Tampereen yliopisto

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DESIGN OF DIODE LASER LIFETIME TEST DEVICE

Faculty of Information Technology and Communication Sciences
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ABSTRACT

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The objective of this thesis was to design and assemble a device for diode laser lifetime testing. This thesis also introduce briefly the history, basics of operation, some applications and manufacturing methods of diode lasers. This thesis was done to Modulight Oy.

At my responsibility was to design the electronics and mechanics of the device. At the beginning of the project some requirements were set to the device. The device had to be able to measure eight diodes simultaneously, setup had to be easily scaled for more simultaneous measurements, it had to be able to drive at least 15 amps of current to a load of 2.5 volts with each channel, it had to monitor and log the current and voltage of each channel and it had to be able to control the temperatures of each channel between 10 and 50 degrees Celsius.

The design started from the schematic of the electronics. For this I used a software called EAGLE. I chose this software because it was a standard design tool at Modulight. The main component of the device was a constant current driver. For this case the best option was to choose predesigned and manufactured ATLS6A201D from Analog Technologies. It was already familiar to me from previous projects so it was a natural choice for me. Analog Technologies also provided comprehensive instructions on how to use their driver in different situations so those could be easily be used as a base of the design.

The next step was to design the layout for the electronics. At this stage the placement of the components and the physical dimensions of the PCB was determined. The main feature to be considered with this design was the large amount of current that the PCB had to withstand. Each channel needed to be able to drive 15 amps of current so the PCB and the connectors on it had to be able to withstand 120 amps. To manage this, I designed six layers to the PCB. This way I could use a full layer of copper for just conducting the current. In the design of the layout I also had to consider the physical shape of the PCB and the attachment of it to the mechanics.

After the layout was designed, the next phase was to design the mechanics. For this I used a software called SolidWorks. One of the requirements was that the device should be easily scalable for more simultaneous measurements. To achieve this, I decided to design the device on a rack self. This way the scaling would be easy just by adding more selves to the set. Most of the component manufacturers offers 3D-models of their product free of charge so basically I just had to combine all these ready-made designs in to one assembly. One of the most important things in the mechanics design was to consider the heat control. Powerful drivers and lasers would both produce a lot of heat that needed to be led away from the setup. I executed the cooling by adding to big heatsinks under the PCB and to fans to blow cool air through both of them. Everything combined the device consisted of rack self, rack frame, PCB, eight peltier elements that were used to control the temperatures of the channels, four fans, two heatsinks and two AC/DC sonverters that were used to provide the DC current for the PCB.

After the designs were done, the PCBs were ordered from a manufacturer. In this case the PCBs were ordered without the assembly of the components because there were relatively few components on the board and we only ordered five of them so it was cheaper and faster to order and solder the components myself.

After all of the parts had arrived I started to assemble the device. The premade 3D-model helped a lot at this stage. After everything was assembled, I did some test to make sure that the device was working as designed. First test was the stability test of the current drivers. For this I used a programmable digital load. Unfortunately the loads maximum current was 14 A so I wasn't able to test the stability at the maximum current. During 200 minute test the current varied only 8 mA which means 0.06%. This kind of stability is really good and is sufficient for this application.

Next feature to test was the heat control. For this I connected load diodes to all of the channels. These diodes turn all of the electrical power driven through them to heat and this way it is good

way of testing the worst case scenario where all of the lasers are broken down and isn’t producing light anymore. During the test the ambient temperature in the room was 20.3 °C and the test time was 114 minutes. During the test the temperature of the heat sinks rose to 33 °C where it stabilized. All of the channels was set to 25 °C and the real temperatures varied between 24.9 °C and 25.22 °C. This kind of stability was moderate but large enough to affect the output power and the wavelength of the lasers.
All in all I think that the project was a success. The device met all of the requirements and it is in use daily at Modulight. Naturally there are also some improvements to be made in the future. The stability of the temperature control should be improved. This could be done for example by improving the thermal contact between the lasers and the heatsinks. I also hadn’t considered the placement of the wiring during the design of the device. This led to a fact that the wires looked quite messy in the device and were little bit on the way when using the device. This could be solved by designing some designated routes for the wiring in the mechanics. I had also forgotten to fire one of the connections in schematic and it had to be added by hand with jump wires to the PCB.
At this moment there are already second version of this device done where the thermal contact between lasers and heat sinks was improved. A third version is also being designed where the scalability is going to be further improved and some designated paths for wiring to be added.

Key words: Laser, diode, electronics, lifetime test

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TIIVISTELMÄ

Tämän työn tarkoituksena oli suunnitella ja toteuttaa laitteisto, jonka avulla pystyy mittaamaan diodilasereiden elinikää. Työssä tutustutaan myös lyhyesti diodilasereiden historiaan, toimintaan, käyttökohteisiin sekä valmistusmenetelmiin. Työ tehtiin Modulight Oy:lle.
Minun vastuullani oli laitteiston elektroniikan ja mekaniikan suunnittelu. Työn aluksi laitteistolle asetettiin muutamia vaatimuksia, jotka sen tuli täyttää. Laitteiston tuli pystyä mittaamaan kahdeksaa laserdiodia samanaikaisesti ja tämän lisäksi laitteiston piti olla helposti skaalattavissa suuremmalle määrälle lasereita, sen piti pystyä ajamaan vähintään 15 ampeerin virtaa 2.5 voltin kuormaan kullakin kanavalla, laitteen tuli pystyä mittaamaan jokaisen laserin virtaa ja jännitettä jatkuvasti ja lisäksi sen tuli pysytä säätelemään lasereiden lämpötilaa toisistaan riippumatta välillä 10 – 50 °C.
Laitteen suunnittelu alkoi elektroniikan kytkentäkaavion suunnittelulla. Käytin elektroniikan suunnittelussa EAGLE-ohjelmistoa. Valitsin kyseisen ohjelman siitä syystä, koska Modulight:lla oli tapana käyttää kyseistä ohjelmistoa kaikkeen elektroniikan suunnitteluun. Laitteen tärkein komponentti oli tasavirta-ajuri. Laserdiodeja käyttäessä on tärkeää, että pystytään ajamaan tasaista virtaa diodin läpi. Tässä tapauksessa paras vaihtoehto oli valita ajuriksi Analog Technologies –yrityksen valmistama ajuri ATLS6A201D. Kyseinen ajuri oli minulle jo tuttu aiemmista projekteista, joten sen käyttö oli luonnollinen valinta. Lisäksi Analog Technologies tarjosi hyvät ohjeet, miten heidän ajureita tulisi kytkeä ja käyttää ja näin ollen pystyinkin käyttämään kyseisiä tietoja kytkentäkaaviosuunnittelun pohjalla. ATLS6A201D ajuri tuki myös suoraan diodin jännitteen ja virran mittausta, joten kytkentäkaavion suunnittelu oli varsin suoraviivaista.
Seuraava suunnittelun vaihe oli layout, jossa komponenttien sijainnit ja piirilevyn fyysinen olemus suunnitellaan. Tässä työssä tuli erityisesti kiinnittää huomiota suuriin virtoihin, joita piirilevyn tuli kestää. Kunkin kanavan tuli pystyä ajamaan 15 ampeerin virta ja kanavia oli kahdeksan, joten piirilevyn ja sen virtaliittimien tuli pystyä kestämään 120 ampeerin virta. Tästä syystä päätin suunnitella piirilevystä kuusikerroksisen. Näin ollen oli mahdollista käyttää kokonainen kerros kuparia ainoastaan virran kuljetukseen. Layoutin suunnittelussa tuli lisäksi ottaa huomioon mekaniikan fyysisen muoto ja se miten piirilevy tullaan kiinnittämään mekaniikkaan.
Seuraavan vaihe oli suunnitella mekaniikka. Tähän käytin ohjelmistoa nimeltä SolidWorks, joka on tarkoitettu 3D-mallien tekoon. Laitteiston yksi vaatimuksista oli helppo skaalattavuus suuremmaksi, joten päätin suunnitella laitteen räkkihyllylle. Näin ollen laitteen skaalaus onnistuisi vain lisäämällä vastaavia hyllykokoonpanoja räkkiin. Suurin osa valitsemieni komponenttien ja osien valmistajista tarjoaa ilmaiset 3D-mallit tuotteistaan, joten minun työkseni tässä tapauksessa jäi käytännössä eri mallien yhdistely yhdeksi kokoonpanoksi. Tärkeä asia, joka tässä vaiheessa tuli ottaa huomioon oli laitteen lämmönhallinta. Tehokkaat ajurit ja laserit tuottavat molemmat kohtuullisen määrän lämpöä, joka tulee johtaa laitteistosta pois. Toteutin jäähdytyksen suunnittelemalla piirilevyn asennettavaksi kahden suuren jäähdytyssiilen päälle, joiden kummankin läpi puhalsi kaksi tuuletinta. Kaiken kaikkiaan laite koostui lopulta räkkihyllystä, räkkitelineestä, jossa hylly oli, piirilevystä, jolla ohjauselektroniikka sijaitsi, peltier-elementeistä, joita käytettiin lasereiden lämmönsäätelyyn, neljästä tuulettimesta, kahdesta jäähdytyssiilestä ja kahdesta AC/DC –muuntimesta, jotka tuottivat laitteen tarvittavan tasavirran.
Suunnittelun jälkeen piirilevyt tilattiin piirilevyvalmistajalta. Tässä tapauksessa järkevintä oli tilata pelkät tyhjät levyt ilman ladontaa, koska levyjä tilattiin vain viisi kappaletta ja komponentteja oli suhteellisen vähän yhdellä levyllä. Näin ollen komponenttien itse juottaminen oli nopeampaa ja taloudellisempaa. Samalla kaikki laitteeseen tarvittavat muut komponentit laitettiin tilaukseen.
Kaikkien osien tultua itse laitteen kasaus alkoi. Kasausta helpotti huomattavasti aiemmin tehty tarkka 3D-mallli. Laitteen kasauksen jälkeen oli testauksen vuoro. Ensimmäisenä testasin laitteen ajaman virran stabiiliuden kytkemällä laitteen ulostulon digitaaliseen kuormaan. Valitettavasti kuorman suurin sallittu virta oli 14 ampeeria, joten en pystynyt mittaamaan virran stabiiliutta laitteen maksimivirralla. 200 minuutin testin aikana ajurin ulostulovirta vaihteli vain 8 mA, mikä tarkoittaa 0.06%. Tämä stabiilius oli erittäin hyvä ja riittää kyseisessä sovelluksessa.
Seuraava testattava ominaisuus oli lämmönhallinta. Asetin laitteen jokaiseen kanavaan kuormadiodin, jotka muuttavat kaiken niihin syötetyn tehon lämmöksi. Tämä simuloi hyvin pahinta mahdollista laitteen kohtaamaa tilannetta, jossa kaikki testattavat laserit ovat hajonneet ja jolloin ne myös muuttavat kaiken tehon lämmöksi. Testin aikana huoneilma oli 20.3 °C ja sen pituus oli 114 minuuttia. Testin aikana jäähdytyssiilien lämpötila nousi 33 °C:een, johon se myös stabiloitui. Kaikkien kanavien ohjauslämpötilaksi oli asetettu 25 °C. Suurin yksittäisen diodin

lämpötilavaihtelu oli välillä 24.9 °C – 25.22 °C. Saavutettu lämpötilan stabiilius oli kohtalainen, mutta kyseinen lämpötilan vaihtelu vaikuttaa jo jonkin verran laserin ulostulotehoon ja aallonpituuteen.
Kaiken kaikkiaan projekti onnistui mielestäni hyvin. Laite täytti kaikki sille asetetut vaatimuksen ja se on tällä hetkellä Modulight:n käytössä päivittäin. Luonnollisesti laitteessa oli myös parannettavaa. Lämpötilastabiiliutta tulee pyrkiä parantamaan eri keinoin esimerkiksi parantamalla laserien ja jäähdytyssiilien välistä termistä kontaktia. En ollut myöskään suunnitteluvaiheessa ottanut huomioon laitteeseen tulevia johtoja, joita loppujen lopuksi oli huomattava määrä. Tämä johti sotkuiseen ulkoasuun ja haittasi myös laitteen käytettävyyttä. Ongelma kuitenkin ratkeaa suunnittelemalla myös johdoille selkeät ja tarkoituksenmukaiset kulkureitit. Lisäksi kytkentäkaavion suunnitteluvaiheessa oli yksi kontakti kaikilta ajureilta jäänyt vetämättä, joka piti lisätä piirilevylle hyppylangoin.
Tällä hetkellä laitteesta on jo valmistettu toinen versio, johon piirilevyllä ollut virhe korjattiin ja termistä lasereiden termistä kontaktia parannettiin. Laitteesta on myös suunnitteilla kolmas versio, jossa on tarkoitus edelleen helpottaa laitteen skaalattavuutta ja suunnitella siisti tapa laitteen johdotuksille.

PREFACE

I’d like to thank my instructor and inspector of this thesis Karri Palovuori for guiding me through this project. I want to thank Modulight for giving me the opportunity to do this project and thesis with them and all of the employees at Modulight for creating a great working spirit and environment for doing this project. I want to say special thanks to Visa Kaivosoja for guiding me with this project at Modulight and Anu Vilokkinen for great mental support. I also want to thank Tampere University of technology and its teachers and professors for giving me a high-quality education that will guide me through my working life and beyond.

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CONTETS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	alternating current
AWG	american wire gage
CAD	computer aided design
IBM	International Business Machines Corporation
IC	integrated circuit
Laser	light amplification by stimulated emission of radiation
LED	light emitting diode
lidar	light detecting and ranging
MIT	Massachusetts Institute of Technology
NTC	Negative temperature coefficient
OLED	organic light emitting diode
PCB	printed circuit board
PDT	photo dynamic therapy
PIDF	Proportional-Integral-Derivative-Feedforward
SMD	surface-mount device
TEC	thermoelectric cooler
E	energy
h	Planck constant
c	speed of light
λ	wavelength
P	power
U	voltage
I	current
f_c	cutoff frequency.

1. INTRODUCTION

Diode laser *(light amplification by stimulated emission of radiation)* is relatively old invention since it was first introduced in 1962 by General Electric's researcher Robert N. Hall. Only weeks after researchers from IBM *(International Business Machines Corporation)* and MIT *(Massachusetts Institute of Technology)* reported that they had also been able to produce functioning laser diodes. First laser diodes were gallium-arsenic based and the wavelength was near infrared. [1]

Since the invention the laser diodes have been developed quite a bit further. Nowadays diode lasers come in multiple wavelengths ranging from visible blue, around 400 nm, to far infrared, around 2000 nm. New materials and structures are also constantly developed to produce different wavelength for new applications. Today diode lasers are used in various devices and applications including computer mice, DVD and Blu-ray players, movie projectors, telecommunications and even medical applications. Some of the advantages of the diode lasers is their small size, relatively cheap price due to their mass production and wide power range.

Modulight Oy is a company that processes and develops semiconductor diodes lasers and also design and manufacture devices that uses these diode lasers. The devices produced by Modulight are used for example in cancer treatments, range finding and telecommunications.

One important phase in diode laser development process is to test the different variations and one feature of diodes that is considered really important is the life time of the diodes. Due to these reasons I was given a task to design and assemble a device that would support semi-automatic lifetime testing of multiple diodes simultaneously.

In this thesis I will first go through the basics principles of diode lasers, how they produce light and how the lasing is achieved. I will also discuss why diode lasers are important nowadays and what they are used for. I also give a quick review to the manufacturing of diodes. After that I am going to tell that what one must take into account when using laser diodes and controlling them with electronics and why it is important to ensure constant current and temperature for the laser diode. Then I will introduce my designing and assembly processes of the life time test setup. I also show the end results and show the results of extensive testing that I did to the device. From the test results the end conclusions and improvement ideas are concluded.

2. BACKGROUND

To understand what is important in controlling and testing the laser diodes it is good to understand what the laser diodes actually are and how they work. In this chapter I will got through the basic structure and function of laser diode.

2.1 Basics of diode laser

Laser diode combines the technology of a laser and a semiconductor based LED *(light emitting diode)*. To understand the basic functionality of the diode laser it is good to introduce the principles both the LED and the laser.

2.1.1 Principle of LED

The light in laser diode is produced exactly same way as in a LED. The function is based on a p-n junction where the n side material is doped with extra electrons and the p side material is doped with extra holes. P-side doping is done by adding some element to the p side semiconductor that has deficient in electrons. This way there will form some extra holes to the p-side. N-side is doped by adding an element with excess of electrons to the N-side material. This way there will be these free electrons in the n-side. When the n side is connected to negative voltage and p side to positive voltage, the electrons and holes starts to travel towards the junction. As they meet in the junction the electrons and holes recombine. Combined electrons are in lower energy state as the free electrons so in this recombination some energy is released. The form, light or heat, and amount of released energy is determined by the material that is used in the p-n junction. This is because the energy difference between free and combined electron differs between different materials. [2] [3]

The used material also directly determines the wavelength of emitted photons and thus light as seen in equation (1)

$$\boldsymbol{E} = \frac{\boldsymbol{hc}}{\boldsymbol{\lambda}}, \tag{1}$$

where E is the energy of emitted photon, h is Planck constant, c is the speed of light and λ is the wavelength of emitted photon. Because the used material determines the energy of emitted photon it also determines the wavelength and thus the colour of emitted light.

Some of the commonly used materials and their characteristics are listed in the Table 1 below.

Table 1. *List of some commonly used materials in LEDs* ***[2]****.*

Wavelength (nm)	Colour	Forward voltage (V)	Material
< 400	Ultraviolet	3.1 – 4.4	AlN, AlGaN, AlGaInN
400 - 450	Violet	2.8 – 4.0	InGaN
450 - 500	Blue	2.5 – 3.7	InGaN, SiC
500 - 570	Green	1.9 – 4.0	GaP, AlGaInP, AlGaP
570 - 590	Yellow	2.1 – 2.2	GaAsP, AlGaInP, GaP
590 - 610	Orange	2.0 – 2.1	GaAsP, AlGaInP, GaP
610 - 760	Red	1.6 – 2.0	AlGaAs, GaAsP, AlGaInP, GaP
> 760	Infrared	< 1.9	GaAs, AlGaAs

In the Table 1 also can be seen that the material affects also to the forward voltage of a LED chip. This also directly affects to the forward voltage of the laser and it in one parameter to take into account when designing a laser.

2.1.2 Principle of laser

Laser is based on stimulated emission of radiation. This means that the radiation, of light in this case, is generated by stimulation. If an electron is in excited state, it can be brought to relaxed state by interacting with a photon. When the excited electron changes state, it generates another photon. This results in two photons, original and the new one. Interesting about this is that these two photons have the same energy state and they are coherent. Further on if these photons come across with other excited electrons, even more photons are generated with the same energy state and coherence. [4]

The problem is that if the photon comes across with an electron that is not excited, the photon will be absorbed and the electron will be excited. To make sure that there will be optical gain, which means increasing number of photons, one must ensure that there will be an excess of excited electrons compared to not excited ones at all times. The increasing amount of photons in same energy state and coherent with each other is the main principle of a laser. [4]

2.1.3 Principle of diode laser

The diode laser is basically just a combination of a LED and a laser. It means that the original photons are generated in a same fashion than in LEDs and then these photons are used to generate more photons by stimulated emission. In a diode laser all this is done inside the same device, inside the p-n junction.

One of the main requirements in a laser is to have and excess amount of excited electrons. This is called populated inversion and in diode lasers it is achieved by injecting a large amount of electrons to the junction with a relatively high current. The amount of current that is needed to achieve the sufficient amount of excited electrons is called lasing threshold. If the current is below this threshold, the device is acting like LED and it emits light randomly. But if the amount of current driven through the device is above the threshold, the device starts to lase. This lasing enables the device to produce really high optical power and because the emitted light is coherent it also enables various ways to control the light beam. [3]

In the Figure 1 an example of current-voltage behaviour of a diode laser can be seen. In the figure the threshold current can be seen at a point where the slope of the curve increases quickly.

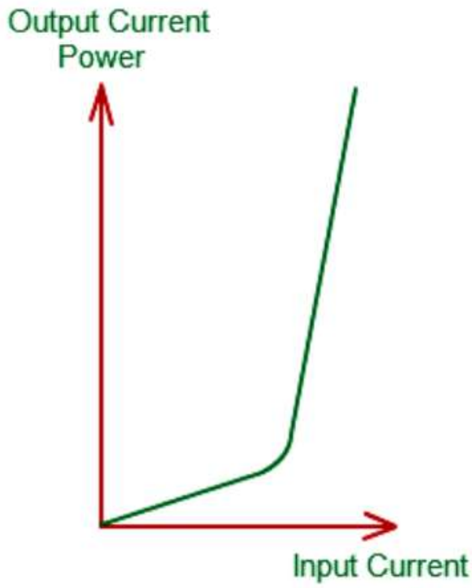

Figure 1. *Example current-voltage diagram of laser diode.* ***[5]***

To further increase the optical gain of a diode laser and to guide the emitted light to same direction some reflective surfaces are created on the ends of the device. To the other end a highly reflective surface will be added and to the other end a partially reflective. This way the photons will travel longer amount of time inside the device stimulating even more electrons. The mirrors also direct the light to leave the device to the same direction, through the partially reflective mirror. In the Figure 2 an example structure of diode laser, including the reflecting sides, can be seen. [3] [5]

The partially reflective mirror is usually done by cleaving the other end of the

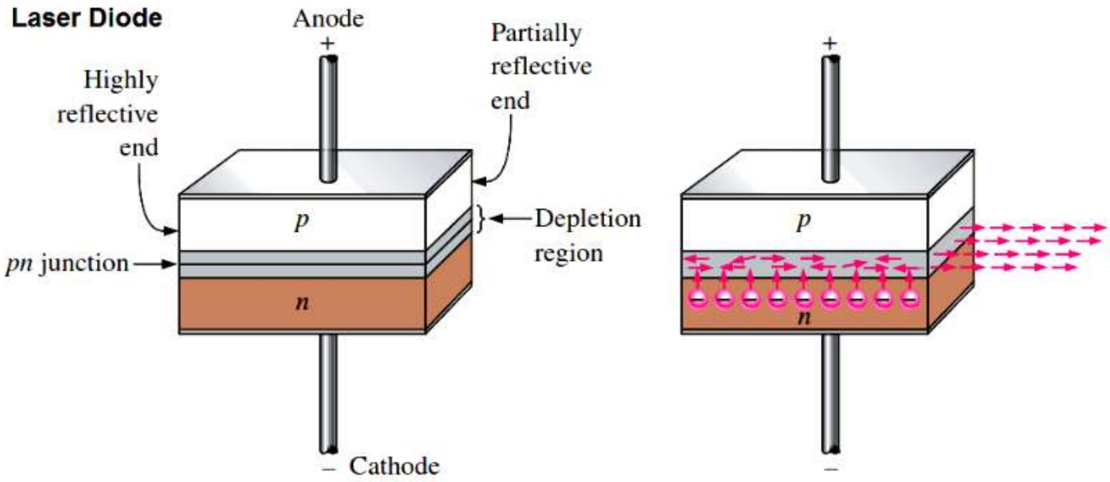

Figure 2. *Structure of diode laser.* ***[5]***

semiconductor material. The material has a crystalline structure so cleaving it causes the material split along the crystal planes creating a really flat surface which acts as a partially reflective mirror. The highly reflective mirror can be done for example with thin gold layer that is separated from the device with some insulating and transparent material to prevent the gold from short circuiting the p and n sides of the semiconductor. [3]

2.2 Manufacture of diode laser

2.2.1 Crystal

The manufacturing of a diode laser starts from the growing of a semiconductor crystal. In this phase a base crystalline structure of the semiconductor is produced. The crystal growth is highly delicate process to ensure the uniform structure of the crystal. It is also important to avoid any contamination in the crystal because these would also ruin the uniform crystal structure. There are multiple ways to grow the crystal for example the Czochralski method, the Bridgman method and the Float-zone crystal method.

In the Czochralski method a seed crystal is dipped in to the pool of molten semiconductor material and then slowly pulled away from it. At the same time as the crystal is pulled from the pool it is also spun around to ensure uniform crystal formation around the seed. The advantages of this methods are that it is relatively easy method to use and it is also possible to observe the growth of the crystal during the pulling. Disadvantage of this method is that the structure of the crystal depends highly on the pulling conditions and even subtle changes in these conditions will affect the growth. [3]

In the Bridgman method the molted semiconductor material is capsuled inside a cylindrical capsule with a seed crystal at the other end of the cylinder. The cylinder is cooled down from that end where the seed is located and as the molten material cools enough, it starts to form crystal around the seed. Using the Bridgman method eliminated the pulling condition variation problems encountered with Czochralski method. [3] [6]

In a float-zone crystal method a feed rod, which is made of solid semiconductor material that has a multi-crystal structure, is pulled through a small heated hole. While going through the hole, the material is going to melt. After the molten material exits the hole it will become solid again and if done properly rearrange to a single crystal structure. [7]

2.2.2 Wafer

After the crystal is grown it is time to slice it to wafers. Before cutting the crystal the crystal structure must be found out to ensure that the crystals are properly oriented in the wafers. The proper orientation of the crystals in the wafers is essential to produce the mirrors at the end of the diode laser device. The crystal structure can be determined by using X-Ray. After determining the orientation the crystal is cut to wafers. The thickness of the wafers can vary quite a lot but it is around 0.4 mm. [3] [8]

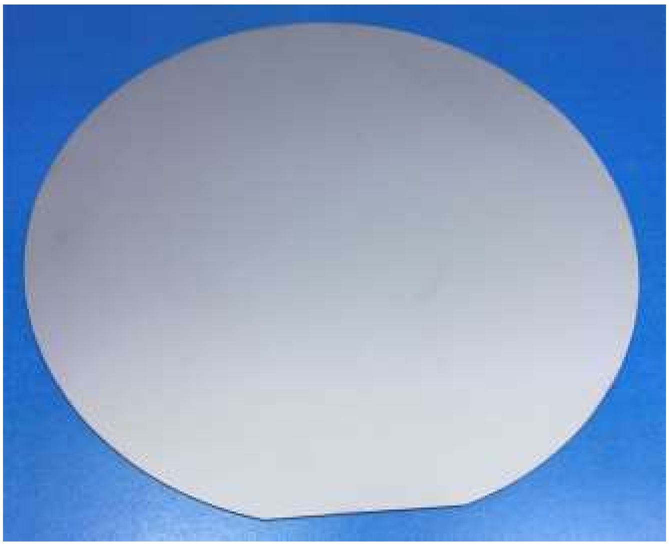

Figure 3. *Clean GaAs wafer.* ***[9]***

In Figure 3 a clean GaAs wafer can be seen that haven't yet been processed. [9]

2.2.3 Process

Next step is to process the wafer to desired semiconductor structure. The processing consists of multiple complex steps like masking, etching, doping, metallization and passivation. These process steps leads to a wafer with semiconductor structure in it. An example of processed wafer can be seen in Figure 4. [3] [10]

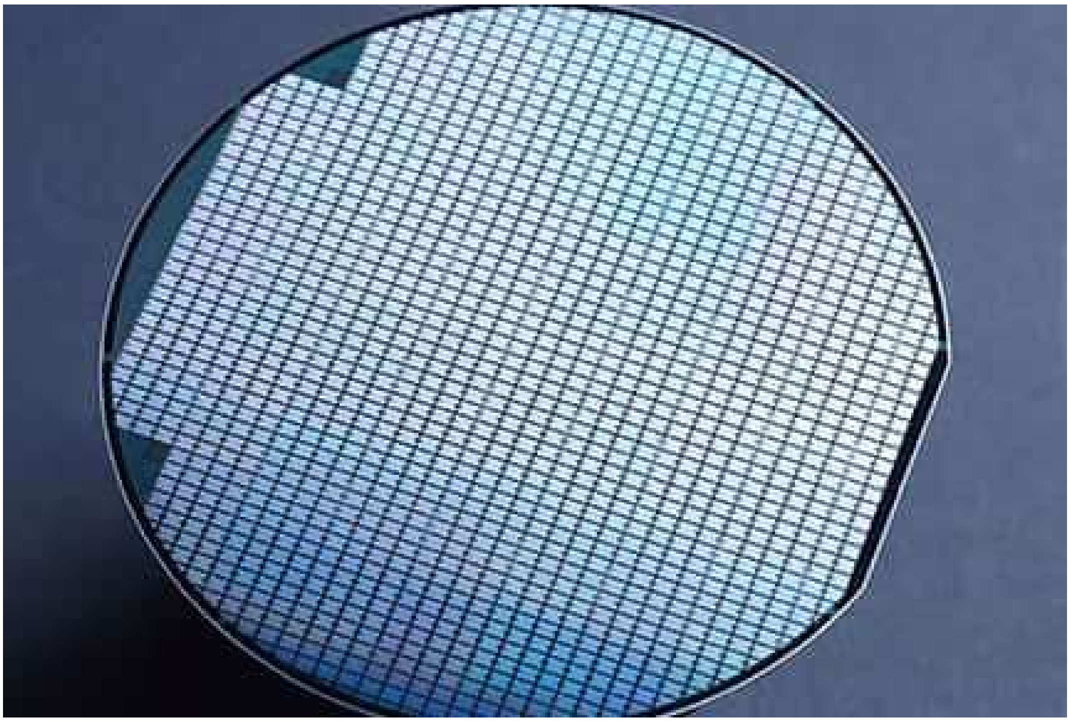

Figure 4. *Processed wafer.* ***[10]***

After the wafer have been processed, it will be cleaved into a single laser chips. At this point a visual inspection is done to the laser chip and all broken or contaminated ones are disposed. The chips that passes are connected to a chip mount usually with gold wires. Gold is used because it has really good electric conductivity properties and gold is easy to mold into a thin wire. A chip connected to a chip mount can be seen in Figure 5.

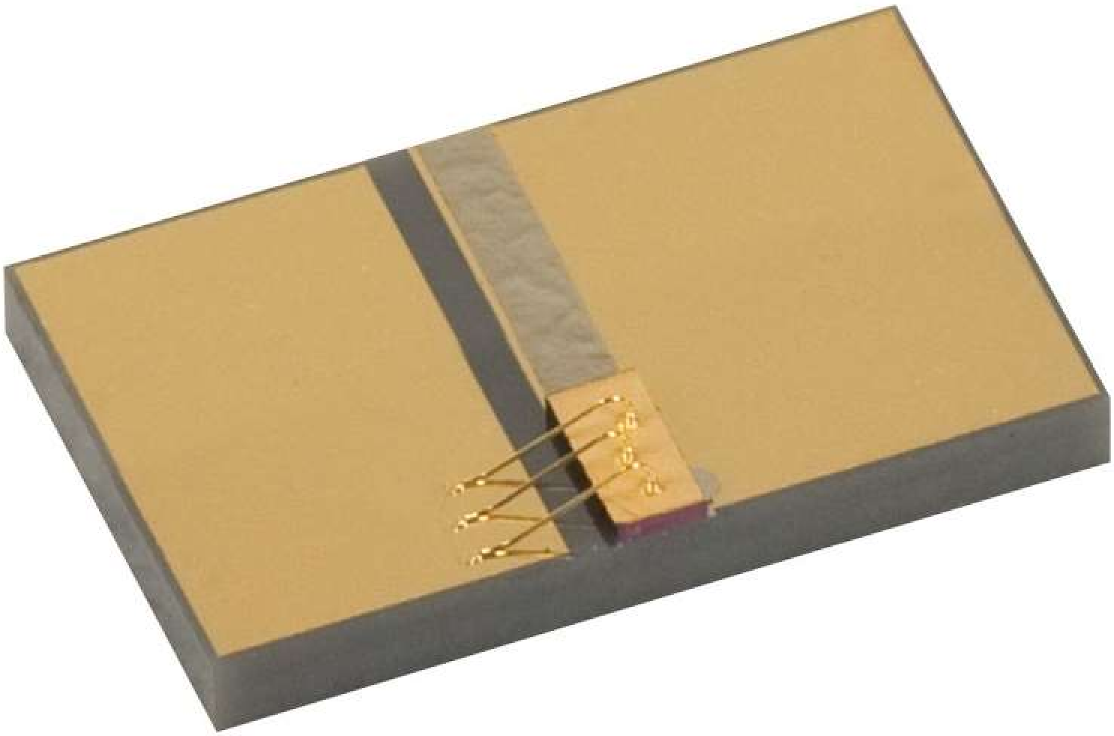

Figure 5. *Laser chip mounted to a chip mount.* ***[11]***

The chips can be connected to a chip mount either way, p-side up or n-side up. The upside is connected to the other pad of a chip mount with wires and the other side is connected directly to the other pad. In the example Figure 5 the chip is connected p-side facing down [11]. The chips are connected to these kind of mound because of easier usability. The pads on the mount are large enough to solder wires on them.

After the mounting the characteristics, like threshold current, voltage and optical power of the laser are tested. The characterization is usually done to every single laser as it is important to know the specs of the laser when using it. Some amount of the lasers from every batch produced are also taken to lifetime test. Since this test is destructive it cannot be made to every single laser but a good estimation of potential lifetime can be made from random test specimens.

Multiple lasers chips can also be combined inside one bigger case. This way the total output power of the laser device can be higher. The output light beams of the individual laser chips are combined using mirrors and lenses and the light is guided out of the device from a single output port. Furthermore this output port is usually designed to be fitted with an optical fiber with which the light can be guided further to where ever the laser light is needed. An example of this kind of module can be seen in Figure 6 [12].

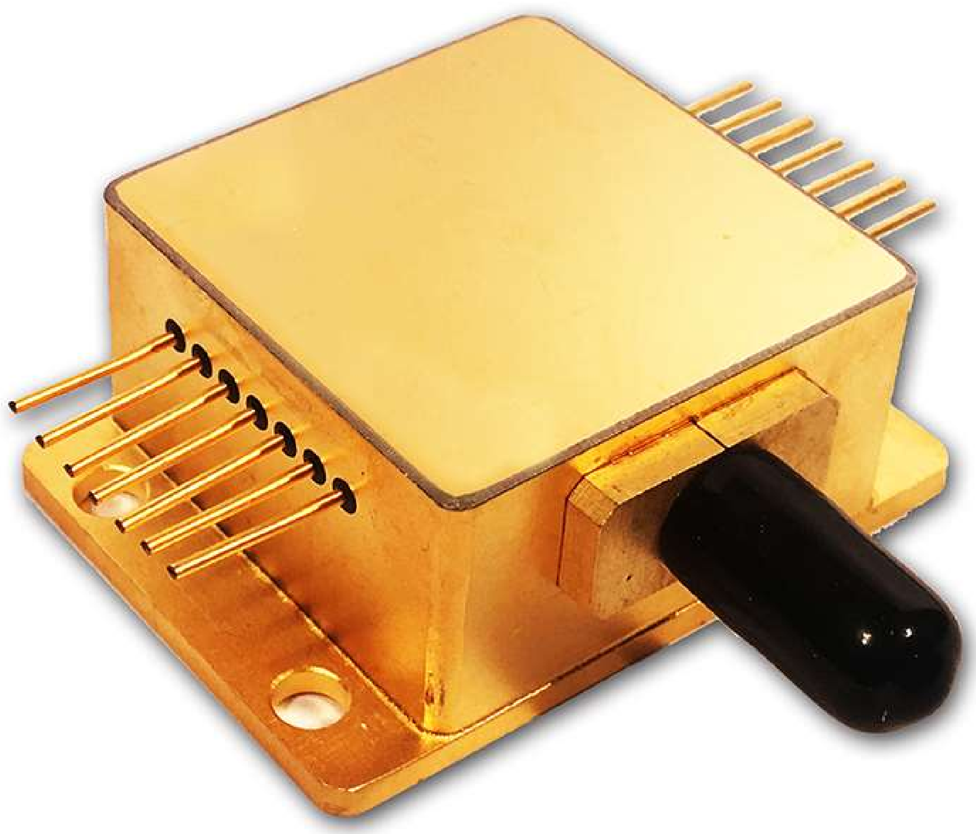

Figure 6. *Multichip laser module.* ***[12]***

In Figure 6 the fiber output port of the laser is covered with a black dust cap. These kind of caps are common to prevent any contamination from entering the fiber port. Usually inside these kind of modules are also assembled a TEC *(Thermoelectric cooler)* for controlling the temperature of the laser, a NTC *(negative temperature coefficient)* to monitor the temperature of the laser and a photodiode to monitor the scattered light from the laser inside the packaging and this way to estimate the output power of the laser device. There can also be seen some pins on the sides of the module. These are electrical connector for all the components and the laser chips themselves that were mentioned above.

2.3 Laser markets

The overall market of lasers have been growing quite rapidly over past few years. The laser market value in 2014 was approximately 9.36 billion dollars and in 2017 it was 12.43 billion dollars. During this time the proportional amount of diode lasers from the market have stayed almost exactly the same, about 44%. At the same time though the amounts of diode lasers produced are greatly bigger that other types of lasers but because of the prices of diode lasers are constantly coming down, the market share of diode lasers have been staying about the same. [11] [12]

The main reason for the past years growth is due to increasing demand for lasers in the consumer markets. Lasers are used for example for manufacturing an OLED *(organic light emitting diode)* display which are becoming the mainstream technology for smartphone displays. Laser themselves have been started to install directly to the smartphones where they are used in 3D cameras and range finding. Other upcoming technology that will possibly greatly increase the demand for lasers is lidar *(light detection and range finding)* for autonomous cars. Overall it can be said about laser markets that the industry is rapidly growing and it is forecasted that the grow rate will become even greater in near feature. [11]

2.4 Diode laser applications

The main advantages of diode lasers are small size, relatively cheap price compared to other types of lasers, wide range of optical power and high efficiency [13]. These advantages are also the reason for why diode laser are usually used in certain applications.

The small size and relatively low price enables the use of lasers in consumer devices. Example of such devices are computer mice and DVD and Blu-ray players. As the laser is one of the most expensive components in these device, the price of laser has great effect on the price of the whole device. And on the consumer markets price is one to most important things.

In the near future diode lasers will probably become more and more common on cars and ships also as autonomous vehicles become more popular. One of the technologies that are used for autonomous vehicles to scan of their surrounding are lidars. Lidar is based on a laser that send a beam of light to multiple direction. As these light beams return to the device the travel times of light beams are calculated and from these travel times a quite accurate map of surroundings can be made.

Cheap price and small size is also one of the reasons why diode lasers are used in telecommunications. Telecommunications and internet connections are nowadays widely based on diode laser produced light transmitted on optical fiber in which the optical signal is transferred.

Another fast growing industry using diode lasers is the medical industry. This is also one of the main areas of expertise of Modulight Oy. In medical industry the lasers are used for example heating, analytical and surgical purposes but one of the newest laser applications are called PDT *(photo dynamic therapy)*. Photodynamic therapy can be used to treat multiple kind of deceases like cancer, acne, virus infections and many more [14]. PDT is based on a combined effect of some light sensitive drug and light. The basic principle of PDT is shown in Figure 7. [15]

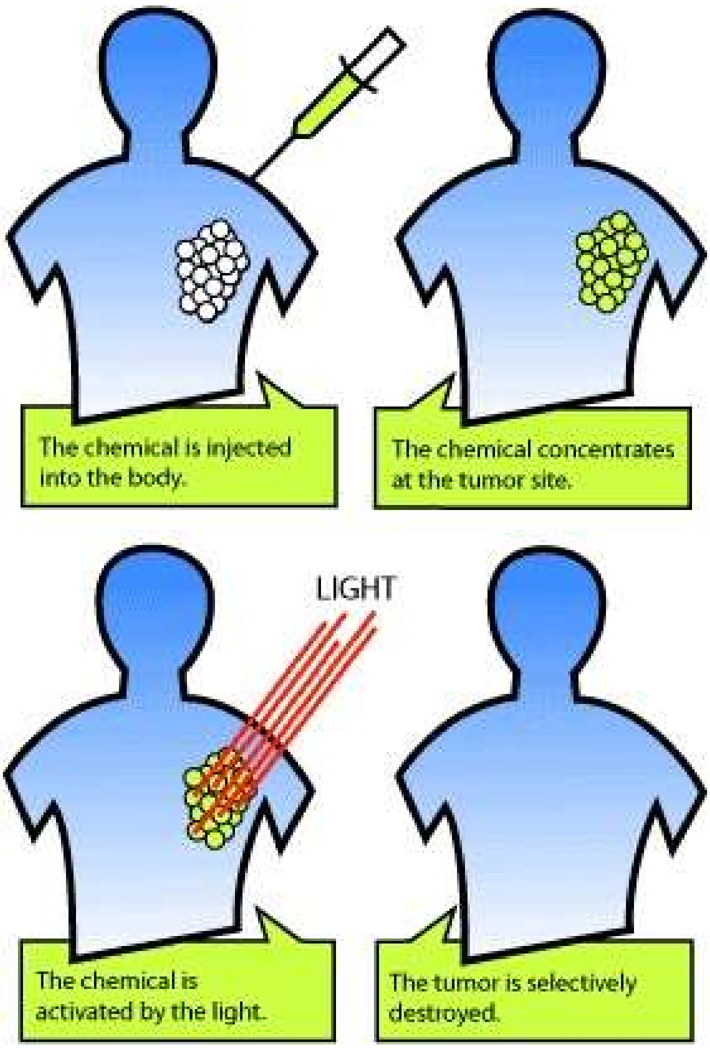

Figure 7. *Principle of PDT.* ***[15]***

The first step in PDT is to give a drug to a patient either orally or by injection. The drug is designed in a way that it is not harmful to any tissue at this point and it also concentrates to a specific tissue in body, to cancer tissue for example. After certain amount of time has passed since the drug is given the next step is to illuminate the targeted tissue with laser light. The PDT drugs are designed in a way that they will be activated only when illuminated with certain wavelengths. When using diode lasers for this illumination the wavelength can be fixed really precisely. This way the drug gets only activated in the target tissue and so the side effects of this therapy are reduced compared to other methods for example chemotherapy in case of cancer.

3. CONTROL OF THE DIODE LASER

3.1 Basics

Laser diodes are controlled almost always with constant current. The reason for this is that the voltage of the laser diode stays almost constant after the lasing threshold when the current and power of the diode is increased. This would lead to a fact that the output power of the diode would be very sensitive for voltage control. When controlling laser diode with current, the power will rise quite steadily with constant slope.

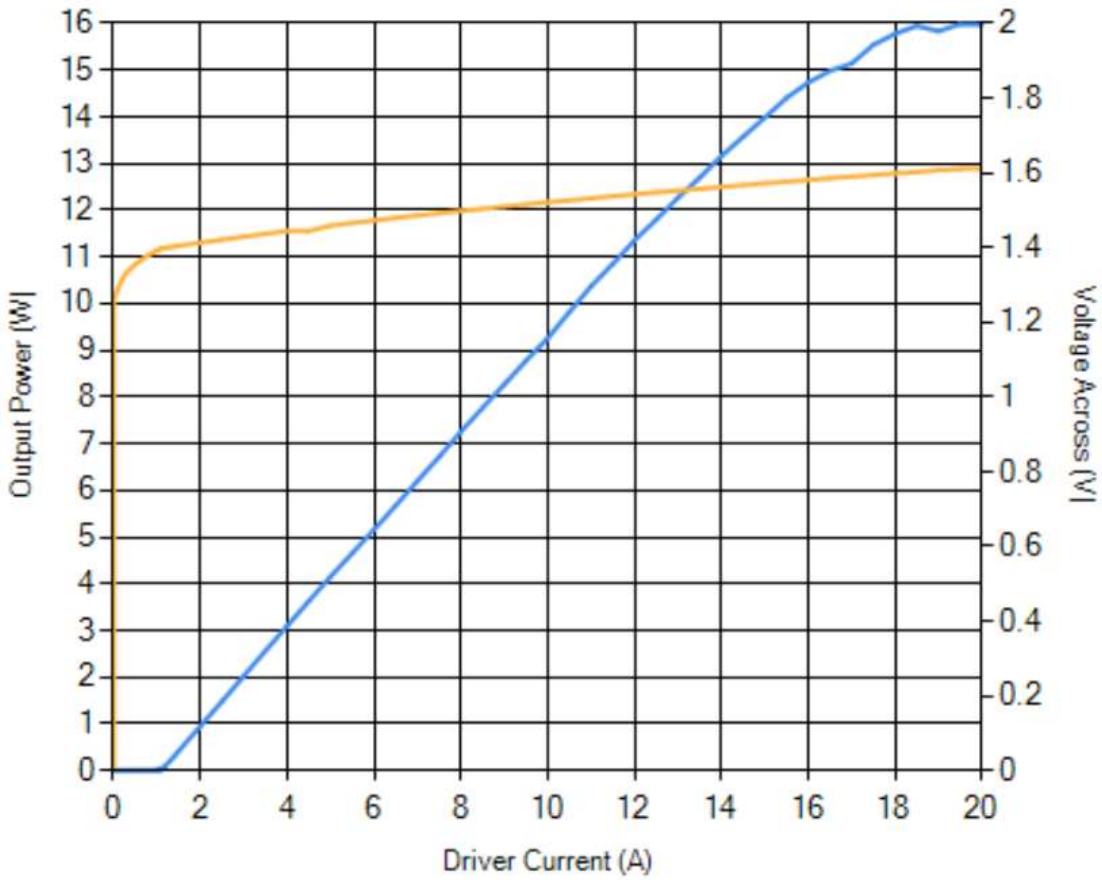

Figure 8. *Behaviour of power and voltage as a function of diode current.* ***[16]***

The behaviour of power, current and voltage can be seen in Figure 6. The yellow line is the forward voltage of the diode and the blue line is the output power. When controlling the diode with current driver, the output power is much easier to set as desired. Though one must ensure that the used current driver can handle the voltage load that the diode is creating at maximum power.

Very often there will be photodiode installed inside the package of laser diode. This photodiode is used to monitor the stability and intensity of the output power produced by the laser diode. There are multiple ways that the laser diode and the photodiode can be connected together. The laser devices are divided into three categories according to the connection type. The types are A, B and C and can be seen in Figure 9.

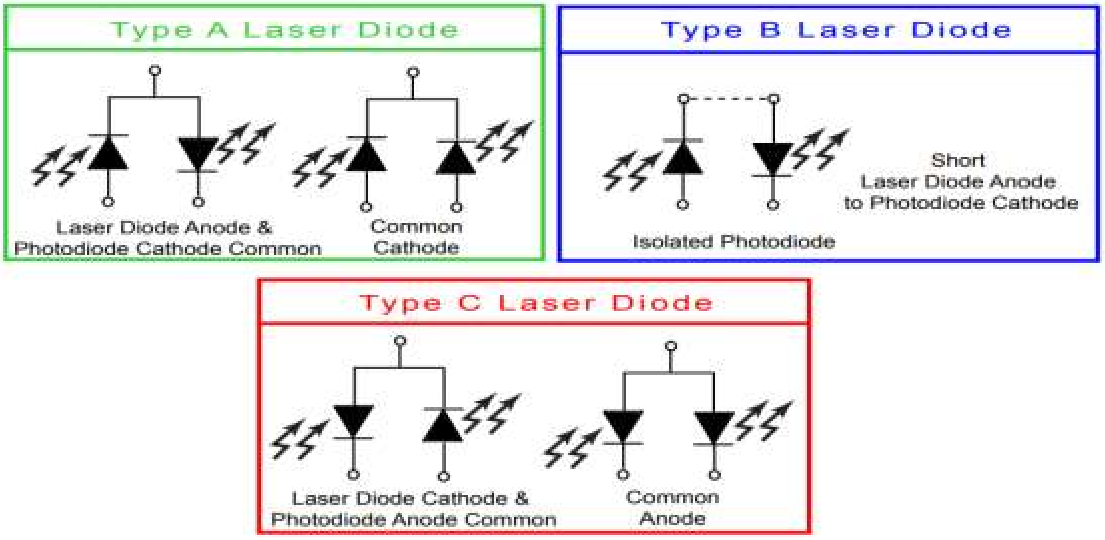

Figure 9. *Different types of laser diode packaging with photodiode.* ***[17]***

Usually the laser diode driver manufacturers give connection instructions for each type of laser diode separately so the user must ensure the type of laser diode that are used before connecting it to the driver.

3.2 Effect of diode temperature on laser characteristics

It is important to be able to control the temperature of the laser diode quite accurately because the temperature have an effect to emitted wavelength and to the output power of laser. One of the main advantages for multiple applications of diode lasers are constant and easily adjustable output power and constant and narrow wavelength spectrum. If the temperature of the laser is not controlled, these properties will not be realized.

There are few reasons why the temperature is affecting the wavelength of the laser. When the temperature is rising, it reduces the energy differences between excited and non-excited electrons. Thus when the photon is released, it will have less energy and also longer wavelength. The temperature will also affect the refracting properties of the active layer which will further make the wavelength longer. [18] [19]

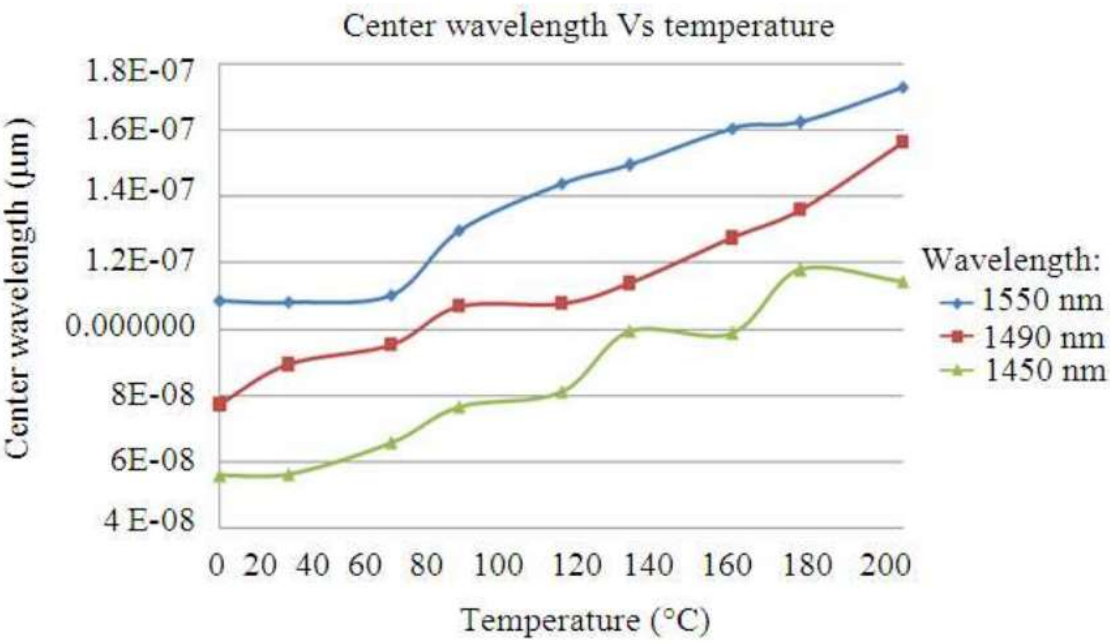

Figure 10. *Simulated effect of temperature to the wavelength of the laser.* ***[19]***

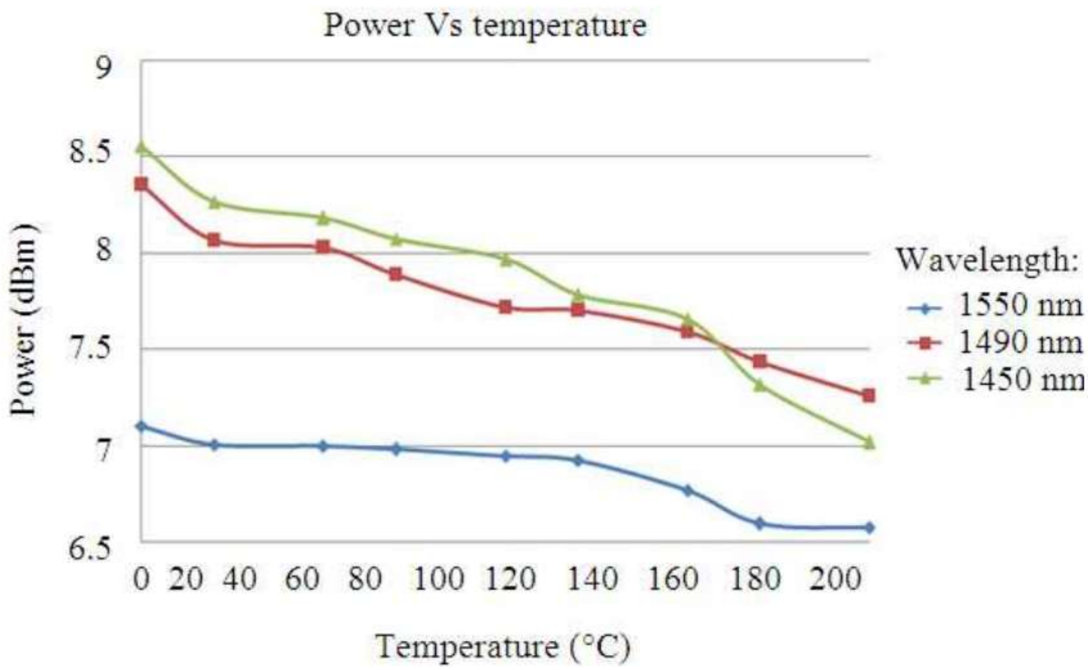

Figure 11. *Simulated effect of temperature to the output power of the laser.* ***[19]***

In the Figure 10 and in the Figure 11 can be seen some simulated effects of temperature to the wavelength and to the output power. The magnitude of the effect of temperature will differ between different lasers and centre wavelengths.

3.3 Effect of diode current on laser characteristics

It is also really important to control the current quite precisely because current will, as described before, have direct effect on the output power of the laser, but the current will also have an effect to the wavelength of the laser diode. The main reason is that the greater current will increase the temperature of the laser diode, but there will also be other effect called band-filling effect. [19] [20]

4. DESIGN

I was given a project to design and assemble a part of a system that would be used to test laser diodes' lifetime. My part was to design current drive for laser diodes, communications between current drivers and control board, laser diodes' mechanical attachment and heat control and power supply for control board, laser drivers and heat control. In Figure 12 the schema of the whole system can be seen. Parts of the system that were part of my project are highlighted with red.

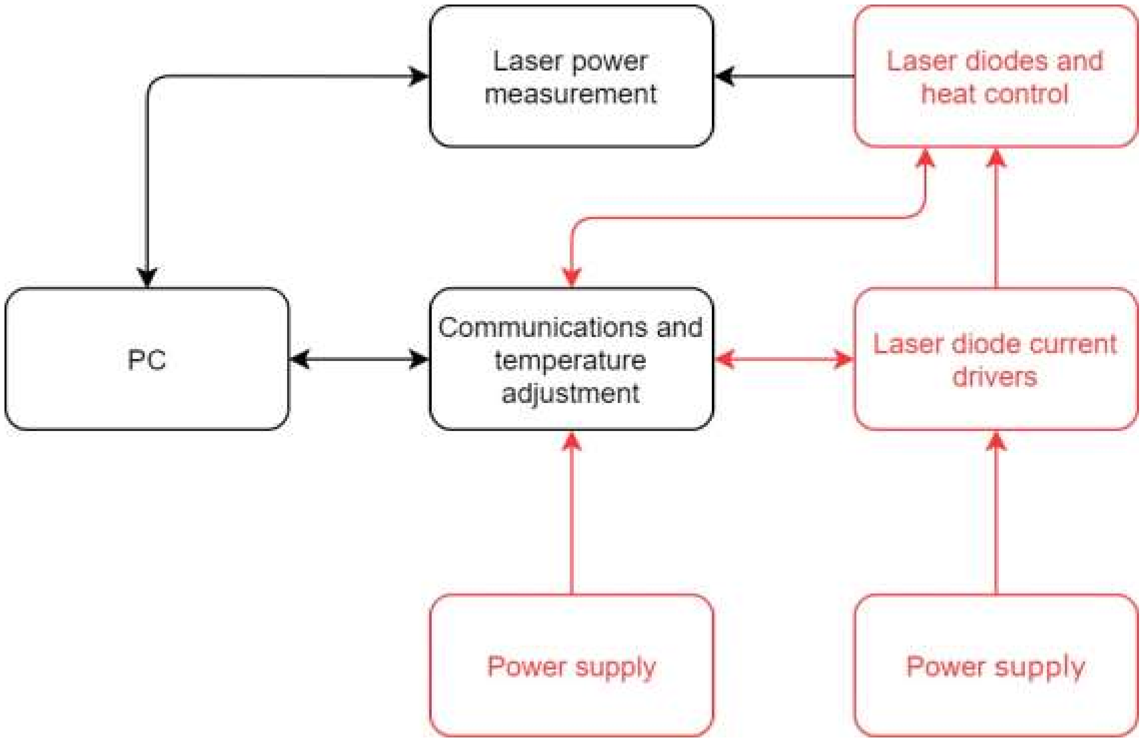

Figure 12. *Schema of the test setup. Parts of this project are highlighted with red.*

The design process can be separated into two individual designing phases. First I designed the electronics and it was done by using CAD *(computer aided design)* software called EAGLE. After electronics I designed mechanics and it was done by using CAD software called SolidWorks.

4.1 Requirements

The requirements and goals of this project were given to me at the beginning. There were only a few requirements but every one of those were necessary to meet for this project to be successful. First requirement was that the device has to have 8 channels for testing simultaneously 8 laser diodes. Second requirement was that every channel has to be able to drive at least 15 A to 2.5 V load. Third requirement was that there has to be diode current and voltage measurement. Fourth requirement was that the use has to be able to control the temperature of laser diode from 10 °C to 50 °C. And last requirement was that the device needs to be an easy way to scale the device up for more simultaneous tests.

4.2 Electronics

The current driver was the essential part of this design so I started by finding a suitable driver. After that I chose other components, for example the power supply, based on the needs of chosen driver. The communications hardware interface between laser driver and control boards was given to me pre-made so I had to design the driver board to support it.

In this case the most cost efficient way was to find and by ready-made current driver from experienced manufacturer. I could have designed my own current driver but it was not worthwhile because I don't have enough expertise on designing constant current drivers to meet the high stability requirement for laser diode current. I chose ATLS6A201D driver from Analog Technologies. The reason was that I had already some experience with this company's drivers and I knew that those will meet up with the requirements. ATLS6A201D is also able to drive up to 6 A to 4.25 V load with 5 V input voltage. These drivers can also be used in parallel so by using three of these drivers in each channels I was able to get output current of 18 A. This way I was able to meet up with the current and voltage requirements set for this project. Device's datasheet also provided detailed example on how to use these in parallel mode. This example can be seen in Figure 13. With good documentation I felt comfortable using this component. [21]

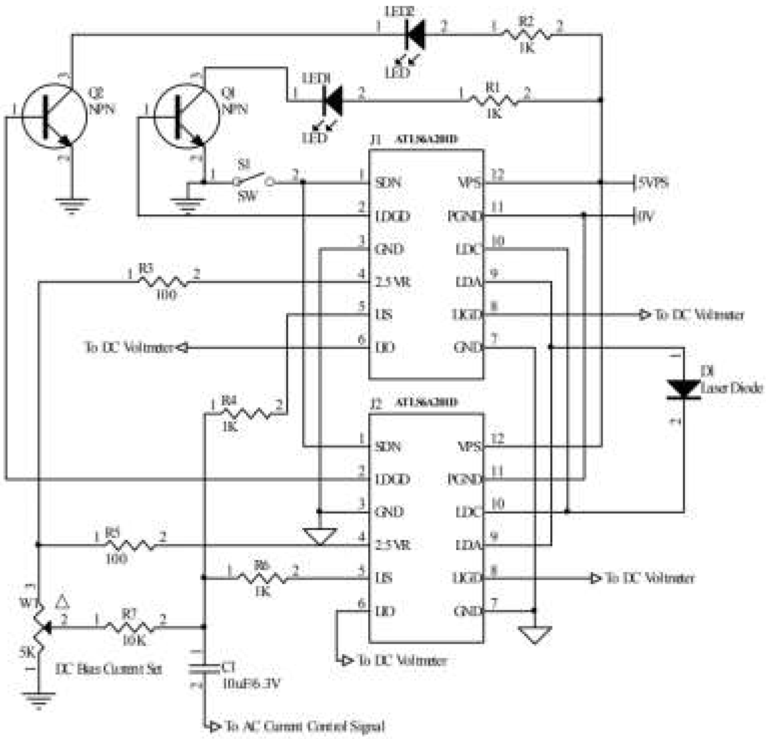

Figure 13. *Example parallel circuit for ATLS6A201D* ***[21]***.

After choosing the driver for the laser diode driver unit, I was able to choose power supply. For choosing power supply it is good thing to estimate the power consumption of the device first. Driver’s efficiency is promised to be at least 85% [21]. Needed power can now be calculated using this equation (2)

$$\boldsymbol{P} = \frac{\boldsymbol{UI \cdot n}}{\boldsymbol{k}}, \tag{2}$$

where P is the power needed, U is the output voltage of drivers, I is the output current of the drivers, n, is the number of drivers and k is the efficiency factor of the drivers. From the requirements we know that the maximum output voltage is 2.5 V, maximum output current of one channel is 15 A, there are total of eight channels in the laser diode driver unit and the efficiency factor is 0.85 [21]. With equation (2) the maximum power needed by the devices can be calculated and it is about 353 W. I also wanted to use as high supply voltage as possible, around 5 V, because that way the supply current will be lower and the PCB (Printed circuit board) can handle the current better. I founded a suitable power supply that met with the requirements. It was MEAN WELL’s NEL-400-5 that has 5 V output voltage and can provide 400 W of power [22].

My task was also to provide power for the pre-made communications and temperature control unit. This unit needs 12 V supply voltage so the same power supply cannot be used for this unit as for the laser diode driver. Basically all the power that the communications and temperature control unit needs is used for temperature control and therefor driving current for TECs. Again some power consumption estimation needed to be done. In the worst case scenario the laser diodes would have forward voltage of 2.5 V and forward current of 15 A, and if the diode is malfunctioning there is a possibility that all of the input power converts to heat in the diode. Even in this case the TECs have to be able to keep the diodes cooled to prevent overheating. The electrical power can be calculated with equation

$$\boldsymbol{P = UI.} \tag{3}$$

In this case the input electrical power for each diode is 37.5 W and thus if the diodes break, they produce 37.5 W heat. I chose TEC CP85438 from CUI Inc. for this. CP85438 is able to transfer maximum of 75 W of heat through it which is more than enough. Although with TECs the power consumption is affected by the temperature of the TEC's hot side and the temperature difference between hot and cold side so more precise estimation is needed.

The temperature of the diodes is wanted to be around 25°C. CP85438's datasheet provides performance figures in the scenario when the temperature of the hot side is 27°C. This is close enough to 25°C for the estimation. Let's assume that we can keep the TEC's cold side, and thus also the heatsink, under 45°C. In this case the temperature difference between hot and cold side is 20°C. From the figure in the datasheet we can see that in this case the needed 37.5 W heat can be pumped with the current of 5.1 A [23]. From the same figure we can also see that with 20°C temperature difference and 5.1 A current the voltage over the TEC will be little less than 9 V [23]. With equation (3) we can now calculate that the maximum power usage of one TEC is 45.9 W and eight TECs is 367.2 W. I chose U6Y007P from TDK Lambda which can provide 400 W of power [24].

4.2.1 Schematic

After all of the main components were decided, I was able to start designing the schematic for the laser diode current driver. I designed the schematic using CAD software called EAGLE. This software was chosen because I was familiar with it but there are also many others that are very similar and can also be used for electronics schematic and layout design like KiCad, DipTrace and Altium.

I started the schematic design from the ATLS6A201D parallel example that can be seen in Figure 13. I just added one more driver to the parallel circuitry. Because the communications interface between laser diode current driver and the communications and temperature control unit was premade, I had to make some changes to the example parallel circuitry. The signals in the interface that had to be addressed are listed below in Table 2

Table 2. *List of signals in the premade communication interface.*

Pin name	Description
VMON(1..8)	Output voltage of current driver for all channels.
LIS(1..8)	Voltage for controlling the output current of driver for all channels.
SDN(1..8)	Signal for shutting down current driver for all channels.
LIO(1..8)	Voltage for reading the output current of driver for all channels.
LDGD(1..8)	Voltage for making sure that the driver is working properly for all channels.
LIGD(1..8)	Voltage for making sure that the output current of the driver is stable for all channels.

To get the VMON signal I connected the output of the current driver, LDA, to voltage divider combined with low pass filter. Example circuit of this can be seen in Figure 14. The low pass filter is there just to remove the possible noise from VMON signal.

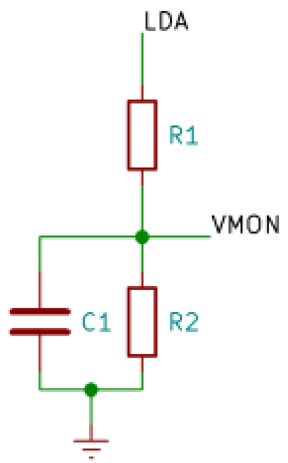

Figure 14. *Voltage divider combined to low pass RC-filter.*

In this kind of coupling the VMON voltage can be calculated with the equation (4) [25].

$$VMON = LDA \cdot \frac{R2}{R1+R2} \tag{4}$$

The LIS and SDN signals could be connected directly to the current drivers. For LIO and LIGD signals I made a simple averaging circuit because I wanted a way to monitor all three drivers in each channel. Example circuit of this is shown in Figure 15.

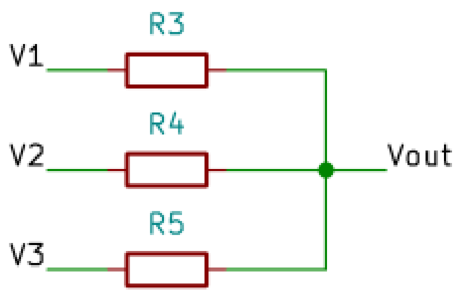

Figure 15. *Voltage averager.*

When the resistances of resistors R3, R4 and R5 are equal, the output voltage of this circuit Vout can be calculated with equation (5) [26].

$$V_{out} = \frac{V_1+V_2+V_3}{3} \tag{5}$$

If one of the three drivers' LIO or LIGD signals differs a lot of what it should be, it can be seen in the averaged signal.

To be able to make sure that all three drivers were okay, I added a simple AND logic port to drivers' LDGD signals. Example circuit can be seen in Figure 16.

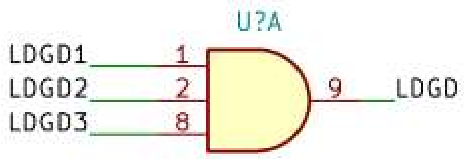

Figure 16. *AND gate.*

This way LDGD signal would be down even if only one of the three drivers weren't working properly. AND gate also needed 3.3 V power to function which I didn't yet have on the board so I added simple 3.3 V linear regulator to provide it. All of these circuits mentioned before had to be multiplied eight times in the design because the device has eight channels.

I also had to choose connectors for power input and drivers' outputs. We used AWG *(American wire gage)* 14 wire to provide the current to laser diodes so for drivers output I needed a connector that supports AWG 14 wire and that is easy to close. Screw terminals would be best option due to their high current rating but those are not easy and fast to open and close so screw terminals couldn't be used. For this purpose I chose TE Connectivity's 194009-1. I could not find precise current rating from manufacturer's datasheet for this connector, but it supports wires up to AWG 14. In the datasheet the manufacturer says that the connector is for “high current” [27]. It has to be confirmed that the connector can withstand 15 A of current in the testing phase.

I had calculated earlier the input power for the current drivers with equation (***2***) and it is 353 W. With 5V input voltage it means that the total input current is 70.6 A. This can be calculated with equation (***3***). For this purpose I chose Molex’s 0039310048 connector. From the datasheet can be found that this connector withstand up to 9 A current per contact with 16 AWG wire [28]. I added one four-contact connector for each channel so the overall current of 70.6 A would be split between 16 contacts. In this case the maximum current per contact will be about 4.4 A.

4.2.2 Layout

After the schematic was done, it was time to design the layout for the laser diode current driver PCB. The layout design was done concurrently with mechanical design because they both affect to each other. The layout design process starts by determining the physical outlines of the PCB which are usually determined by the mechanics where the PCB will be fitted. Also the mountings of the PCB and the locations of the connectors have to be designed to fit the mechanics. Once the outlines of the PCB have been drawn the next step is to determine the placement of the components.

First thing to do is to decide whether to use through-hole components or surface mounted and whether to assemble the components on both sides of the PCB or just on one side. The advantages of the through-hole components compared to surface mounted are that they are more robust, reliable and can withstand more physical stress which is the reason that through-hole components are used more in military and aerospace products. The advantages of the surface mount components on the other hand are that they are cheaper to assemble because there isn’t a need for additional holes and they are smaller and there for higher component densities can be achieved. In the Figure 17 an example of through-hole and surface mounted resistors can be seen. [29]

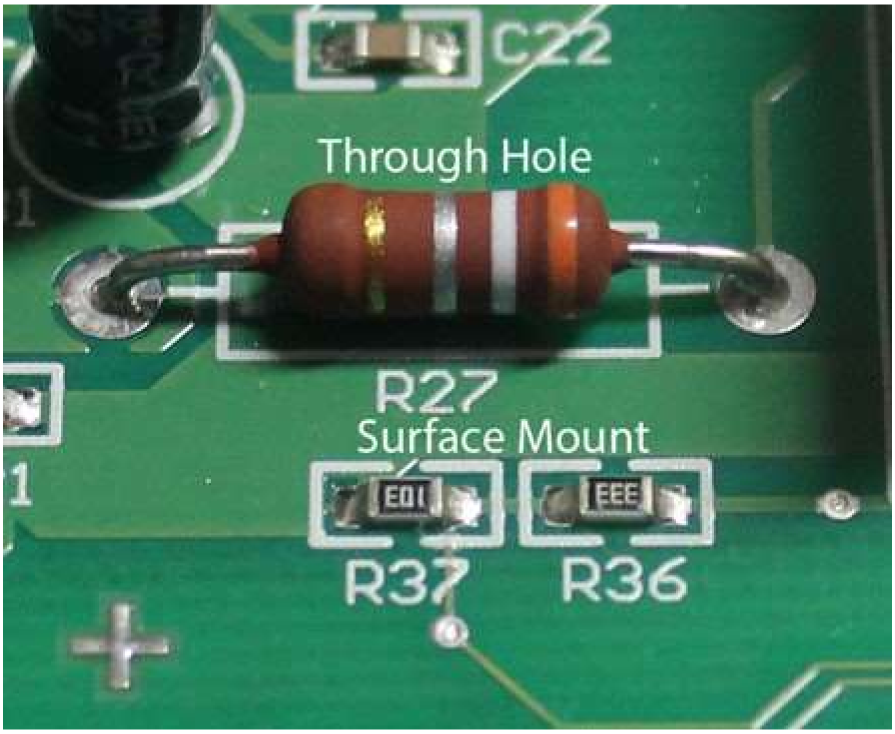

Figure 17. *Through-hole and surface mounted resistors.* ***[42]***

For this project there wasn't any need for extra robustness so the choice was surface mount components. Also because of the outlines of the PCB were determined by the size of the heat sinks below the PCB, as seen in the Figure 19, there was more than plenty room for the components. For this reason I decided to design all of the components to the same side of the PCB. This way the assemble of the components will be easier and also cheaper. Because of the large size of the PCB determined by the mechanics in this project there wasn't any issues to find a place for all of the components. Usually the space is much more of an issue and more time and effort have to be used to find a suitable place for the components. While placing the components you also have to consider the routings to and from all of the components so wirings between the components will be possible to design also.

One design element is also do decide how many layers do you need or want in the PCB. If the mechanics restricts the size of the PCB or you want to do as small PCB as possible for some other reason, then it is viable to use more than two layers on the PCB. With more layers it is much easier to route all the necessary routings between components. For this project one of the main issues to take into account was the relatively high currents that the PCB had to endure. To ease this I decided to make the PCB as six layer. This way I was able to use very large coppers pours in multiple layers to support high currents. I poured almost entirely two layers for ground signal and also two layers for 5 V signal. This way I could be sure that the PCB could handle the high current, up to 70.6 A. Also the output of each individual driver would have quite high current so also these had to be designed to withstand at least 15 A. Another factor that demands for more layers and large copper pours can be heat management. If you are using some high power components they usually need a large amount of copper to dissipate all the produced heat to.

After I had finished the placement of all of the components it was time to start designing the wiring between the components. When designing wirings there are some things that have to be considered. Firstly with all of the wires the width of the wire needs to be decided. The main factor in this is the amount of current that the wire will need to withstand. The more current the wire will be conducting the wider it has to be. Some recommended widths for 35 µm thick copper are given in the Table 3.

Table 3. *Recommended trace widths for 35 µm thick copper layer.* ***[30]***

Current (A)	Trace width (mil)	Trace width (mm)
1	10	0.25
2	30	0.76
3	50	1.27
4	80	2.03
5	110	2.79
6	150	3.81
7	180	4.57
8	220	5.59
9	260	6.60
10	300	7.62

Other thing to consider is the routing of possible high speed signals' traces. When there are some high speed signals on the PCB, some extra care is needed with the design. High speed signals will always transmit radio waves to the environment and to minimize the unwanted effect of these radio waves on other signals it is good practice to enclose the traces of high speed signals between ground planes. In this project I didn't have any high speed signals that would have needed extra attention.

Also when designing traces it is not good to design sharper than 45° to the traces. There are two reasons for this. In sharp corners the length of the wire has a significant difference on the inner and the outer bank of the corner. This will change the impedance of the trace and cause electromagnetic radiation. Other factor is that during the manufacture process of the PCB some acid can be caught in the corner of the trace which will etch the trace further than wanted [31].

It is also good design practice not to design so called hidden traces between the legs of ICs because this way when inspecting the soldering it might seem that there is an unintended short circuit between the legs. Some examples of the good, marked as “OK” and bad, marked as yellow circles, design practices can be seen in the

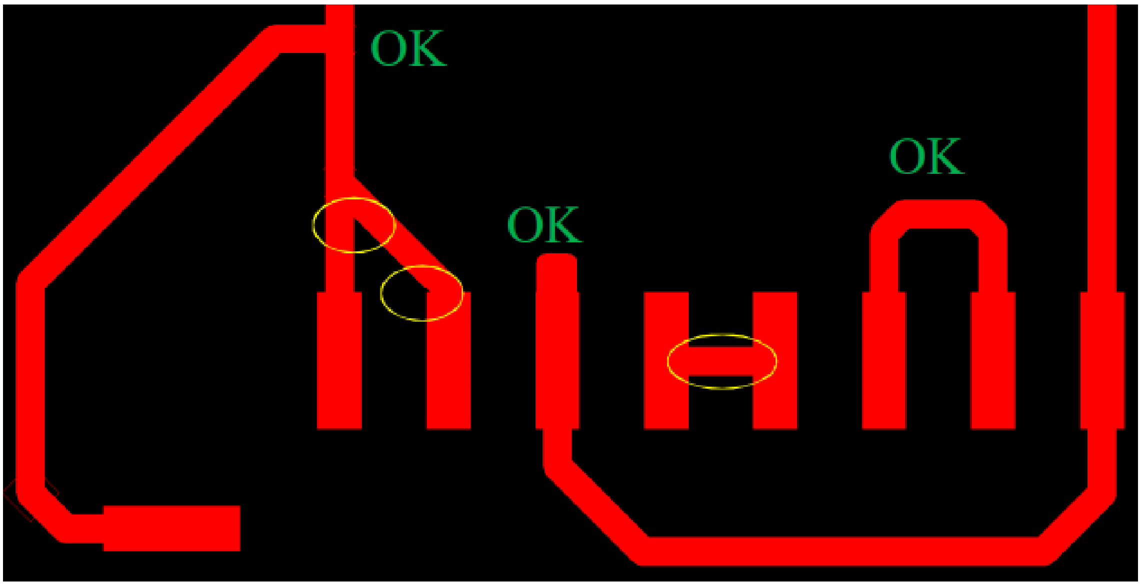

Figure 18. *Examples of good and bad design practices.* ***[32]***

4.3 Mechanics

The mechanics design was done using the CAD software called SolidWorks. I started the mechanics design by thinking of a way to make the system easily scalable to support more channels. I decided to use standardized 19-inch rack for this purpose and I found a rack self RSVS1921BK1 from Hammond Manufacturing. This self was really good for my purposes due to multiple reasons: it has sliding hinges to easily pull the self out from rack, it has ventilation holes on the bottom that makes the design of cooling much easier and it has large enough area that I can with everything on it [33]. As a bonus the manufacturer is also providing the 3D-model of the self so it was easy for me to start the mechanical design on top of this self [34].

Another important thing was the cooling of laser drivers and laser diodes themselves. It would also be really good to get the diodes as close to the drivers as possible to minimize the wire length. So it would be ideal to use heatsink that big that all of the drivers and the laser diodes could fit on it. Instead of using one really big heatsink I decided to use to smaller ones that would cool half of the drivers and lasers each. The heatsinks I chose were 511-12M from Wakefield-Vette. From my experience on cooling lasers I also knew that it is necessary to add fans to the heatsink to provide cooling that is efficient enough. I chose to add two fans on both heatsinks. The used fans AFC1212D-F00 from Delta Electronics because those had the right width to fit the heatsinks and they used 12 V which I already had available [35]. The mechanics design can be seen in the Figure 19 and the numbered parts are listed in the Table 4.

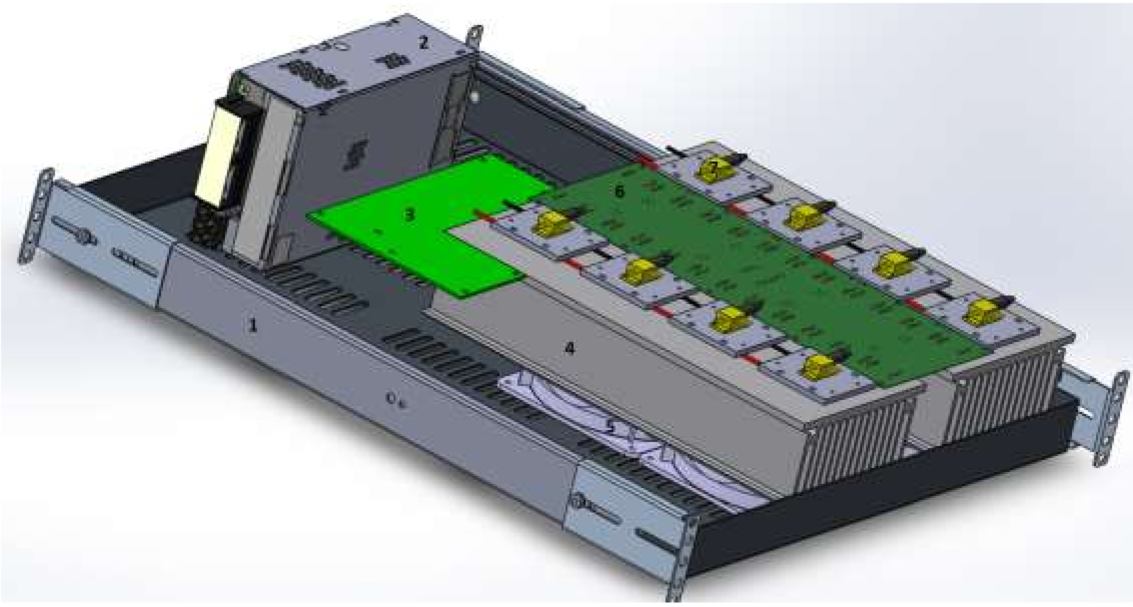

Figure 19. *Mechanics design.*

I placed the two heatsink side by side leaving a small cap between. The TECs are placed between the small metal plates and the heatsinks. The metal plates are on top of the TECs just because the laser diodes cannot be mounted directly on top of the TECs because you cannot make holes to them. I placed two fans on the bottom of both heatsinks that blow the air through them. The current drivers are located at the bottom side of driver PCB. The 5 V power supply for the driver PCB is missing from the mechanical design, because I didn’t have 3D-model for it. The mechanical parts are listed in the Table 4.

Table 4. *List of mechanical parts.*

Number	Description	Source of 3D-model
1	Rack self	Manufacturer [34]
2	12 V power supply	Modulight 3D library
3	Communications and temperature control PCB	Self-produced
4	Heatsink	Manufacturer [36]
5	Fan	Manufacturer [37]
6	Laser diode current driver PCB	Self-produced
7	Laser diode package	Modulight 3D library

This kind of 3D design is really good way to make sure that everything will fit in the space that is available. It will also help during the assembly of the device.

5. ASSEMBLY

After the layout and the mechanics design were done it was time to order the components and PCBs. With 3D design it is really easy to make sure beforehand that everything will fit together nicely and this way it will make the assembly phase much easier.

5.1 Electronics

When only a few PCBs are needed and you don't have a lot of components on it, it is usually faster and cheaper to solder the components by yourself. In this case I needed only one PCB and it had 157 components on it so I decided that the best solution is that I ordered the PCB from PCB manufacturer unassembled and that I solder the components myself. I had already taken this into account during layout design and chosen 0603 SMD *(surface-mount device)* packages. The 0603 packages are 1.6 mm by 0.8 mm and are still quite easy to solder by hand. In this PCB 0603 packages are the smallest ones so overall the soldering process will be quite straight forward. The empty PCB can be seen in Figure 20.

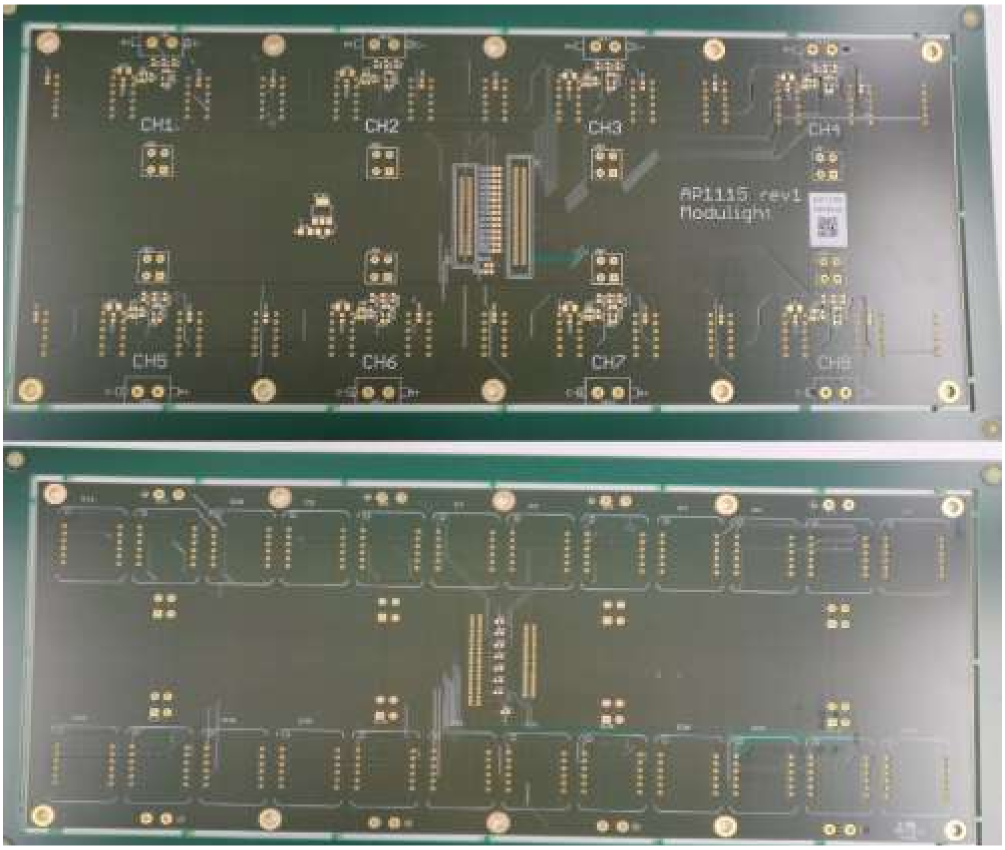

Figure 20. *Top and bottom sides of unassembled PCB.*

Usually when hand soldering it is best to first solder any ICs *(integrated circuit)* on the PCB because those are harder to solder after there are other components attached near them. I had few ICs on board AND gates in SOT-23-6 packages and some operational amplifiers in SOT-23-5 package so I started the soldering from those. After all the ICs were soldered next in line was all the passives, the diode drivers and finally all the through hole connectors.

It is also necessary always to check your soldering results after hand soldering. For optimal soldering the pads on the PCB and the pins of the component needs to be thoroughly wetted from the solder. In the Figure 21 there is an example of good soldering on SMD component.

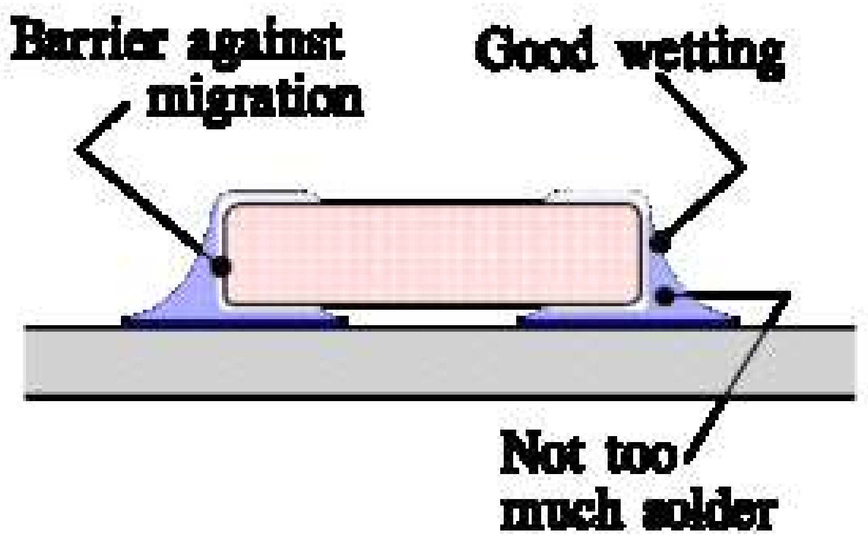

Figure 21. *Example of good soldering.* ***[41]***

I checked all of the connections and made sure that they were good enough. Bad soldering can cause bad electrical connections and thus the PCB might not work at all or it might function incorrectly. Bad soldering can also shorten the lifetime of the device and it will decrease the mechanical durability of the device. In the Figure 22 there is one example of my soldering viewed through a magnifying lens. In this example can be seen that the solder of the right side pad looks good but the left side pad of the component is not wetted properly. This kind of defect can be fixed just by reheating the pad with iron or additionally add some soldering flux to the pad before reheating.

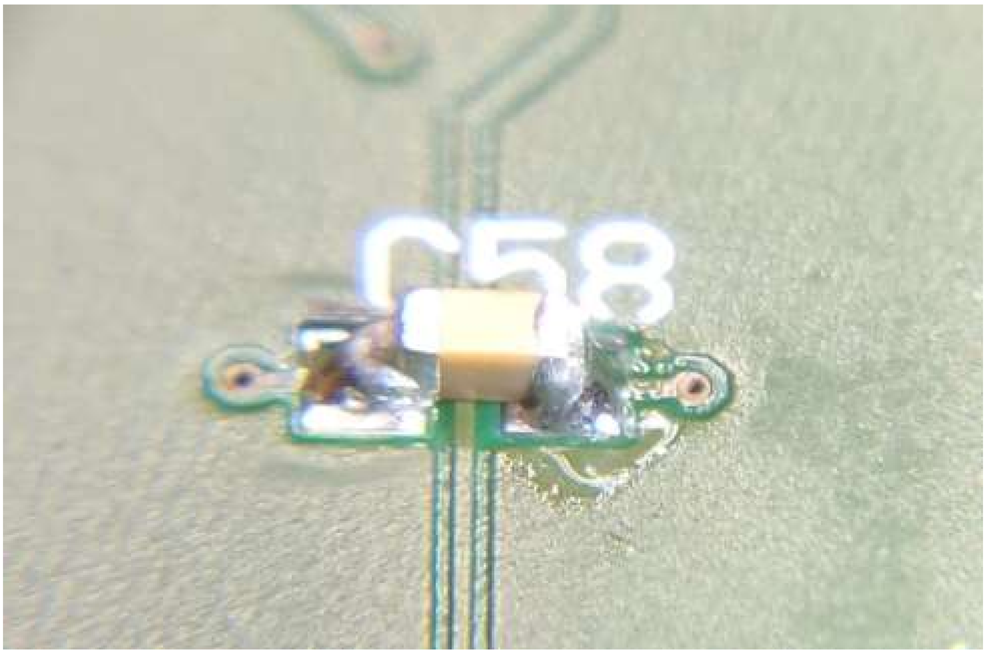

Figure 22. *Example of my soldering.*

There were also quite a lot of wiring to be done after also the mechanics were assembled. All of the four fans from the bottoms of the heatsinks and the communications and temperature control PCB needed to be wired to the 12 V power supply. Also all of the eight TECs and eight temperature sensors measuring the temperature of the metal plates under the lasers needed to be wired to the communications and temperature PCB. The 5 V power supply needed to be wired to the driver PCB.

I also had to design a way to supply 230 V AC *(alternating current)* current for both of the power supplies. When using this high voltages the electrical safety is always the main concern because it can be lethal. For the inlet power socket I chose Shurter's DD12. It has built-in fuse slots for both live and neutral wires. This way the power will be cut out faster in the case of short wiring of either the live or neutral wire. DD12 also has built-in filter for filtering out some interference from electricity network and a built-in switch that could be used as main power switch for the whole device [38]. From power socket I wired the 230 V to emergency stop switch. The emergency stop adds security and with this switch all the power can be easily shut down in case of emergency. This kind of emergency stop is also a requirement for all call 4 laser devices. If the maximum power of the laser exceeds 0.5 W it is considered to be able to burn skin and cause devastating and permanent eye damage even when viewed indirectly [39]. From emergency switch I wired the 230 V to both power supplies. It is also really important to make sure that all of the metal parts in the device are grounded properly. This way one can ensure that in the case of short wiring either of the live or neutral wires of the inlet power the fuses in the power sockets will go off instead of some parts getting high voltage on them. To ensure good grounding I connected the rack tray, both heatsinks, both power supplies' cases and the rack itself to the ground pin of the power socket.

5.2 Mechanics

The assembly of mechanics basically consisted of drilling fastening holes to the rack self for all of the components. Also the PCB needed to be fastened on top of the heatsinks and the fans needed to be fastened to the bottom of the heatsinks. I got all of the measurements and the right positions from my previously done 3D design. Then I just needed to measure the holes carefully using a caliper. Before starting to drill the metal it is always important to do the starting pivot using the center punch. The starting pivot guides the drill bit to the right spot. It is also important to use some lubricant while drilling metal to avoid overheating. After the holes were made it is also important to remove possible the sharp edges around the hole with bigger drill bit. [40]

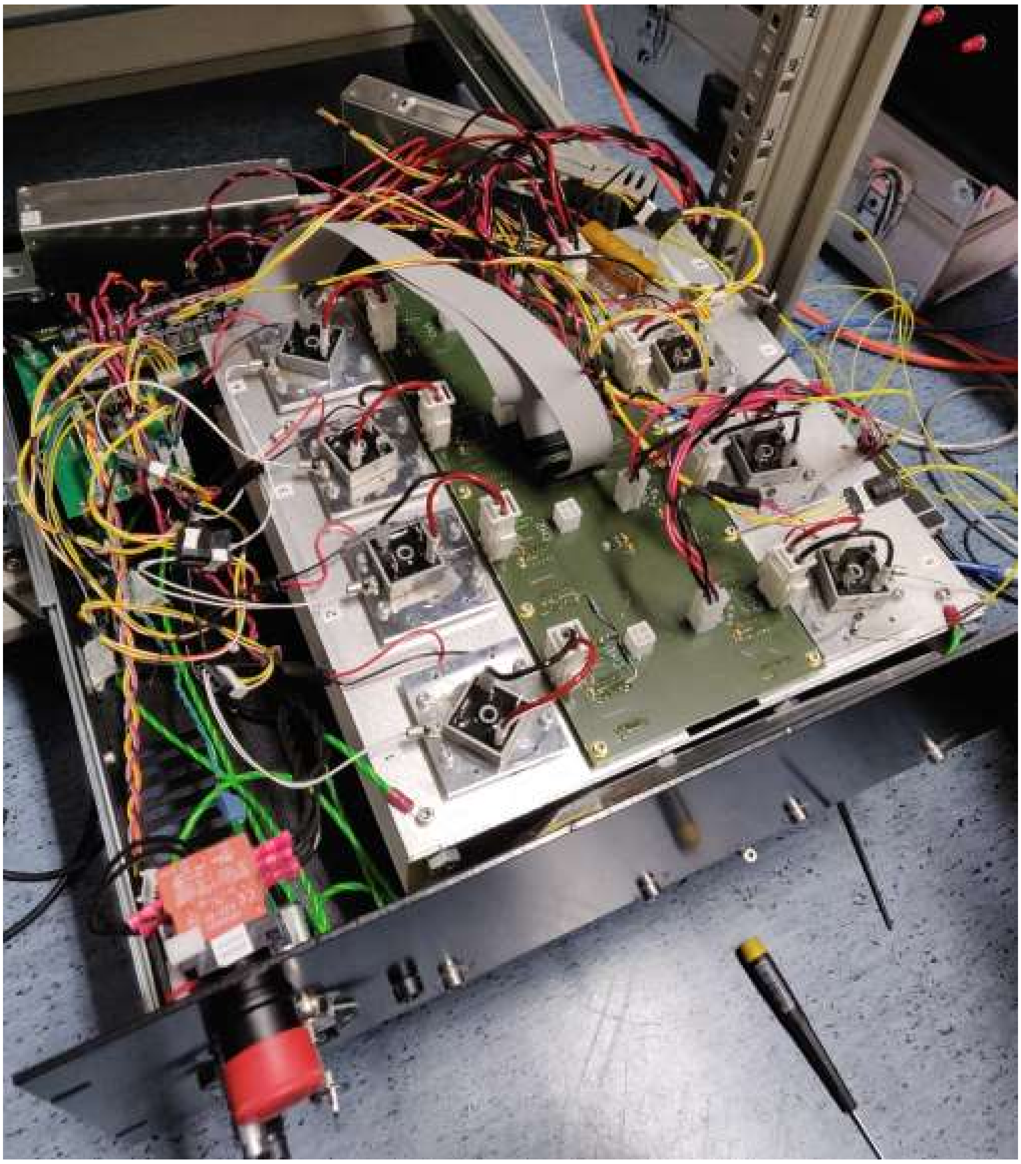

Figure 23. *End result of assembly.*

In the Figure 23 the end result can be seen. In the front plate there can be seen the emergency stop button attached under which is a key lock for added security. The key lock is wired in a way that the device cannot be turned on without the key in place. There can also been seen the two relatively large heatsinks on top of which the main PCB and the TECs are attached. There are two fans under both heatsinks that cannot be seen in the Figure 23. The fans help to transfer the heat produced by laser away from the heatsinks. The fans are placed in a way that they blow air into the heat sink from below. Other end of the heat sink is blocked by a metal plate to guide the air to the two AC/DC converters and this way provide cooling also to them. The AD/DC converters converts the 230 V AC current to 12 V and 5 V needed by the electronics. On top of the TECs are some steel plates for the laser packages to be attached to. On the steel plates there are also some NTCs temperature sensors attached to measure the temperature of the plate.

These sensors are used to control the temperature of the steel plate and this way also the temperature of the laser package. In this setup there were some dummy diodes instead of the lasers for testing purposes At this point the device also looked quite messy because of the loose wiring but the idea of this project was to create functional proof of concept device. Though it was obvious that the wirings should be designed more properly to the next version of the device.

6. TEST PHASE

After the assembly was done some tests were needed to make sure that the test device met the requirements set in the beginning of the project.

6.1 Current stability

The first test was to determine the stability of the drivers. It was done by connecting the output of each channel individually to the programmable electronic load. I used BK Precision’s 8502 for this purpose. Unfortunately the load’s maximum input current was 15 A so to make sure that I wouldn’t brake the load I used 14 A for this test.

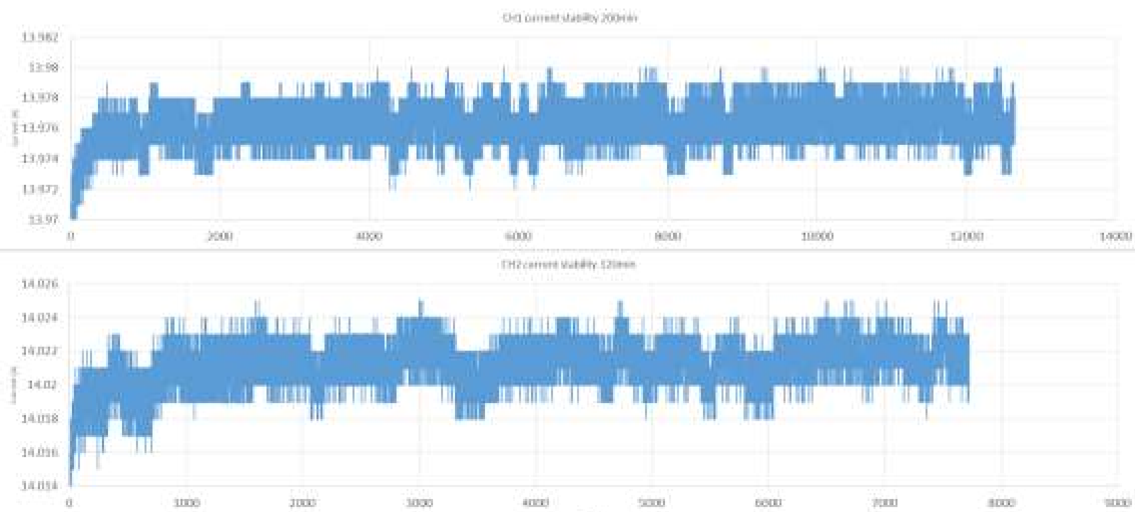

Figure 24. *Current stability of channels 1 and 2.*

In the Figure 24 test results of channels’ 1 and 2 stability can be seen. Current was set exactly to 14 A in both channels. During 200 minute test the current with channel 1 the current changed maximum of 8 mA. This is only about 0.06%. The offset in channel 1 was 24 mA which is about 0.17%.

During 120 minute test with channel 2 the current changed maximum of 6.5 mA which is about 0.05%. The offset with channel 2 was 21 mA which is 0.15%.

According to the test results explained above it can be said that the current drivers are really stable and that the stability requirements are easily met. The offset can be improved still by calibrating the control unit. Though usually the current driver offset is affected by the temperature of the driver so even this wouldn’t be practical fix. This phenomenon can be also seen in Figure 24 as in the very beginning of both tests the current is slightly rising due to the increasing temperature of the drivers.

6.2 Temperature stability

The other important thing to test was the stability of temperature both lasers themselves and the heatsinks. Both of these measurements were done simultaneously in one 180 minute test. The device was loaded with seven load diodes and one load resistor. One resistor had to be used since I only had seven diodes available.

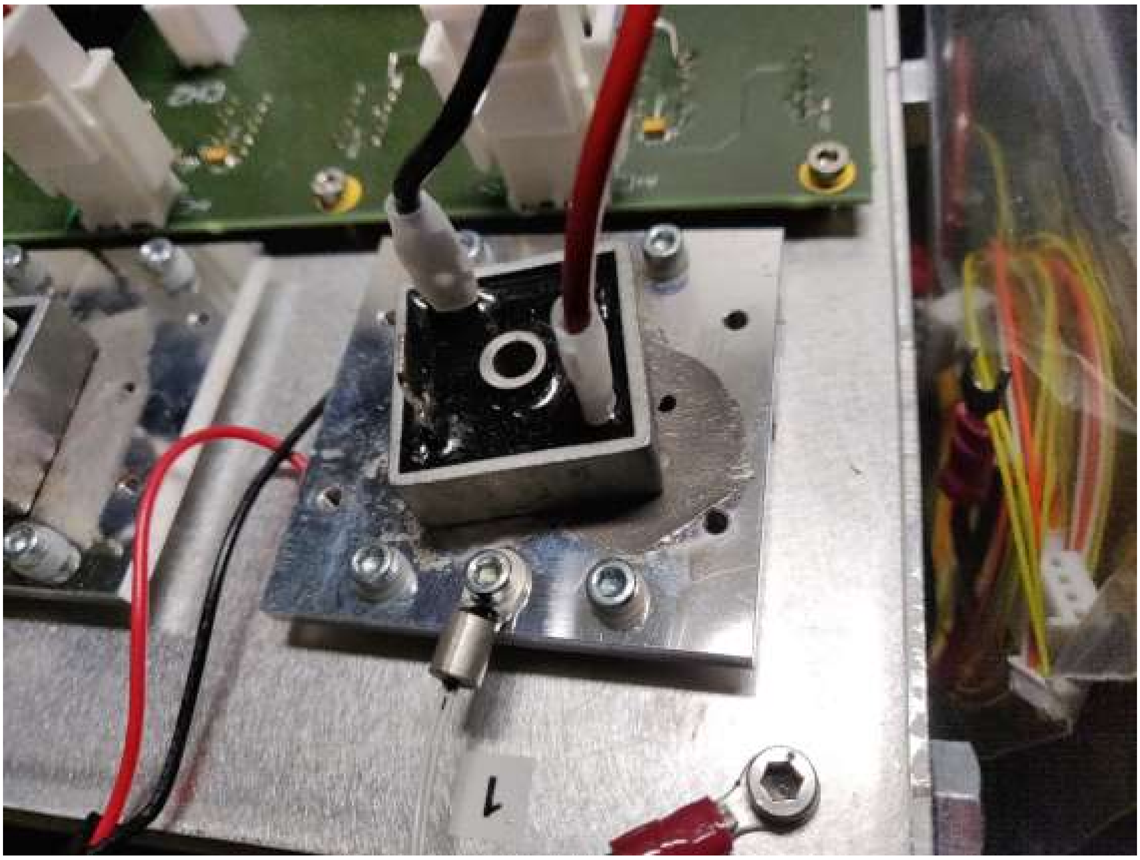

Figure 25. *Connection of load diode in temperature stress test.*

In Figure 25 the attachment of load diode can be seen. The diode was soldered directly to wires connected to the driver PCB. Diode’s casing was attached to the heat plate with some thermal compound in the same way that the laser modules will be. The TEC that is keeping the diode cool is located under this heat plate. In the Figure 25 also the temperature sensor can be seen connected to the heat plate with screw and white wires diverting away from it. This temperature sensor is used to monitor the temperature of the heat plate and thus the diodes themselves. Furthermore this temperature information is used to control the voltage of the TEC under the heat plate.

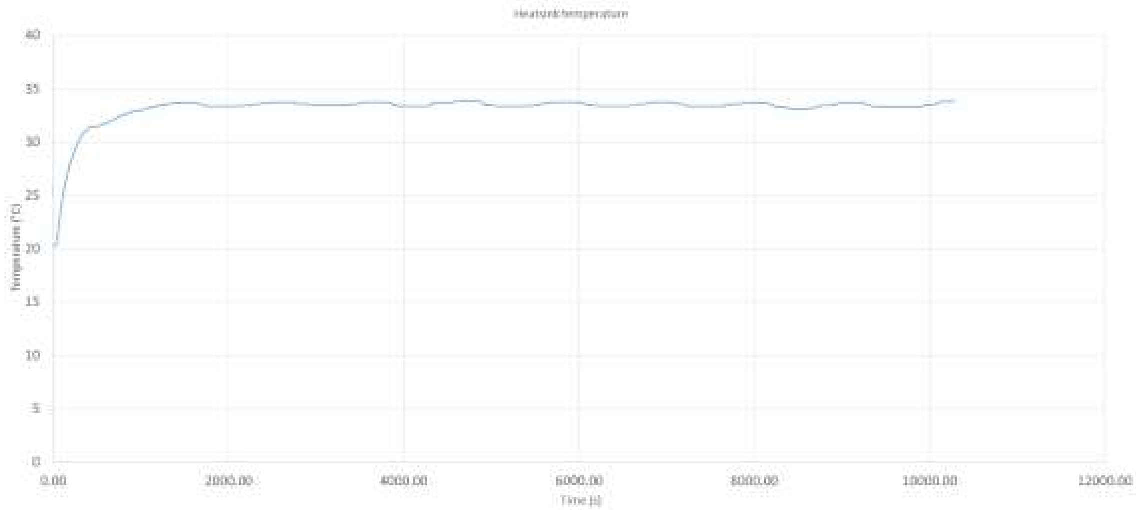

Figure 26. *Temperature of heatsink during stress test.*

In the Figure 26 can be seen the temperature of the big heatsink under the current drivers and TECs. From this figure the most important thing to notice is that the temperature of heatsink is stabilizes to some value over time. If the temperature would continue rising, it would mean that the heatsink cannot lose the heat fast enough. In this case though the temperature seemed to be stabilizing around 34°C which means that the heatsink is large enough and it has efficient enough active cooling from the fans.

In the Figure 26 there also can be seen some slow oscillation. This is probably caused by the controlling software of the TEC voltages. The software uses PIDF-controller *(Proportional-Integral-Derivative-Feedforward)*. The oscillation could probably be decreased by tweaking the parameters of the PIDF-controller but this section of the device was not on my responsibility and it is out of the scope of this thesis.

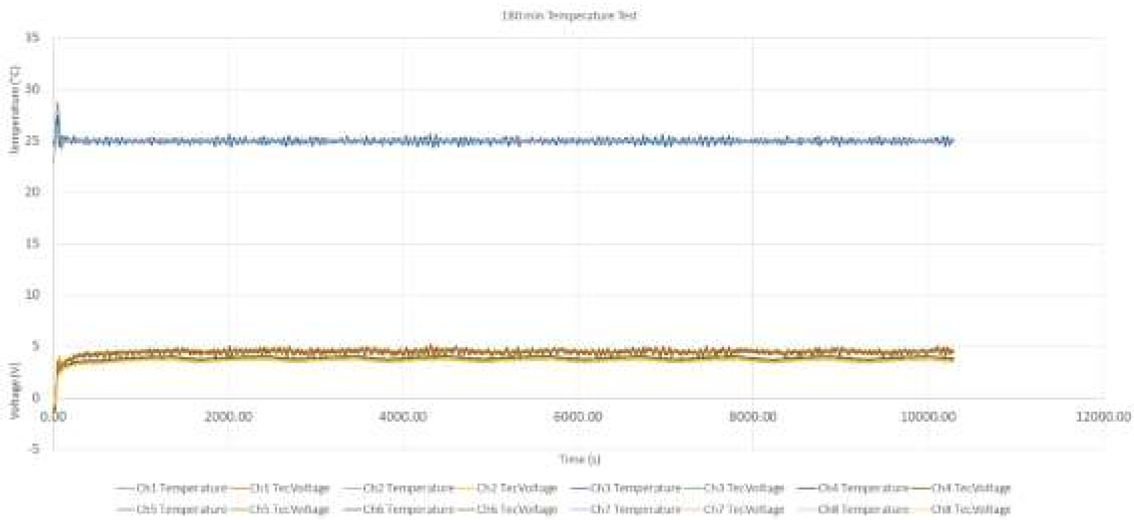

Figure 27. *Channel temperatures and TEC voltages during stress test.*

In the Figure 27 the temperatures of each channel and the voltages of each TEC can be seen. In this test the temperatures of each channel was set to 25°C because that would also be the temperature of the diodes during lifetime tests. From this data can be seen that at the very beginning when the channels were turned on the temperature in all channel had clear increase. This increase was noted by the temperature control system and thus the voltages of TEC were increased also to compensate the increased heat load. After this small temperature spike at the beginning the temperature stabilized around 25°C in all channels and the voltage of TECs little under 5 V.

The slow oscillation effect that was seen in Figure 26 can also be seen in the TECs' voltages in Figure 27. Again this is caused by the PIDF-controller. The controller is affecting the power of TECs and thus it is also affecting the temperature of the heatsinks. The amplitude of the oscillation is so low that it doesn't have relevant effect on the functionality of this device as can be seen in the temperatures of the channels.

In Figure 27 can also be seen that the temperature of some channels have much more higher frequency variation than some other channels. I took a closer look at this and in the Figure 28 and Figure 29 is shown a closer look to channel one and two.

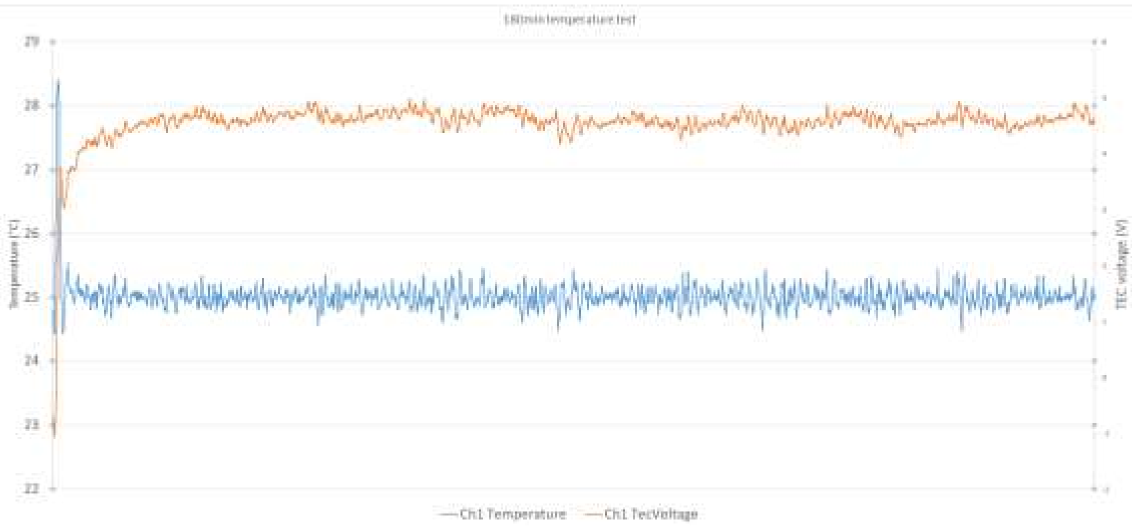

Figure 28. *Temperature and TEC voltage of channel 1 during stress test.*

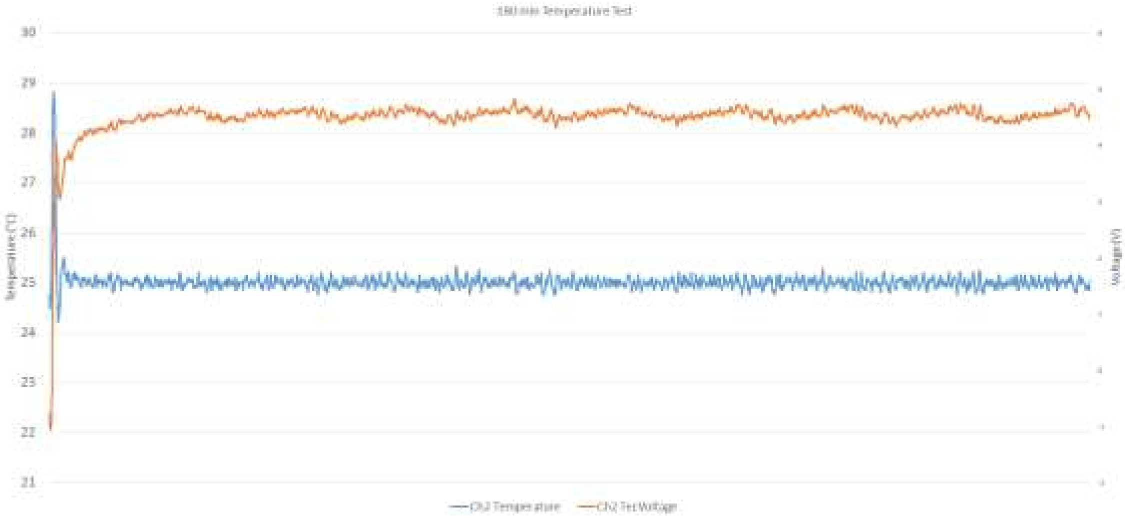

Figure 29. *Temperature and TEC voltage of channel 2 during stress test.*

In the Figure 28 can be seen that the temperature of channel 1 varied about 1°C around the desired 25°C. In the Figure 29 can be seen that the temperature of channel 2 varied only about 0.5°C. The difference between channels was caused by less than optimal thermal connections between the temperature sensor and the heat plate. When the temperature sensor was loosely fitted to the heat plate it caused the temperature to vary more. Also the thermal connection between the heat plate and TECs and between TECs and heatsink is really important to ensure efficient heat flow.

7. CONCLUSIONS

The overall experience of this thesis work was really good. It have been motivating to do a project that really have been necessary for the company. During this project I have also learned a great deal about electronics design which is my main point of interest but I have also learnt a lot about diode lasers, heat control and mechanics design. I think that these kind of multi field projects are always the most interesting ones.

7.1 Areas of improvements

As always there are some improvements that could be made to this device. The easiest one to point out is one mistake that I did during the schematic design. I forgot to connect the current measurement output signal from the drivers to the communications connector. This resulted that the connection was also missing from the final PCB so it had to be added by hand with jump wires. These kind of mistakes are quite usual to my experience and fortunately they are often also quite easy to fix in cases where only a few PCBs are made. Though if big batch of PCBs are ordered and they all consisted this kind of error it could be catastrophic. For this reason always a smaller batch of PCBs should be ordered first and test that they are designed correctly.

Another notable area of improvement was the messiness of the device. This was mainly caused by the many wires that were going across and on top of the device. In addition to looking messy the wires also made it harder to use the device as they were going across the laser modules and thus they made it harder to access and change the modules. This could be fixed by designing the routes for the wires already in the 3D model. This way there will be dedicated space for wires and this will solve the issue.

One problem was also the instability of the temperature in some channels as found out during the testing. This was caused by the bad thermal contact of used temperature sensor and thus it was easy to fix. Though this showed how important it is to test this kind of thing before taking the device into use. In this case the varying temperature would have caused the power and wavelength to vary also which would not have been ideal for the lifetime tests.

The writing process if this these could have also been better planned. The project itself was mainly done during the autumn 2018 but I started the writing process at the beginning of 2019. This resulted that I wrote about things that I had done quite many months ago. I would have been better to write the thesis as the same time as I was working on the project at work. I should also have done an exact schedule for the writing of this thesis. With the schedule it would have been easier to finish this work on time. I also started another school during the writing process of this thesis which further delayed the process. Initially I had planned so that the writing process would be ready at summer 2019 but it got delayed until October 2019 which is over a year later than I originally started the project at Modulight.

7.2 Successes

Nevertheless there were also a lot of successes the biggest of which was that the device did meet all of the requirements that was set at the start of the project. The device is also used daily at Modulight for the lifetime tests of diode laser, exactly what is was designed for. It is always very motivating to see that your design is working and used.

I also learned a lot about electronics design. During the project I designed a PCB from scratch to finished board. It was really good in terms of learning that I got to design basically this whole device from scratch independently and alone. This way I was able to experience all of the design phases myself and I was also able to experience that how the different design phases, schematic, layout and mechanic, affect one and other. The fact that one engineer designs something from beginning only by him/herself is actually quite rare as the design work is usually divided to separated parts so that one engineer only designs a portion of the full PCB. This is done because it is usually more effective and it is also easier to spot design flaws when working together with someone or with a larger group. Though it was really good for learning that in this case I was able to do the whole design myself.

During this project I also got a lot more experience in the CAD software that I was using. I had used the EAGLE software before for electronics design but during this kind of project I got a lot more experience in particular when designing bigger multi sheet designs. During school projects the designs were always simple enough to fit the schematic on one sheet and the layout to be two layered. In this case my schematic took three pages, which is still very little, and the layout was six layered. During this kind of bigger projects I was able to learn a lot more about the EAGLE software and how to manage bigger schematics and multi layered layouts with it.

Before this project I also had very little experience with the 3D design tool SolidWorks. I only knew the basics and hadn’t really used it before. Although I did not draw any new 3D models myself during this project I got a lot of experience on how to do assemblies from existing models. I also learned how important and useful in assembly it is to have accurate and good 3D model of the whole device.

The project also included some heat control design. Even though I didn’t have a lot of experience or education on those topics, I got introduced to this kind of design also and I realized how important it is to take the heat control into account during every design phase of the project. It was also really nice variation to design work to assemble the device myself.

It was also a big personal success for me that I was able to finish this thesis work simultaneously when I am carrying out my pilot studies.

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