Construction and design of a high-power double-pass laser diode amplifier

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Abstract

Diode lasers have many benefits, but it is very hard to make diode lasers that have both high spectral purity and high intensity. In this masters thesis a diode laser amplifier with a gain of G=4 is constructed. The amplifier is a double-pass semiconductor laser amplifier and the active region is 100 μm broad.

The amplifier is operated at 793 nm using an external cavity diode laser as master laser.

This thesis also includes an overview of some aspects of the theory of laser diodes relevant to the field of amplification in semiconductors. Different aspects associated with the design of the amplifier constructed in this work are also considered both from a scientific and from a cost-efficiency point of view. The possibility of achieving even further amplification towards G=10 and beyond is also discussed.

Contents

1. Introduction

The purpose of this Masters Thesis is to design and construct a laser diode amplifier for the Photon-echo group at Atomic Physics at LTH.
The amplifier will work in conjunction with an already existing external cavity diode laser (ECDL). This laser has an output of 60 mW and the goal for this thesis is to amplify this to 500 mW without changing the frequency and with minimum change in spectral purity.
Having a larger intensity is almost always beneficial and the explicit reason to build this amplifier was:

- To improve multi-bit data storage using photon echoes[1]
- For use in pulse compression experiments[2]
- For use in any future experiment where the ECDL is used

The reason for adopting this scheme, and not to build a powerful laser to start with, is that it is almost impossible to achieve high power and small linewidth at the same time in a single diode laser.
Much about the design of the amplifier was left open and a great deal of time was spent on finding exactly what kind of lenses, amplifier and physical appearance that would result in the best performance.

1.1 The diode laser in a historical perspective

After the invention of the first ruby laser back in 1960 by Maiman the idea of a semiconductor laser was not far away. In 1962, the first lasing action in semiconductors was reported. The first heterostructure laser came in 1969. Only one year later, further work led to the first CW (continuos wave) heterostructure laser working at room temperature.
The diode laser revolution had begun.
The possibility of mass-producing diode lasers at an affordable prize soon made them come into the market in applications such as CDs, DVDs, fiber optical communication and as alternative coherent sources in science. Their main benefit and the reason for the diode lasers extraordinary success lies in the low production cost, their small size and the easy way to integrate diode lasers with electronic circuits.
Some people think that the "photonic" revolution has just begun and as we are heading into the new century new applications will form and new areas be opened.

2. Theory

This section will briefly describe some of the relevant theory of the project. It is however outside the scope of this thesis to go into detail and there is no need either since literature on the subject covers everything to satisfaction.

2.1 The semiconductor laser

The semiconductor laser is basically a forward biased pn-junction with optical feedback. The pn-junction provides the electrons and the cavity guides the light.
A picture that indicates the different parts of the laser is seen in fig 2.1.
The lasing takes place in a small part of the laser diode called the active region. Different lasers are often characterised depending on the appearance of the active region.
Typical dimensions for the active region are about 1 μm height, 3-4 μm wide and the length is a few hundred micrometers.
Extremely thin (≈100 Å) regions are called *quantum well* lasers or *multiple quantum well* (MQW) if there are many connected quantum wells. Extreme width (≈100 μm) is called *broad area* laser (BA).

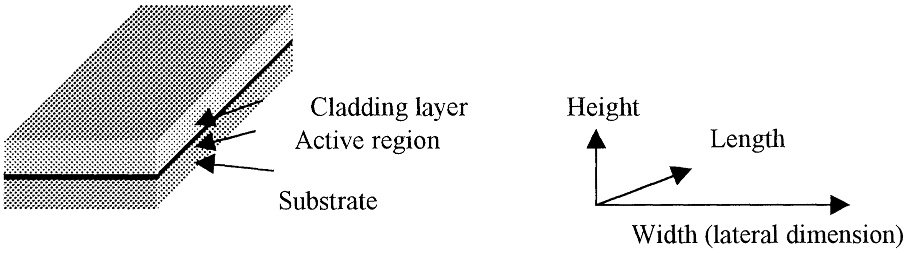

Figure 2.1 The semiconductor laser

Another way of dividing diode lasers into subgroups is by their guiding mechanism. This is also connected to the geometry of the active region.
Gain guided lasers have a wider active region than is actually emitting. This is because one part of the active region provides more gain than other parts and this results in guiding of the beam. The most common way to achieve this is by a metal stripe that directs the current to a limited part of the active region. The advantage of the gainguided laser is the fabrication simplicity. Drawbacks are that they provide quite poor guiding mechanism and their emission frequency depends very strongly on the current.
Index guided lasers have a better and more stable mode structure although the fabrication process is a lot more difficult. The active region is here laterally confined by a lower refractive index material, which provides the guiding effect.

As was indicated by the first sentence of this section the laser constitutes of two important parts, the cavity and the pn-junction (the active region) and these will now be described in more detail.

2.1.1 The cavity

It is impossible to get laser action without optical feedback. The optical feedback is often accomplished by mirrors, but could also be produced by gratings or by distributed reflection over a certain wavelength region (distributed feedback lasers (DFB), distributed bragg reflectors (DBR)).
In a diode laser the most common way to produce feedback is to cleave the diode with atomic resolution in such a way that the end facets will act as mirrors. For a typical semiconductor this will result in a reflectivity of R≈0.3, in accordance with the Fresnel equation.

$$R = \frac{(n_t - n_i)^2}{(n_t + n_i)^2} \qquad (2.1)$$

The cavity will now only support a certain number of frequencies called longitudinal modes e.g. those that show constructive interference during a roundtrip in the cavity.
In the other dimensions, height and width, the feedback is often far too small to sustain lasing but nevertheless their appearance is far from unimportant.

The layers above and below the active region, called cladding layer and substrate, almost always have a lower refractive index than the active region itself. This forms a waveguide that will keep the light from escaping. Since the height of the active region is very small, typically 1 µm which is comparable to the wavelength of the light, only certain spatial electromagnetic modes are supported. The diode is usually constructed to support only a single one of these modes.

The effect of the lateral confinement has already been discussed and it results in the distinction between gainguided and indexguided devices.

2.1.2 The pn-junction

Apart from the need of a cavity, the medium inside the cavity must also show optical gain. The current passing through the device provides the gain. In short, the diode laser is just like any other laser and must have *population inversion* in order for gain to be larger than absorption.
Carriers are injected into the thin active region where they recombine radiatively. Since it is important to concentrate the carriers to the active region a double heterostructure is often used (fig 2.2). Two larger bandgap materials surround the active region and the carriers thermalize in the active region and are thereafter unable to escape. They are forced to recombine.

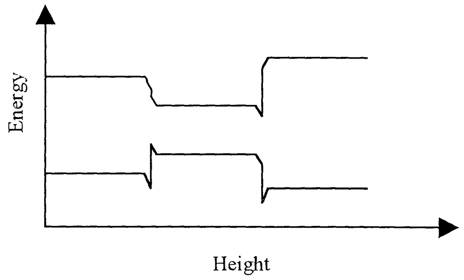

Fig 2.2 Bandgap of a double heterostructure

The current at which the stimulated emission starts to dominate is called *the threshold current* I_{th}. The current where the material gain equals the absorption is called the *transparency* point.

The recombination does not have to be radiative. The *internal quantum efficiency*, defined by equation (2.2), is a measure of how many of the recombinations that produce photons.

$$\eta_{\text{int}} = \frac{R_{radiative}}{R_{total}} \qquad (2.2)$$

$R_{\text{radiative}}$ is the radiative recombination rate and R_{total} is the total recombination rate.

The internal quantum efficiency is often close to 100% in modern diode lasers.

2.1.3 The external cavity diode laser

An external cavity diode laser (ECDL) is a laser that uses a grating to form an external cavity. A typical set-up can be seen in fig 2.3 below. The end facet facing the grating is often antireflection coated, especially if the laser is to be tuned without modehopping. The benefit of using an ECDL is that the laser frequency can be shifted in an easier and more controlled manner than otherwise. It is possible to maintain single mode lasing while tuning the ECDL over a small wavelength interval.

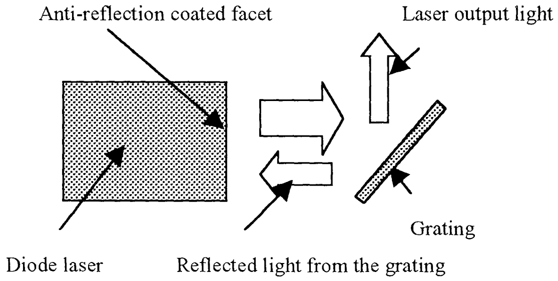

Figure 2.3 An external cavity diode laser in a Littrow set-up

2.1.4 Laser diode dependence on temperature

There are several reasons to control the temperature of a laser diode. The most important one is that if the diode becomes too hot it might sustain catastrophic damage and suffer breakdown. Catastrophic damage is connected to temperature since the propagation and creation rates of defects are strongly dependent on temperature. Catastrophic damage usually occurs in regions of large assemblies of defects. Even if the laser is kept below such a temperature the lifetime could be seriously shortened.
Apart from the threat of breakdown, temperature is very important since many laser diode characteristics depend on it. These characteristics include power, efficiency, frequency, refractive index, spatial modes, gain and size of the diode.
All these effects are very hard to separate from each other and usually everything is combined to an average drift of the frequency and the occurrence of *modehops*.

During a modehop the laser suddenly shifts to another (longitudinal) mode and the reason for this is the following. The gain peak continuously drifts towards lower energy with increasing temperature and if the laser only has a single mode, there will be a point when the next cavity mode will be closer to the gain maximum. When this happens, the laser emission will spontaneously change to that mode. The rate at which the gain peak changes is approximately 3 Å/K.
Due to the thermal expansion of the laser and changes in the refractive index the frequency is not stable in between modehops either, but will change with about 1 Å/K. The refractive index increases with increasing temperature.

This is the background for the importance of a good temperature control since even a few mK will change the frequency of the emitted light. In some areas such as in an amplifier, the frequency of the light is not determined by the gain curve of the laser but instead of the injected frequency. Such devices are not as temperature dependent as normal diode lasers but maintaining a stable temperature can in some cases, especially if the end facet reflectivity is high, still be of considerable importance.

It could be commented that when you speak about a modehop free laser it means that no modehops occur in the laser frequency when tuning the laser using e.g. an external grating in an ECDL. There also exist truly modehop free lasers such as DBR lasers but this will not be discussed further here.

The threshold current of laser diodes also depends on temperature. Often this is expressed in the form[8]:

$$J_{th}(T) = J_{th}^{0} \cdot \exp\left(\frac{T}{T_0}\right) \qquad (2.3)$$

T is the temperature, T_0 is called the base temperature, J^0_{th} is the threshold current density at T=0. T_0 depends on what kind of laser diode it is. Quantum well lasers often have less T_0 than bulk lasers for example. The drift in threshold current has several reasons but the main cause is that the electron distribution gets more smeared out at higher temperatures.

2.1.5 Laser diode dependence on current

Changes in current, as with temperature changes, affect many laser characteristics. Most of these effects derive from changes in two areas, namely changes in the electron distribution and changes in the temperature.
The bandgap of the material will shrink with increasing current due to the formation of so called bandtail states. But even though the bandgap decreases the actual gain peak of the emitting material will increase in energy.
After the threshold current has been reached stimulated emission becomes the dominant recombination mechanism and further increase in current will not increase the electron density but instead shorten the radiative lifetime.
This results in the other major parameter affecting the emission frequency, temperature, to take over. Increase in current beyond threshold will shift the frequency towards lower energy due to increasing temperature.

Another feature of interest is how the output power depends on current. Before threshold most of the radiation will be spontaneous emission and the output power will be very low. Beyond threshold the output power will increase quickly and a typical L-I curve (Light-Current) can be seen in fig 2.4. This sudden increase in photon density will in turn lower the electron concentration.

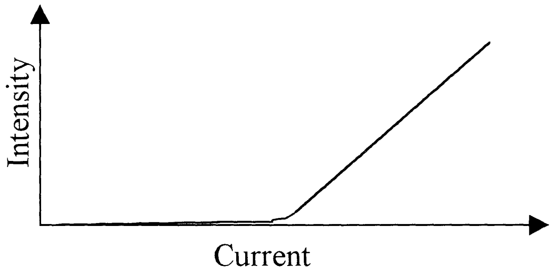

Fig 2.4 A typical L-I curve.

The electron density also affects the refractive index. An increase in electron density will decrease the refractive index of the material. This can in some cases lead to an anti-guiding effect in the device but this is to some extent prevented by increasing temperature. The increase in current will namely lead to heating effects and as stated in the previous section this will lead to increase in refractive index.

When considering the overall impact of changes connected to an increase of the current in a laser diode it is very hard to make predictions without numerical calculations and modelling.

2.2 Injection locking

If a laser is subject to feedback or light injection from another laser its behaviour will be affected. The response will depend on the exact way the light is coupled into the laser. Strong feedback for example often results in the formation of a new cavity, a phenomenon used in an ECDL for example. A small feedback can improve the output power as well as the linewidth but it is more often a cause for linewidth enlargement and destabilisation of the laser. When the light input is not laser light feedback but intentionally injected light from another coherent source, another phenomenon could appear. What could happen is that the laser that experiences the injected light (slave) will be forced to emit light of the same frequency as the injected light (originally emitted by the other source, the master oscillator). This is called injection locking.

The frequency difference between the master and the slave can not be too large however and the interval also depends on the injected intensity. The dependence of the locking range can be seen in[3] Eq (2.4) and it has been verified experimentally[4].

$$\Delta\omega_{lock} = \frac{2\cdot\ln\left(\frac{1}{R}\right)}{T}\cdot\sqrt{\frac{I_1}{I_0}} \tag{2.4}$$

R is the reflectivity, T is the transit time for one cavity round trip, I_1 is the injected intensity and I_0 is the free running intensity of the slave laser. It is good to remember that the locking range strongly depends on the reflectivity as will be discussed later on.

Finally it is well worth noting that the phenomenon of injection locking is not at all something only connected to lasers. It is a general non-linear effect that can occur in electronic oscillators[5] as well as in two pendulums sitting beside each other on the same wall[3,6].

2.3 Amplification

There are several different ways that have been invented over the years to amplify an optical signal. In this section I will outline the most common and important ways.

But first, why do you want to amplify an optical signal at all?

The reason for this is that in many areas the intensity of the laser beam is of importance.

A too small signal may not be detectable and the information will then be lost. In other areas such as non-linear optics, certain phenomena scale quadratic with intensity and more or less disappear if the intensity is small.

Today telecommunication and the use of optical fibers are growing by the minute. But sending an optical signal down a fiber will attenuate it and eventually it will not be possible to read out the signal without errors. A simple solution to this problem is to amplify the signal before it has diminished too much.

In the field of research, the use of diode lasers is very common. The reasons for this are their compactness, reliability, long lifetime, easiness to integrate in electrical systems and their price. Often it is preferable to have both as high intensity and as small linewidth of the radiation as possible. Unfortunately this may be very hard to achieve. The reason is that if you want high intensity you need a large lasing area but a large lasing area will spontaneously emit light into several lateral modes.

A solution to the problem in this case is to inject the output from a low-intensity single mode laser, into a larger laser.

The fiber amplifier and the semiconductor laser amplifier, are two large subgroups[7] within the field of laser amplification and I will describe them later in more detail.

To distinguish amplification from injection locking it is easiest to consider a laser that is driven below threshold but above transparency. This means that any optical signal travelling in the medium will experience gain but due to losses predominantly at the end facets, the gain is not enough to sustain laser operation. However, if a signal from the outside is injected into the laser the signal will experience gain as it passes through the material. When the optical signal has passed through the medium it will have increased in strength, i.e. amplification has occurred. The great difference between this case and the injection-locking scheme is that here there is no original signal that locks to the injected light.

The most common way to achieve the amplification in practice is to have a material with high material gain but without a cavity. This would for example be the case for a standard laser diode with one or both facets antireflection (AR) coated.

The occurrence of amplification would still be there if the laser is driven above threshold but in that case it would be more appropriate to speak about injection locking.

As was noticed in formula 2.4 the locking range strongly depends on the reflectivity R, and if one end facet is AR-coated the injection range will be very large. This fits well with the discussion above and it has also been experimentally verified that AR-coated semiconductor diode laser amplifiers have an amplification range in the same region as their gain profile.

Two main equations that govern the complex amplification behaviour in a semiconductor laser are[8].

$$g = \frac{dg}{dn}(n - n_0) \qquad (2.5)$$

$$\frac{dn}{dt} = \frac{J}{e \cdot d_{las}} - \frac{n}{\tau} - \left(\frac{dg}{dn}\right)\frac{(n - n_0) \cdot P}{A_m \cdot \hbar \cdot \omega} \qquad (2.6)$$

g is the cavity gain coefficient, n is the carrier concentration, n_0 is the carrier concentration at transparency, J is the current density, d_{las} is the height of the active region, P is the optical power, τ is the carrier recombination time and A_m is the area of the optical mode.

Under continuous operation or when using pulses much longer than the carrier recombination time the equations can be simplified and the equation for the steady-state gain coefficient is.

$$g = \frac{g_0}{1 + \frac{P}{P_s}} \qquad (2.7)$$

P_s is the saturation power (see section 2.3.1) and g_0 is the unsaturated gain coefficient.

The change in optical power per unit length is proportional to the gain coefficient.

$$\frac{dP}{dz} = g \cdot P \qquad (2.8)$$

The overall gain G for a signal travelling the length L in an amplifying medium can be calculated by integrating eq (2.8).

$$G = \frac{P_{out}}{P_{in}} \exp\left(g_0 \cdot L - \frac{G-1}{G} \cdot \frac{P_{out}}{P_s} \right) \qquad (2.9)$$

2.3.1 Saturation

The physical cause for saturation is that the increase of stimulated emission results in a decrease of the carrier population. This decrease results in a lower gain. Because of saturation there is a point where an increase in injected light power almost do not result in any increase in output power. This can also be understood in terms of energy. A certain amount of energy is stored in the diode. If the input energy is much larger than the energy stored, most of the energy in the diode will be extracted. The gain will however be very small.

Even if saturation does not have to be a problem in itself a special phenomenon called *cross-channel* saturation can occur if an amplifier is used at two different frequencies at the same time. Ideally the gain for each channel would only depend on the power in the channel itself but unfortunately the power in other channels can also cause saturation.

2.3.2 The semiconductor laser amplifier

The semiconductor laser amplifier (SLA) is a laser diode that uses the stimulated emission effect to amplify an injected signal. The signal that is about to be amplified is coupled into the laser diode and the direction of the output might be forwards (single pass amplifiers) or backward (double pass amplifiers).

Amplifiers in general show a dependence on the polarisation of the coupled light. This is not hard to understand since most laser diodes run in either TM (Transverse Magnetic) or TE (Transverse Electric). TE is the most common and the reason for this is that the confinement factor for TE modes are slightly higher and this result in less losses and higher gain. In some areas this is not much of a problem since it is possible to change the polarisation in the direction of maximum gain, but in other applications there is no choice and the gain polarisation dependence could be a problem. In this thesis we could arbitrarily choose direction of polarisation for the input field with a half-wave plate and therefore I will not discuss the problem further.

2.3.2.1 The single pass amplifier

The single pass amplifier is just what the name suggests, it is an amplifier in which the light is injected at one side and extracted at the other end. There are however a variety of ways how to do this. The active region could be formed as in fig 2.5a, which is just a normal diode laser. An alternative is the broad area diode laser in fig 2.5.b, which due to its larger area has the possibility to reach higher output intensity. A third alternative is seen in fig 2.5.c. This is known as a flared or tapered amplifier. With this construction it has been possible to achieve a large amplification. The widening of the active area is formed to match the beam divergence in the material. In this way can the gain be constant throughout the material and the risk of filamentation decreases. Filamentation occurs spontaneously if there are regions with a large unused electron population. All the models are AR-coated at both facets. The reasons for this are many. A decrease in reflectivity will increase the coupling efficiency. It will also enlarge the injection locking range, increase the threshold current and prevent disturbing internal reflections. The last point is of extra importance if the amplifier is designed for very short pulses.

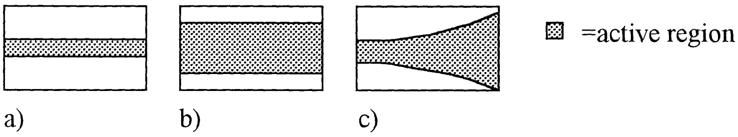

fig 2.5. a) a normal laser diode b) a broad area diode c) a flared amplifier

2.3.2.2 The double pass amplifier

The idea behind the double pass amplifier is that a larger gain length will increase the amplification. A problem with the single pass amplifier is, as was pointed out, that in the area close to the injection, the light is not intense enough to extract all available energy from the inverted system. One solution that was mentioned was the flared amplifier. Another solution is to let the signal pass twice through the active region. If the injected signal is small enough not to saturate the material in the beginning of the amplifier, the second pass will be able to extract more photons.

The benefit of easy extraction of the amplified signal that single pass amplifiers have is a problem that has to be solved in double pass amplifiers. One way to do this is to enter the laser diode at a small angle as indicated in fig 2.6. This makes it easier to single out the amplified beam from the ASE (Amplified Spontaneous Emission). This technique can unfortunately not make use of the entire amplifier. The injected beam never passes some areas as can be seen in fig 2.6.

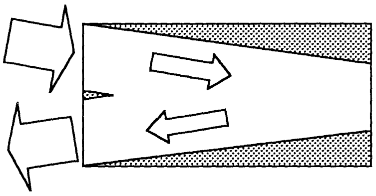

Fig 2.6 A double pass amplifier, injection at an angle

Another technique for extracting the amplified light is to use an optical isolator (see section 3.4). In this case the injected light is sent in without inclination and the entire area of the amplifier can be used. This technique also has its drawbacks. Since the amplified light is actually directed at the isolator, the extinction ratio has to be extremely high. For high power amplifiers it may not even be possible to achieve ratios high enough without introducing significant absorption.

2.3.3 The fiber amplifier

This type of amplifier is the most commonly used within the telecommunications area. The reason for this is very simple. The optical signal is transmitted through an optical fiber. The amplification in a fiber amplifier occurs inside the fiber and therefore coupling-losses could be kept at a minimum. Besides that, a fiber amplifier is usually quite long (1-100 m) and can provide a very high gain.
The fiber is doped with a rare earth substance, usually Er^{3+}, and is pumped by another laser.

2.4 Noise

The quality of the beam in terms of noise will change, unfortunately to the worse, after amplification. Hopefully only ASE will be emitted, but if the current is high enough or if the light is not coupled well enough into the amplifier, cavity modes of the amplifier might start to lase.

Noise can be a large problem or no problem at all; it depends on whether the experiment, where the laser is going to be used, is sensitive to the intensity or the intensity/nm. It may also depend on whether the noise is coherent or not.
For the experiments where this amplifier will be used, noise should not be a large problem if it is incoherent or if it is spread equally over a large bandwidth. The FWHM of the ASE in semiconductor amplifiers is typically 10-20 nm. This equals 4.5-9 THz. In the experiments where the amplifier will be used only the noise within 10 GHz will be a problem.
In this interval a signal to noise ratio of 1000 to 1 will be enough.
This means it is enough with a signal to noise ratio of almost 1 to 1 if the ASE is divided evenly in frequency.
Even if the ASE in reality is not evenly divided, the calculation is good enough to prove that even if the signal is noisy it can be of use.

3. Construction and design

The focus of this thesis was on the construction and design part. Since much of this work is hard or uninteresting to describe I will let the result speak for itself. I will however describe the parts used in the set-up and where relevant make comments on the choice of equipment or method used.

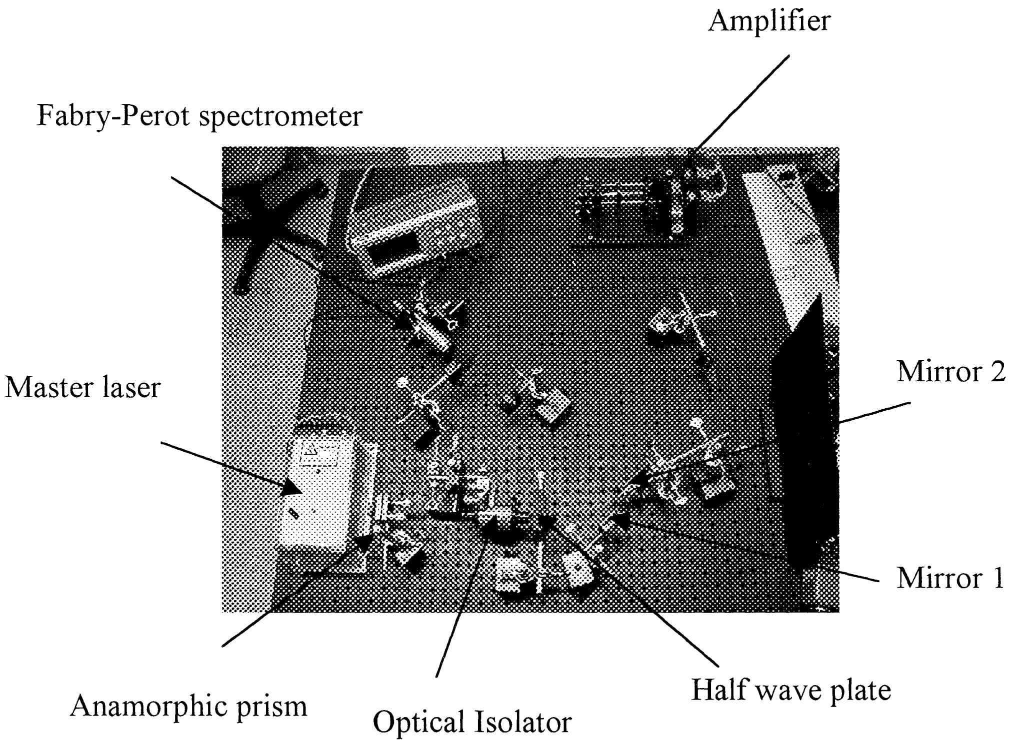

Fig 3.1 The set-up

The experiments were done with the set-up shown in fig 3.1. The master laser sends out a beam that passes through the anamorphic prism pair and through the optical isolator. It passes through a half-wave plate and is reflected at mirror 1. It hits the entrance mirror of the amplifier, which directs it towards the cylindrical lens, the aspherical lens and finally the laser diode (see section 3.5). At the rear facet of the diode, it is reflected and the now amplified beam takes the same way back at a slightly different angle until about half of the beam is reflected at mirror 2, indicated in fig 3.1. The beam finally hits a Fabry-Perot spectrometer and the signal is measured on the oscilloscope.

3.1 The master oscillator

Originally the amplifier was supposed to use the laser described in reference [9] as master oscillator (the first laser). In the end the laser described in reference [10] (the second laser) was used in the set-up. I will without going into too much detail describe the two systems, their purpose and their differences.

The first laser is an external cavity diode laser, which uses a Littrow grating for feedback into the diode. An electro-optic (EO) crystal with electrodes is placed inside the cavity.

The optical path length of the crystal can be tuned by varying the voltage across the crystal and in this way the frequency can be shifted 10 GHz.
All components inside the resonator are antireflection coated for minimum losses.

The second system is quite similar in the sense that it also has a Littrow configuration with an EO crystal to shift the frequency with. The main difference is that the electrooptical crystal in the first laser is designed to prevent modehops and that the first laser is build monolithically to give increased stability. This results in a better frequency stability of this configuration. The output power is also larger for the first laser (60 mW).

3.2 The broad area laser diode

We used a C-type high power laser diode from Sacher Lasertechnik. The model number is BA 0810-100-1.5. The front facet was antireflection coated ($R=2\cdot10^{-5}$ at 802 nm) and the back facet was coated for a reflectivity $R>0.95$. Before the laser diode was antireflection coated the free running frequency was 810 nm and the maximum output was 1500 mW CW. The width of the active region of the device is 100 μm and the height is 1 μm. The length of the laser diode is unusually large, 1500 μm (This was the length specified by the distributor. The actual length is slightly larger). This last fact unfortunately makes it impossible to achieve a double pass with a large incident angle. The threshold current was 500 mA before AR-coating. Due to the increased threshold current the wavelength of the laser was shifted down to 802 nm. The reason for this is the gain dependence on injected carrier density.

After lengthy discussions it was decided that we would use the broad area double pass concept for this thesis project. The reasons for this were:

- Flared amplifiers are difficult to come by and very expensive
- Regular single pass amplifiers have some drawbacks. The drawbacks are that you need to AR-coat both facets and the gain length is about half of the double path amplifier.
- Most of the articles we found about the subject used the double pass scheme[11,12,13].

Of the two alternatives for separating the output mentioned in section 2.3.2.2, the alternative with injection at an angle was chosen. The reason for this was that according to some articles, disturbing ASE could also be spatially filtered out. Secondly, the isolator used (section 3.4) was not good enough for usage in the right angle approach.

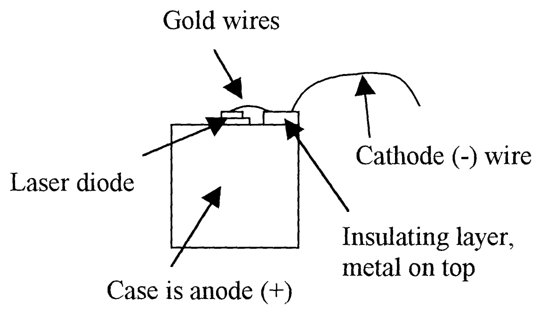

Fig 3.2 Electrical connections to the C-type laser diode

3.3 The lens system

To couple the injection beam effectively into the amplifier the beam profile must fit into the active region of the diode. After the anamorphic prism pair the beam waist was measured to be 1.35 · 1 mm.
To reach the desired beam radii of 0.5 μm · 25 μm (which is one-half of the height and one quarter of the width of the active region) at the facet of the diode, a combination of a cylindrical and an aspherical lens was used. The cylindrical lens (CVI-0149, CLCX-25.4-50.9-C-780) was AR-coated at 780 nm and had a focal length of 100 mm. Its purpose is to focus the light in the lateral dimension.

The aspherical lens (Thorlabs C330TM-B, f=3,1 mm) focuses the now elliptical laser beam to the size where it fits the entrance of the diode.

The calculations were done for a beam of dimension 3 · 3 mm which was larger than the actual dimension of the beam.
There were two main reasons for not using the actual beam dimension when calculating the focal lengths of the lenses.
Firstly a telescope could always be used to enlarge the beam if desired and secondly a smaller beam would require a shorter focal length of the aspherical lens. This is no problem in itself but even a 3.1 mm focal length was significantly shorter than used in other papers on amplifiers.
Since there might be a reason for this, a reason that was not obvious, we choose to expand the beam afterwards if necessary.

The original plan was to try and inject the light at a small angle as shown in fig 3.3.
This plan was initially given up because it was thought to be easier to achieve frequency locking, going in at right angle. In the end it turned out that the first plan was easier and better after all. In the experiments where we received the results in section 4, the light has taken the path in fig 3.3.

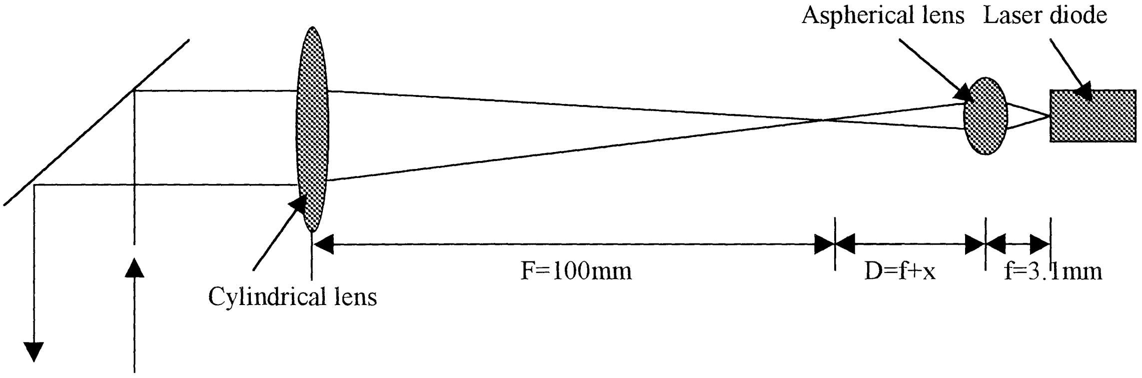

Fig 3.3 The system of lenses

The focus in the junction plane of the diode is the front facet, since the diode acts as a waveguide in that dimension. In the lateral dimension it is not obvious that the optimum is to focus the beam onto the front facet. The optimum is probably to have a nondiverging beam all the way through the diode but in this matter we have not come to a definite conclusion yet. It may be possible that focussing at the front facet or back facet would be better. Unfortunately it is very hard to determine where the focus actually is even when the set-up has been configured. The reason for this is that it is hard to measure the distances needed for such a calculation with sufficient precision.

3.4 The optical isolator

Diode lasers are very sensitive to optical feedback. Therefore it is common to protect the master laser with an optical isolator. The heart of an optical isolator, also called optical diode, is the Faraday rotator. The Faraday rotator is usually set to rotate the polarisation of the input light by 45 °. In contrast to a half-wave plate, this rotation direction is independent of which direction the light propagates. If the Faraday rotator is inserted between two polarisors it is possible to let only light propagating in one direction pass. Light propagating in the other direction will be damped by typically 30-40 dB.

Since diode lasers are very sensitive to optical feedback it is also common to combine two optical isolators into a single one. This optical isolator will typically reach extinction ratios as high as 60 dB. The optical isolator used in the set-up is model IO-5-793-HP from OFR (Optics for research). It is set to have maximum transmission (>92%) and isolation (38-44 dB) at 793 nm. The aperture is 5 mm in diameter. The reason for choosing this isolator and not an isolator with a higher extinction ratio was only a matter of money. 60 dB isolators are twice as expensive. The transmission is less for those isolators though.

Rotating the exit polarisor (right hand side of fig 3.4) until the damping is at a maximum will fine-tune the isolator. It is possible to fine-tune the isolator to any wavelength within 5% of the designed one. The transmission will then go down but the extinction should be quite constant.

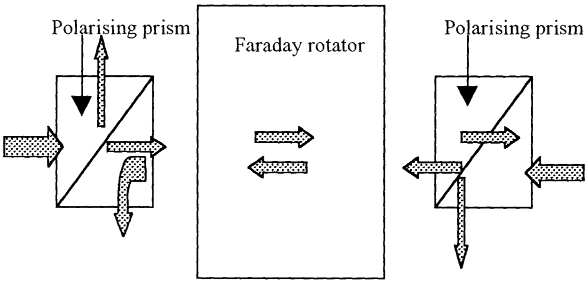

Fig 3.4 Optical Isolator.

3.5 The mount

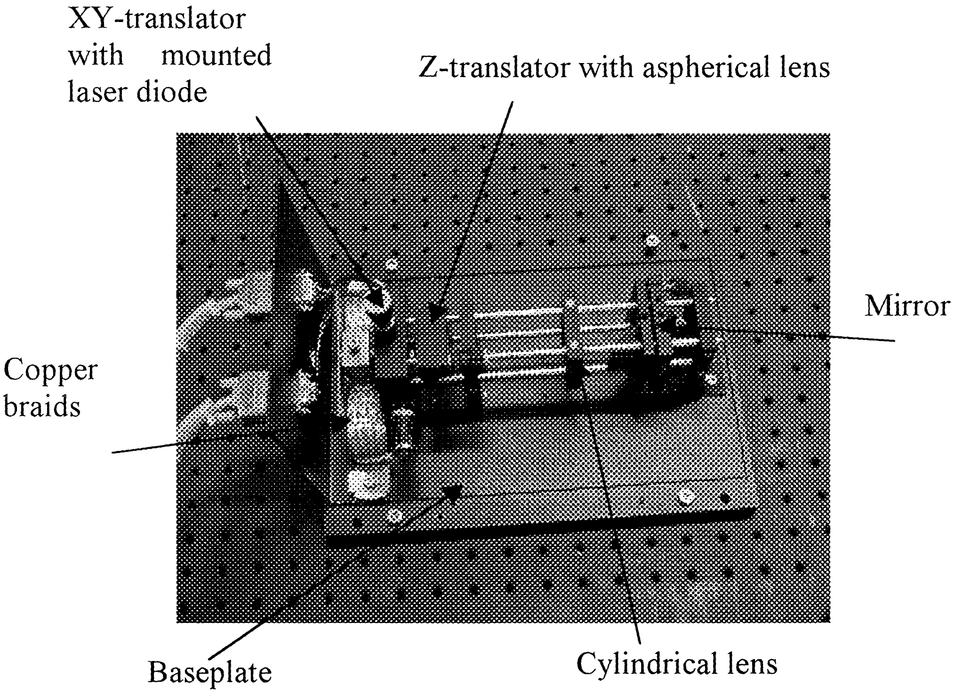

Fig 3.5 The amplifier

The mount is composed of the following articles:

- A base plate, iron (Manufactured in the Atomic physics workshop)
- four rods, stainless steel (Thorlabs, ER8)
- A Z-translator (Thorlabs, SM1Z)
- A XY-translator (Thorlabs, ST1XY-D/M)
- A kinematic mount for the entrance mirror (Thorlabs, KC1/M)
- An adapter for the aspherical lens (Thorlabs, S1TM09)
- Two rigid stabilisers (Manufactured in the Atomic physics workshop)
- A holder for the cylindrical lens (Manufactured in the Atomic physics workshop)
- The laser diode holder (Manufactured in the Atomic physics workshop)
- Cables and other electrical connections (Manufactured in the electronic workshop)
- Three copper braids for heat conduction (ELFA 55-097-81)

3.6 The laser diode driver

The laser diode driver was an SDL-824. It was able to provide up to 10 A but more than 2 A were never needed. The laser driver is a device, which apart from supplying current also protects the valuable diode from harmful transients or noise. It has also several useful functions such as a current limiter, pulse modulation possibilities etc. This specific driver also had the possibility of being used as a temperature controller but this feature was never used since our temperature sensor was not compatible with the driver requirements.

3.7 The temperature control

Attached to the back of the laser diode is a peltier cooler (Melcor OT2.0-66-F0). The cooler can withdraw at most 8.89 W. This value can only be reached if there is no temperature difference between the heatsink and the diode. Since the amplifier produces less than 8.89 W, one cooler is enough under the condition that the heat sink temperature does not increase.
A reason for choosing a peltier cooler is that its small dimensions suit a diode laser. A temperature sensor was attached to the same copper plate as the peltier cooler.
A medium sized copper block was attached to the backside of the peltier cooler. From there the heat dissipated through copper braids to a large heat sink, the base plate.

Diode lasers are very sensitive to changes in temperature. This sensitivity comes partly from the fact that the bandgap shrinks with temperature and partly from the expansion of the size of the laser with temperature. The second part will affect the resonance frequency of the cavity and could result in mode-hops.
Since the frequency of the slave laser is not determined by the gain profile but by the injected frequency it is not as sensitive to temperature disturbances as normal lasers. The ripples in the gain profile due to residual reflectivity of the facet are the only reason for temperature adjustment of the slave. These ripples will of course change when the temperature changes and you always want to be on a gain peak, not in a valley.
Another reason for the peltier cooler is that the heat generated in the diode has to be transported away or the temperature could rise to levels where the diode would start to degrade. The overall performance of any diode laser is strongly dependent on temperature and a low temperature is always desirable.

4. Results

After the amplifier was assembled, a series of tests were done in order to check its performance. Both the stand-alone amplifier and the complete system were tested but special attention was paid to the latter.

4.1 The stand alone amplifier

Even if the amplifier never will be used as a laser it is still of some interest to check some of its basic characteristics. Fig 4.1 shows a L-I curve. The threshold current is approximately 0.6 A which is 0.1 A higher than before the AR-coating.

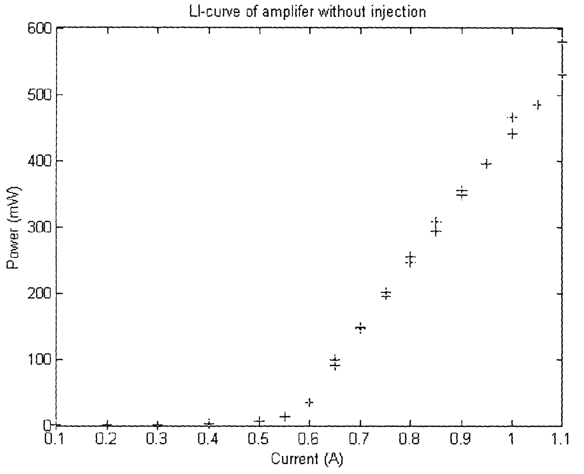

Fig 4.1 L-I curve of the standalone amplifier

The threshold current depended on temperature as any other diode laser, but this drift was never specifically measured. The laser diode is designed to withstand 2 A but unfortunately some of the golden wires providing current to the diode from the cathode were not properly attached. Approximately 6-7 wires or 1/3 of all wires were off so we set a new current limit of 1.3 A. In fact this was never any problem, since at such a high current the laser diode could not function properly as an amplifier. This was partly due to ASE feedback into the master laser and partly due to cavity modes inside the amplifier. This will be discussed in more detail in section 5.

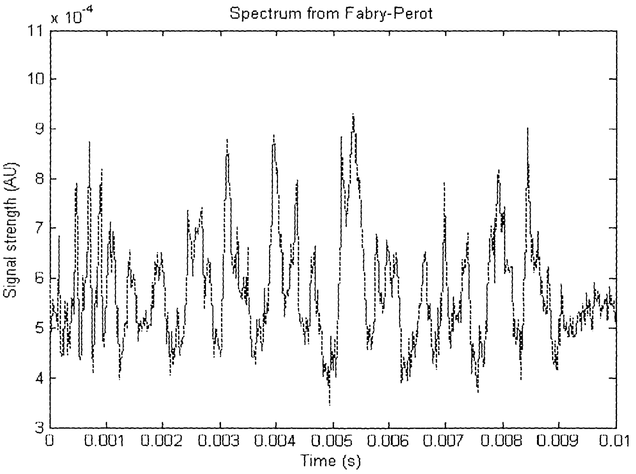

Fig 4.2 Spectrum of the free running amplifier

A spectrum of the amplifier is shown in fig 4.2. Although the picture in not clear it is easy to see that the periodic variation is not due to noise. The picture indicates that the free running laser is emitting light into several modes, which is consistent with theory. The current was I=1.14A.

4.2 The complete system

Several spectra were taken and the effect of various laser characteristics on the spectrum was investigated. In all experiments, the output power from the master laser was the same P=43 mW. In comparison with the free-running case the most significant change in the spectrum was the existence of an injection locked signal. This is clearly shown in fig 4.3. The current to the amplifier was I=0.61 A. The first three peaks are generated when the ramp voltage falls back to the start level just before a new scan. The next three peaks are repeats of the same injection locked signal.

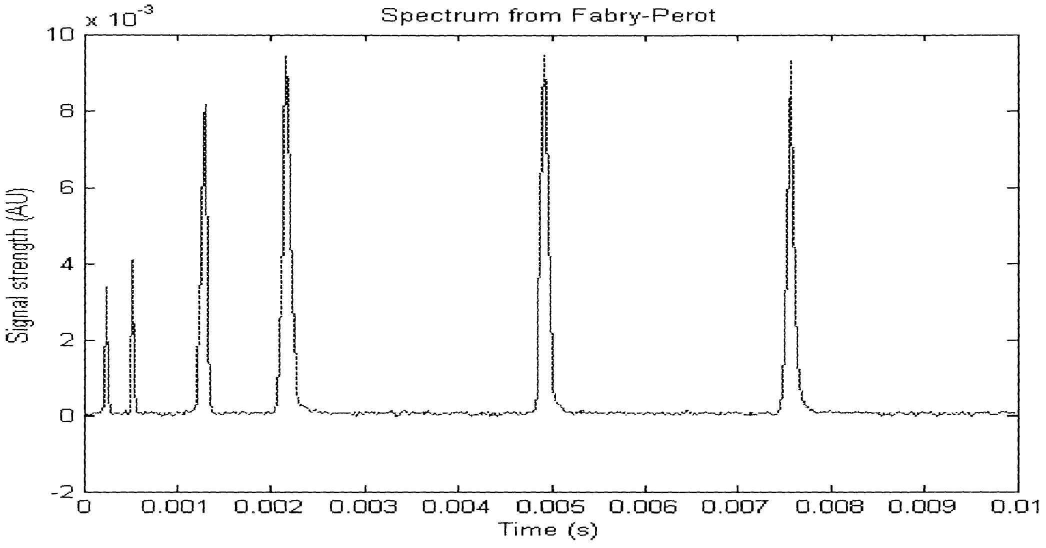

Fig 4.3 Spectrum of the injection locked amplifier.

Tests, like changing the current of the amplifier, were performed that showed that the signal was not a reflection from the master laser.

When varying the voltage to the EO-crystal in the master laser and thereby shifting the frequency of it, the frequency of the amplifier also shifted. When the current to the amplifier increased, small side peaks turned up. Fig 4.4 clearly shows when this happens. The current is I=0.62 A. These side peaks were often unstable in time and often resulted in making the large peak unstable as well.

These side-peaks turned out to be injection locked components from the master laser, and they shifted in the same way as the main peak when the voltage to the EO-crystal changed. When the current increased further, new side-peaks showed up and at even higher

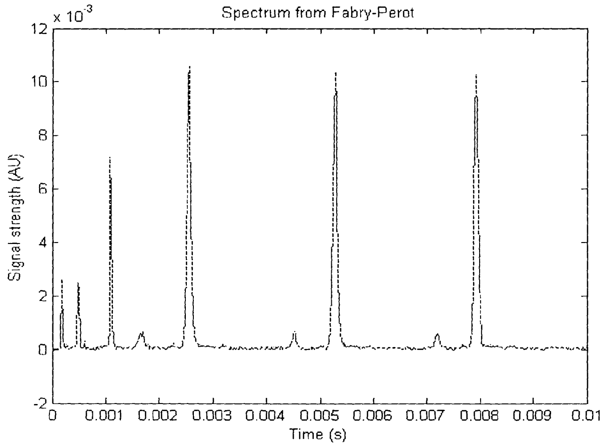

Fig 4.4 The creation of a side mode

current, laser modes of the free-running amplifier began to appear. The current for creation of these side-peaks and free-running modes depended strongly on how well adjusted the injection system is, but the pattern was always the same. First side-modes appear at some current level and at a still larger current, features connected to the amplifier itself appear. After investigation it turned out that these side-modes are connected to light going from the amplifier, through the OI and into the master laser. This light disturbed the frequency pattern of the master laser, which results in the side-mode emission. By suppressing the light going from the amplifier into the master laser, we were able to drive the amplifier at much higher current without the appearance of side-modes. At high current (I>0.85 A) they eventually reappeared. This value turned out to vary quite a lot, depending on how much light was coupled back into the master laser.

One of the major problems turned out to be how to measure the ratio of the amplified signal to the ASE. Since the amplified radiation unfortunately couldn't be completely spatially separated from the ASE (This was probably because the diode was so long, 2mm, making large angle exit and entrance impossible) some method of measuring the signal-to-noise ratio had to be invented. One method of doing this is to measure the intensity in the free-running mode and in the injection locked mode and to compare the spectra after subtracting the background. This is done in fig 4.5.

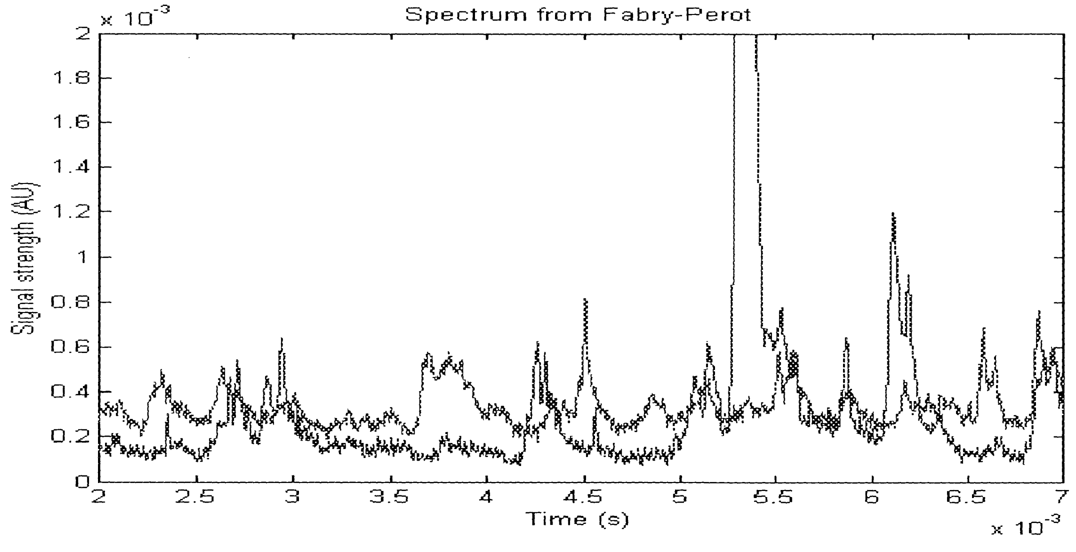

Fig 4.5 Spectrum of frequencylocked signal and of free-running signal. Both with background subtracted.

The ASE is strongly suppressed but still remains. The power of the free-running radiation was P=154 mW and increased to 169 mW when injection locked. The current was I=0.85A.

The intensity of the amplified beam comes from two different parts. Firstly the output power of the amplifier increases and this extra power can safely be ascribed to the injection locked mode. The second and larger part comes from the decrease in ASE. In fig 4.5 27 % of the output power in the free-running mode is redirected into the injection locked mode. This value has been calculated under the condition that the signal from the Fabry-Perot spectrometer is linear in intensity.

Another way of measuring how much of the radiation that is redirected from the ASE is to look at the light from the amplifier that is directed towards the master laser. Since the amplified beam should travel along a different path and not go back towards the master laser, this light is probably ASE. Fig 4.6 shows a measurement of the light travelling in the backward direction with and without injection.

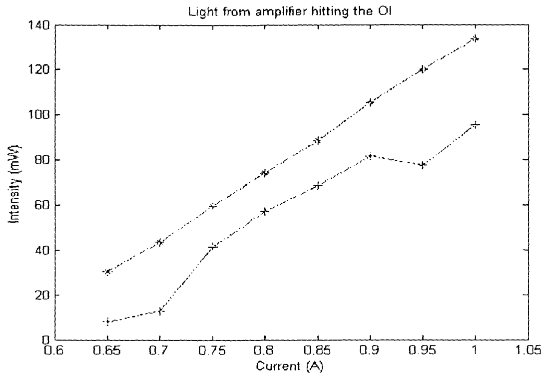

Fig 4.6 Light directed at the OI from the amplifier. '*' is without injection and '+' is with.

It is clear that a large fraction of the ASE is redirected somewhere else since this light is reduced when the injection beam is turned on. At low current almost 75% of the ASE is redirected into the injection locked beam. At higher current this ratio decreases to about 25-30%. This is pictured in fig 4.7. It is important to note that these ratios may be angle dependent.

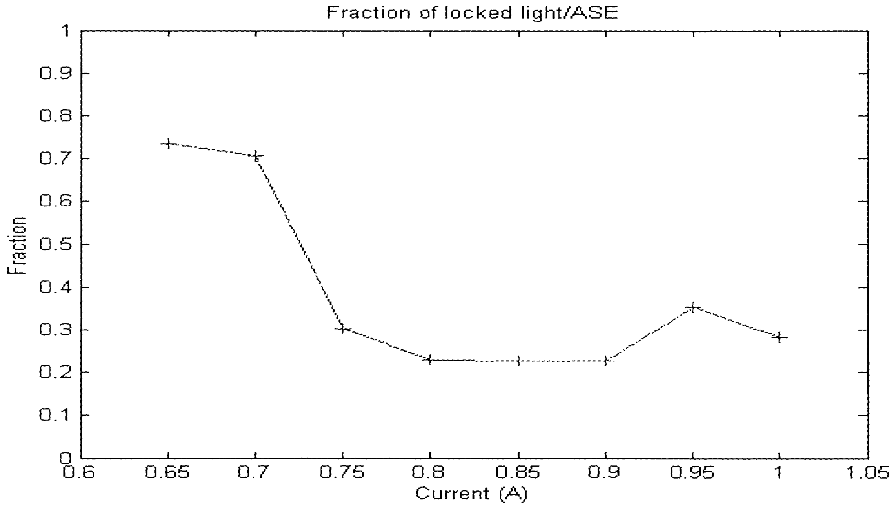

Fig 4.7 The ratio of injection locked light to ASE as measured from the amplifier radiation at the OI.

If these ratios are compared to the value of 27 % obtained by direct measurement of the intensity at the Fabry-Perot spectrometer, they actually agree quite well. For a current of 0.85 A the value should be between 25 and 30 %. The fact that they agree makes it more likely that the different ways to measure the intensity of the amplified beam are equally good. A ratio of 27% is not as high as expected but the point where this ratio drops from 70% to 30% could probably be pushed to higher current with a little bit of optimisation.

Since it is possible to filter out at least 50% of the ASE spatially with little or no loss in intensity of the amplified beam, this means that less than 15% of the ASE will remain at low current.

Experiments on exactly how much ASE could be filtered out spatially were not performed.

Fig 4.8 shows a L-I curve of the injection locked system. The output power of the injection locked amplifier increases almost linearly. The output power of fig 4.8 can unfortunately not be compared to the free-running power in fig 4.1 because the power measured in fig 4.8 is from only a part of the beam. On average the power from the injection locked system is about 20 mW larger than the free-running. This value has not been measured with satisfying accuracy however.

It is possible to make predictions on how much amplification it is possible to achieve.

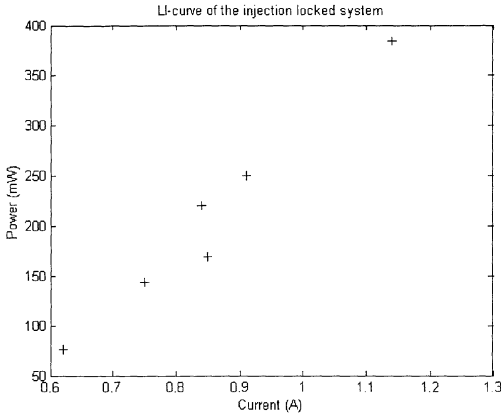

Fig 4.8 L-I curve of injection locked system

From this reasoning, the output power of the injection locked part of the radiation could be described empirically as:

$$P = 20 + c \cdot P_{freerunning} (mW) \qquad (4.1)$$

$P_{freerunning}$ is the intensity of the entire beam (fig 4.1), c is the ratio in fig 4.7.

For high spectral purity (I<0.7 A) the output power is P=120 mW (70% injection locked, $P_{free\ running}$=150 mW). This gives a gain G=2.8.

For lower spectral purity (I=1.1 A) the output power is P=171 mW (27% injection locked, $P_{free\ running}$=560 mW). This gives a gain G=4.

From this it seems as if the highest amplification occurs for the highest current (I=1.14 A in this case). Since you have to consider that the spectral purity decreases with increasing current this is not the same as saying that the amplifier should be driven at this current level

Fig 4.9 shows a spectrum taken at I=1.14 A. Side-peaks are evident in this picture and they are much more pronounced than possible features in the ASE.

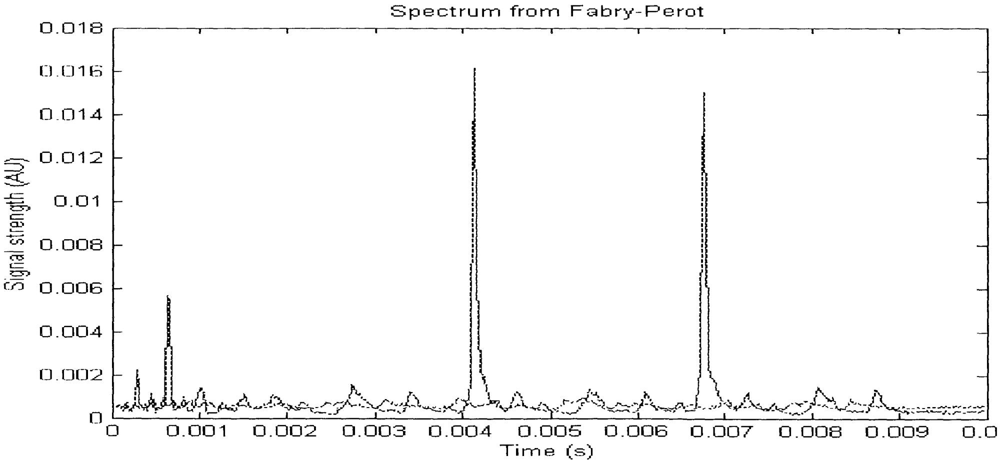

Fig 4.9 Spectrum taken at I=1.14 A

5. Discussion

This section is divided into one discussion concerning the design and construction of the amplifier and one discussion about the results in the previous section.

5.1 About the construction and design

Although I encountered many challenges and realised a lot of mistakes during the construction of the amplifier most of the problems could be met. For those that I still consider problems, I have ideas on how to solve them. I will not discuss the problems with finding and receiving the equipment. All that needs to be said is that it almost always takes more time than the companies promise and the only way to be sure you get it at all (and that you get what you actually ordered) is to be stubborn.
The first real problem with the design turned out to be that the holes in the base plate were in the wrong places. The reason for this was that the XY-translator did not look the way I expected. Using one stabiliser instead of three solved this. We feared that the amplifier would be very sensitive to vibrations but it turned out that it was as sensitive as the master laser. Therefore the loss of two stabilisers was not critical.

The second problem turned out to be the current supply. The connecting wire to the cathode was off and we solved the problem by using a mechanical connection. To assure good connection we used a connector that worked as a spring. We could have attached the wire by conducting glue or by soldering it. Another possibility would have been to use a bonding machine. Conducting glue turned out to shortcut due to resistive heating at currents above 1 A. Soldering could heat the diode too much and the soldering material could condense on the facet destroying the AR coating.

Bonding would have been a good idea but the bonding machine could not reach the surface of the cathode.

The third problem was that the diode heated the amplifier too fast. This was solved when we soldered the copper braids to the copper piece connected to the copper rod. If the amplifier is run at very high current (>1.15 A) for long time (>30 min) there is still a small problem connected to heating. The voltage supply to the peltier element is not able to provide enough voltage and the temperature will slowly increase. This could be solved by using a more powerful driver or by increasing the temperature conductance to the baseplate from the copper braids.

The next comment is that in this construction it is not possible to rotate the diode or the cylindrical lens with any ease. Since less light will couple into the diode if the cylindrical lens and the diode are rotated with respect to each other, there might be much to win by using a rotation device such as Thorlabs CRM1.

Another problem was the length of the diode, which has been mentioned before. A shorter diode could have had a larger entrance angle, making it possible to separate it from the ASE in a better way.

The gain profile of the diode was not centred on 793 nm as we had hoped for. Exactly where the gain maximum is was never investigated but during occasions when the master laser jumped from single to multimode the amplified signal increased significantly. This multimode lasering occurred at 798 nm and this justifies the assumption that the gain peak is not at 793 nm.

It also turned out that it was very hard to improve the amplifier by decreasing the temperature. This should shift the gain maximum towards shorter wavelength. Unfortunately the decrease in temperature also decreased the laser threshold of the amplifier and thus shifting the gain profile towards longer wavelength. This was not investigated thoroughly but at least there was no obvious benefit by increasing or decreasing the amplifier temperature.

The injection beam size was not the same as the outgoing beam either. The outgoing beam dimension was 2.05 · 1.6 mm (though it had been calculated to 3 · 3 mm, based on an emitting spot size of 1 · 50 μm) and the injection beam was 1.35 · 1 mm. This would imply that the focus is too large in the waveguiding direction. This would of course lead to a decrease in efficiency. A telescope could possibly help sort out this problem.

5.2 About the results

Since the amplifier was never truly optimised the results should be taken as a lower limit of what may be possible to achieve. It should be possible to amplify the signal between 3 and 4 times without too much ASE. The major problem, limiting the efficiency of the amplifier turned out to be the side-modes that arose due to light from the amplifier entering the master laser. If a better OI had been used this should not have been a problem but these are very expensive as stated in section 3. But even without using a better OI it should be possible to get less light coupled into the master laser. One such possibility could be to increase the length between the OI and the amplifier or to use a spatial filter since the injection beam is smaller than the ASE.

Since modes from the amplifier itself only show up at very large currents optimising this should make it possible to run the amplifier at currents as high as I=1-1.2 A without loosing too much spectral purity. A guess is that this alone could double the gain.

The halfwave plate used in the experiment had a lot of burnmarks and an AR coated new halfwave plate would increase the light coupled into the diode by 5-15%.

In conjunction with usual optimisation (Adjusting the mirrors, the entrance angle, the focus and so on) it should not be impossible to reach a gain as high as G=10. I would on the contrary be very surprised if it wasn't possible to reach such a gain, if all the things mentioned above and in section 5.1 are done.

I also find it worth noting that it was easier than I ever expected to achieve frequency locking. Basically all that had to be done was to match the beam from the master laser going into the amplifier, with the beam going out from the free-running amplifier.

The amplifier should be driven just below threshold. When a small signal from the amplified beam appeared on the oscilloscope it was just to watch the signal and try to improve it by adjusting one optical component at a time.

6. Outlook and conclusion

It is always very hard to foretell the future but a few things are direct follow-ups to this project. Those follow-up projects are also what I'll discuss here.
Firstly the characteristics of the amplifier system needs to be checked thoroughly. These characteristics include temperature dependence and stability, frequency stability, studies of the ASE. The ASE frequency and spatial distribution, dependence on current, injection power dependence, finding optimum values of current and injection power are other things that could be investigated.

These studies should probably be done after some optimisation of the system has been performed. Examples of such improvements and optimisations have been given in the previous section.

It could also be of interest to check whether the amplifier obeys Eq (2.4).

The issue about the ASE dependence on current is of great importance since less light will be available in the amplified beam if the ASE is large, as seen in section 4. However since the amplification could increase if an ASE background could be tolerated, it may turn out that it is beneficiary to drive the amplifier at a current where a large part of the light is ASE.

Apart from these issues that are directly connected to this thesis a series of new experiments could now be done in the data storage and pulse compression.
Hopefully both with improved results. In the data storage experiment the hope is that the amount of stored bits will increase when more power is used.
In the pulse compression experiment the hope is that the photon echo could be compressed even further as more power will make a larger scan possible.

When the original master laser becomes available it will naturally be of interest to see how well the amplifier can perform in conjunction with that. My own hopes are that the result will be significantly improved, as we will be able to run the slave laser at a higher current.
The original master laser may be less sensitive to light from the amplifier. However, it may also be the other way around. Either way, it will affect the performance of the amplifier.

There is also a mechanical follow-up. It is the question as to whether the amplifier and the original laser should be put on a common baseplate. The reason for this is purely a practical one, since movement of one of the components necessitates troublesome adjustments. It has however turned out to be easier than expected to achieve frequency locking and therefore this may not be worth the trouble.

The conclusion of this thesis is that it has been experimentally verified that the concept of frequency locking and amplification in semiconductors is a good possibility to increase the intensity of a diode laser. A gain of G=4 was reached but the possibility of increasing this to G=10 seems high. It turned out to be easier than expected to achieve frequency locking and harder than expected to distinguish the amplified beam from the ASE.

The aim for this thesis was to reach 500 mW output power for an injection power of 60 mW. That is a gain of G=8.3. This was never reached in this thesis but I still consider the work with the amplifier a success. Another aim was that the spectral purity should be preserved and from the results it can be seen that the spectral purity will be preserved if the current to the amplifier is kept low enough. This is also a success. What remains is a matter of time, money and patience.

7. Acknowledgements

I would like to thank my supervisor Stefan Kröll for the opportunity to work with this thesis at the photon echo group and for his encouragement in times when the amplifier was a no more than a pinhole in a bale of hay.

I would also like to thank Lars Levin, my assistant supervisor, for all of his time, all his answers and all of our discussions.

I am thankful to Nicklas Ohlsson and Mattias Nilsson for their help in the lab and for our lengthy discussions over a cup of coffee.

Without the aid of Göran Werner in the workshop there would have been no amplifier and without Åke Bergkvist there would equally have been no laser, and I thank them both for taking time both when things went wrong and when they worked.

Krishna Mohan, Tomas Cristiansson and Jonas Sandsten have all been very helpful and listened to my ideas and thoughts.

Gabriel Somesfalean was always there when I needed to borrow equipment.

I also want to thank my family and my beloved girlfriend Anna for encouraging me and for their concern and love.

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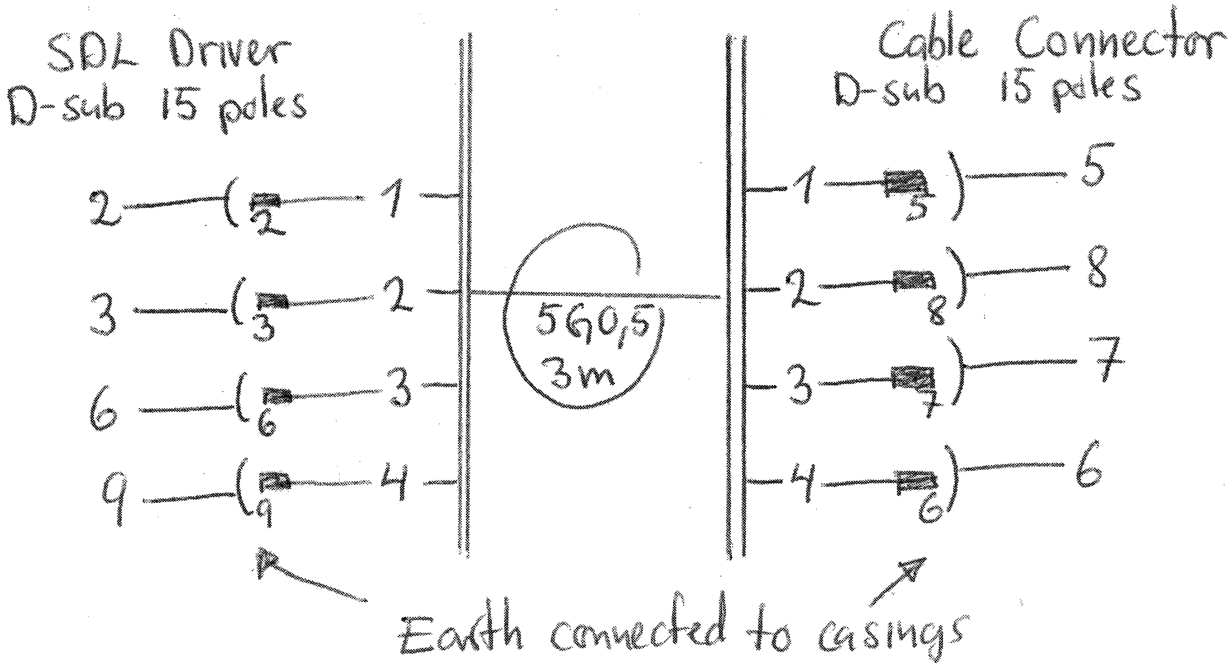
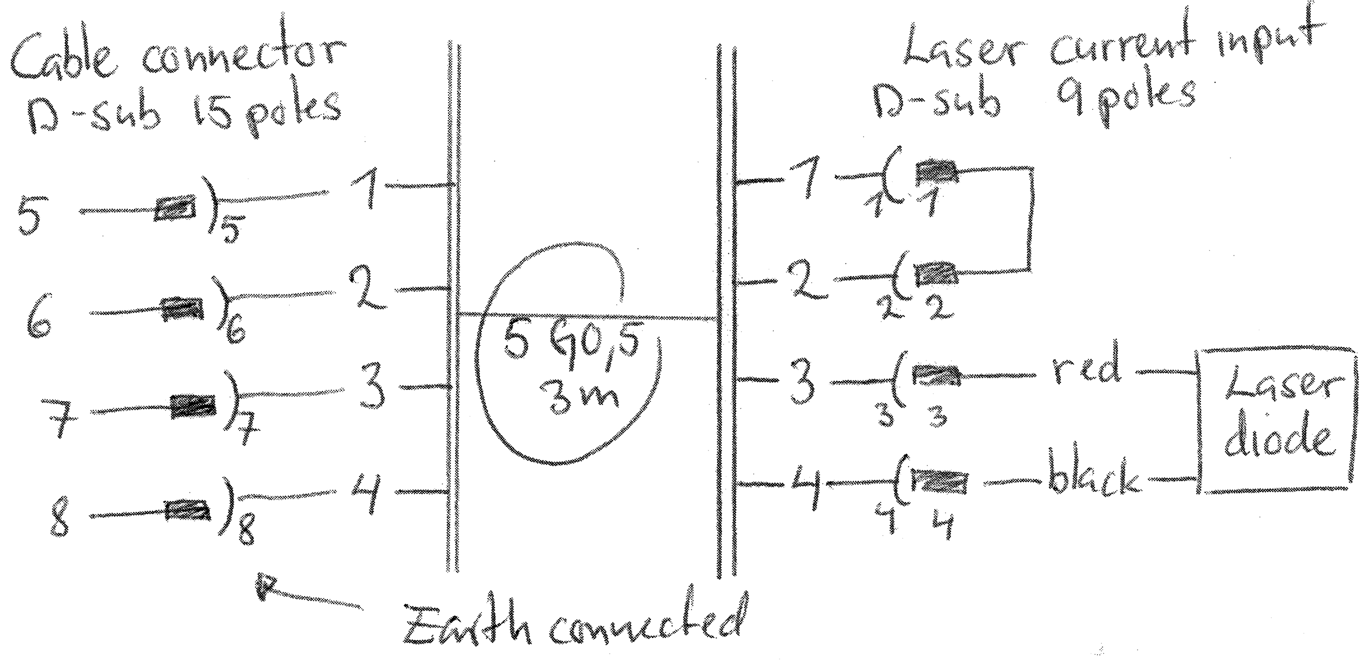
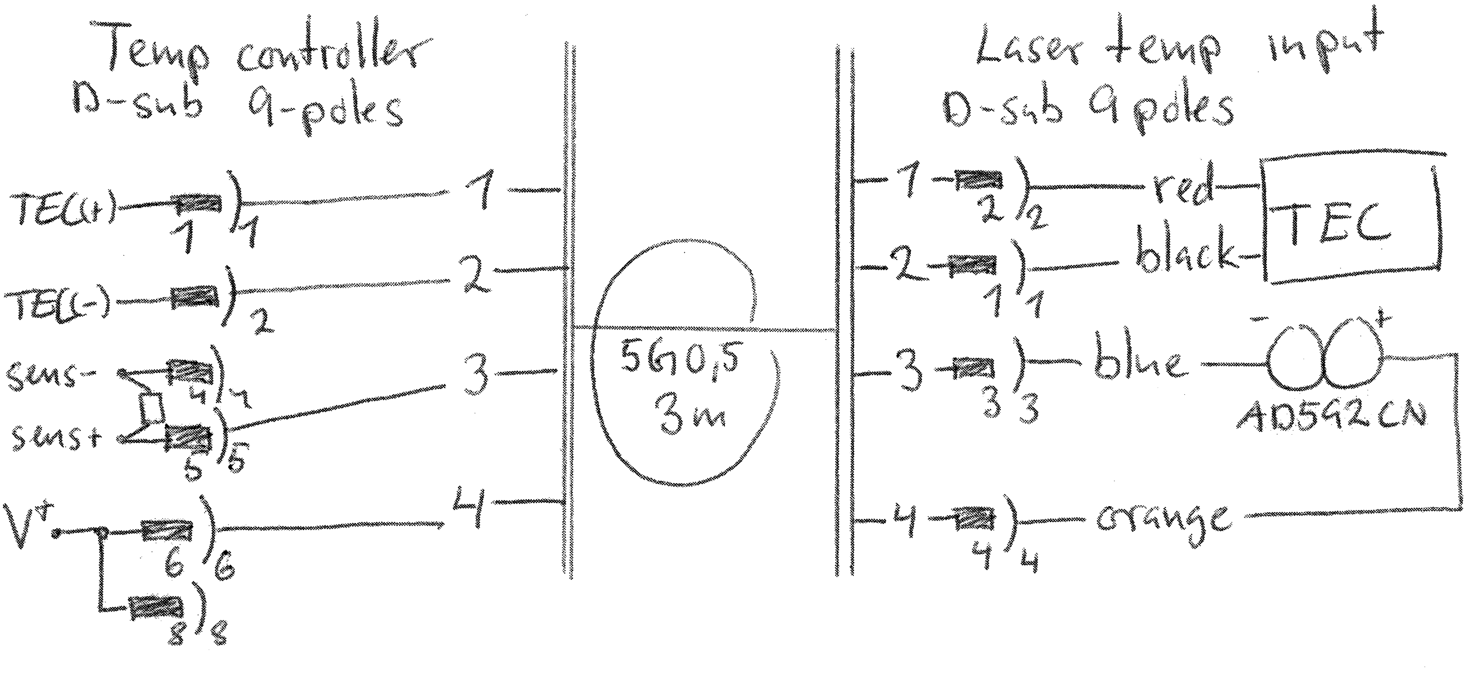
Appendix A

Drawings of mechanics and electronics

ELECTRONIC CONNECTIONS

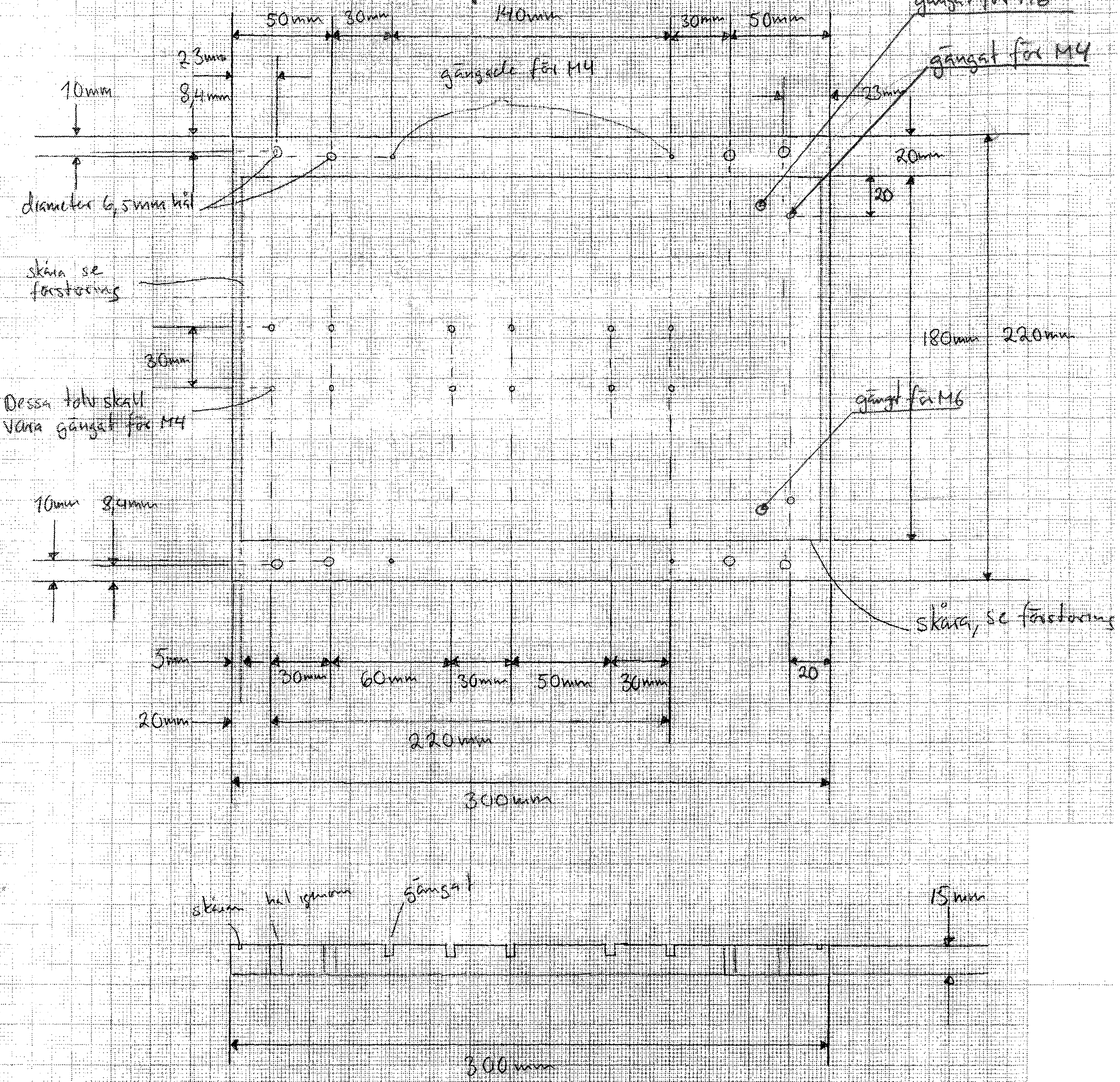




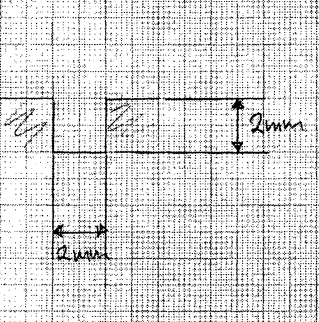


MECHANICAL DRAWINGS (In swedish)

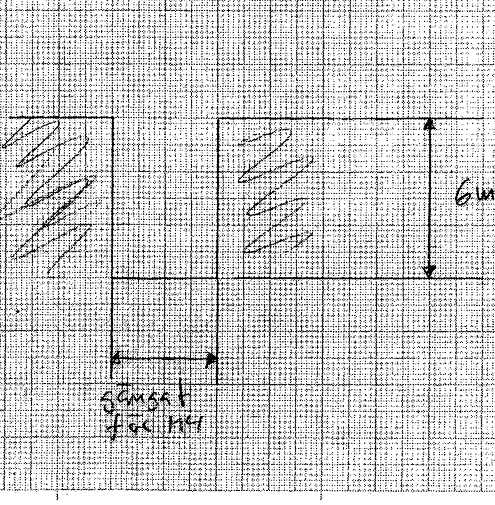
Base plate



Förstoring skäran



Förstoring gängorna

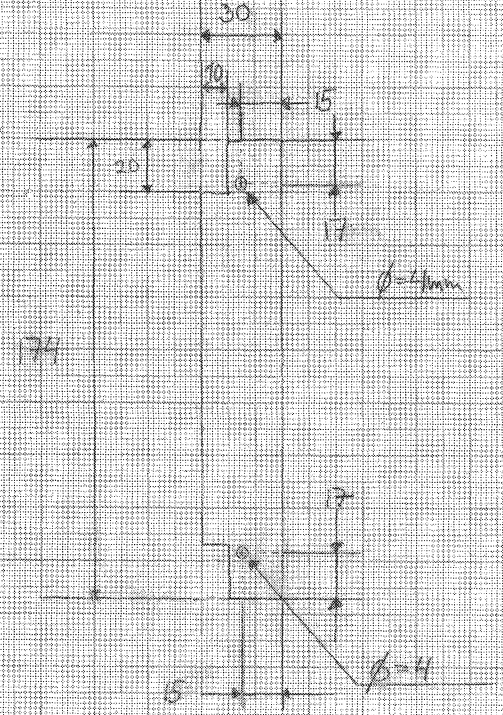


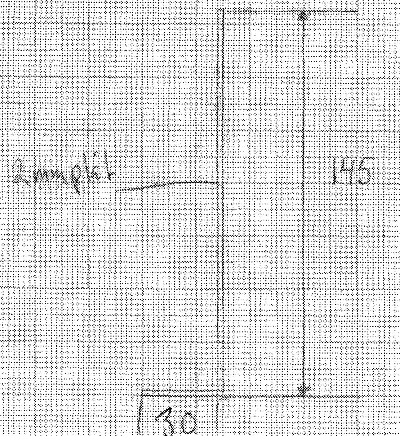
Back panel of amplifier

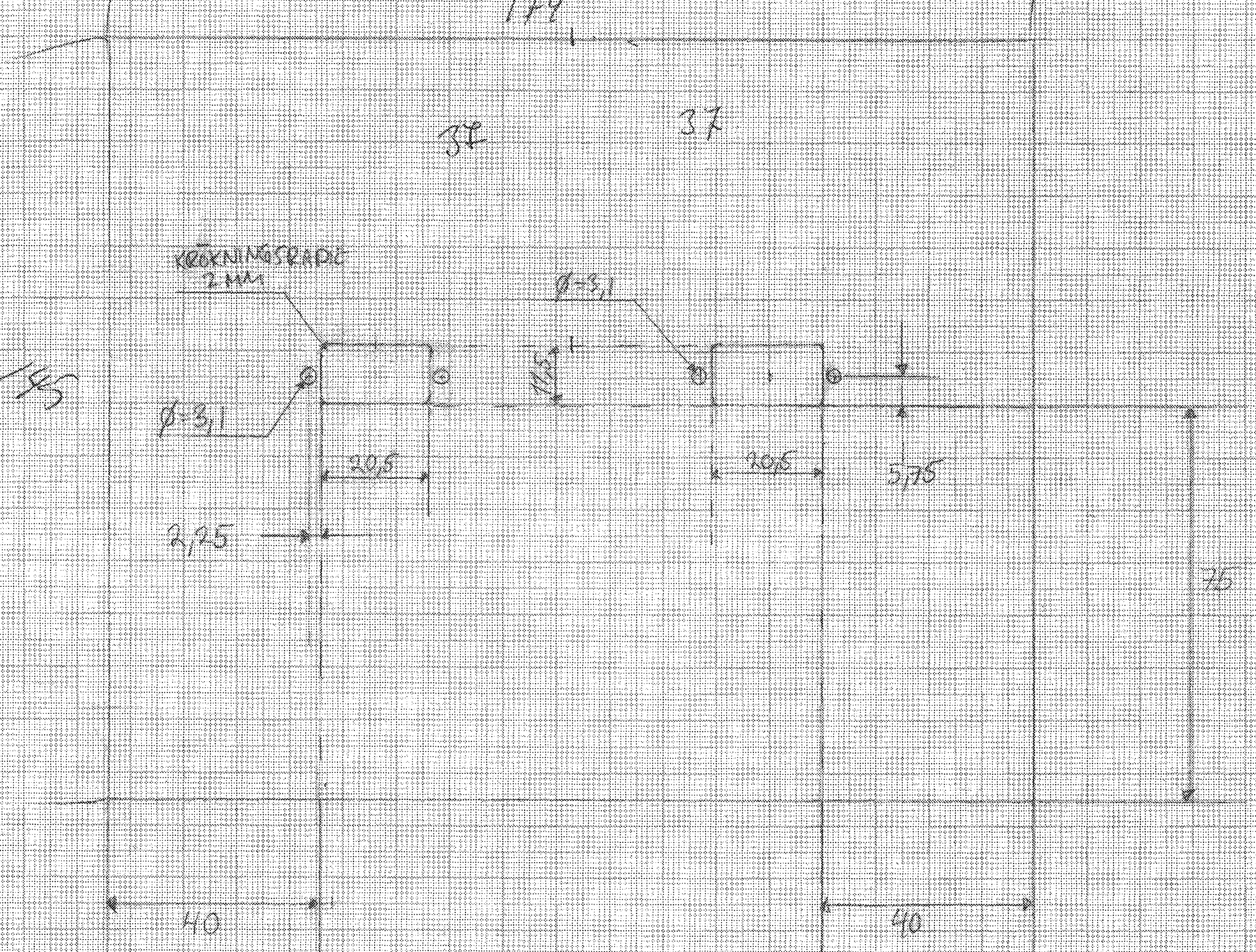
(space for 2x D-sub 9poles)

175 x 174

57
50
37



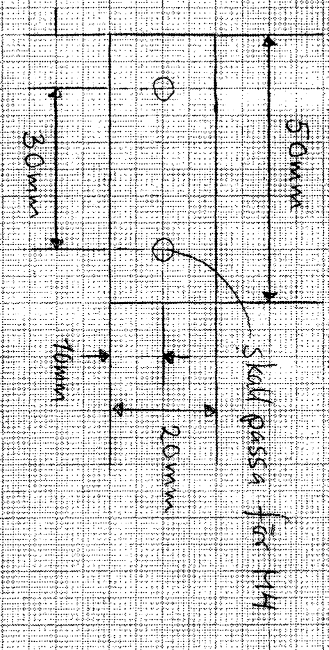


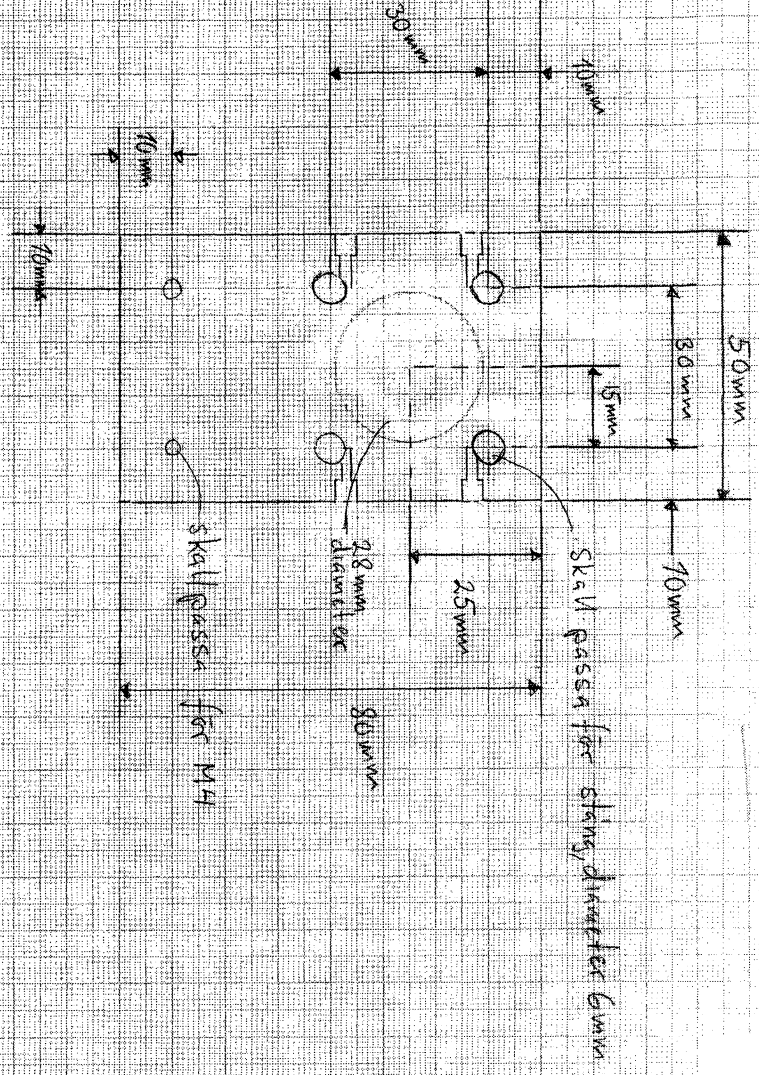


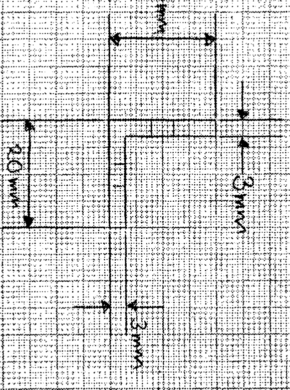
2x stabiliser + 4x device for attaching stabiliser to baseplate

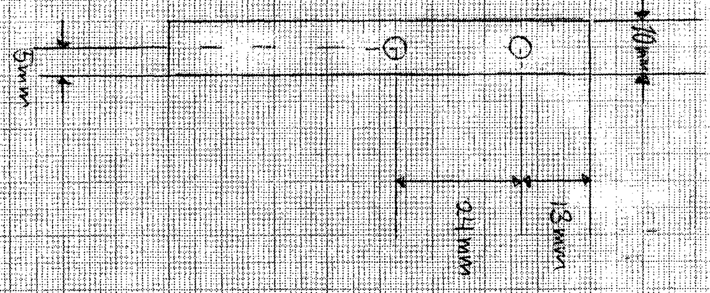
②

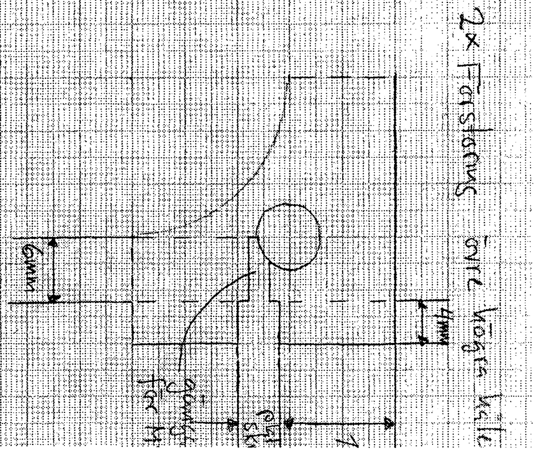
①







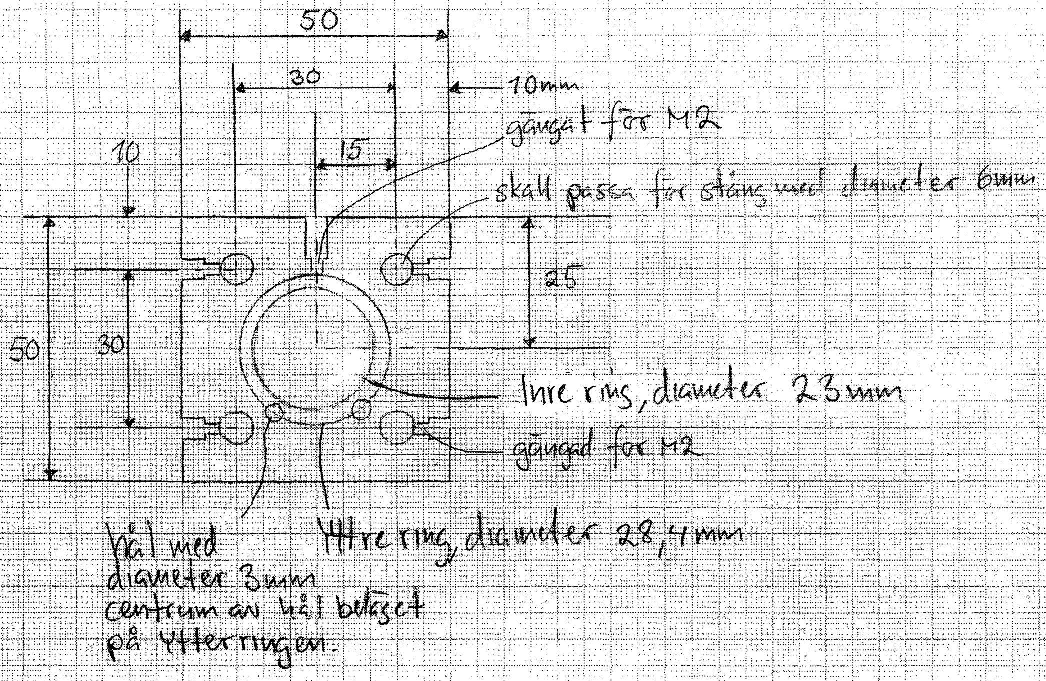


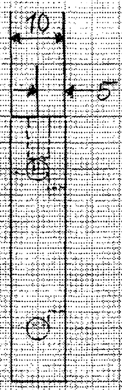


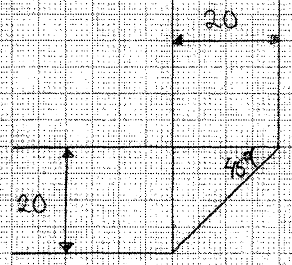
1× holder for cylindrical lens
1× 45° mirror holder

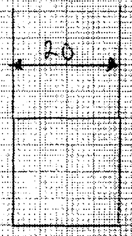
Alla mått i mm

material : aluminium (eloxerad)







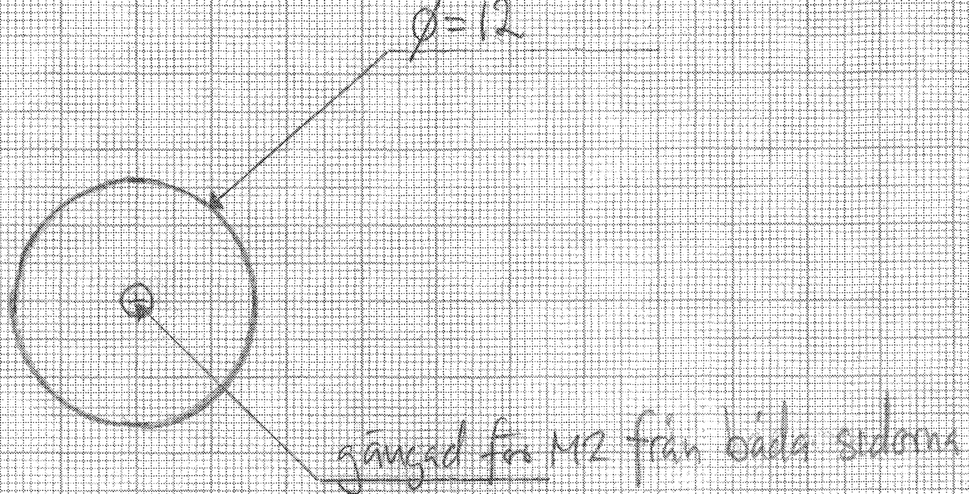


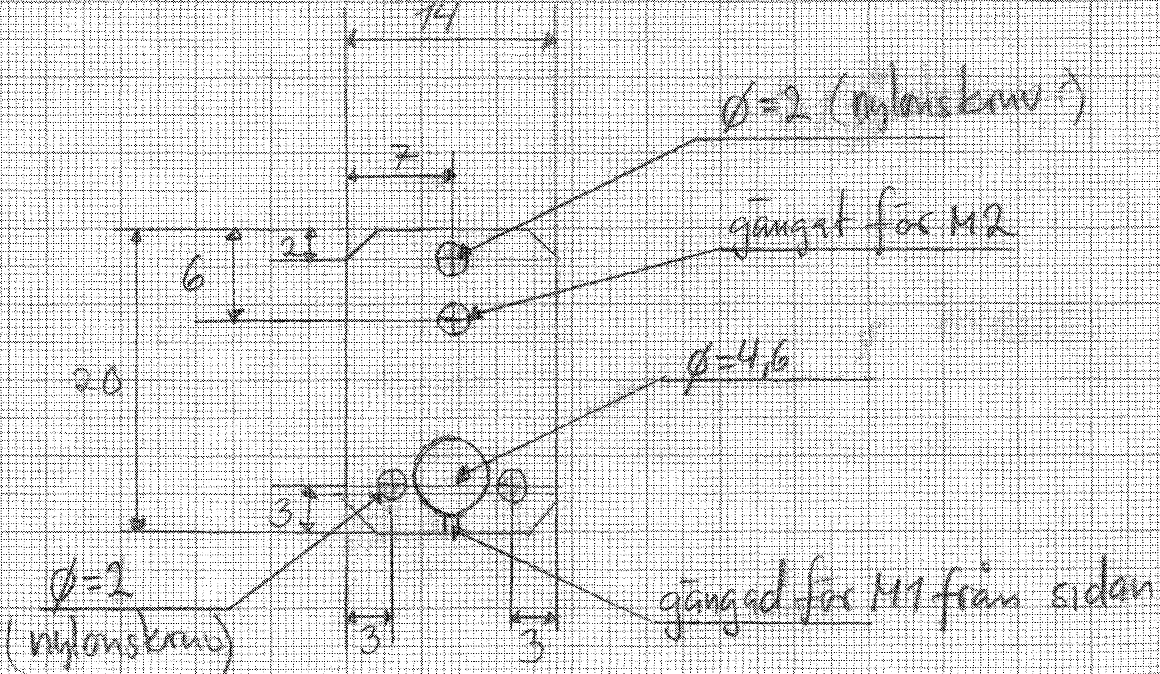
A3L – 1×1 mm

408.11

Laser diode holder + copper rod (part of heatsink)

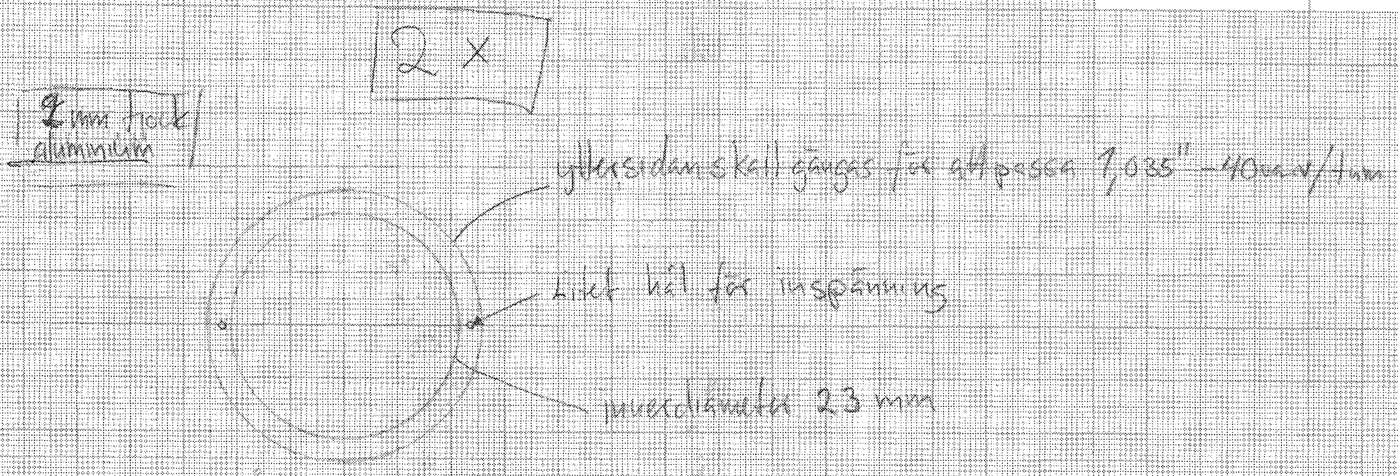
30mm tjock
koppar

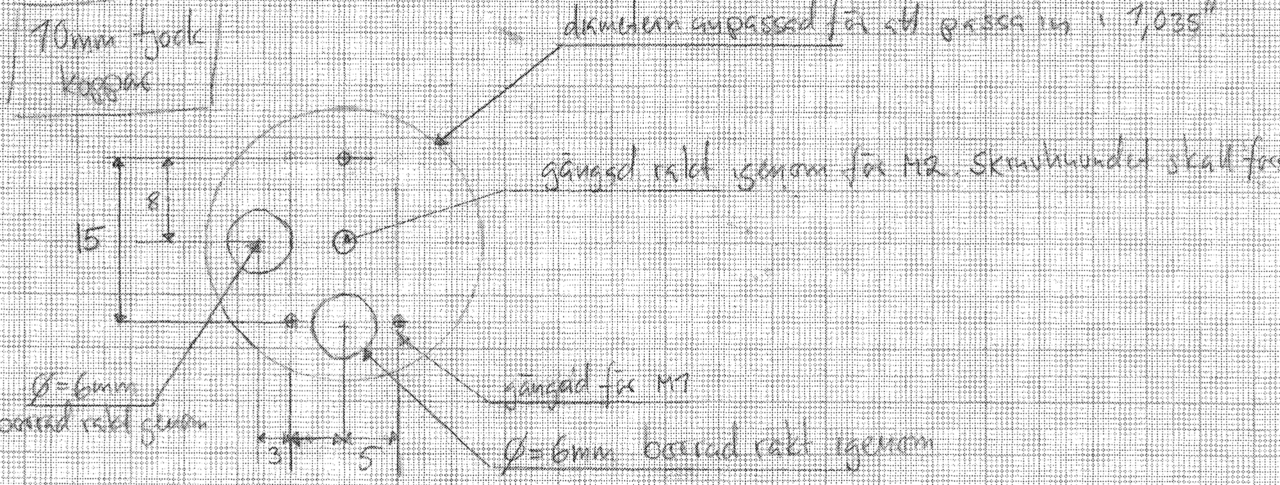


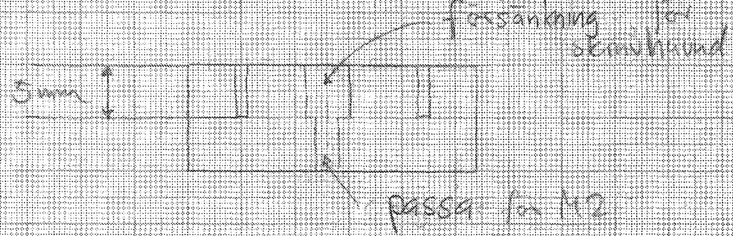


A 3L – 1 X 1 mm
408.11

- 2 aluminium rings to fasten the laser diode holder to the X-Y translator
- 1 holder for peltier element and temperature senor







A3L - 1X1 mm
408.11