Design and Development of Air Cooled 100 Watt Blue Diode Laser

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of BS-MS dual degree in Science

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Certificate of Examination

This is to certify that the dissertation titled **"Design and Development of Air Cooled 100 Watt Blue Diode Laser"** submitted by **Yateendra Sihag** (Reg. No. MS15019) for the partial fulfillment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. Sanjeev Kumar	Dr. Ananth Venkatesan	Dr. Kamal P. Singh (Supervisor)

Dated: June 17, 2020

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Kamal P. Singh at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Yateendra Sihag
(Candidate)

Dated: June 17, 2020

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Kamal P. Singh
(Supervisor)

Acknowledgment

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Abstract

Laser is one of the most important discovery in 20th century. It has evolved since its start off in both improve performance and tremendously increased in variety. It has got wide range of applications in medical science, fundamental research, time keeping and applications in industries to name a few. High power lasers are inevitable in current industrial applications like welding, cutting, marking etc. Before blue LEDs were discovered by Shuji Nakamura (2014 Nobel Laurette) in 1990, infrared lasers were used for industrial purposes which required complex cooling and sophisticated setups.Ever since, blue diode laser technology is evolving. Despite various constraints to build a low cost high power laser of 100 Watt scale, we take the challenge of building a prototype of the same utilizing this blue laser diode.

In this MS thesis we demonstrate the complete journey of how we started from scratch, working with blue laser pointer to reach the well developed 100 Watt blue diode laser. Heat management, focusing multiple beams to a tight spot, compact setup design and voltage spikes in electrical instruments are the major challenges in the development of high power laser. We demonstrate, by our design, a set of different cooling mechanisms and power supplies to overcome them and thereby increasing the performance of laser. We have already made $\approx$100 Watt power laser and trying to push this limit further.

Contents

Chapter 1

Introduction

1.1 Background

As with many areas of physics, laser physics has a vibrant history. The word laser is an acronym for Light Amplification by Stimulated Emission of Radiation. What distinguishes lasers from conventional light sources is their unique ability to produce a highly intense beam of light with minimal divergence over vast distances. Unlike other light sources, it emits light which is coherent, collimated, monochromatic and directional.

The development of lasers has been a turning point in the history of science and engineering owing to its broad applicability. Albert Einstein laid the foundation of laser technology in 1917 [1]. His work predicted the phenomenon of stimulated emission, which form the basis of all laser operations. After a break of almost 40 years, the technology further evolved in 1960 when the Hughes lab built the first ruby laser having wavelength 694 nm. Subsequently, the bell labs developed CO2 laser which use gas as the medium instead of crystals. The evolution of the laser has been long and complicated [2]. laser are ubiquitous in both scientific research and industrial applications; it has a wide range of applications in medical procedures, bar-code readers, blu-ray, spectroscopy, material processing etc. Many have explored the many possible aspects of laser physics to usher in the most important of new applications.

The selective timeline in fig.1.1 outlines the crucial breakthroughs, and advancements in laser technology are:

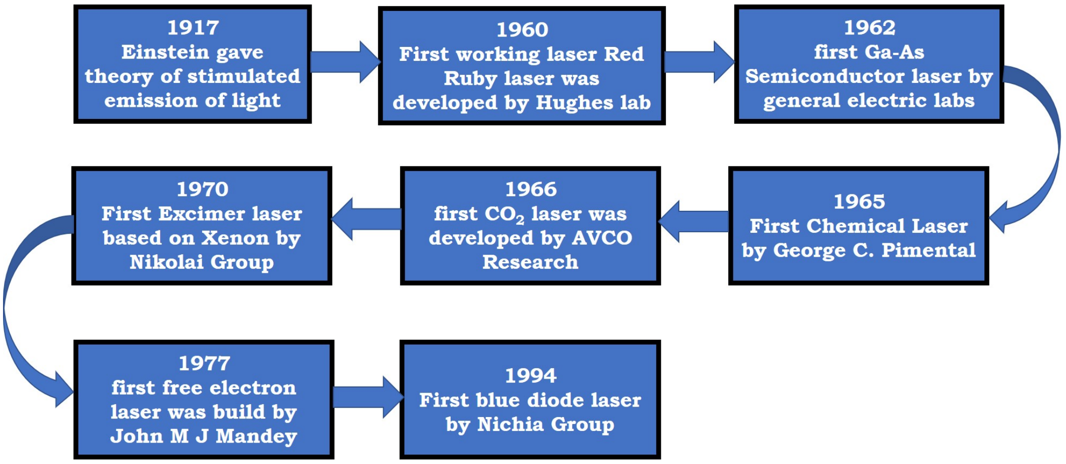


Fig. 1.1: Selected timeline of historical developments in LASER technology.

1.2 Diode Lasers

The laser diode [3, 4, 5] is a semiconductor device similar to Light-emitting diode(LED) which is fabricated using direct band-gap semiconductors. They are electrically pumped semiconductor lasers[6] in which the gain is generated by an electrical current flowing through a p–n junction to emit coherent light. Semiconductor lasers were invented back in the year 1962 by Robert N. Hall. In just 40 years they have turned into essential devices in both scientific research and everyday life. The choice of the semiconductor material determines the wavelength of the emitted beam, which in today's laser diodes range from UV spectrum to the infra-red. With their high output powers[7] , brilliance, and excellent energy efficiency, diode lasers are suitable for numerous applications which includes material processing[8, 9], telecommunication, holography, medical, defence and security systems.

What makes laser diodes stand apart from the several other laser technologies is their compact size and low production cost. The diode laser technology is highly energy efficient as they convert current to coherent light in a highly efficient manner which brings the best efficiency figures among all the current laser types. When operated under proper conditions, diode lasers can be very reliable during the lifetimes of tens of thousands of hours. However, much shorter lifetimes can result from several factors, such as operation at too high temperatures and current or voltage spikes.

In the longer term the drawbacks of gaseous and solid-state lasers may be challenging due to their bigger size and less efficiency. The diode lasers provide an alternative technology to replace these old and heavy lasers.

1.2.1 Motivation: Why blue diode laser ?

Older laser technology like IR lasers needed a lot of efforts to process highly reflecting non-ferrous metals such as copper, gold etc [10]. In efforts to overcome these problems faced by the IR and DPSS lasers, in the year 1992, a Japanese scientist named Shuzi Nakamura(2014 Nobel Laurette) [11, 12] invented the first efficient blue LED [13, 14], and four years later the first blue diode laser was invented. since then the technology is continuously improving and has a wide range of applications especially in industries, Blu-ray etc. Blue diode laser [15] technology has proven to be a milestone in the industrial sector. This technology has offered an alternative to the processing of yellow metal like copper and gold [16]. It has replaced the older laser technologies in the processing of highly reflecting metals, as yellow metal absorbs blue laser twenty to thirty times better than IR, making it the desired laser technology for such processes. previously used blue lasers were constructed using frequency doubling of IR or dpss lasers [17] but these conversion process leads to high power losses, complex cooling requirements and sophisticated setups and in contrast to that the new diode laser enables the direct emission of 450 nm, without further frequency-doubling and therefore with higher energy efficiency.

Another reason for the shift from older laser technologies to blue laser technology is its lifetime. The lifetime of InGaN Blue diode laser is 20000 hours at 25°C and it can be operated up to 65°C without significant reduction in a lifetime, something that is not achievable with the IR lasers and other old lasers. While the older laser technologies were only able to cut the yellow metals, blue laser technology has made it possible for the first time to weld the thin sheets and films.

Another reason why blue laser technology is preferred over other older laser technologies is its short wavelength. With wavelength 450 nm that is so close to the wavelength of UV light, its range of applications increases sharply. Its potential is immense in environmental and biological systems because its short centre wavelength of 445 nm falls near the UV light, which broadens its application spectrum [18]. Another irrefutable advantage of blue laser technology is its narrow waveguide. We chose to work with a blue diode laser because of the smaller size of diodes, which made it possible for us to make a handheld high power laser.

1.3 Research objectives

A major focus to physics and engineering in the twenty-first century is to miniaturise technology while improving efficiency, thus increasing output per square inch. This can be seen from the increasing number of transistor devices on a single chip as characterized by Moore's law. At the same time, efforts are made to reduce the size of LASERs while increasing their power output. Such miniature technology aides in both industrial applications and research. However, even though a lot of similar innovations have been made, a handheld high power laser emitting blue light has still not been produced. The main objective of this research is to answer the question: *Can we design and develop a 100-Watt handheld blue laser technology ?*

The main problem that this blue laser technology faces is that it is still in its young stage, and only a very few research labs [19, 20] are working on the development of this diode laser technology, making it commercially unavailable. The blue laser is made by combining several diode beams, so the major challenge to face for making a blue diode laser is to focus these laser diode beams in a small region. Another major challenge that we faced was the heat management. The efficiency of these laser diodes is around 30%, so heat management becomes an issue in such a compact setup of multiple laser diodes. Also, we need to consider the fact that laser diodes need drivers to run, and for a handheld laser, we require power supplies that can deliver a huge amount of power while being lightweight.

To overcome these challenges while making handheld high-power laser, we used multiple laser banks, each comprising of 8 diodes. We worked through different geometries to find the most efficient one to work with. To take care of the heat management issue, we used different cooling mechanisms such as water chillers, heat sinks, and fans. To focus multiple laser beams at a point we used a magnifying glass of 75 mm diameter which focused them sharply in a radius of few μm range. We make use of multiple step-down transformers and linear power supplies as laser diode driver in our setup. As for the power supply, we used different Li-ion and LiPo batteries which can run for a longer period and are lighter in weight.

1.4 Thesis outline

The goal of this thesis project was to design and develop a high power blue diode laser which could produce an output power of 100W. In order to achieve this goal, we designed various laser setups with different power supplies and cooling techniques. Our main focus was on designing a handheld air cooled high power laser which would also have applications in the future. Our journey started with the characterization of the pointer laser and it ended after we had developed a complete set up of a 100 Watt blue laser.

In the second chapter, we describe the early stage experiments we carried out for the purpose of characterization of the three different semiconductor lasers. Characterization is a fundamental step to begin working with lasers.

In the third chapter, we describe the second step undertaken while building the high power laser (100 Watt): we used a laser diode bank consisting of 8 diodes, worked with different power supplies and used several different cooling techniques to make sure that the laser diode bank can produce a stable output power of 30 Watt and no electrical spikes or heating problems arise.

In the fourth chapter, we describe how we designed the setup for a 100 Watt laser. To make the setup very compact and handheld, we again used high RPM cooling fans, press-fitted the diode banks between two copper plates of thickness 6 mm and four heat sinks. This time, we directly connected the laser with two 5 V - 60 A switch mode power supplies and removed all the buck connectors which were used in the 30 Watt laser. To ensure the proper functioning of all the three laser diodes, we plotted temperature against time for each diode bank in different situations and made changes in the setup according to that. To verify the maximum output power of laser we plotted the output power of laser versus input applied voltage curve which gave us the output power of laser $\approx$100 Watt at 6 V.

In the fifth chapter, we described the concluding remarks and the future plans for the laser.

Chapter 2

Early Stage Experiments

2.1 Laser characterization

To begin working on lasers, characterization[21] is one of the most important and fundamental steps to assess the detailed properties of the laser beam. In general a full characterization involves measurement of beam parameters such as beam profile (spatial energy distribution), beam divergence, wavelength and spot size, to name a few. Many applications of lasers rely heavily on stability and precise control of the emitted radiation. Also, a laser is itself very sensitive to temperature. Hence, for an optimum functioning of the laser setup it is mandatory to measure these characteristics.

2.2 Characterization of red pointer laser

To became familiar with lasers and their properties, we started with red pointer laser which is a low-power class-1 laser. To characterize it and assess its detailed properties we devised a laser driver module consist of LM317T voltage regulator,resistor,capacitor and 9V battery as shown in Fig.2.1.

2.2.1 Schematic and experimental setup

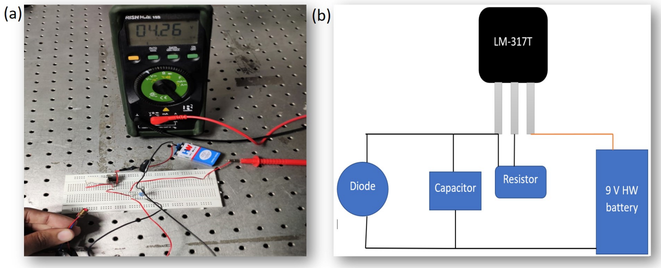


Fig. 2.1: Red pointer laser setup: (a) experimental setup (b) schematic setup.

2.2.2 Beam characterization

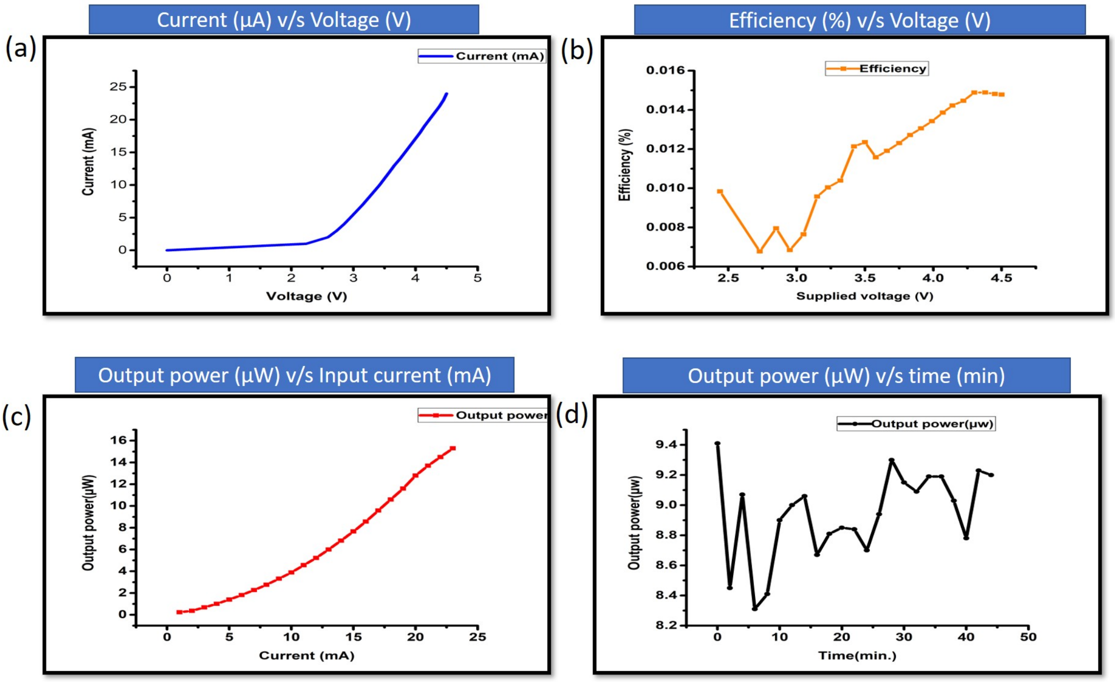
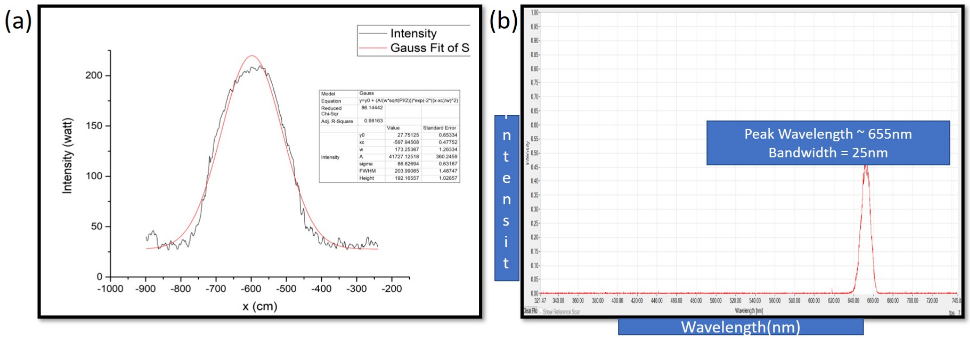


Fig. 2.2: Laser beam characterization curve: (a) the I-V characteristic curve of red pointer laser diode, (b) variation in efficiency of laser with voltage (c) variations in output power with input current (d) variation in output power of laser with time



Model	Gauss		
Equation	y=y0 + (A/(w*sqrt(PI/2)))*exp(-2*((x-xc)/w)^2)		
Reduced Chi-Sqr	86.14442		
Adj. R-Square	0.98163		
		Value	Standard Error
Intensity	y0	27.75125	0.65334
	xc	-597.94508	0.47752
	w	173.25387	1.26334
	A	41727.12518	360.2459
	sigma	86.62694	0.63167
	FWHM	203.99085	1.48747
	Height	192.16557	1.02857

Fig. 2.3: Laser beam characterization curve: (a) gaussian beam profile of laser, (b) Intensity versus wavelength plot.

2.2.3 Observation

The beam characterization plots shows that the threshold voltage required to light up the red pointer laser was found to be 2.6 V 2.2 (a) and the maximum output power was observed to be 16 microWatt at 4.6V and 25mA current (Fig.2.2 (c)). The beam profile (Fig.2.3 (a)) of the laser was Gaussian and the centre wavelength of the laser was found to be 655nm with a bandwidth of 25nm (Fig.2.3 (b)). The fluctuation of output power with time clearly demonstrated the laser's heating effect(Fig.2.2 (d)). The efficiency plot(Fig.2.2 (b)) showed that the laser is a highly inefficient one, a characteristic found in most of the pointer lasers.

2.3 Characterization of 405 nm violet laser

2.3.1 Schematic setup

We wanted our high power laser to be designed in such a way that it be handheld, that is, it should be operable with an external battery source rather than an ac power supply. In order to achieve this, we started with the characterization of a 405 nm violet laser (an I-V characteristic plot gives us crucial information about the current and voltage range required for the laser to function) using 9 V batteries. We connected the batteries in a series combination to increase the input current to a level sufficient for lighting up the diode (as shown in fig.2.4). The potential drop across batteries, resistor and photo diode was measure with time in the oscilloscope.

We designed some linear power supplies using multiple high voltage resistors and potentiometers to step down the input voltage of the 9V battery (in order to avoid damaging of the laser diode from a high voltage). The linear power supplies wasting a lot of power in the form of heat was a major problem with this setup. Also, changing the output power of the laser required continuous replacement of resistances.

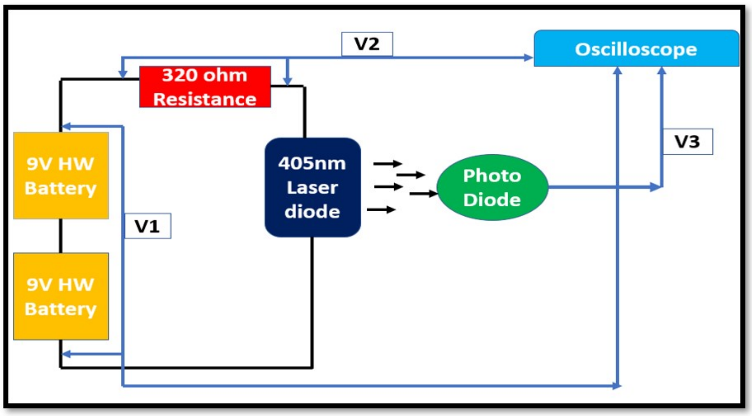
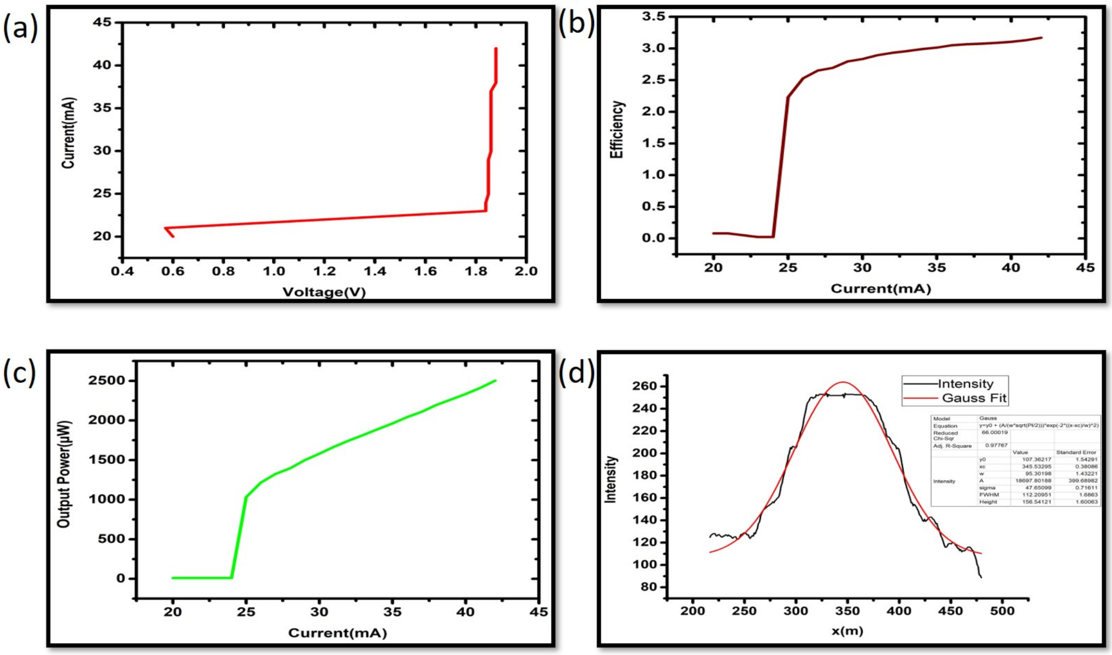


Fig. 2.4: Schematic setup of 405 nm Violet laser.

2.3.2 Characteristic plots



Model	Gauss		
Equation	y=y0 + (A/(w*sqrt(PI/2)))*exp(-2*((x-xc)/w)^2)		
Reduced Chi-Sqr	66.00019		
Adj. R-Square	0.97767		
		Value	Standard Error
Intensity	y0	107.36217	1.54291
	xc	345.53295	0.38086
	w	95.30198	1.43221
	A	18697.80188	399.68982
	sigma	47.65099	0.71611
	FWHM	112.20951	1.6863
	Height	156.54121	1.60063

Fig. 2.5: Violet laser characterization curve: (a) the I-V characteristic curve of violet laser, (b) variation in efficiency of laser with current, (c) Variations in output power with current, (d) beam profile of 405 nm blue laser.

2.3.3 Observation

The threshold voltage for emission of the violet pointer laser was found to be 1.9 V(Fig.2.5 (a)) and the maximum output power was observed to be 2.5 mW at 4.6 V and 43 mA current(Fig.2.5 (c)). The beam profile of the laser was Gaussian and the centre wavelength was found to be 405 nm(Fig.2.5 (d)) . The laser efficiency(Fig.2.5 (b)) was observed to be only 3.5%, again reaffirming the fact that pointed lasers have low efficiency.

2.4 3.5 Watt Laser characterization and different experimental setups

We characterize every laser with help of a power supply which has variable current and voltage. After having carried out the characterization and having found out the range at which the laser operates, our next aim was to develop a setup in which the laser can run with help of a laser diode driver which would mediate between the diode and the battery source. Depending on the current rating of the batteries, we developed different laser diode drivers so that the laser could function in a similar way as it would with an AC power supply. We first tried to operate the 3.5 Watt laser with the power supply we used for the 405 nm violet laser but it was found that the power of the laser did not rise above 300 mW. So, we replaced the 9V battery with a rechargeable Li-ion battery (6 V, 7 Ah). In order to lower down the voltage of the battery, we connected a step down DC-to-DC buck converter with an attached potentiometer (which provides the required voltage to the laser diode. The diode worked perfectly with the Li-ion battery.

2.4.1 Schematic and experimental setup

The linear power supply in Fig.2.4 consists of 9 V HW batteries. Since the resistors worked perfectly with the 405 nm violet laser, we implemented the same setup except that we increased the current rating of the power supply using multiple batteries in a parallel combination(as shown in Fig.2.6). But increasing the current rating only made the maximum power of the 3.5 Watt diode reach up to 300 mW. This setup did not work with other different arrangements of non-rechargeable batteries and even after making multiple changes in the setup design.

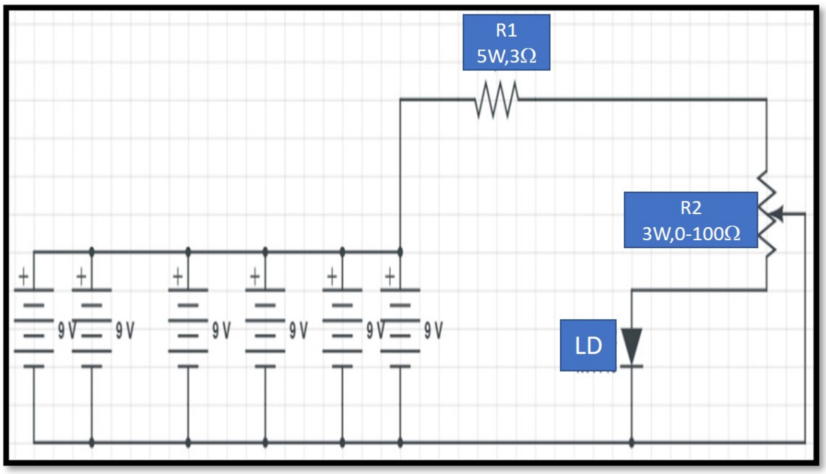


Fig. 2.6: Schematic setup of 3.5 Watt diode laser with 9V batteries.

In the new experimental setup designed to run the 3.5 Watt diode laser (shown below Fig.2.7 and Fig.2.8) we used 6 V-4.5 Ah Li-ion battery with a step down DC-to-DC buck converter. With this setup we were able to obtain the expected maximum power of the laser diode i.e 3.5 Watts (measured with the power meter). The buck converter in the setup drops down the input DC voltage to the voltage required to run the laser diode. The potentiometer in the buck converter gives us the freedom to change the output power of the laser.

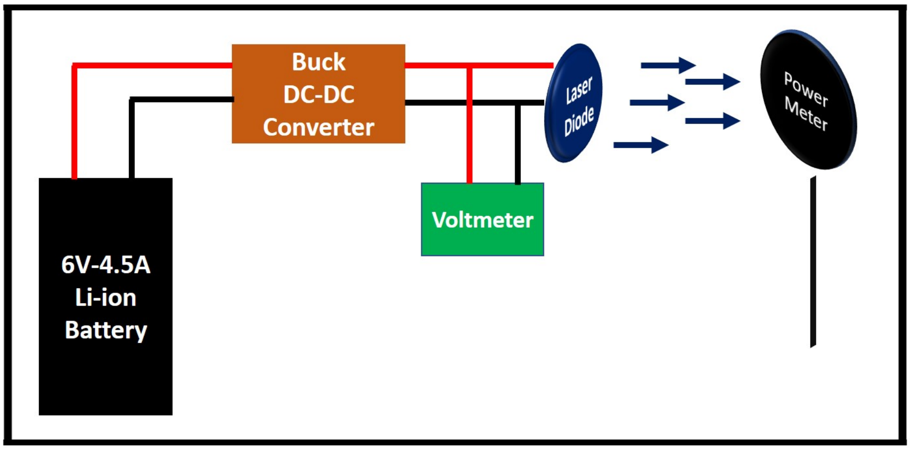


Fig. 2.7: Schematic setup of 3.5 Watt diode laser with Li-ion batteries.

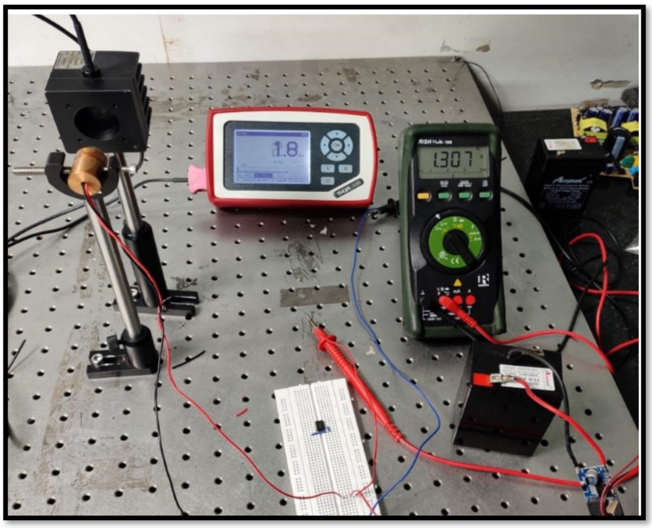


Fig. 2.8: Experimental setup of 3.5 Watt diode laser with Li-ion batteries.

2.4.2 Beam characterization

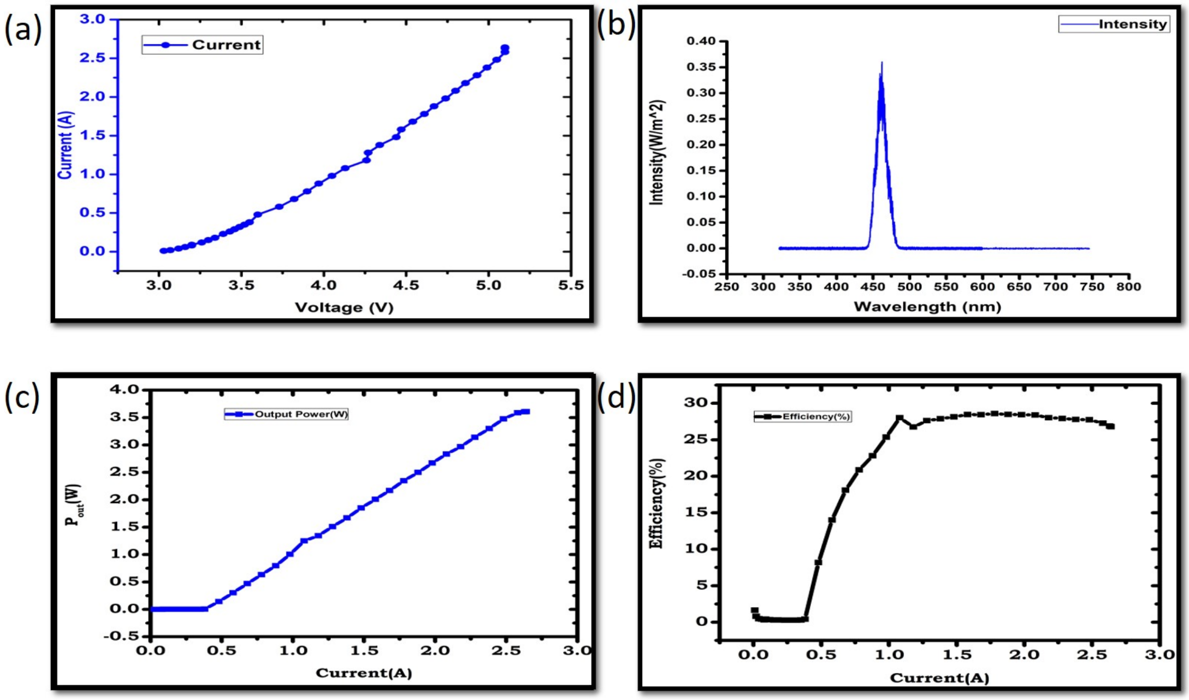


Fig. 2.9: 3.5 Watt blue laser characterization curve: (a) the I-V characteristic curve of 3.5 Watt laser, (b) intensity versus wavelength plot, (c) variations in output power with current, (d) variation in efficiency of laser with current.

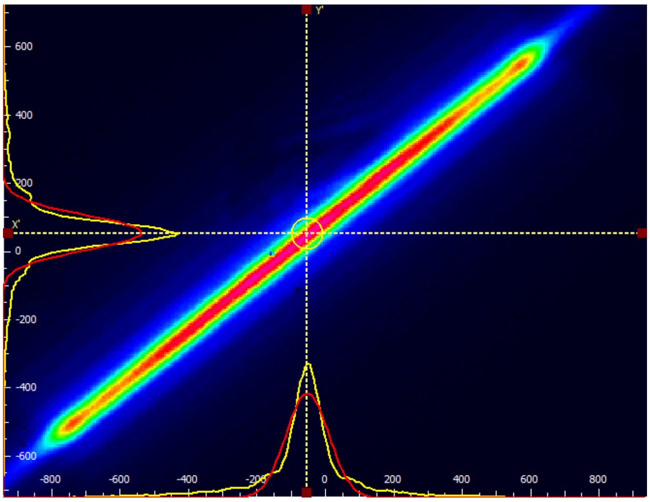


Fig. 2.10: Beam profile of the 3.5 Watt diode laser.

2.4.3 Observation

The I-V characteristic plot (Fig.2.9 (a)) clearly shows that the threshold voltage required to run the 3.6 watt laser diode was 3.2V. The output power versus input current plot (Fig.2.9 (c)) shows that the maximum power emitted by the laser diode was found to be 3.6 Watt and the required voltage and current for attaining maximum power were 5.1 V and 2.6 A. The efficiency versus current plot (Fig.2.9 (d)) shows that the maximum efficiency of the laser diode was 30%, observed at 1.2A and decreases a little to 28% when the laser was operated at its maximum power. The center wavelength of the diode was observed to be 450 nm, with a bandwidth of 30 nm(as shown n Fig.2.9 (b)). The beam profile of the laser measured was a line as shown in Fig.2.10

After running the diode for a few minutes at maximum power, we observed that the output power of the laser diode continuously decreased due to heating up of the diode.To deal with the problem of heating, we press-fitted the laser diode between two heat sinks as shown in Fig.2.11 for proper dissipation of heat to take place

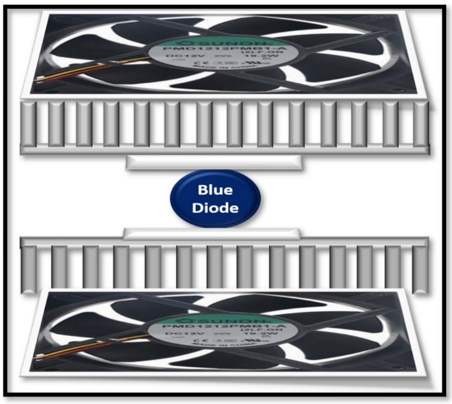


Fig. 2.11: 3.5 Watt blue laser diode press fitted between TEC plates.

Thermo-electric cooling (TEC) [22] is also a good option for cooling the laser diodes in general but we decided not to use it. This is because according to their principle, the TEC plates re-emit 2.5 times the heat emitted by a laser diode. In order to cool them we would have needed much bigger heat sinks and installing them would have compromised with the compactness of the setup. In addition, they would have required a high input current (3A), that would have also degraded the performance of our battery.

2.5 Chapter conclusion

In this chapter we did the characterization of different class of lasers(from pointer lasers of class 1 to the most dangerous pointer lasers of class 4)to assess the detailed properties of laser beam. To make laser handheld we designed multiple laser driver circuits and run them with various DC power supplies(different output voltages) of rechargeable and non rechargeable batteries(AA,AAA,Li-ion,LiPo). We observed some output power fluctuations in the 3.5 Watt laser pointer which later introduced us with the heating issues of class 4 lasers.

Chapter 3

Stage 2 Experiments : 30 Watt Laser with single bar

In the Second Stage of the experiment, we worked on different techniques to raise the power of the laser from 3.5 Watts to 30 Watts. We used different power supplies and tested multiple cooling techniques to optimize the performance of the laser. To analyze heat dissipation from the heatsinks we used the COMSOL Multiphysics software (Appendix A.3)

3.1 Laser setup design

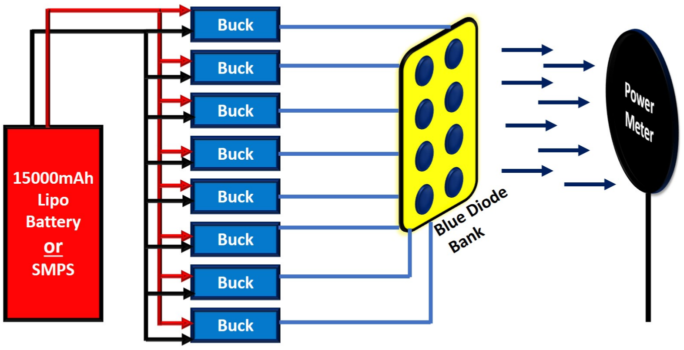


Fig. 3.1: Schematic setup of 30 Watt diode laser with eight step down buck converters.

Continuing with the previously used compact size (6 V-4.5 Ah and 12 V-7 Ah) Li-ion batteries proved to be a hindrance in our goal of raising the power of the laser because of their low current rating. We also wanted to maintain the compactness of the setup. So we avoided the use of a bigger Li-on battery or a multitude of them, as it would have made the setup heavier. Instead, we used a four-cell 15000 mAh Lithium-ion polymer (LiPo) battery which is similar to a Lithium-ion battery but with the difference that it uses a solid

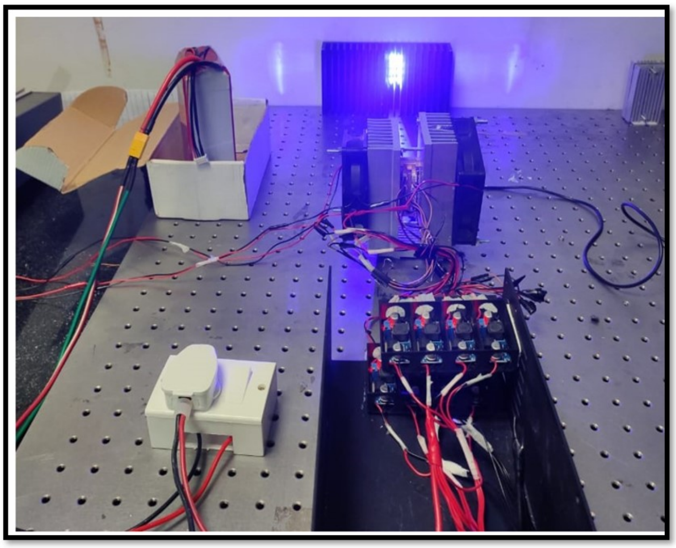


Fig. 3.2: Experimental setup of 30 Watt laser.

polymer electrolyte in it. The advantages of using a LiPo battery are its light weight and its low self-discharge rate (5% per month). These advantages associated with the new battery made its use completely suitable for the required laser setup. We used DC-to-DC buck converters(Appendix A.1) to drop down the output voltage of the battery from 14.8 to 5.10 V (required to run the laser diodes). All the buck converters were connected in parallel with the LiPo Battery and each of them was connected directly to the laser diodes on the output side as shown in Fig.3.1. Connecting all diodes in parallel with each other gives us the freedom to monitor each diode's power individually and also gives us the ability to turn each of them on and off independently. One added advantage of the parallel combination is that the failure of one of the diodes does not affect the functioning of the others. We also installed a plug-socket system in the setup to make the laser more convenient to use. Choice of the plug plays a very important role in a DC setup since unlike an AC setup, the positive and negative terminals of the laser should be carefully connected with the positive and negative terminals of the battery. Failing to do this may lead to damage of the laser setup. In order to overcome this problem, we installed a three-pin plug(shown in Fig.3.2).

Later due to an unknown battery failure we replaced the LiPo battery with a switch mode power supply (12 V-12 A) in the above experimental setup Fig.3.2, keeping everything else in the setup same as before. This also gave us the advantage that the output power of the laser now remained stable for longer durations.

3.1.1 Spot size of the laser beams

The blue laser consists of eight blue laser diodes each with a power of 3.5-4 Watts. Unlike other lasers, its beam profile is a line. The Fig.3.3 (a) shows spots produced by eight beams of the diode bank on a cardboard. We have focused the laser diode beams together with the help of a magnifying glass (as shown in Fig.3.3 (b)).The spot size of the focused beam was found to be between 3-5 mm.

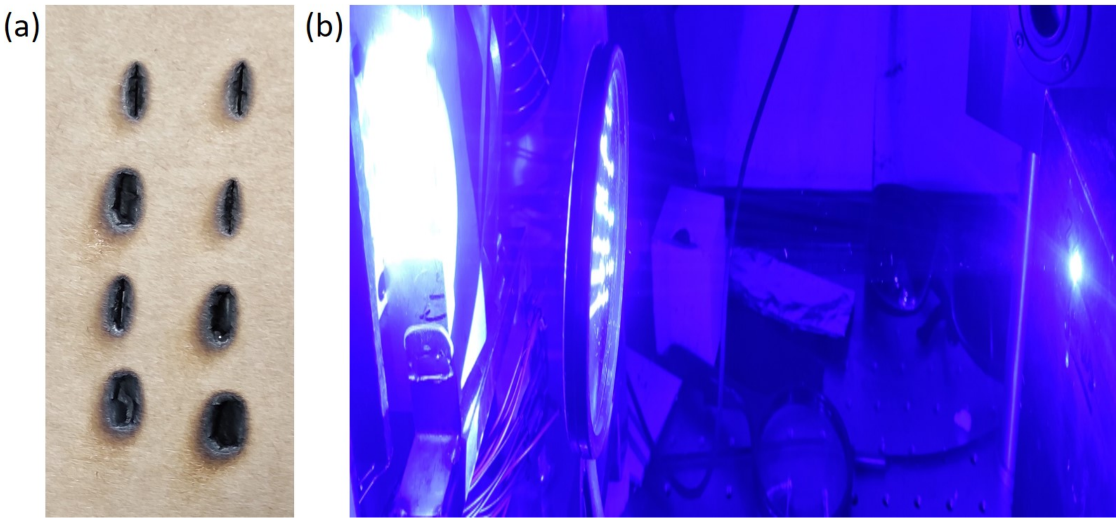


Fig. 3.3: Projection of laser beam: (a) spot sizes of eight laser beams without lens, (b) tightly focused eight laser diode beams with focusing lens

3.2 Different cooling mechanisms used

3.2.1 Laser diode without a heatsink

Heating issues are very common in electronic devices. Their proper cooling results in longer lifetimes and a higher efficiency. The efficiency of blue laser diodes is 30%, which means that 70% of the supplied power gets wasted in the form of heat energy. This can be seen from the temperature vs time plot (Fig.3.4). The temperature of the laser rises from 0 to 57°C in just 60 seconds and a further rise in temperature may cause damage to the laser diodes. High temperature rise rate and slow cooling rate of the laser (as evident from the figure) makes it clear that it is very necessary to have a cooling system installed in the setup for its proper functioning.

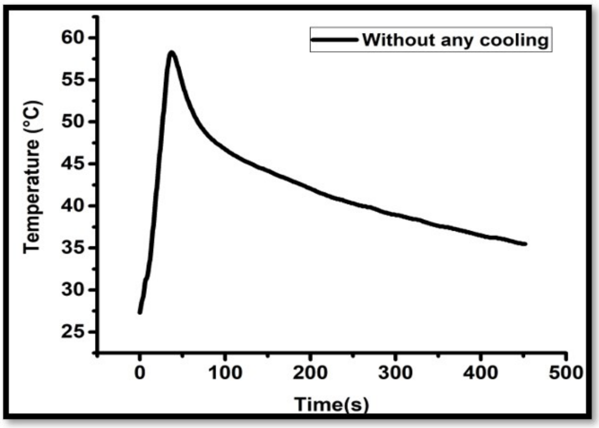


Fig. 3.4: Variation in temperature of laser diode bank with time in absence of heatsinks

3.2.2 Cooling with 3-inch fans placed at a distance

Heatsinks are components specifically designed to cool off devices through dissipation of heat. They can be used either passively or else, in active cooling systems (combined with fans, for example). Heat dissipation capability of the heatsinks depends upon the material they are made up of and their geometry. We press fitted the laser diode bank between two aluminium heat sinks and used two 3 inch fans (placed at a distance from the heatsinks) for cooling, as shown in Fig.3.5.

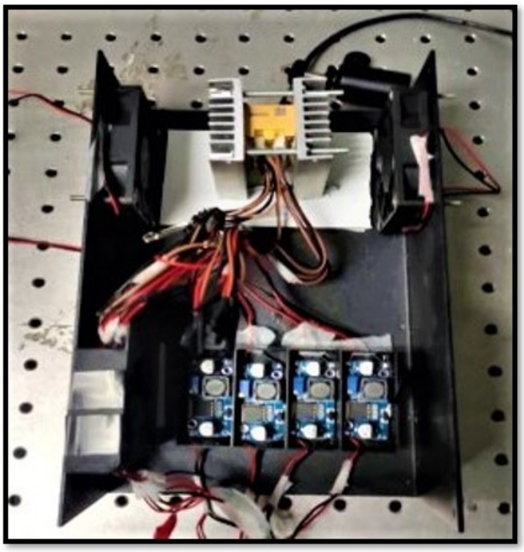


Fig. 3.5: Experimental setup of laser diode fitted between two smaller size heat sinks.

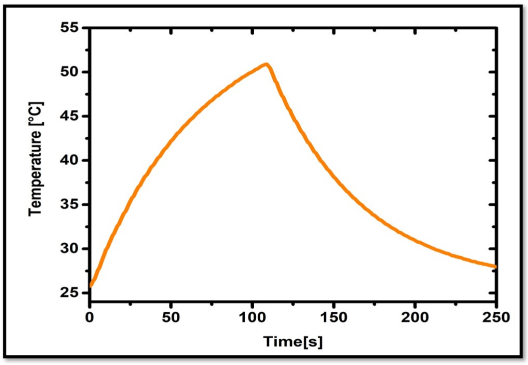


Fig. 3.6: Variation in temperature of laser diode bank with time.

Observation

The Fig.3.6 depicts the effectiveness of the heat sinks(as shown in experimental setup Fig.3.5) in lowering down the temperature of the laser. The rate of heating got halved and the temperature of the laser diode bank reached 50°C after 100 seconds in this case. This shows the high efficacy of the heat sinks as in their absence, the temperature would reach 58°C after 60 seconds.

3.2.3 Cooling with a water chiller on one side and a heatsink on the other with a 3-inch fan on the top

The introduction of heatsinks in the setup decreased the rate of temperature rise of the laser, but it did not halt the rise (clearly visible in the fig 3.6). In order to stabilise the temperature of the laser we used the water chiller cooling technology. Water chillers are one of the most widely used heat dissipating devices all over the world. We press fitted the diode bank in between a water chiller and the heatsink, with an attached exhaust fan as shown in Fig.3.7

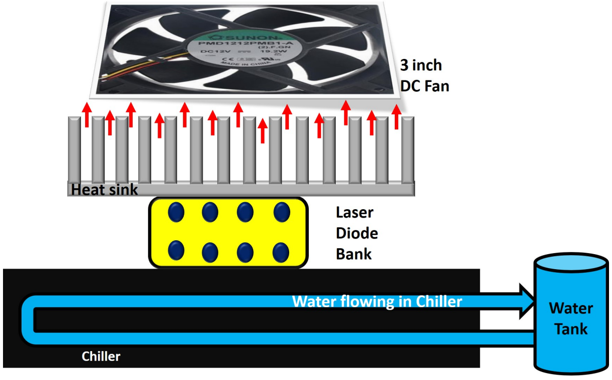


Fig. 3.7: Schematic setup of laser cooling with water chiller.

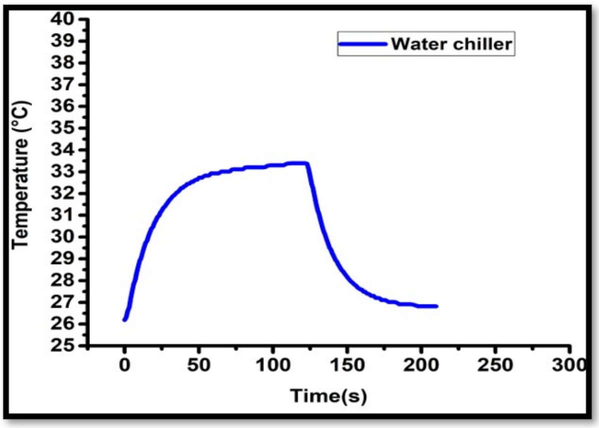


Fig. 3.8: Variation in temperature of laser diode bank with time.

Observation

The temperature of the diode bank rose from 26°C to 32°C as we switched on the laser, but after 60 seconds of use the temperature almost stopped increasing (the slow increase of temperature in this phase can be attributed to the water in the chiller heating up) . The temperature got almost stabilized at around 35°C as shown in Fig.3.8. When the laser was turned off, the temperature fell exponentially from 35°C to 26.5°C in just 35 seconds. Heating up of the water of the chiller can be easily minimized by use of distilled water instead of tap water and also by using a condenser.

3.2.4 Cooling with larger heatsinks and attached 3.5-inch fans

The laser diode bank worked perfectly well with the water chiller setup as it displayed only little variation in temperature but we also needed the laser to be handheld. In order to accomplish that goal we redesigned the setup. We installed larger heatsinks and larger exhaust fans (3.5 inch). This time we attached the fans directly to the heatsinksas shown in Fig.3.9

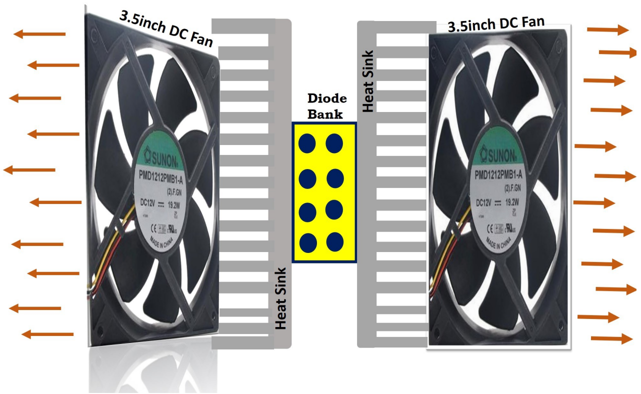


Fig. 3.9: Schematic setup of laser cooling with large heat sinks and 3.5-inch cooling fans.

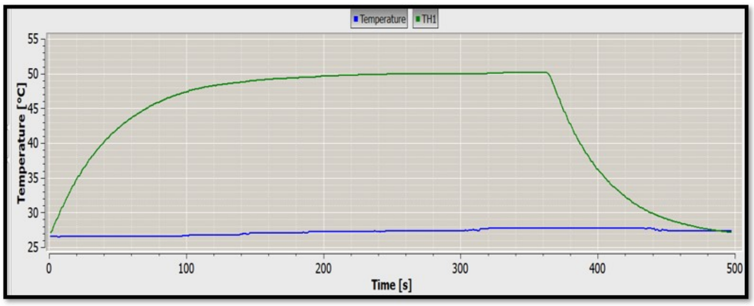


Fig. 3.10: Variation in temperature of laser with time in presence of smaller heatsinks and 3-inch fans.

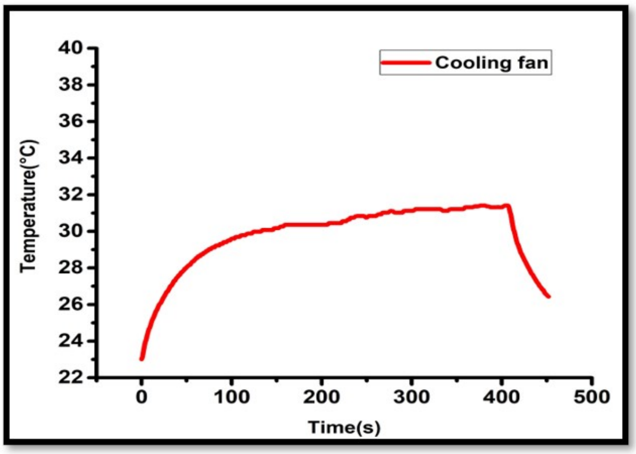


Fig. 3.11: Variation in temperature of diode bank with time for improved setup(larger heatsinks and 3.5-inch fans).

Observation

The temperature versus time plot (Fig.3.10) with only one minor change in the previous setup Fig.3.5 (we retained the heatsinks and fans but attached the fans directly to the heatsinks) shows that the temperature of the laser starts becoming stable at 50°C. This temperature is still very high. So to lower it down, we replaced the smaller heat sinks and 3-inch fans with larger heat sinks and high rpm 3.5-inch fans. The Fig.3.11 shows that the temperature of the laser became stable at 35°C after a few minutes. We ran the laser for 420 seconds and found that the rate of increase in temperature of the laser was very slow. Also, the temperature was almost constant throughout. The use of larger heatsinks and cooling fans also improved the cooling speed of the laser, as it took only 50 seconds to cool the laser from 35°C to 26°C.

3.3 Chapter conclusion

In this chapter we worked with the laser diode bank (consist of 8 blue diodes stacked together). To power up the laser bar we used different Li-ion and LiPo batteries. We used buck converters as laser driver to drop down the output DC voltage of battery from 14.8 V to 5.10 V(required to run laser diodes). We used different cooling techniques like water chillers, heatsinks, fans etc to cool the laser diode bank and analyzed their cooling performances by plotting temperature versus time plot.

Chapter 4

Stage 3 Experiments : 100 Watt Laser with tripple bar

4.1 Laser setup design

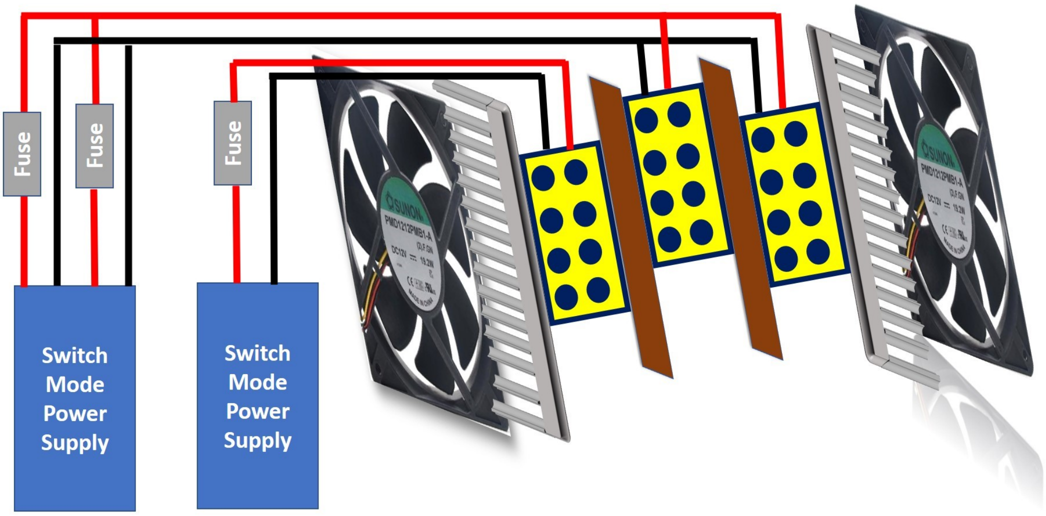


Fig. 4.1: Experimental setup of 100 Watt laser.

To raise the power of the laser we added two more laser diode banks to the previous setup. We also added two more copper plates (with dimension 15.7 x 10 x 6 cm^3) and powered the diode banks with Meanwell switch-mode power supplies (5 V-60 A) as shown in Fig.4.1.

In the previous setup of 30 Watt laser(Fig.3.1), we found that the step-down buck converters were getting heated up with an increase in the laser run time and their output power too decreased with time. So we replaced them with switch mode power supplies (output voltage of 5 V and a maximum current rating of 60 A). We ran the laser setup with these SMPS' for a greater amount of time but did not face the issue of heating or fluctuation in their output power. The SMPS' were able to deliver the power required to light up the diodes, and hence proved themselves to be ideal for installation in the setup. Initially, we directly connected the cooling fans to the copper plates but that didn't work well. So, we installed two more heat sinks in the setup. We ran the laser setup for several minutes to analyse the amount of heat produced in the system, and made changes to the setup according to our needs.

4.2 Experimental setup

4.2.1 Laser setup with copper plates and 2 aluminium heatsinks

High thermal and electrical conductivity of copper makes it one of the best metals for use in a heatsink. Since copper has a high heat dissipation rate, we used two copper plates (with dimension 16x6x10 mm^3) between the laser diodes, while maintaining the compactness of the setup. In the first experimental setup (Fig.4.2) we press-fitted the three laser diode banks and the two copper plates between the heatsinks and cooled the laser diodes with four cooling fans.

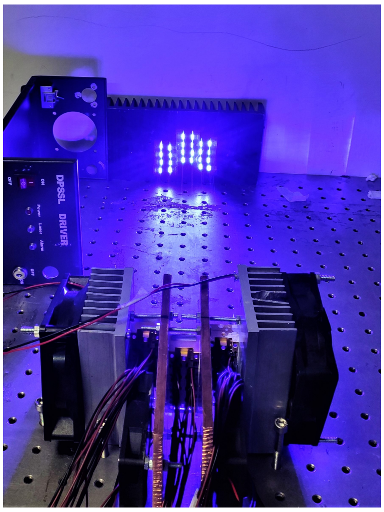


Fig. 4.2: Three laser diode banks press-fitted between copper plates and heatsinks with four cooling fans.

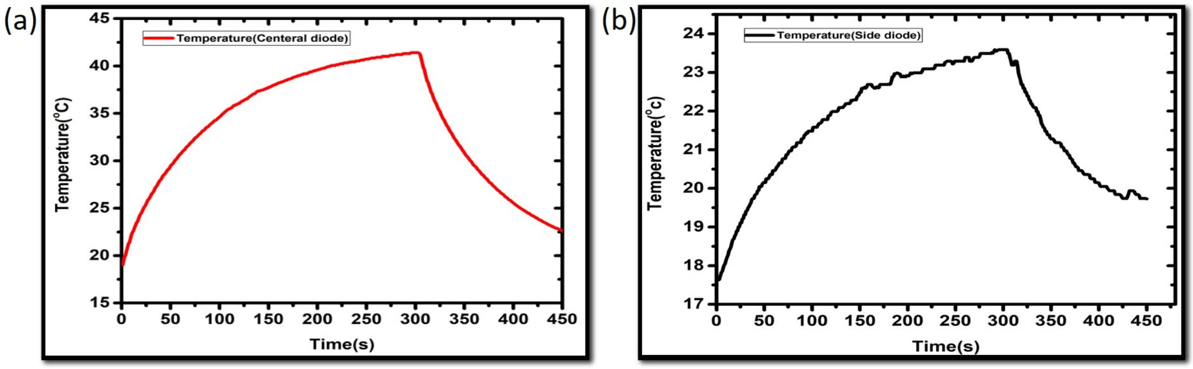


Fig. 4.3: Temperature versus time plot: (a) variation in temperature of central diode bank with time, (b) variation in temperature of side diode bank with time.

Observation: Temperature versus time plot

In the first setup (Fig.4.2) with only two aluminium heat sinks we found that the temperature of the central laser diode bank (Fig.4.3 (a)) started to become constant at 40°C. The temperature versus time plot (Fig.4.3 (b)) shows that the temperature of the side diode bank becomes constant at around 24°C.

We operated the laser for six minutes, and throughout this period we observed that the output power of each individual laser diode bank remained constant. It was falling when we had used the step down buck converters. Also no heating up of the SMPS' was observed.

4.2.2 Improved design of laser with addition of two extra aluminium heatsinks

We revised our setup and improved the design by adding two extra heatsinks with copper plates. We also replaced the earlier fans with those with a higher rpm (as shown in Fig.4.4) .

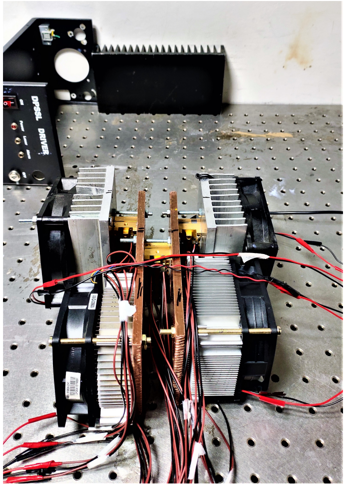


Fig. 4.4: Improved laser setup design with extra heatsink and high rpm cooling fan.

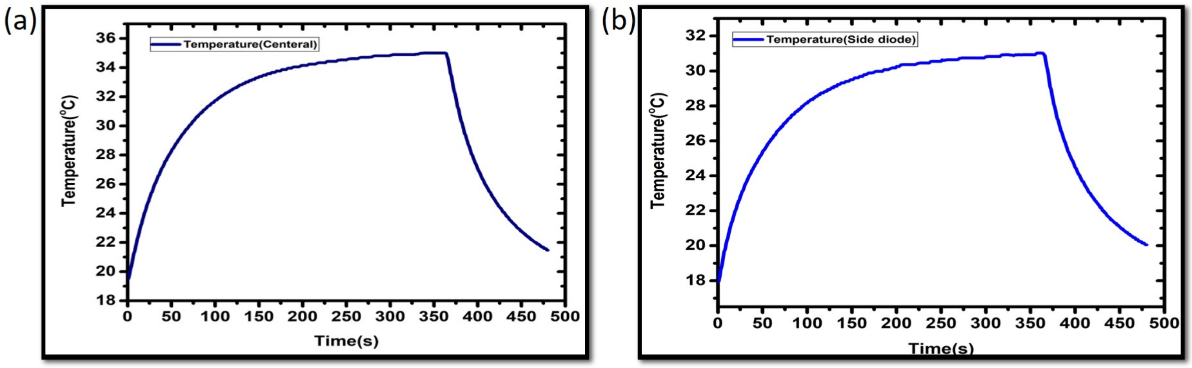


Fig. 4.5: Temperature versus time plot: (a) variation in temperature of central diode bank with time, (b) variation in temperature of adjacent diode bank with time.

Observation: Temperature versus time plot

In the revised setup described above, to optimize the temperature of the central diode bank we changed the configuration of the diode banks and also added two more heatsinks with big cooling fans at the two ends of the copper plates. The laser was again run for six minutes and this time the temperature of the central diode bank stabilized at $35°C$ (as shown in Fig.4.5 (a)). The temperature of the adjacent diode bank now stabilized at a little higher temperature 31°C (as shown in Fig.4.5 (b)) compared to the previous setup (Fig.4.3 (b)).

4.3 Housing of laser in the box

4.3.1 SOLIDWORKS design and the final setup

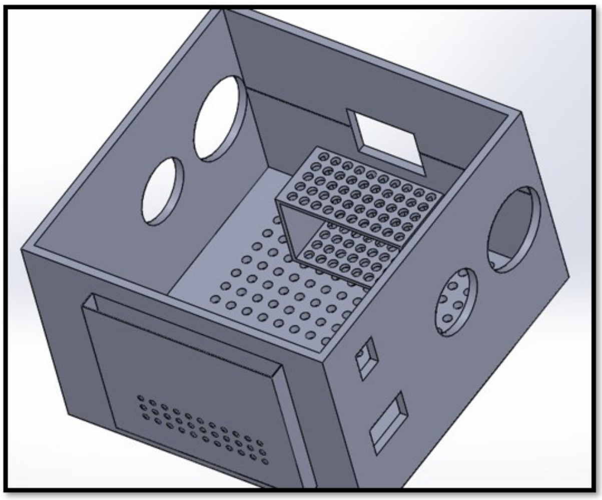


Fig. 4.6: The top view of laser box designed in SOLIDWORKS.

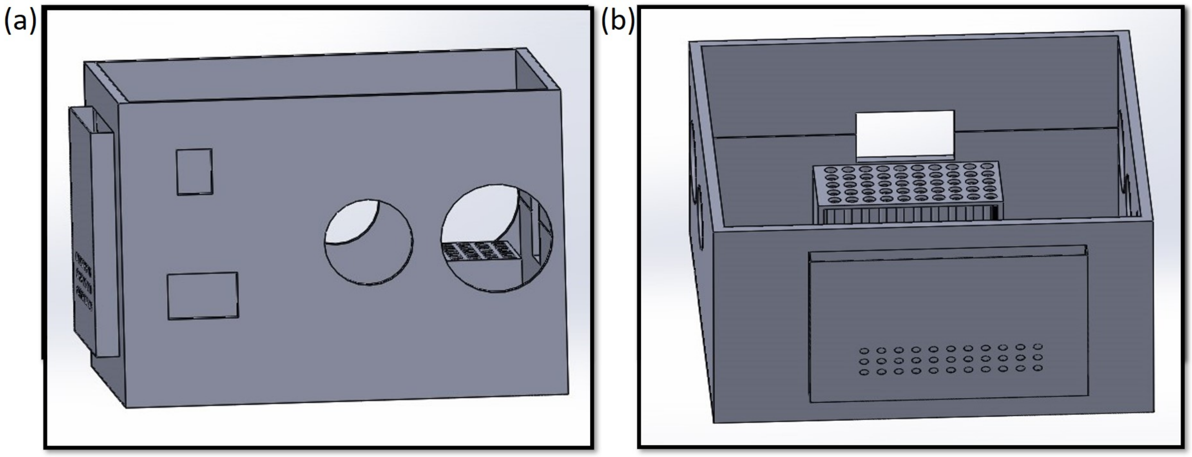


Fig. 4.7: Laser box: (a) side view of the laser box designed in SOLIDWORKS., (b) rear view of the laser box designed in SOLIDWORKS.

One of the most important things required for a high power laser is the housing of its setup. High power lasers are very sensitive and need extreme care. Hence, it was very important to carry out the experiments with the laser in a closed box rather than on an optical table since the latter doesn't provide us with an appropriate degree of freedom for the experiments (a box can be used to carry the laser to any other place, including the external surroundings). The box prevents dust from accumulating on the setup and also makes it easier to handle the laser. Since multiple diodes are used in the setup, the presence of many electric wires can also lead to confusion about which wire to plug in the switch in order to run a particular diode. A box solves that problem.

To design the laser housing box it was required to put the intuitive ideas about the box into reality. So, we first designed the laser box as shown in Fig.4.6 and Fig.4.7 in the 'SOLIDWORKS' software which is an extremely powerful computer-aided design software and utilizes mathematical equations to build parts from scratch. It helps in performing 2D and 3D modelling, and provides the basis for design, simulation and manufacturing of any part. We developed several such designs in the software and then printed them using a 3D printer to give us an idea about how the real box would look like and what problems would be needed to be taken care of. The main objective was to make a box that would be spacious and ventilated. For the safety of the laser, we installed 25 A type C Miniature Circuit Breakers in the box as switches and also installed 30 A fuses to tackle any instant short circuits. For the power supply, we used Meanwell Switch mode power supplies for running the laser diodes and the cooling fans separately.

4.3.2 Temperature versus time plot when laser housed in the box

After installing the setup in the box(as shown in Fig.4.9) we found that the temperature of the laser during its running time had increased. In the previous case where the laser setup was openly placed on the optical table, the highest temperature that the central laser diode bank(fitted between the copper plates) reached was 34°C which had now changed to 42.5°C for the same interval of time (as shown in Fig.4.8). The rise in temperature can be attributed to the fans having become inept at cooling the laser compared to before since they had now been placed in a closed environment (surrounding air also plays a major role in cooling the laser setup.). Also the previous experiment(shown in Fig.4.4) was carried out in the winters while we performed the second experiment in the month of March having a surrounding temperature difference of 5-8°C.

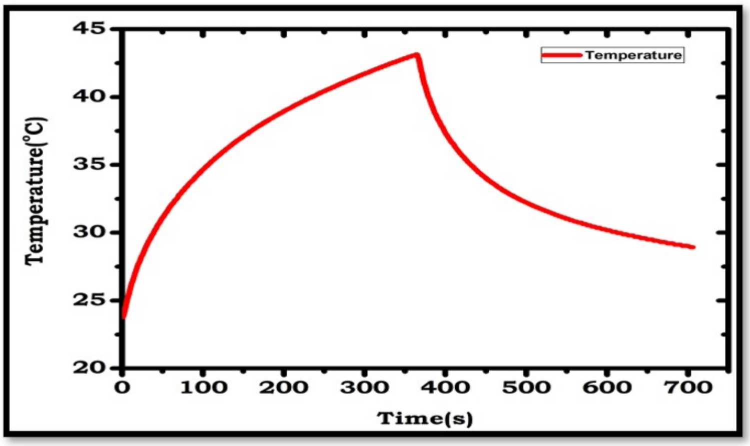


Fig. 4.8: Variation in temperature of central diode with time.

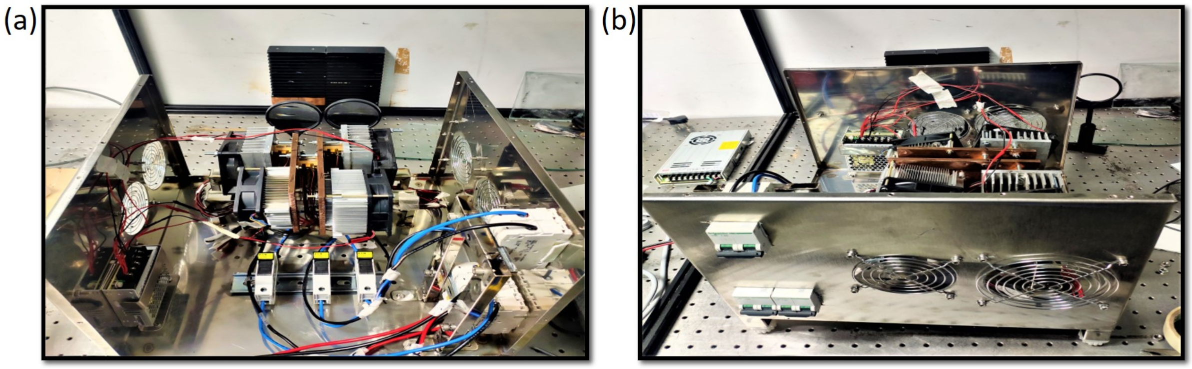


Fig. 4.9: Laser housing in the box: (a) rear view of the laser box., (b) Side view of the laser box.

4.3.3 Laser running at full power

As electronic devices become more powerful, they generate more heat. The temperature vs time plot (as shown in Fig.4.10 (a) and Fig.4.10) shows the rise in temperature of the laser. It starts to stabilise at 50°C for the centre diode bank. The corresponding stabilising temperature for the adjacent right diode bank was observed to be 48°C. The rise in temperature of the laser can be justified by a decrease in the efficiency of the single laser diode (shown in Fig.2.9 (d)).

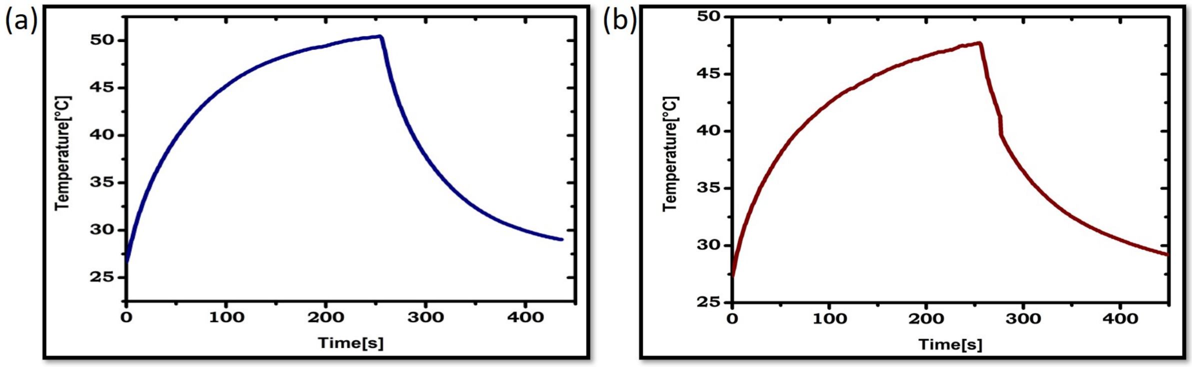


Fig. 4.10: Temperature versus time plot: (a) variation in temperature with time for central laser bank at full power, (b) variation in temperature with time for adjacent laser bank at full power.

4.3.4 Variation in output power with applied voltage

The output power of the laser was measured with respect to the applied voltage(shown in fig4.11). The maximum power of the laser that was observed was 9̃0 Watts. The laser power was not became constant at 5.7 V which shows that it can further increase , but due to the limiting input voltage we were not able to increase the voltage of the SMPS to above 5.76 V. As the power of each diode lies in the range of 3.6-4.1 Watts. So by extrapolating the curve of the output power we might get the output power of the laser to be close to 100 Watt. In origin software we did the linear fitting(blue line in Fig.4.11) to extrapolate the output power curve which shows that at 6 V applied voltage the power of laser becomes ≈100 Watts.

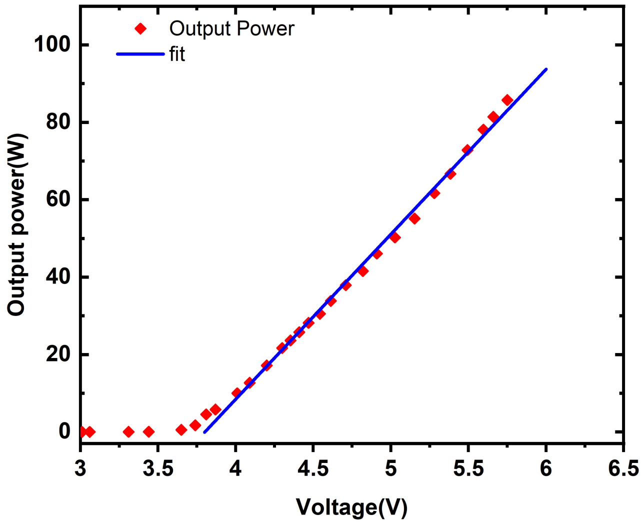


Fig. 4.11: Output power of laser with applied voltage.

4.3.5 Variation in temperature of center laser diode bank

The central laser diode bank is fitted between two 6 mm copper plates and is the one which is facing the maximum amount of heat and dissipating it with the help of two heat sinks placed at the back of the copper plates. As we have already seen from the previous temperature plots, the central diode bank comes to equilibrium at a higher temperature compared to the adjacent laser diode bank. So just by calculating the equilibrium temperature of the central diode bank we can give an estimate of the temperature of the other two diode banks. We have plotted the temperature versus time plot(as shown in Fig.4.13) for the central diode bank when only one of the lasers was switched on, when two lasers were switched on, and when all three laser diode banks were switched on(Fig.4.12)

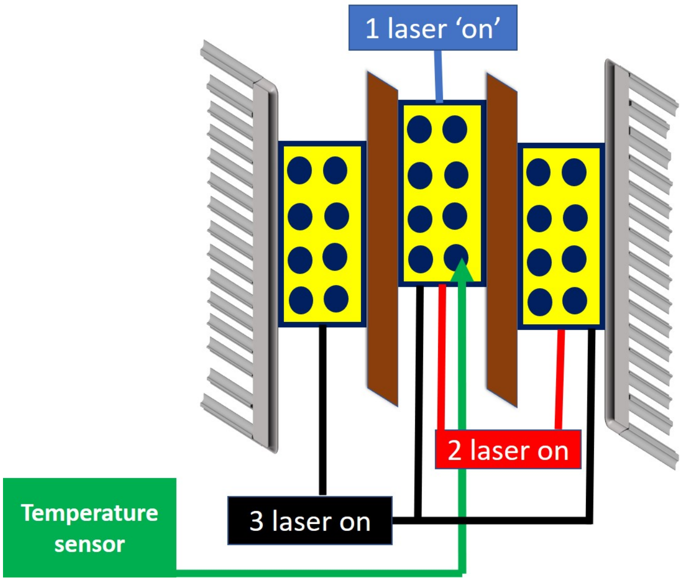


Fig. 4.12: Schematic figure of laser operation.

The laser was switched on for 30 minutes and at full power(black) the temperature of the laser got stabilized at 49°C. When two lasers diode banks(red) were switched on then the equilibrium temperature that was reached was 42°C, and when only one laser diode bank was switched on, then the laser came to equilibrium at 36°C.

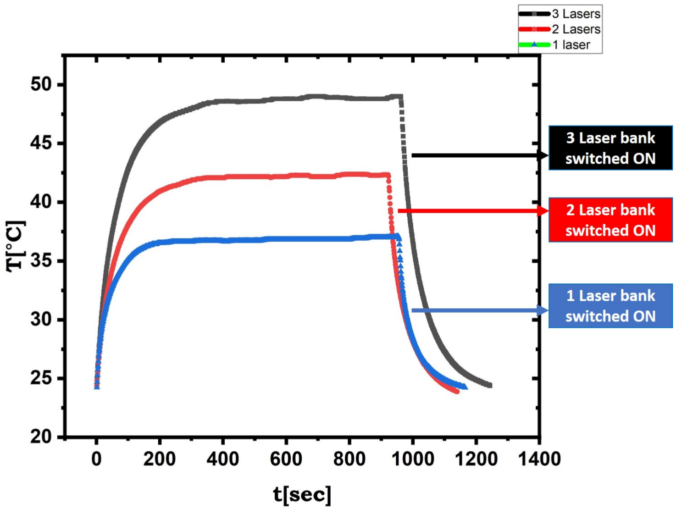


Fig. 4.13: Variation in temperature of central diode with time at different output powers.

4.4 Chapter conclusion

In this chapter we scaled up the laser power from 30 Watts to 100 Watts. To power up the laser, we used switch mode power supply(instead of batteries) which works on AC power. The advantage of using AC power supply over batteries was their constant input power for longer time intervals which DC batteries failed to deliver. To make the setup compact we press fitted the three laser bars between two copper plates and 2 heatsinks. To optimize the laser performance and cooling it down, we installed multiple cooling fans of different rpm in the setup. We used SOLIDWORKS software to house the laser in the box. We plotted the temperature versus time curves for all different setup geometries and analyzed them. To find the output power of laser we plotted the rise in output power of laser with applied input voltage.

Chapter 5

Conclusion and future plans

5.1 Concluding remarks

This thesis discusses the design and development of a high power blue diode laser. As an outcome, we have achieved the 100 Watt power mark of the blue diode laser. At every stage of the development of the laser, we faced multiple challenges including, changed batteries, diode drivers, the geometry of setup, cooling methods etc. The laser consists of 24 blue diode lasers with individual power of 3.5-4 Watts each and a combined power output of 100 Watts. We have designed different linear power supplies and used multiple voltage converters to make sure that the laser diodes get the required input power supply. To make sure that the setup is lightweight and compact, we have used a variety of batteries from AA cells to Li-ion batteries to LiPo batteries. Variation in the cooling techniques came with the rise in power output of the laser. To increase the power and efficiency of the laser, we have tested different cooling mechanisms such as with water chillers, air cooling, TEC and then plotted the variation in temperature of laser with time for all cooling styles. To optimize the system and its performance, we simulated its working using Multiphysics simulator COMSOL(Appendix A.3) and SOLIDWORKS(4.3.1).To obtain a tight focus, we have used the Magnifying glass to focus it within the range of 8cm. We are improving and scaling up regularly.

5.2 Future plans

We are planning to improve the thermal design of the laser set up so that it can run for a longer time. We also aim to fibre-couple multiple beams. We plan to convert this CW laser to Pulsed laser via both electrical and optical(femtosecond) method. Our ultimate target is to increase the power of laser up to 1 KW.

Appendix A

Electronic Components

Electronic components changed has the lifestyle of the world. They are the vital components used in each and every device ranging from a small toy to the biggest industrial machines, everything consists of various electronic components. The Quality,reliability and durability of electronic component enhances the performance of the device. Faulty electronic parts can cause an end product to malfunction. In our laser setup we have tested various electronic components to enhance the safety and performance of laser which includes MCB switches, high quality fuse, Switch mode power supplies to name a few.

A.1 Buck: DC to DC Converter

Buck and Boost are DC to DC converters, which takes the voltage from DC sources and converts the supplied voltage into another DC voltage level.like a transformer, they essentially just change the input energy into a different impedance level. So whatever the output voltage level, the output power all comes from the input; there's no energy manufactured inside the converter. Buck converter decreases the voltage level(while stepping up the input current) and as the name suggests Boost converter increases the voltage level.laser diodes need certain amount of voltage to run them. Too much power can destroy them or less power may not able to run them.In the laser setup we used step down buck converter with LiPo batteries which cuts the voltage level of battery from 14.8V to 5.0V required to run the laser diode.Buck is switching converter who provides much greater power efficiency then linear regulators which only lowers the voltage by dissipating heat, but do not step up the output current.

The buck converter circuit consists of four main components:

- Switching transistor
- Inductor
- Capacitor

- Diode

A.1.1 Working

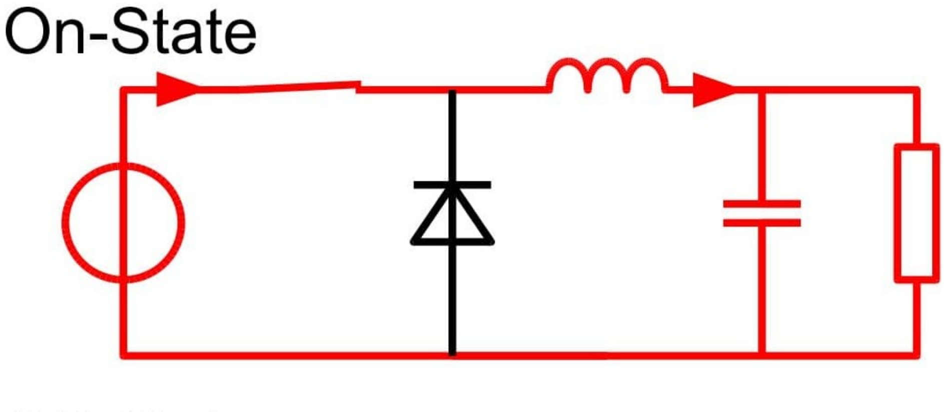


Fig. A.1: Switching transistor in 'on' state.

When the transistor switch is turned on, current begins to flow through L, C and the Load. The magnetic field in the inductor, therefore, build up, and as the inductor is storing the energy the current in the load is restricted in the beginning so the current in the load and charge on capacitor(C) builds up gradually.also during the 'on' period the diode(D) remains in reverse bias and large positive voltage drops across the cathode of the diode.

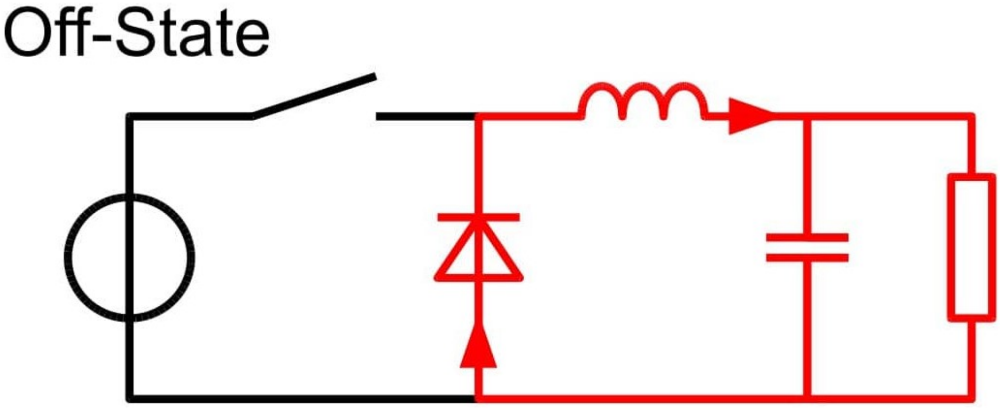


Fig. A.2: Switching transistor in 'off' state.

When the transistor switch is turned off then the inductor(L) opposes any drop in current by suddenly reversing its emf, and supplies current to the load itself via the diode(D) which is now forward bias.once the inductor's energy begins to fall than to keep the current flowing in the circuit, the capacitor becomes the main source of current until the next 'on' period.

The output voltage of the buck converter can be varied by changing the duty cycle(D) which is defined as a fraction of one period in which the system is active or in 'on' state.

$$D = Ton/T$$

In terms of voltage

$$D = Vout/V\ \mathrm{in}$$

or

$$D = Iin/Iout$$

The duty cycle in our system was

$$D = 5.1/14.8 = 34\%$$

A.2 SMPS: Switch Mode Power Supply

The Lipo battery was replaced by switch mode power supply(SMPS)[23, 24] which acts as AC to DC converter. The SMPS offers wide range of advantages in terms of size, weight, cost, efficiency and overall performance. The diode laser was working perfectly fine with the switch mode power supply without any fluctuation in output power

A switched mode power supply is an electrical power supply that incorporates a switching regulator to convert electrical power efficiently.The switching regulators turned on and off at very high frequencies, and similar to buck converters the storage components such as inductors or capacitors to supply power when the switching device is in non-conduction state. SMPS transfers power from a DC or AC source to DC loads. The pass transistor of a switching-mode supply continually switches between low-dissipation, full-on and full-off states, and spends very little time in the high dissipation transitions, which minimizes wasted energy. This higher power conversion efficiency is an important advantage of a switched-mode power supply.

The main components of a basic switch mode power supply are:

- Input rectifier and filter
- High frequency switch such as MOSFETs
- Transformer
- Output rectifier and filter
- feedback and control circuit

Block Diagram of SMPS:

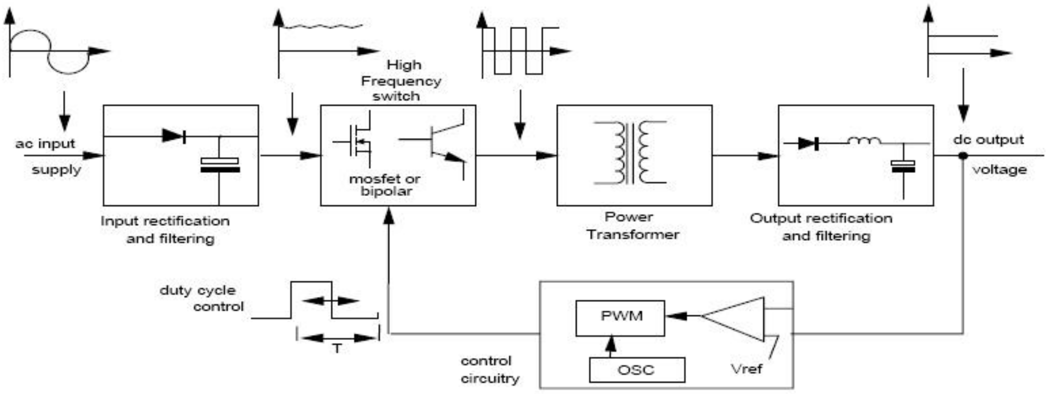


Fig. A.3: Functional block diagram of switch mode power supply

A.2.1 Working of SMPS:

1. The AC input supply signal is given directly to the rectifier and filter circuit which in output gives an unregulated DC.
2. The resulting dc voltage is fed to high frequency switch(MOSFET) which switches ON and OFF according to variations.
3. Subsequently, the high frequency AC voltage is supplied into the primary winding of a high frequency transformer.
4. The output signal from the resulting transformer secondary winding voltage is again rectified and filtered, to get the required DC voltage.
5. This regulated output voltage which is then given to the control circuit, which is a feedback circuit. The final output is obtained after considering the feedback signal.

A.3 COMSOL Simulations

COMSOL Multiphysics is a cross-platform finite element analysis, solver and multiphysics simulation software which is designed with real-world application in mind. The efficiency of diode lasers is 30% which means 70% of supplied power wastes in the form heat generated. To cool the diode laser we randomly tried different heat sink designs which somehow worked after several efforts, for the single 3.5watt diode. But the applicability of these hit and trial methods was not possible for the diode bank of 30 Watts output power. So to deal with this heating issue we use COMSOL Multiphysics Simulator which provides a real-world environment to develop optimized heat sink design.

The Software gives a fast estimation of the cooling performance of heat sinks of different materials and dimensions and helps in designing heat sinks which can properly dissipate the heat from the system. The simulator also helps you to predict how heat flow will take place if the current setup is to be replaced with bigger setup and what changes in dimension of the heat sink and cooling fan should be made without dealing directly with the setup.

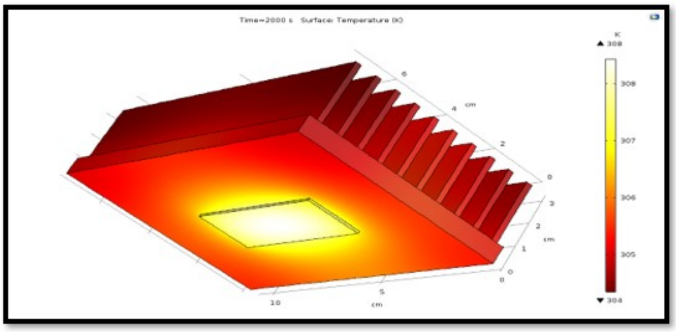


Fig. A.4: Flow of heat in the heat sink

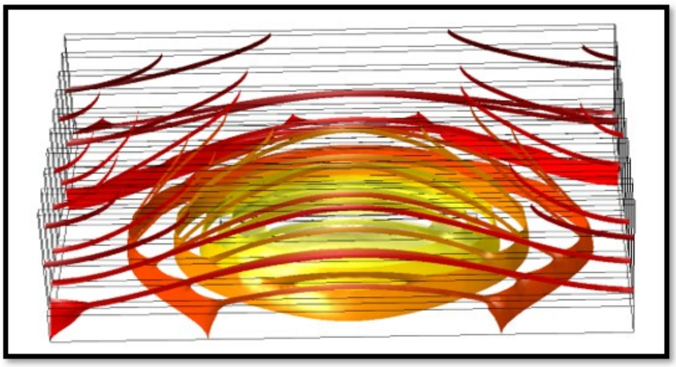


Fig. A.5: The temperature isotherms in the heatsink

Observation

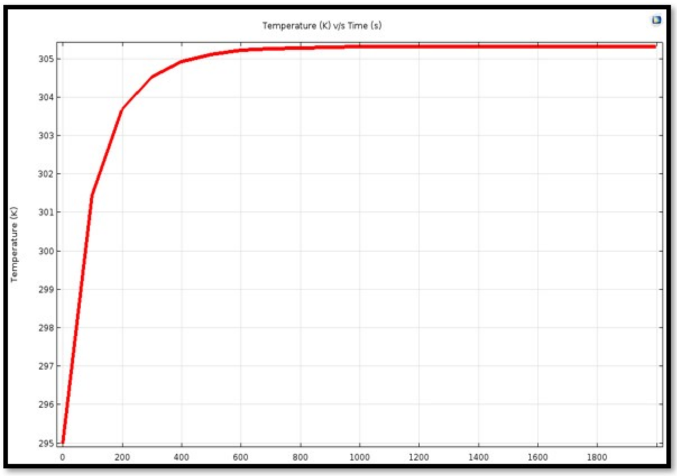


Fig. A.6: The temperature vs time plot in COMSOL Simulator

In the COMSOL Simulator[25], we designed the heat sink module exactly of the same dimension and provide the same cooling environment. The plot in fig.A.6 shows the variation in temperature of the laser diode with time for the heatsink designed by COMSOL Simulator. The plot shows that the temperature of laser diode bank comes at equilibrium point after reaching 32° and becomes constant after that.we have witnessed the similar results in the experimental setup too, where we used the same dimension heatsink, cooling environment and found that the temperature of laser become becomes constant at 35°C.

A.4 Temperature sensor

Almost all the electronic devices generate heat in some form and proper management of heat dissipation is required for them to function properly. Lasers are also highly sensitive to temperature which is directly proportional to the output power of the laser. Higher the power of the laser, more will be the heat dissipated by the diodes. All kinds of high power lasers generate heat, be it the gaseous laser, solid-state laser or the diode laser. Any spike in the temperature of the laser can affect its performance or even damage it completely. So better management of heat leads to a higher efficiency of lasers and increases their lifetimes. In our experimental setup, to monitor the temperature of the diode laser, we have used Thorlabs TSP01. It is a temperature monitoring sensor which can continuously measure the temperature of the diode. But the problem with this sensor is that it requires a computer to display the temperature of the laser. Since it is not possible to carry a laptop with the laser, we devised a temperature sensor[26] connected with an Arduino and a screen to display the temperature. The whole temperature sensor setup was operated with a 9 V battery.

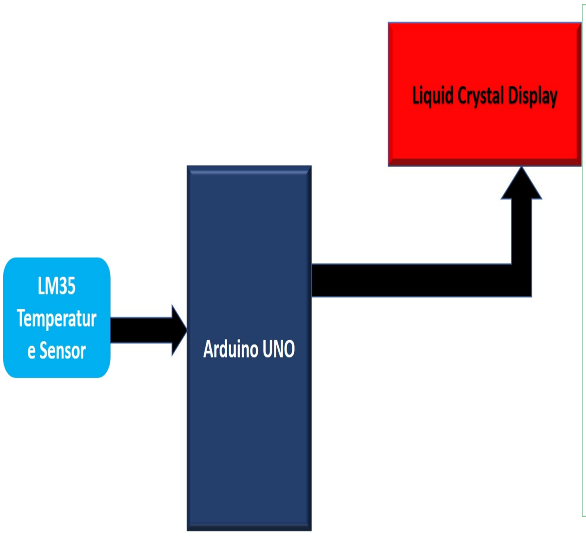


Fig. A.7: The block diagram

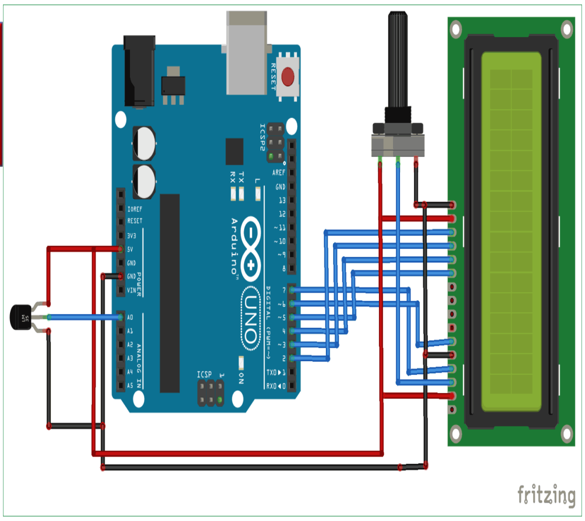


Fig. A.8: Circuit diagram for Digital temperature sensor.

The Arduino based digital temperature sensor used by us is shown in fig.A.9. It displays the current ambient temperature and the temperature changes of the laser on an LCD unit in real time. In this sensor, the Arduino communicates with an LM35 temperature sensor and a 16x2 display unit. We can divide it into three sections - the first section senses the temperature by using the LM35, the second section converts the temperature value into a suitable number in Celsius scale. This is done by the Arduino. Finally, the last part of system displays the temperature on the LCD (demonstrated in the above block diagram).

The Arduino Uno controls the whole process. An LM35 temperature sensor is used for sensing the environment temperature.

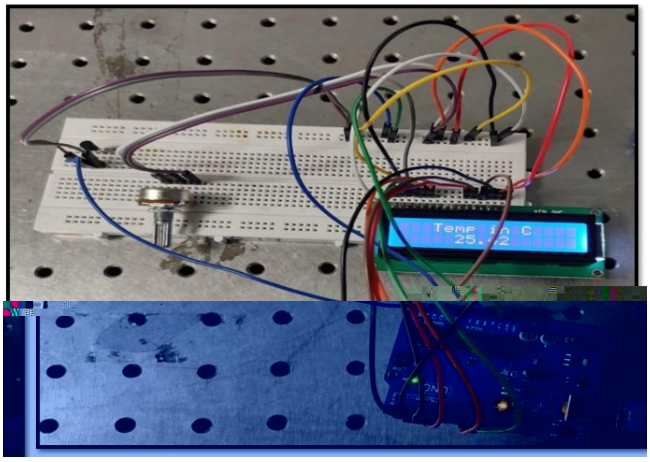


Fig. A.9: Experimental setup of temperature control sensor.

A.5 Laser safety precautions

- Before turning on the laser pointer, always be sure that it is pointed away from yourself and others.
- Never look directly into any laser beam, regardless of power.
- Remove all unnecessary shiny reflecting surfaces from the work area.
- Wear eye protection-large plastic lensed eyeglasses or safety goggles.
- While working with the high voltage always wear the anti static wristbands.
- Alignment of beams and optical components should be performed at a reduced beam power whenever possible.
- High-intensity beams that can cause fire or skin damage (mainly from class 4 and ultraviolet lasers) and that are not frequently modified should be guided through opaque tubes.
- All windows should be covered with blinds, shades or other non-flammable barriers that reduce transmission of the beam to acceptable levels.
- Finally, never assume anything without checking it out for yourself! Don't take short-cuts!

A.6 Laser Operating Protocol

1. First of all, measure the input AC power supply voltage using the multimeter (AC mode). Make sure that it is in the range of 230-240V.
2. Check that all the cooling fans are working properly after having switched on their power supply.
3. Now switch off all the MCB switches (an off sign should be visible on them), put on the laser protection eye glasses, check that the blockers are placed in front of the laser and remove all reflecting material from the optical table.
4. Put the knob of the temperature control sensor inside the central diode bank and connect it with the laptop to continuously monitor the temperature of the laser using the TSP01 software.
5. Now, switch on the laser power supply and carefully check the output DC voltages of both the Meanwell SMPS's. The voltages should not exceed 5.4V.
6. Now, turn on the three MCB switches one by one and make sure that each diode bank emits eight blue light beams.
7. Immediately turn off the MCB switches in case you detect a smell of something burning and check all the connections immediately after.
8. After using the laser, turn off all the MCB switches
9. Finally, turn off the cooling fan switch when the temperature of the laser falls below 26°.

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