [3]), and the principle behind multilevel lasers is to pump to a higher level which has a very fast natural decay rate ($A_{32,43}$ is large). The atoms then decay to a lower energy level, where they can be stimulated to lase. Using a 3-level 4-level laser configuration a stable population inversion is possible. If the 4-level scheme is used as on figure 2b there will be close to no stimulated absorption between the lasing levels 2 and 3, because the population N_2 will be close to zero. The atoms will quickly decay from level 2 to level 1.

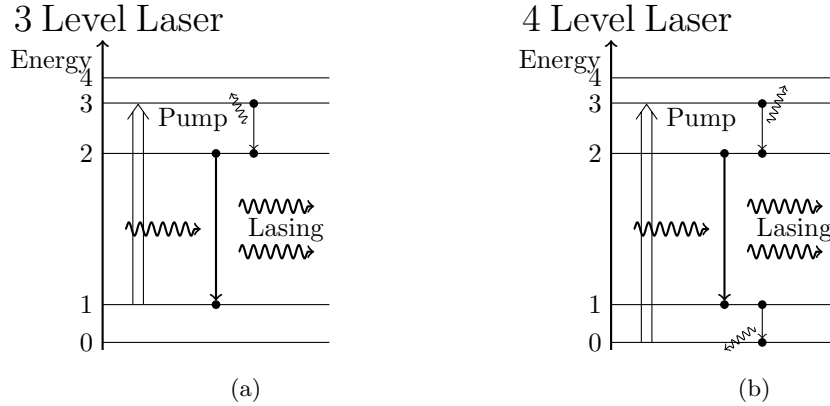


Figure 2: Schematic drawing of a 3 and 4 level laser system

2.2 Gain

If stimulated emission is the dominating effect when photons pass through the gain medium, we say there is a gain the system. The gain from a single pass through the gain medium is, in practice, not very high. By placing the gain medium between two mirrors, reflecting the photons back and fourth, a cavity is created. A cavity generally consists of two mirrors, which, in the case of a laser cavity, are semi transparent. This

lets a fraction of the photons escape. It is this fraction, or loss, that becomes the laser beam.

If the gain is higher than the losses the system is not in a steady state, and a constant population inversion cannot be obtained. When the gain exactly balances the losses, we call it the gain threshold.

By building a cavity around the gain medium we also constrain the system to only gain photons whose frequency fulfills the standing wave equation between the mirrors. This is because all other photons will interfere destructively with each other and cancel out. The spectral spacing between two allowed frequencies is called the free spectral range, and depends on the optical length of the cavity and the speed of light:

$$\Delta\nu = \frac{c}{2nL}, \quad (6)$$

where n is the refractive index of the material inside the cavity.

The gain is frequency dependent, as the chance of stimulating emission is higher if the energy of the stimulating photon is close to the transition energy (the difference between the ground and excited state). Therefore the gain can be thought of as a profile rather than a constant. This can be seen on figure 3. Often multiple modes are able to lase at the same time, but if one mode is stronger than the others it will saturate the gain medium for all the other modes. This will lower the overall gain curve and lead to only one mode placed right at the gain threshold, being the only frequency left lasing. This is called mode clamping and is an important part of the ECDL as I want to achieve a stable, single mode (and frequency) laser.

By changing the cavity length, the spectral arrangement of modes shift spectrally relative to the gain curve. This means that a new mode will start lasing and is called a mode hop. Depending on the type of gain medium and cavity this can be up to several THz. By only varying the cavity length marginally, it is possible to change the frequency without mode hopping, this is called modehop free tuning and is normally restricted to a few tens of GHz.

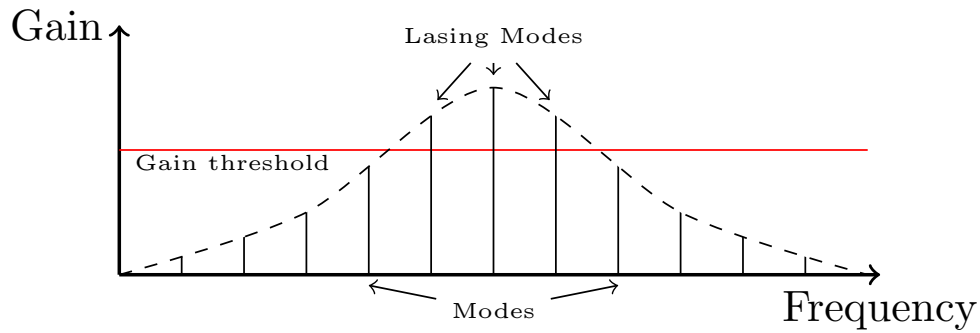


Figure 3: An example of a gain curve. The dashed line is the gain curve, the dotted line is the gain threshold. The solid vertical lines represent modes, i.e. standing waves in a cavity. Only the modes over the gain threshold will lase.

3 ECDL

The ECDL is the heart of my setup and a throughout characterization of the laser is therefore important. In this section I will explain how a diode works and how I built my ECDL and achieved single mode lasing, including a discussion of the two most common used configurations: the Littman-Metcalf and the Littrow. I will show measurements of the four main characteristics of the ECDL: The output power, the polarization, the beam profile and the frequency stability.

3.1 Solid state diodes in ECDL configurations

A semi conductor diode laser emits light through electron-hole pair recombination which can happen either spontaneously or by stimulation. The electron-hole pairs are created by driving a current over the diode effectively creating a population inversion. It is still possible to stimulate absorption instead of emission, but as long as the population inversion is maintained by the current, it is highly unlikely to happen.

By itself a diode is not single mode. This is due two things. First of all the bandstructure of semi conductor materials leads to a continuum of accepted photon energies. Accepted here meaning photons which are able to participate in a stimulating absorption or emission process. This makes the gain curve extremely wide.

The second thing preventing single mode lasing is the cavity of the diode itself. The cavity is created by polishing the ends of the gain material making them semi reflective. The cavity, however, has a very low finesse, meaning that the loss is very high leading to a high lasing threshold. On the other hand, the length of a diode cavity is very small, leading to a large mode spacing. But because of the extremely wide gain curve, the large mode spacing does not prevent multi mode lasing.

The consequences of the bandstructure and the cavity finesse are that the light emitted from a diode laser is mostly composed of ASE.

To achieve single mode lasing two things must be achieved. Firstly, some kind of mode selector must be utilized to single out a frequency. Secondly, the single frequency must be fed back into the gain medium. This is done by building a second cavity around the diode - creating an ECDL.

In this project the cavity consists of a diffraction grating and a mirror as seen on figure 4. The diffraction grating diffracts the light in an angle which depends on the wavelength, effectively acting as a mode selector. The 1. order diffraction is then reflected off a mirror and back on the grating, diffracting it back into the diode itself. By creating a cavity around the diode with a higher finesse we lower the gain threshold, leading to a larger output power and, with the grating, a single frequency laser. The laser output is the 0. order diffraction from the grating.

By gluing the mirror to an adjustable mount we are able to increase the cavity length and the angle on the grating. Both influence the modes in the cavity leading to a tunable frequency over tens of THz.

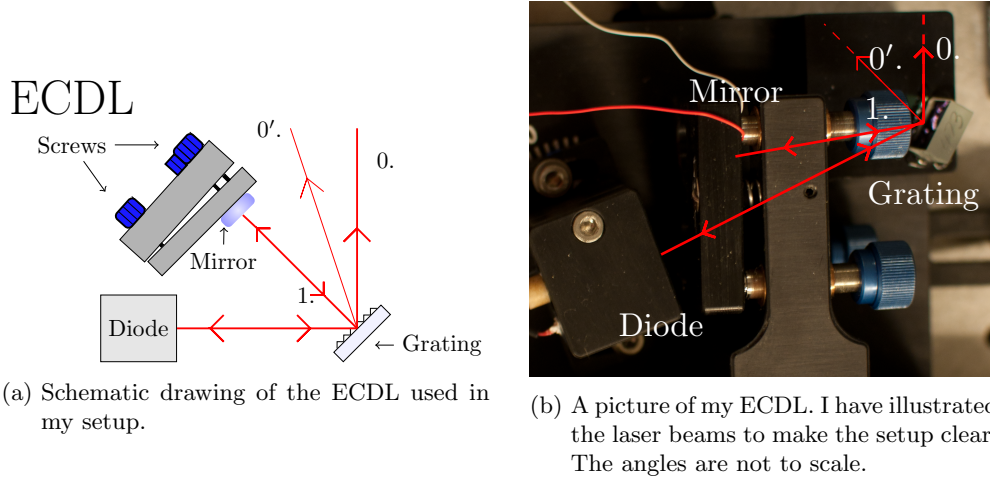


Figure 4: The Littman-Metcalf ECDL configuration used in my setup. The mirror is connected to a standard mount with tuning screws in three corners. This makes it possible to rotate and translate the mirror, changing the length of the cavity and the angle on the grating. The laser output is the 0. reflection from the grating, labeled 0. The 0'. is the 0. reflection from the mirror. It is not used and is considered lost.

3.2 My ECDL

In my setup, seen on figure 4, a grating and a mirror is used in a so called Littman-Metcalf configuration [5]. This is one of the two most common ways of building ECDL's, the other being the Littrow [5]. The big difference between the two being whether or not a mirror is added after the grating.

A Littrow configuration exploits the blazing angle of the grating, which is the angle where the 1. order is reflected back at the incident angle. In a Littrow configuration the grating is rotated or moved to select different modes which inadvertently rotates the output beam. This can be troublesome when using the ECDL in a larger setup and tuning over a wide frequency range (30THz). The Littman-Metcalf only rotates the mirror, maintaining a stable output angle. If the frequency tuning is of the order of 10^2 GHz, the change in output angle is negligible. The Littman setup comes with a lower output power compared to the Littrow as the 0. order reflection from the mirror is lost (Labelled as 0.' on figure 4).

My ECDL is built with a 1060 nm GaAs semiconductor diode laser from EagleYard [6]. It is mounted in a tubular housing containing an aspherical lens, with a focal length of 3.1 mm, which collimates the diode output. The housing is temperature stabilized with a peltier element in the mK range [7]. The housing is attached to a much larger base which holds the mirror and the grating. For specifications of the diode and wirediagrams for the peltier element see appendix A.

The mirror can be adjusted with the screws for coarse tuning and a small piezo-electric crystal is mounted on the mirror to give < GHz tunability. I have achieved a

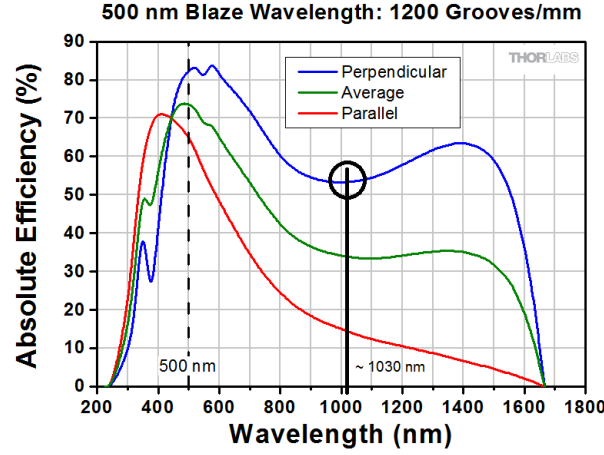


Figure 5: Absolute Efficiency determines how much is diffracted from the ruled grating used in my ECDL and how much is lost due to surface scattering, imperfections and transmission. The grating used is a GR13-1205 from Thorlabs [8]. My laser is polarized perpendicular to the grooves, but utilizes the grating twice, leading to an effective reflectance of 30%.

tunability between 280 THz (1070 nm) and 304 THz (986 nm).

The grating used is a GR13-1205 from Thorlabs [8] with 1200 grooves per mm. Figure 5 shows how the reflectance depends on wavelength. It was chosen because the peak reflectance is far away from the diodes wavelength and therefore the power fed back into the diode will be low, decreasing the chance of damaging the diode. The diode is partially linearly polarized perpendicular to the grooves (this will be shown in section 3.2.2) and is diffracted twice, so the total reflectance is at most 30%.

3.2.1 Output Power

I have measured the output power as a function of the current over the diode, without injecting the mode selected light into the diode. As previously mentioned the output is therefore primarily ASE. The plot is shown in figure 6 where I have measured with increasing and decreasing current to rule out any hysteresis effects. The errorbars on the power measurements range from 0.0005 mW to 0.005 mW, which is smaller than the dot size, so I have excluded them from the plot. The diode itself is able to output just over 1.5 mW of multimode ASE with no injection. This is lower than data sheet for the diode, because the measurement is done after the reflection off the grating.

At 110 mA there seems to be a threshold where the power starts increasing. This suggests that the diode supports multi mode lasing, i.e. the gain threshold has been reached, but mode clamping cannot happen as the gain curve is too wide compared to the mode spacing.

To investigate the lasing abilities I have also measured the output power as a function of current, this time with injection. The data is shown on figure 7. The zoom in reveals a gain threshold between 15 mA and 20 mA, where the laser suddenly starts to

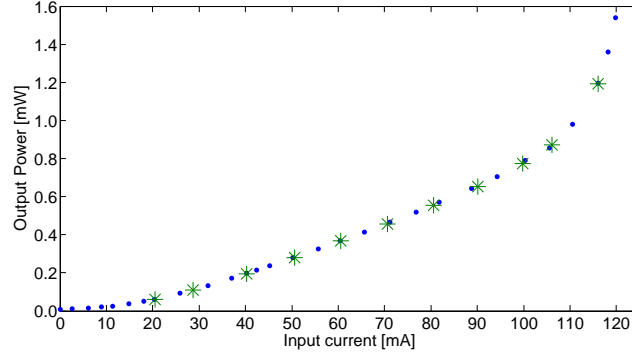


Figure 6: Output power versus input current for the noninjected ECDL. The dots are measured with increasing current and the stars with decreasing. At this level no hysteresis is observed. The errorbars have been omitted due to their small size.

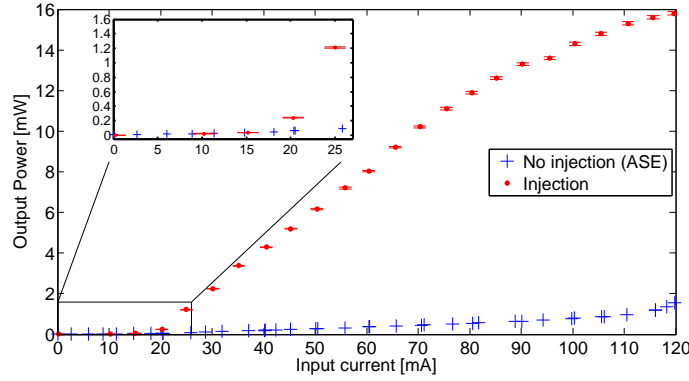


Figure 7: Output power versus input current with and without injection. The blue stars are the ASE output from figure 6 while the red dots are the laser output with injection. The zoom in shows the gain threshold between 15 and 20 mA, where the laser starts to strongly gain intensity. The errorbars on the ASE are so small that they are omitted.

strongly gain intensity. We see a linear correlation between input current and output power between 20 mA and 80 mA. This is normal for continuous wave diode lasers operating in a steady state [5]. The linear correlation decreases above 80 mA, which means the amount of available electrons, that can be excited to produce electron-hole pairs, is being depleted.

Even though the laser becomes single mode above this threshold, there will still be some ASE in the output. The ASE will at most be the same as when the diode was not injected, meaning that 10% or less of my output light at 120 mA is ASE from the small diode cavity, and is negligible.

3.2.2 Polarization

The polarization of the ECDL is measured with a Glan Thomson (GT) prism. The GT prism is a birefringent crystal which acts as a polarizing beam splitter. I send the beam through the GT and rotate it around the k-vektor of the beam. By measuring the power of the transmitted light I will be able to determine how linearly polarized the light is.

Due to the GT only allowing the light polarized parallel to its optical axis to propagate, there will be a simple relation between turning angle of the GT and measured power:

$$P_{mes} = P_0 \cos^2(\theta), \quad (7)$$

where θ is the angle between the optical axis of the GT and the polarization of the laser. On figure 8 the output power is plotted against the angle. I have fitted equation (7) plus a constant to the data, to make the cosine dependence clearly visible.

The degree of polarization can be calculated by using the stokes parameters: $S_1 = \frac{I_0 - I_{90}}{I_0 + I_{90}}$, where 0 and 90 refer to parallel and perpendicular relative to the table, it can be calculated that about 75% of the light from the diode is linearly polarized parallel to the table.

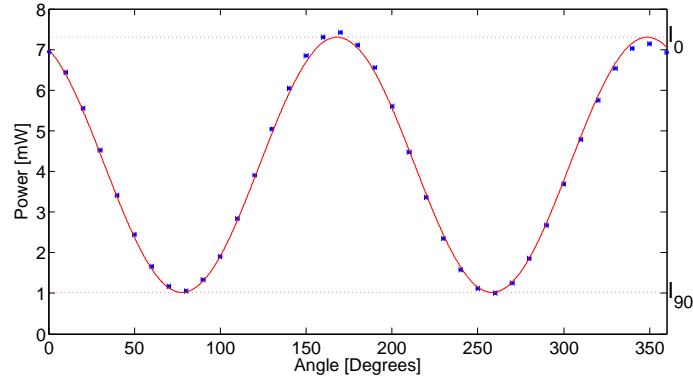


Figure 8: Plot of the power output as function of the angle between polarization axis and the optical axis of the GT. The blue dots are the datapoints. The largest error is the angle which is included as horizontal errorbars. To make the cosine dependence clear I have fitted equation (7) to the data with a red line, it is mainly to guide the eye so I have excluded the fitting and goodness parameters.

3.2.3 Beam Profile and Divergence

According to EagleYard [6], the diode emits a TEM_{00} transversal spatial mode. This is the lowest order Gaussian mode, and means that the intensity distribution orthogonal to the propagation direction follows a Gaussian profile. A Gaussian beam can be characterized by the following set of parameters [3]:

$$\text{The radius of curvature :} \quad R(z) \quad (8)$$

$$\text{The waist :} \quad w_0 \quad (9)$$

$$\text{The spot size :} \quad w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2} \quad (10)$$

$$\text{The Rayleigh length :} \quad z_0 = \frac{\pi w_0^2}{\lambda} \quad (11)$$

$$\text{The Divergence or Numerical Aperture :} \quad NA = \frac{\lambda}{\pi w_0^2} \quad (12)$$

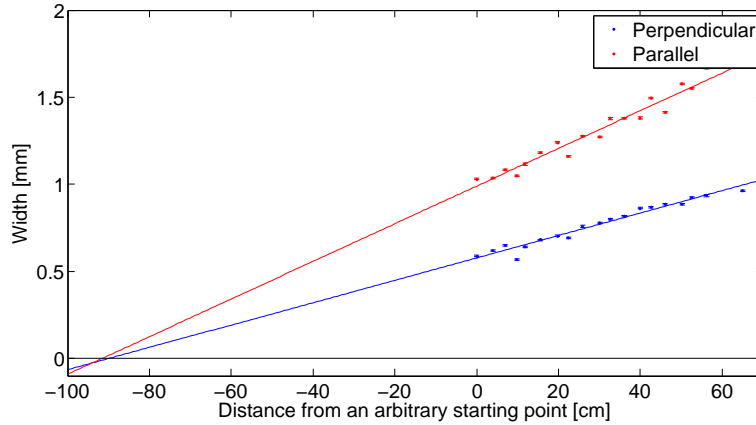


Figure 9: Measurements of the beam width at different distances from an arbitrary starting point, by extrapolating a linear fit I am able to determine the waist position. With this the rest of the beam parameters can be determined. Parallel and perpendicular are axis relative to the table surface.

To measure the beam profile I use a CCD camera and measure the intensity at varying distances and calculating the halfwidth at $\frac{1}{e^2}$ intensity. The data is plotted on figure 9 where perpendicular and parallel are the axis relative to the table surface. The data shows what seems like two different Gaussian beams, instead of one. This is due to the beam profile being ellipsoid instead of circular. This is a common sight in diode lasers [5]. Nothing is lost in treating the two cases separately.

I have fitted a straight line to both datasets as the waist size becomes linear in distance when sufficiently far from the waist:

$$w(z) \approx w_0 \frac{z}{z_0}, \quad z \ll z_0. \quad (13)$$

By extrapolating the data to zero the waist position can be found.

By combining the equations above I have calculated the waist size, Rayleigh length and divergence. The results can be found in table 1.

	Perpendicular	Parallel
Waist position	-89.86 ± 0.04 cm	-91.55 ± 0.05 cm
Waist size	0.26 ± 0.02 mm	0.15 ± 0.01 mm
Rayleigh length	198 ± 26 mm	71 ± 9 mm
Divergence	1.29 ± 0.08 mrad	2.16 ± 0.14 mrad

Table 1: Calculations of the beam parameters based on measurements.

When a Gaussian beam propagates through an optical element such as a lens, it is transformed into another Gaussian beam with a different set of parameters. This makes it easy to calculate how Gaussian beams propagate throughout an optical setup [3]. By collecting the parameters of the Gaussian beam in the variable q :

$$q(z) = \frac{1}{\frac{1}{R(z)} + \frac{i\lambda}{\pi w^2(z)}}, \quad (14)$$

the ABCD raytracing can be used to calculate the characteristics of a beam after an optical element:

$$q_f(z) = \frac{Aq_i + B}{Cq_i + D}, \quad (15)$$

where A, B, C, D is determined by the optical path of propagation. Being able to calculate this is extremely important when I want to use the ECDL with the fiber amplifiers, as it involves coupling the laser to a fiber, where especially the divergence is an issue.

3.2.4 Frequency Stability

To measure the frequency stability I have used a wavemeter with a resolution of 10^{-6} nm. I have measured the wavelength for an hour and after 30 minutes turned the temperature controller off. The data have been converted to frequency and are shown on figure 10.

It is clear that the temperature controller is able to suppress modehopping. In the first ten minutes after the temperature controller was turned off the laser made three distinct mode hops. The first and last mode hop have a size of 1.2 GHz while the second has a size of 2.4 GHz. This quantization is because of the free spectral range (see equation (6)). As I do not know the refractive index of the diode, I cannot guess how many modes are hopped at a time, but it is reasonable to assume that the second hop is over twice the amount of modes as the first and last.

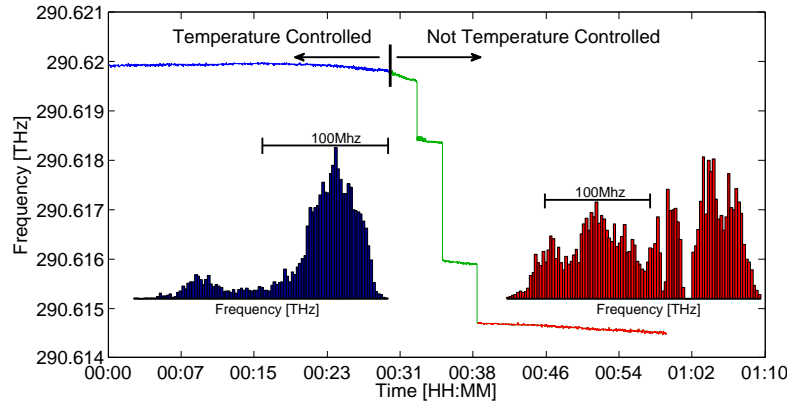


Figure 10: The stability over time of my ECDL. After 30 minutes the temperature controller was switches off. Over a time period of less than ten minutes three distinct mode hops were observed. The blue histogram is from the blue data set with temperature controller set. The red histogram is from the red data set without a temperature controller. The errorbars have been omitted due to insignificance.

The blue histogram is from the temperature controlled data while the red histogram is from the 38 minute mark, after the modehops, and onwards. The spread in the frequency is considerably lower with the temperature controller than without. In conclusion the temperature controller not only supresses modehopping but also lowers the spread of the frequency. There is still a drift even in the temperature controlled data. This is because the ECDL is completely exposed to vibrations in the surrounding air which can influence the external cavity. To increase the stability I could place the mount inside a box and guide the beam out through a window. I could also temperature stabilize the whole mount instead of only the diode. Due to time constraints this was not possible.

4 The Larger Setup

The experimental setup I will reuse, and in which the ECDL is to be used, is shown on figure 11. It consists of the ECDL, two Ytterbium doped fiber amplifiers, each 1 m in length, and an SHG crystal.

A fiber amplifier is an optical fiber with an Ytterbium doped core, making it a gain medium. A population inversion is maintained by pumping the fiber optically, i.e. sending the light from Pump 1 into the fiber and stimulating absorption, thus creating a population inversion. The mirrors are dichromatic meaning that they allow transmission for wavelengths under a certain limit and reflect wavelengths over. This will be used to guide the Pump and my ECDL (commonly referred to as the seed) into the fiber from the same end. What is left of Pump 1 after going through fiber amplifier 1 is removed at the second dichromatic mirror, as it just continues straight onwards. A new beam from Pump 2 is then used to pump the second amplifier. At last the residue of the pump 2 light is filtered out.

The fiber amplifiers are needed because the SHG process originates from a second order power expansion of the electric field and only emerges in systems with high intensity. As was seen on figure 7 the diode itself only outputs 15 mW. But with a fiber amplifier I should be able to achieve close to one watt of input power.

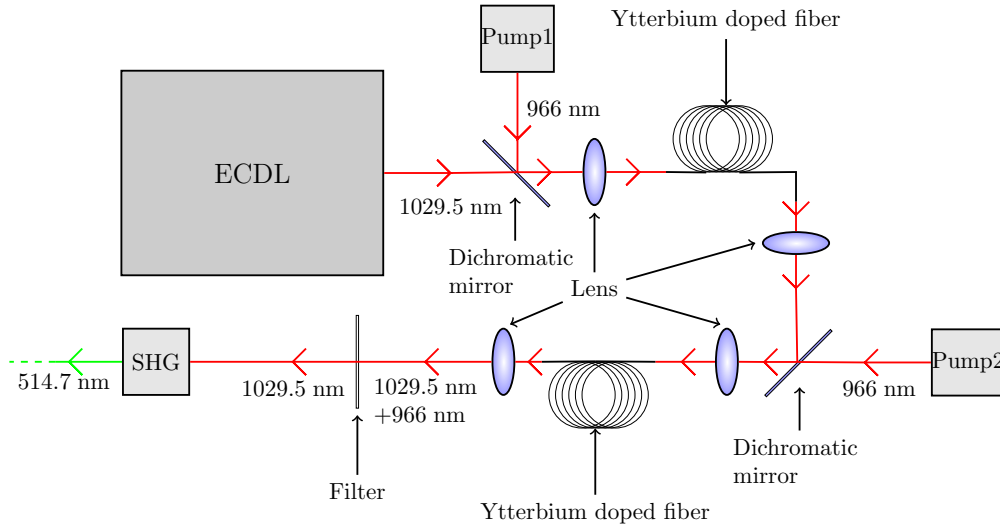


Figure 11: This setup consists of my ECDL and part of the setup previously used to generate 579 THz (517 nm) light. With the ECDL it will be used to generate 582.5 THz (514.67 nm).

5 Fiber Amplifier

In section I will explain how a fiber amplifier works and outline the difficulties involved in coupling to the first fiber.

5.1 Fiber Amplifiers

The fiber amplifiers consists of an Ytterbium doped, dual clad, polarization maintaining, optical fiber.

Taking it one property at a time, the core is doped with Ytterbium leading to an absorption and emission spectrum as the one seen on figure 12a. The cross section is proportional to the gain, and shows that at 925 nm stimulated absorption will dominate whereas at 1025 nm stimulated emission will. This is effectively a multi level laser, which I can pump at 925 nm and gain at 1025 nm. In my setup Pump 1 and 2 are two identical diodes supplying 75 mW at 4 A with a wavelength of 966 nm. I would have preferred 925 nm due to the larger difference between absorption and emission, but it was not available to me.

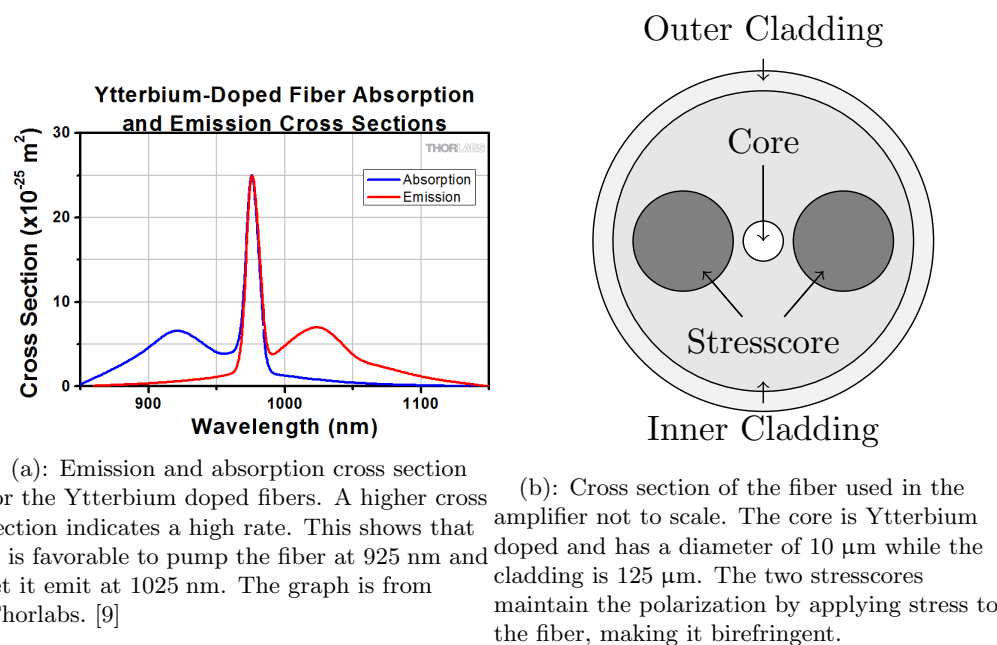


Figure 12: The specifications for the Ytterbium doped, dual clad fiber.

The fiber is designed to guide light in both the core or the cladding and therefore has an inner and an outer cladding. The pump light is guided through the inner cladding and each time it passes through the core some of it is absorbed. This is done to spread the absorption throughout the length of the fiber and reduce the risk of damaging the fiber. When the seed is then guided through the core it is in turn amplified.

The polarization maintaining property comes from the two stress cores. They induce a permanent stress in the fiber, turning it birefringent. If the light enters with a polarization along either the slow or fast axis, the polarization will be maintained.

5.2 Coupling to the fiber

In the setup, the seed and the pump are coupled from free space into the same end of the fiber. This is done with a dichromatic mirror as explained in section 4 and with a lens with a focal length of 8 mm. The biggest problem is accepted divergence for the core and the cladding. The divergence of the seed must be much smaller than the divergence for the pump, this is to ensure that they are guided separately.

The accepted divergence, is also called the Numerical Aperture (NA) of the fiber is 0.46 for the cladding and 0.08 for the core. Using the theory of Gaussian beams from section 3.2.3 I have calculated the ABCD matrix corresponding to the setup:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & l \\ 0 & 1 \end{bmatrix}, \quad (16)$$

where l is the distance from the waist to the lens, f is the focal length of the lens (8 mm) and d is the distance after the lens. If q_i is chosen with the waist as start parameters it reduces to:

$$q_i(z) = \frac{1}{\frac{1}{R(z)} + \frac{i\lambda}{\pi w^2(z)}} = \frac{-i\pi w_0^2}{\lambda}, \quad (17)$$

as the R at the waist is infinite.

By solving equation (15) with our q_i it is simply a question of equating the real and imaginary part. Note that the only unknown variable will be d . By exploiting that the curvature at the new waist will also be infinite it is possible to find an expression for d at the new waist. This is simply inserted into the imaginary part to find the waist size. I have done this for my setup and the results can be found in table 2.

	Perpendicular	Parallel	Fiber restrictions
Waist position	8.04 mm	8.04 mm	
Waist size	1.5 μm	0.85 μm	10 μm
Numerical Aperture	0.22	0.39	0.08

Table 2: Calculation of the beam profile after the 8 mm lens just before the fiber. The results show that it is not possible to do therefore I need to adjust my beam profile before entering the lens.

As the results in table 2 show, the divergence of my seed is too large to be guided in the core. This means that it does not pass through the gain medium and thusly

isn't amplified. As the seed is still able to be guided in the core, a fine transmission through the fiber can still be measured.

Due to time constraints I have not been able to proceed any further in obtaining the 514.67 nm light.

I would suggest placing a telescope before the lens, to minimize the divergence of the beam. By using cylindrical lenses, the divergence in the parallel and perpendicular direction can be corrected individually.

The placement and focal lengths of the telescope can be calculated by writing up the ABCD matrix for the setup with two extra lenses:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_3} & 1 \end{bmatrix} \begin{bmatrix} 1 & l_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & l_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & l_1 \\ 0 & 1 \end{bmatrix},$$

where $f_{1,2}$ are the focal lengths of the telescope, f_3 is the focal length of the lens at the fiber, $l_{1,2,3}$ is the distance before the telescope, between the telescope and after the telescope respectively.

By numerically simulating different values for l_1 and l_2 with different telescope focal lengths available in the lab, I suggest placing two telescopes according to table 3. This should bring the divergence below the maximum value, ensuring a good coupling to the core.

	Perpendicular	Parallel
Distance from waist	0.8 m	1 m
Telescope length	0.07 m	0.07 m
Focal lengths	150 mm, -50 mm	150 mm, -50 mm

Table 3: Suggestions for telescope placement.

6 Conclusion

In conclusion I have managed to build an ECDL with a tunability between 280 THz (1070 nm) and 304 THz (986 nm), which is in range of the two desired wavelengths 1029.5 nm and 1034 nm.

I have obtained an output power of 16 mW at 120mA, with a gain threshold at 20 mA and a polarization which is 75% linear.

I have observed the stability added by the temperature controller and I have determined the waist and divergence to 0.26 ± 0.02 mm and 1.29 ± 0.08 mrad for the perpendicular orientation and 0.15 ± 0.01 mm and 2.16 ± 0.14 mrad for the parallel. I have calculated that the divergence after the fiber lens is between 3 and 4 times too large to couple the ECDL into the fiber. This has made my unable to guide the ECDL into the SHG crystal and I have therefore not been able to conclude if the crystal can be used to create the desired 514.67 nm light.

A future course of action could be to place to telescopes at the positions indicated in table 3. This should ensure the seed became guided in the core and lead to an amplification. The guiding into the second fiber should not be difficult, as the setup has been used before, and the divergence of the beam leaving the first fiber will match the divergence tolerance of the second fiber. From there it is simply a matter of pointing the amplified seed in the direction of the crystal.

If the desired frequency can be obtained, the ECDL needs to be stabilized if it is to be used to probe the transition. I suggest doing this by thermally stabilizing the whole mount and placing it inside a box. This will eliminate the worst thermal and air vibrational fluctuations.

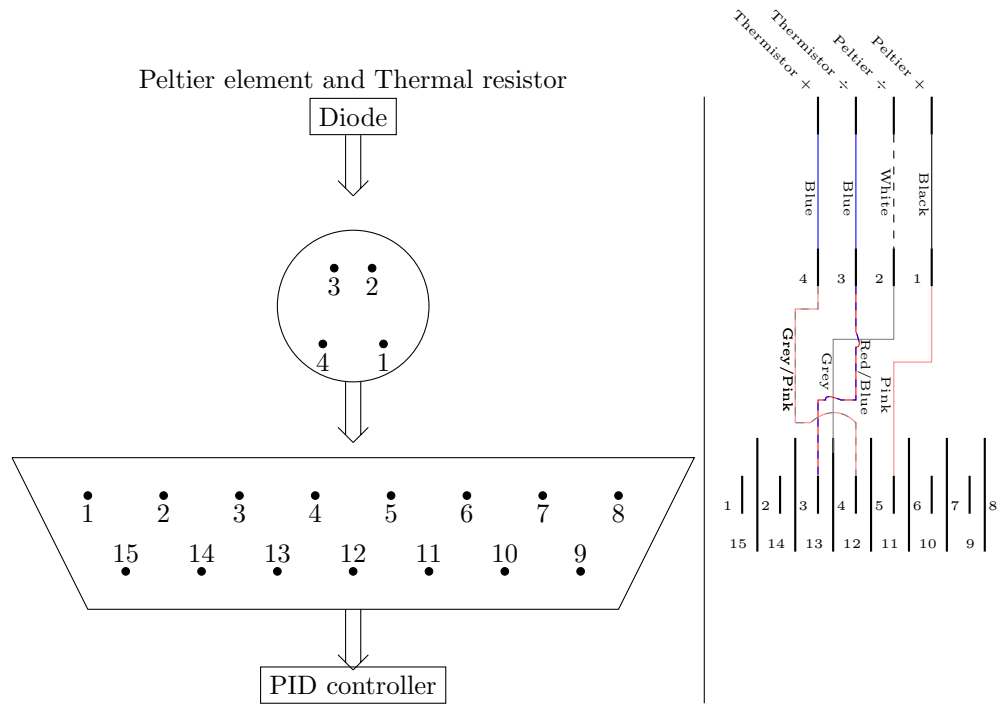
7 References

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A ECDL configuration

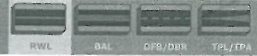
A.1 Wire diagram for temperature controller



A.2 Diode data sheet



Laser Diode – Test Protocol

Part-No.: **EYP-RWE-1060-10020-0750-SOT01-0000**Serial No.: **BA 01735**

Specific Data of the Laser Diode (25 °C):

I at n.A.mW [mA] n.A.

U at 104 mA [V] 1.85

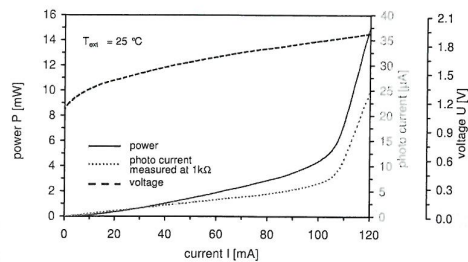
 λ [nm] 104

Threshold Current [mA] n.A.

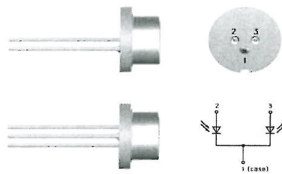
Slope [W/A] n.A.

PUI characteristics and spectrum are measured below threshold without feedback from an external cavity resonator. Laser parameter are not

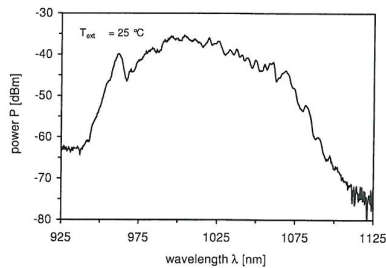
P-U-I Characteristics



Package Outline:



Spectrum



Class 0 ESD sensitive device
according to JEDEC22-A114C



IEC 60825-1



Complies with 21 CFR 1362.10 and 1362.40

Packed: Oct. 30th, 2007

Signature: *D.B.*

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A.3 Diode mounting instructions

