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Faculty of Electrical Engineering
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MASTER'S THESIS

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ÚSTAV RADIOELEKTRONIKY

CONTROLLABLE LASER SOURCE FOR BIRD REPELLING

ŘÍZENÝ LASEROVÝ ZDROJ PRO PLAŠENÍ PTACTVA

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

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BRNO FACULTY OF ELECTRICAL
UNIVERSITY ENGINEERING
OF TECHNOLOGY AND COMMUNICATION

Master's Thesis

Master's study program **Telecommunications**

Department of Radio Electronics

Student: Bc. Hana Vrtělková   **ID:** 186236

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TITLE OF THESIS:

Controllable laser source for bird repelling

INSTRUCTION:

Get acquainted with laser radiation, beam generation methods, adaptation of the optical characteristics, laser source powering requirements, relevant operating principles, and human or animal eye-related safety rules. Choose a suitable approach to scare birds by using a laser beam. Select the target parameters of the beam concerning its geometric character, wavelength, power, and its distribution in the track; such parameters must observe applicable specifications as defined within relevant laser safety classes. Select potentially suitable modulation schemes to adjust the beam intensity. Formulate an approach to designing the radiation source and its optical components; the method should be outlined in such a manner as to enable you to assemble the device. Design electronic circuits to safely supply power to the laser source and to modulate the intensity of the generated beam. Use a microcontroller with a suitable interface to ensure user setting of the modulation schemes (stationary mode, flashing with a pre-defined period and alternation, random selection of parameters, and other modes). Assemble and implement the designed device, verifying its parameters via applicable measurement procedures.

RECOMMENDED LITERATURE:

[1] JOHNSON, M. Photodetection and Measurement: Maximizing Performance in Optical Systems. New York: McGraw-Hill, 2003.

[2] HOBS, P.C.D. Building electro-optical systems, making it all work. New York: John Wiley & Sons, 2000.

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Chair of study program board

ABSTRACT

This diploma thesis deals with the issue of scaring birds and their humane scaring using lasers. The work also discusses the safety of lasers, the problem of the driver circuit of laser diodes, beam collimation and its extension so that the output power of the beam does not exceed the maximum value of the output power of the class 2M laser.

KEYWORDS

Bird scaring, bird deterrent, bird control, laser, laser safety, laser diode, driver circuit, ESP32.

Author's Declaration

Author: Bc. Hana Vrtělková

Author's ID: 186236

Paper type: Master's Thesis

Academic year: 2020/21

Topic: Controllable laser source for bird repelling

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

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  *The author signs only in the printed version.

ACKNOWLEDGEMENT

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Introduction

This thesis is devoted to Controllable laser source for bird repelling. It deals with actual abundantly used methods of bird repelling and takes into account why is laser repelling advantageous technique to be used.

Considering the behaviour of birds, their ability to habituate to different scaring techniques and what should be done to slow down the time during which they will habituate to scaring technique. Also considering properties of birds' eyes, their sensitivity to radiation and colours resulting in selection of suitable colour for bird repelling.

It also deals with lasers, laser beam and sources of the laser beam. The fundamental principle of laser and properties of laser radiation are discussed. Later on is the thesis focused on laser diodes as suitable source of laser radiation for bird repelling. The basic types and characteristics of the laser diodes are discussed.

Laser safety is another comprehensive topic which has to be considered when using lasers for bird repelling. Safety classes of lasers are described including their basic characteristics. Limits of laser radiation safe for human and therefore birds' eyes are given. This limits affect following design of the device used for bird repelling.

Optics used with laser diodes for laser beam collimation and for reduction of the output power of laser diodes comply the level of the output power set for laser of class 2M.

Mentioning something about laser diode driver circuit and comparing discrete and integrated driver of laser diode. Also mentioning some advantages, integrated drivers have over discrete ones.

Safety glasses for work with laser diode are selected. The proper optics for chosen laser diode is selected when considering safety limits of laser safety classes.

Appropriate heat sink for laser diode is designed. The selection of components used in the design of laser diode driver circuits is described and the design of laser diode driver is done.

1 Bird control

Bird control is not considered as much important issue, but it should be because birds bring risks. Over 50 diseases and ectoparasites which are transmittable to humans is carried by bird droppings. Also, property can be damaged in several ways by the mess birds leave behind. Pipes can be clogged by nests and nesting material or present fire hazards near electrical wires. Even cleaning up after birds is not cheap. Birds also causes crop losses when eating grains, fruits, and sown seeds, and breaking branches when roosting. These are several reasons why bird control is an important issue. [1, 2]

Bird dispersal techniques are used to reduce bird conflicts with humans safely and efficiently. To find food, avoid danger, and locate mates for bird is crucial their vision and hearing. Birds perceive colours invisible for human (even ultraviolet range) and the effectivity of scare devices relying on vision depends on the visibility of the object, some minor poorly visible objects could be ignored as "visual noise". To make the dispersal technique effective, bird must perceive it as a threat. [3]

Commensal birds and nuisance wild birds are two categories of problem birds. Controls are divided into five categories: exclusion/relocation which is the most passive, repelling, trapping, suppression and poisoning/killing which is the most aggressive control. For development of control strategy, it is important to understand the offending bird category, its biology and habits and analyze what are the birds doing, what is the goal of client and his tolerance. The goal of bird control is to use the least aggressive strategy that will meet the requirements of the client. [4]

First step is to identify the bird species. Commensal birds (pest birds) are unprotected species which can be legally controlled by any appropriate method, when non-target species (birds, animals, and people) are not injured. First thing to be considered is sanitation – can resources such as food and water be eliminated or made unavailable to the birds? If not, then the appropriate control must be used. [4]

Second step is the control. The goal is to exclude the birds without any damage of the aesthetics of the structure to be protected and meet the budget. To provide effective control it is necessary to know the biology and habits of the bird species. Methods of control like suppression, trapping and killing birds are generally unpopular and non-lethal methods are used instead. Today a staggering variety and ingenuity of the bird control is available. [4]

Several methods used for bird control follow.

1.1 Methods

The greatest efficiency is achieved by combining several methods and not giving bird a chance to habituate to the deterrents. Old solutions like scarecrow can work at the beginning especially if it can be moved by wind but without any legible threat for the birds when they are around, birds will quickly habituate to the frightening technique. Methods must be chosen according to the species of the birds we want to repel. [3]

For the exclusion of the birds from area can be used nets or wires, which prevent bird access. Mesh size of nets depends on species and if the nets are installed inaccurately, it can increase surface area for bird nesting and loafing. It can also trap bird inside the net which can lead to more damage when birds try to escape and potentially to death. There are several ways like metal flashing, wood, or stone placed on ledges at a 45° angle or more which will exclude birds from loafing or nesting. Also, products that exclude birds by making bird uncomfortable trying to use a ledge causing them minimal amounts of pain. Variety of anti-perching spikes are available but in windy weather can cause a death by pushing birds toward the spikes. Shock strips producing a slight electrical shock to bird landing on them can be also used. But strips must be kept clean to prevent the stripes from shorting out. [3]

Some chemical repellents are lethal to any bird that any birds that ingest it. Before dying birds show signs of distress that frighten rest of the flock. Polybutene-based products are tactile repellents. Contact with the feet of the bird is uncomfortable. Repellents come in form of gels, tars or similar material and should be used with caution because high heat can break some down and can stain or run. When the surface of the product is covered with dust or dirt the efficiency is decreased. Applying repellents to the grass can help disperse birds from problematic area. On the market are available a variety of products but there are registered only two active ingredients (methyl anthranilate and anthraquinone) for use on turf. [3]

As frightening auditory techniques can be considered sounds representing alarm or distress calls. Alarm calls suppose to warn the flock that the threat is near and distress calls are made by the birds when they are injured or traumatized. The reaction of the birds is dependent on the time of the year in relation to breeding, frequency of predation risk and some other things. Sound must be used at volume birds are accustomed to hearing, playing it louder is not helpful. When alarm and distressed calls are repeated, birds will habituate to them in the absence of any threat. Also, generic sounds can be used (gun shot, car horn). It has immediate results but when not accompanied by pain or discomfort birds will habituate to it quickly. Also, pyrotechnics are used as effective dispersal tool. They produce loud

sounds, some of them even flash of light and puff of smoke. But person must have permission and it is not suitable to use it close to people's homes. Propane cannons and gas exploders use blast that sounds like a shotgun to deter the birds. If used to go off at specific time intervals, habituation is very common. Cannons can be also fired remotely only when the birds appear which can prolong the time birds will need to habituate. [3]

As auditory-visual techniques are considered remote control vehicles like boats and aircraft which can be deployed in a threating manner and therefore successfully scare birds. But certain level of skill is required, and time and money for development. Their use is limited by weather. Dogs are also used successfully for repelling the birds, but they may get bored over time and stop chasing the birds. Live raptors under control can be used, but this kind of repelling is expensive and requires extensive training. Compressed air can be used directly or indirectly to disperse birds from roosting, loafing, or feeding areas. Direct use means that the air is directly blown onto birds, while indirectly the air is used to move with hoses which can scare birds when seeing it. Also, high-pressure water sprayers are used effectively for dispersing roots. But some birds can associate sound of the water sprayer pump and leave before being sprayed. [3]

Visual deterrents use stimulation of an innate avoidance or learned response which is often reinforced by another control technique. Scarecrows, dead birds, predator-like devices, effigies, plastic owls, and predators are used without significant success because birds habituate to them quickly. They quickly learn that effigies left in the same location over a longer time do not represent a threat. Also, scarecrows used for long time have limited value in deterring. The movement must be added or additional control, which will prolong the period which birds need to habituate to the deterrents. Flagging and other materials moving in wind are used but having mixed effects as visual repellents. Flashing pie pans, aluminium foil, coloured ribbon, plastic bags, and any other items suspended to blow in the breeze, cause birds a neophobic response. Bright lights (spotlights, strobe lights, flashing lights) disperse birds for short period of time. [3]

Some species of birds have been effectively scared by red or green lasers. Red lasers work more effectively in dark while green lasers work both in low-light conditions and dark. Lasers must be used with caution because of their range and that they can potentially affect human vision. Laser beams can not point toward the sky (just scanning the ground), due to the risk of striking the cockpit of an aircraft – can cause flash blindness resulting in hazardous situations for people. [3]

1.2 Birds, lasers, and suitable colour

Human eyes detect light with three types of retinal cone photoreceptors, for red, green, and blue light which corresponds to long, medium, and short wavelengths which means that human vision is "trichromatic". Blue receptor of human eye can perceive some UV wavelengths, but they are filtered out by eye's lens and cornea before they reach the retina, probably to protect the eye against the damage. Bird eyes have cones like those of humans for long-, medium-, and short-wavelength. But birds' vision is tetrachromatic which means that in addition they have a cone type. This type enables birds to detect wavelengths in the near ultraviolet range (300-400 nm). Also having a "double cone" (function is not clearly understood), and retinal oil droplets with carotenoid pigments (help screen out extraneous wavelengths). [5] At figure 1.1 is a comparison of human and bird eye.
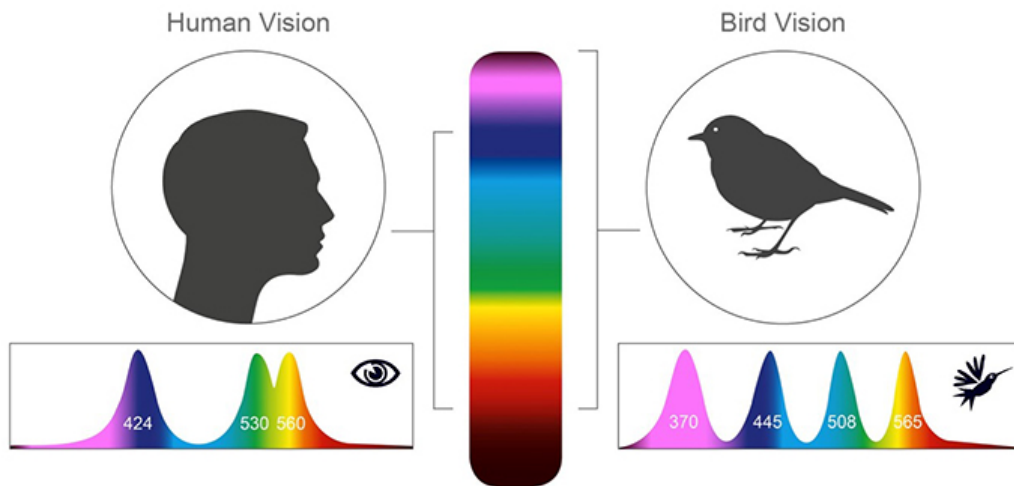
Fig. 1.1: Bird and human vision. [6]

When being in visually obstructed habitats like long grass swards, starlings respond slower to danger. They also react slower when having heads down in obstructed habitats than down in open habitats. The possibility of employing their peripheral field of vision make the reaction times quicker. The actual and perceived risk of predation is affected by the degree of visibility and social environment. It is harder to obtain information on the presence of predators with increasing distance between flock members and decreasing visibility. [7]

Laser technology is now common bird detergent technique and research using low-power lasers is ongoing. The most common type is the handheld laser resembling small handgun. There are other formats like a rifle which produces narrow spot of light for more precise targeting, and a laser "stick" resembling conventional torch.

The advantages of laser control are that the laser is silent, environmentally safe, simple to use, and non-lethal. The disadvantage is that it is ineffective in strong sunlight. It has main use between dusk and dawn, so it is the most effective to control species active during darkness or dawn/dusk and for the control of roosting birds. Most common handheld lasers have wavelength 650 nm and laser output 50 mW or wavelength 532 nm and output lower than 50 mW. Most species can be controlled by laser although some of them habituate quickly as to most scaring devices. This method is most effective for nocturnal birds and birds active in low-light conditions. [9]

There is one problem when using lasers as bird scaring device. Laser beam is visible over a large area in darkness and can disturb non-targeted bird species or protected birds (in urban environments, for example). [9]

Function of bird lasers is based on production of a large visible point of light which can scare away problem birds. For many bird species the light is associated with predator-like behaviour and they flee away when perceive the visible light pattern. Lasers which produce wide beam are the most effective for bird deterring. Generally, the best results seem to produce green beams. [8]

Bird lasers are especially useful when it is desirable to move birds from their roots. When disturbing birds from roosts in and around warehouses, barns, and close to airport terminal, laser are particularly suitable instead of invasive audio deterrents. Repeatedly treat roosting sites at dawn and at dusk is an effective technique which provide enough time for birds to find alternative roosts outside the control area. Using the beam of light slowly approaching the roosting site and leaving an escape path for birds is the most effective technique with predator-like manner. For bird lasers can not be used high-power lasers and laser safety is essential. [8]

Research has shown that shining the beam directly into the eyes of the target species is more effective, which brings the question about laser safety. Research by National Wildlife Research Centre in the USA confirmed even uninterrupted exposure of eyes to laser beams it appeared to be no physical damage to the eye. Generally, the most damaging radiation is filtered very efficiently by the avian eye, and exposure to the laser beams should not damage the avian eye. [9]

As mentioned before, green lasers are achieving best results. It is because the green lasers are brighter than any other laser colour which is an advantage since bird repelling is done during the daytime. This is the reason why green colour laser diode has been chosen for laser scaring device. [10]

As others scaring methods, for laser to remain effective it will be needed to compliment this method by other scaring techniques or anti perching products.[9]

Laser diode PLT5 520 from OSRAM with output power of 50 mW and wavelength equal to 520 nm with optical components will be used.

2 Laser

Laser (Light Amplification by Stimulated Emission of Radiation), a device that consists of artificial light obtained by amplifying electromagnetic waves using resonator. A laser is created when the electrons in atoms in special glasses, crystals, or gases absorb energy from an electrical current or another laser and become "excited." It typically produces a very narrow beam of radiation. The emission generally covers an extremely limited range of visible, infrared, or ultraviolet wavelengths. [11, 12]

2.1 Fundamental principle

Laser emission is shaped by the rules of quantum mechanics, which means that atoms and molecules can only have discrete amounts of stored energy. The atom has the lowest energy when all its electrons are in the orbits which are nearest to the nucleus of the atom (ground state). Electrons which absorb energy can move to outer orbits, atom has higher energy level, and this state is called "excited". This state is not stable, and electrons tend to drop to lower-energy levels while emitting the extra energy as light. [13]

Einstein recognized that this emission could be produced in two ways. First way is a spontaneous emission when photons are emitted without outside intervention. The second way is stimulated emission, when a passing photon stimulates an atom or molecule to emit light. The energy of the passing photon must match the energy that an electron would release spontaneously when dropping to a lower-energy level. [13]

To make the laser work a condition known as population inversion must be reached. It is a state when higher-energy configurations predominate. There is some process which must selectively excite atoms or molecules to reach population inversion. A laser is created when the electrons in atoms in special glasses, crystals, or gases absorb energy from an electrical current or another laser (bright light) and become "excited". [12, 13]

2.2 Structure

The basic structure of any laser is based on an active medium (either a gas or semiconductor) where can be produced the population inversion. Laser gases are contained in cylindrical tubes and the excitement of the gas is said to "pump" the laser. Solid-state lasers use semiconductors or transparent crystals with small concentration of light-emitting atoms. [13, 14]

To build up the light energy in the beam an optical resonator is needed. It is formed by placing a pair of mirrors (reflectors) facing each other. The light is oscillating through a medium repeatedly and the intensity is increased with each pass. Laser radiation escapes due to a partially reflecting mirror in the assembly. [13, 14]
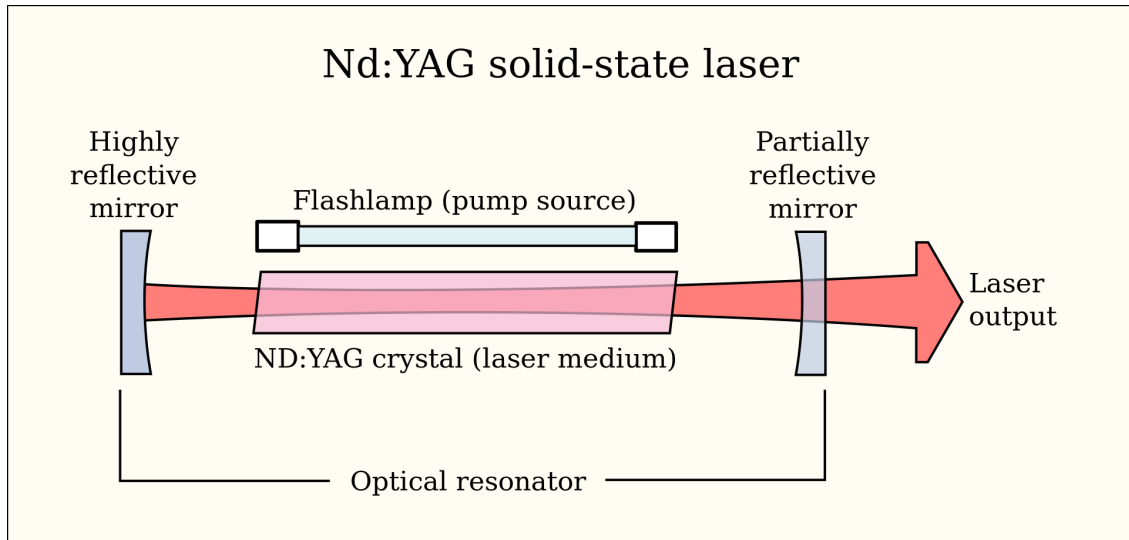

Fig. 2.1: Laser structure. [15]

2.3   Laser beam

Laser beam is generated with a laser device with wavelength from 180 nm to 1 mm. Such light has some very special properties as excellent directivity and convergence, the ability to constantly maintain wavelengths, etc., and are used in leading edge processing applications with high added value. [13]

The released light is monochromatic. Which means that it contains one specific wavelength of light (one specific colour). The wavelength of light is determined by the amount of energy released when the electron drops to a lower orbit. It also depends on the material, because it can support stimulated emission over a limited range of wavelengths. [13, 16]

The light is also coherent. Spatial coherence is when the waves (or photons) at any two points randomly selected on the plane have a constant phase difference over time. The spatial coherence is characterized by coherence length. If the centre wavelength of the range emitted is λ, and the range of wavelengths emitted is $\Delta\lambda$. [13, 17, 18]

This coherence length is defined by equation 2.1 [13]

$$l_c = \frac{\lambda^2}{2\Delta\lambda}.$$

(2.1)

Temporal coherence is the ability of light to maintain a constant phase at one point in space at two different times, separated by delay τ. The narrower is the range of wavelengths, the more coherent the beam is. [13, 17, 18]

The light is very directional. It has a very tight beam and is very strong and concentrated. Laser beams are assumed to be collimated (have parallel rays) they always diverge to some degree. The beam divergence defines how much the beam spreads out over increasing distance from the optical aperture. Beam divergence is defined by the full angle. In laser diodes, beam divergence is specified with two values because of the presence of astigmatism (rays that propagate in two perpendicular planes have different image point). [14, 16]

The beam divergence is defined by equation 2.2

$$\Theta = \frac{\lambda}{\pi w_0},$$

(2.2)

where λ is wavelength of the laser beam, π id constant and w_0 is half-width of the beam at its narrowest point.

The beam diameter refers to the diameter of the laser beam measured at the exit face of the laser housing. [14]

Fig. 2.2: Lasers. [19]

3 Laser diode

Laser diodes is a semiconductor device similar to Light-emitting diode. Diode is pumped directly with electrical current which can create lasing conditions at diodes p-n junction. Since laser diodes are made of semiconductor materials, they do not require the fragile glass enclosures or mirror alignment typical of gas lasers. The resulting ruggedness and small size allow laser diodes to be used in environments and spaces in which other types of lasers cannot operate. [20]

"These lasers can have emission ranges from the blue (400 nm) to the IR by combining elements from Groups III and V or Groups IV and VI, respectively. This large emission range combined with the small device footprint, low operating current, low operating cost, and high efficiency makes semiconductor lasers one of the most important and widely used classes of lasers in use today." [21]

3.1 Types

Fabry-Perot laser diode. This is the simplest type of semiconductor lasers. Reflective mirrors which form a Fabry-Perot laser cavity, are created by two parallel ends of the semiconductor cleaved along the crystal axis. Optical power is typically optimized by applying optical coatings to the mirror facets. The laser emission is taken from the low-reflectivity front facet and high-reflectance on the back facet to reduce the overall mirror loss. Semiconductor medium has quite broad gain spectrum and supports lasing over many longitudinal modes of the Fabry-Perot cavity, typically operating with multiple longitudinal modes. By altering the temperature and/or current the output power and wavelength that a laser diode displays can be tuned. Fabry-Perot laser diodes have emission wavelengths from the visible region to mid and far infrared. Semiconductor optical amplifiers are realized as Fabry-Perot amplifier. For the device to stay below the laser threshold, relatively weak reflections are utilized. Those reflections can substantially increase the amplifier gain. [21, 22] Structure is shown at figure 3.1.

Heterostructure laser diode. It is because of the step change of refractive index. Simple semiconductor laser diode is made up of metal contact on the top of the p-type material. Another metal contact is at the "bottom" of the n-type material. Among the p-type and n-type materials is intrinsic/active region (n-type material) which is used to increase the volume of active region, so more electrons and holes can accumulate at the junction. More electrons can recombine with holes which results in better output power. Input terminals are connected to metal plates. Laser light is emitted from elliptical region which must be considered if we want to use laser diode for special applications. This type of laser diode is suitable for optical fiber
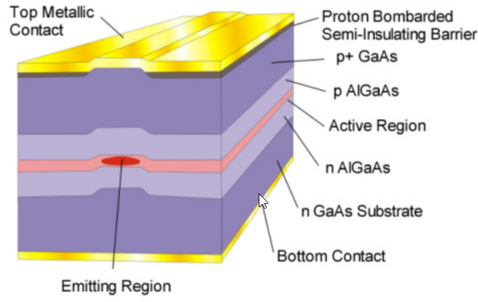
Fig. 3.1: Fabry-Perot laser diode. [23]

bonding. This type has threshold values of optical current from 10 mA to 250 mA and output optical power typically from 5 to 25 mW. [24, 25] Structure is shown at figure 3.2.
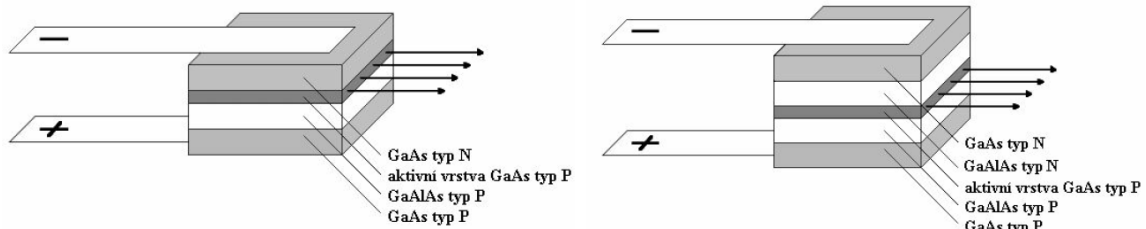

Fig. 3.2: Heterostructure Laser diode. [23]

Another type of laser diode is DFB (distributed feed back). The resonator of this type is realized without mirrors using diffraction gratings. The function is based on a periodic change of the refractive index in the direction of propagation. Distributed feedback is created by permanent bonding of wave propagating to opposite direction using Bragg scattering. Diffraction grating is created by etching on the surface of the active layer. It has narrow spectral line. It is used as a source for integrated optical circuits and as a source in optical fiber communications (1300 nm and 1550 nm). [25] Structure is shown at figure 3.3.

Another type is QWL (quantum well laser). It has double heterostructure. The active layer/region called quantum well is so narrow (less than 20 nm) that during the generation of optical radiation quantum confinement occurs. The wavelength of the light emitted by a quantum well laser is determined by the thickness of the active region rather than just the bandgap of the material from which it is constructed. QWL require fewer electrons and holes to reach threshold than conventional double heterostructure lasers. It has very narrow spectral line. Threshold current starts at
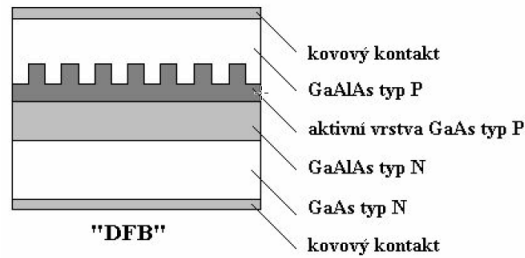
Fig. 3.3: Distributed feedback Laser diode. [25]

tens of mA and optical power is up to tens of mW in continuous wave regime. It has efficiency about 80 %. [25, 26] Structure is shown at figure 3.4.
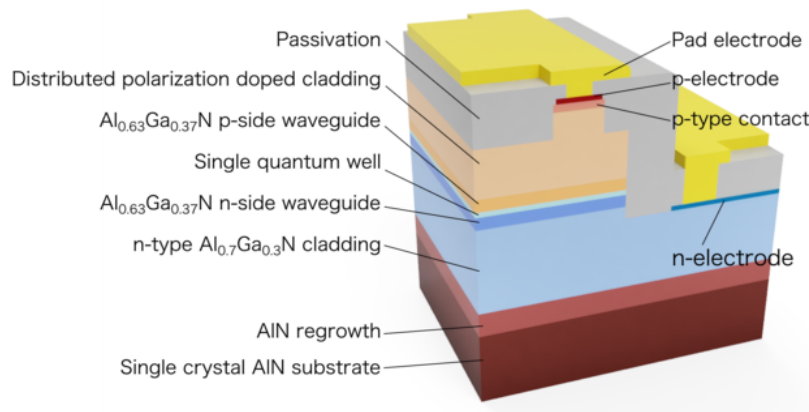

Fig. 3.4: Structure of Quantum well laser. [27]

3.2 Packages

One of important parameters when choosing laser diode is package. Several forms of diode packaging exist when each form has its own advantages and disadvantages. Forms of packaging can be divided into several types: TO can (includes TO can pigtail), butterfly and submount/C-mount packaging. To select right packaging the requirements and intended use must be considered. [21]

TO cans are one of the most predominant options for laser diodes packaging. The package is cylindrical and it often hermetically sealed. The common diameters of package are 3.8 mm, 5.6 mm, 9 mm, and 9.5 mm. TO can consists of a laser chip, a photo diode used for monitoring of the power at the back facet, and a heat sink. Because of the standardized sizes, TO cans are interchangeable but we must be aware of the pin configuration. This type of package is widely available in a

multi-mode of wavelengths and is relatively cheap. Like all diodes, they will require thermal regulation that needs to be user supplied. TO cans also come pigtailed with either single-mode, polarization-maintaining, or multi-mode fiber. [21] Shown at figure 3.5.

Fig. 3.5: TO can packaging. [21]

Butterfly packages use the same chips as TO cans. This package contains many components inside the packaging itself which makes it more "plug-and-play". Besides the laser chip and monitoring photodiode it contains an integrated thermo-electric cooler and thermistor. Because of integrated temperature elements it can give more accurate measurements of chip temperatures and better thermal regulation when used with a proper proportional integral derivative temperature cooler. Are also fiber coupled with single-mode or polarization-maintaining fiber and are available in many popular telecom wavelengths. [21] Shown at figure 3.6a.

C-mount and submount laser diodes are special packages which are normally used for higher power diodes or mid-infrared sources. It provides greater thermal contact with laser chip and the package which results in more efficient temperature regulation. For these packages is required additional setup. The package does not contain monitor photodiode, so the user must be cautious to avoid overdriving. There is also no integrated thermistor or thermo-electric cooler, so all temperature regulation must be done by the user. The C-mount and submount package is ideal for mid-infrared applications. [21] This package is shown at figure 3.6b.

3.3 Characteristics

"Semiconductor lasers offer the benefits of efficiency, electrical pumping, and the ability to easily integrate with modern electronics which contribute to their ubiquitous usage. However, some of their output characteristics, are considerably less than

(a) Butterfly packaging. [21]
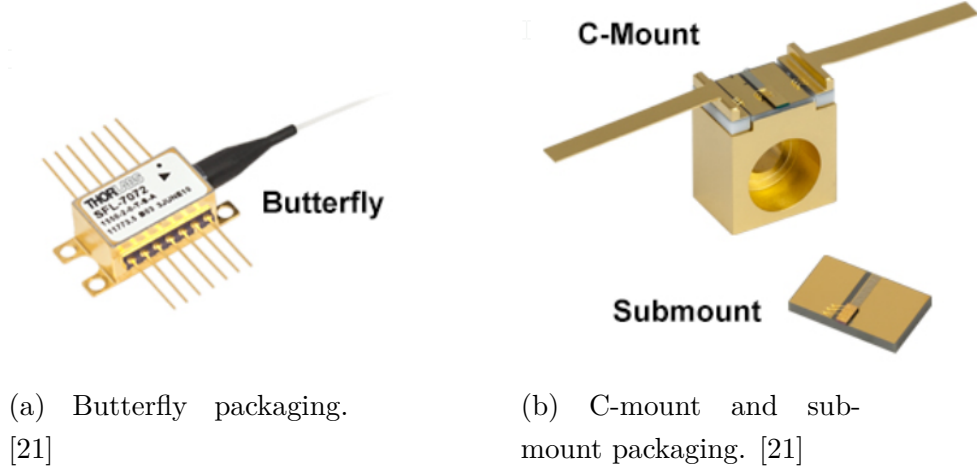
(b) C-mount and sub-mount packaging. [21]

Fig. 3.6: Butterfly, C-mount and submount packaging.

what can be achieved with other types of solid-state lasers. The small and asymmetric junction region from which radiation is emitted leads to a laser beam that does not possess an ideal TEM00 mode and is highly divergent, spreading unequally in two directions." [28]

The range of *output powers* for laser diode can be quite wide due to the large number of semiconductor materials and device architectures. Low-power laser diodes typically operate with a few tens of mA to over 100 mA. High power multi-mode laser diodes can operate with more than 10 A. [28]

Threshold current and threshold density. Important parameters of laser diode are the degree to which they emit light when current is injected into the device. It results in the Output light vs. Input current curve referred to as L.I. curve. [20] "As the injected current is increased, the laser first demonstrates spontaneous emission that increases very gradually until it begins to emit stimulated radiation, which is the onset of laser action. The first parameter of interest is the exact current value at which this phenomenon takes place. This is typically referred to as the threshold current and is denoted by the symbol I_{th}. It is a current at which the device begins to lase. The efficiency of the laser in converting electrical power to light power is determined by the slope of the L.I. curve, denoted by the change in output power over the change in current $(\Delta P/\Delta I)$." [20] The threshold current is dependent on the laser device's semiconductor material and the structure of the device waveguide. It is also dependent on the size and area of the laser device. Rather than comparing the threshold values of current of different devices, it is more appropriate to compare threshold current density (J_{th}). It is determined as division of the experimentally obtained threshold current value I_{th} and the area of the laser. Low threshold current density value is always desirable. It is a direct

indication of the quality of semiconductor material of the laser device. [20]

Slope of the L.I. curve. It is desirable to get as much light at the output of the device with as little input current as possible. To increase the input current slowly and yet achieve rapid increase of the output light emission. The slope of the L.I. curve above the threshold current is denoted ($\Delta P/\Delta I$). It tells us how many watts of power the laser outputs for every 1 ampere increase in its input current. [20] L.I. curve is shown at figure 3.7.
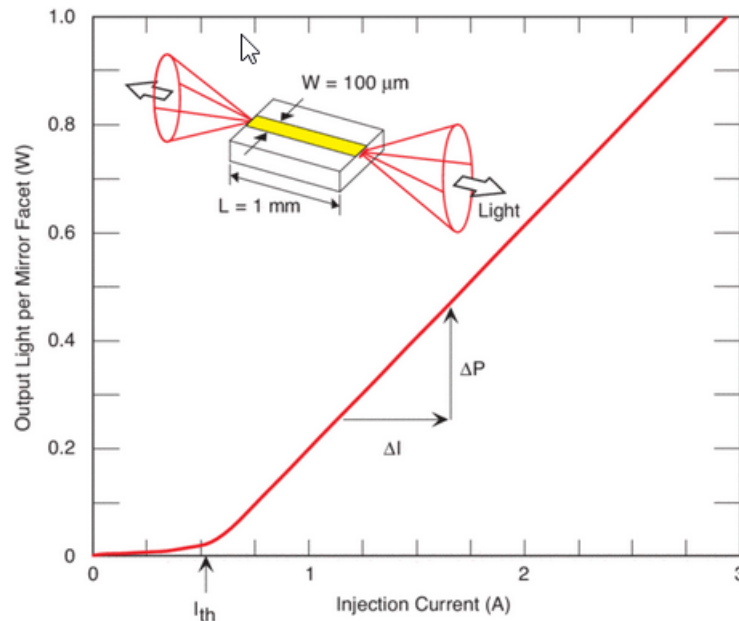

Fig. 3.7: Atypical L.I. curve of high-power laser diode. [20]

Characteristic temperature. It is important that the laser diode performs well at elevated temperatures. Especially temperature of high-power laser diodes rises significantly due to the amount of generated power. Characteristic temperature of laser diode T_0 is a measure of the temperature sensitivity of the device. Higher values of T_0 indicate that the threshold current density increases less rapidly with increasing temperature. [20]

Effects of electrostatic discharge. Laser diodes are extremely sensitive to electrostatic discharge. Laser diode must be protected during handling. Person handling it must be properly grounded and should use conducting finger guards. It is necessary to use a socket when soldering diode and make all electrical connections to the socket, for example transistor socket in which laser diode can be inserted. [20]

3.4 Cooling

Most laser diodes are extremely susceptible to temperature effects. Diode lifetime, threshold current, lasing wavelength, lasing power, mode hoping, and linewidth are several of the properties that are heavily influenced by the temperature of a diode. General rule is that diode's lifetime is decreased by half for every 10 °C rise in temperature. Without adequate thermal regulation, thermal effects and damage can take place. [21]

To obtain specific output power an appropriate cooling is required. Operating at the maximum rating for the junction temperature stated in the respective data sheet will significantly reduce the lifetime of the diode. [29] Calculation of junction temperature can be done using equation 3.1: [29]

$$T_{\text{junction}} = (U \cdot I - P_{\text{opt}}) \cdot R_{\text{th}} + T_{\text{case}}, \tag{3.1}$$

where [29]

P_{opt} is the optical output power,

U is the operating voltage,

I is the operating current,

T_{case} is the temperature of the package, and

R_{th} is the thermal resistance (junction to case).

Significant reduction of the output power can be caused by insufficient cooling, especially at high power levels or temperatures. Illustration of influence of temperature at the output power for blue PLPT9 450D_E A1 multi-mode laser is shown at figure 3.8. The worst case is that the output power will drop to zero within the specified operating range. Cooling system should be reviewed in case that a laser diode does not reach the specified optical output power at specified maximum operating current. [29]

The way laser diode is mounted on a cooler influence thermal resistance (junction to heat sink) $R_{\text{th,JH}}$. Various configurations of thermal connection to a TO90 package (PLPT9 450D_E A1) to a highly thermally conductive heat sink (copper) are shown at figure 3.9. Blue areas indicate thermally connected surfaces. Usage of a low conductive heat sink material (PCB board) will increase the thermal resistance. [29]

Simulation results for given thermal connection given at figure 3.9 performed for PLPT9 450D_E A1 blue laser are shown at figure 3.10. Low temperatures are indicated by dark bluish colours, while increase to high temperatures is indicated by light bluish to red colours. The lowest thermal resistance $R_{\text{th,JH}}$ is achieved by
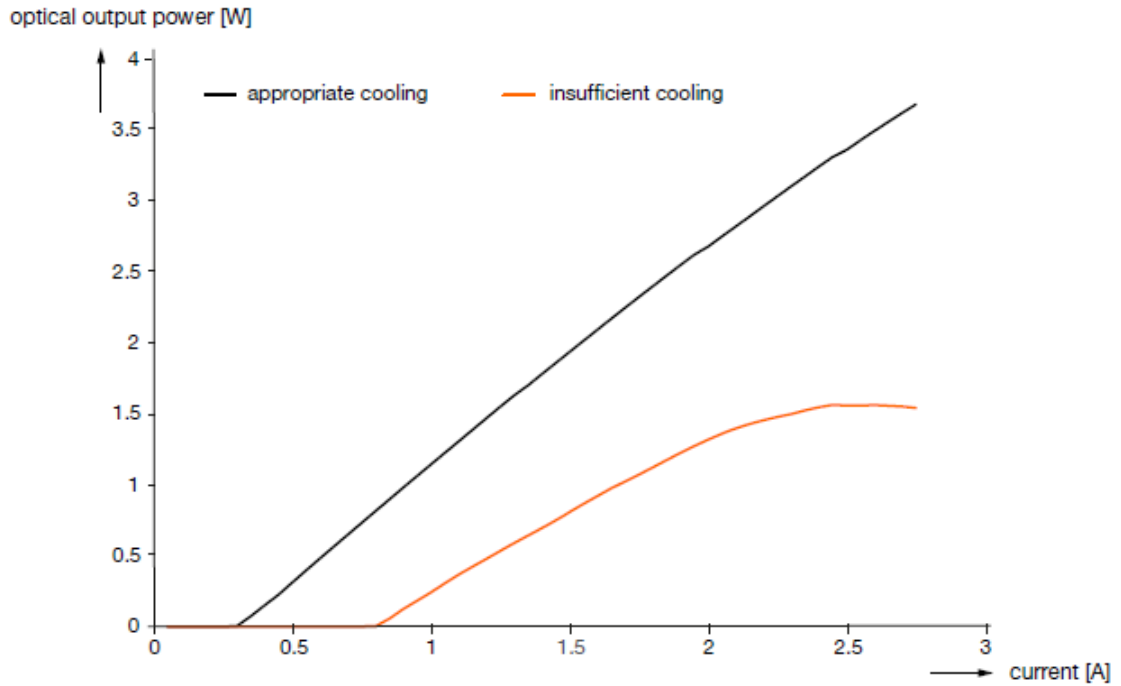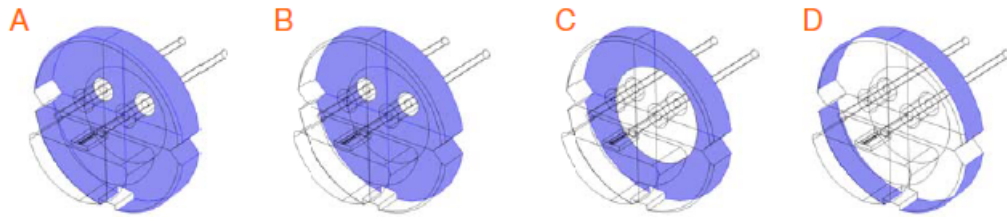
Fig. 3.8: Dependency of optical power on cooling. [30]

Fig. 3.9: Various configurations of thermal connection [31]

a complete thermal baseplate contact of the package. Reduction of the connected increases thermal resistance. [29]

Choosing appropriate cooler is necessary. Here are theoretical calculation to determine maximal thermal resistance of the cooler used for a diode. As a first step it is necessary to calculate maximal power dissipation.[33] It will be calculated using equation 3.2: [32, 33]

$$P = (U \cdot I) - P_{\text{opt}}, \tag{3.2}$$

where [32, 33]

P is power dissipation,

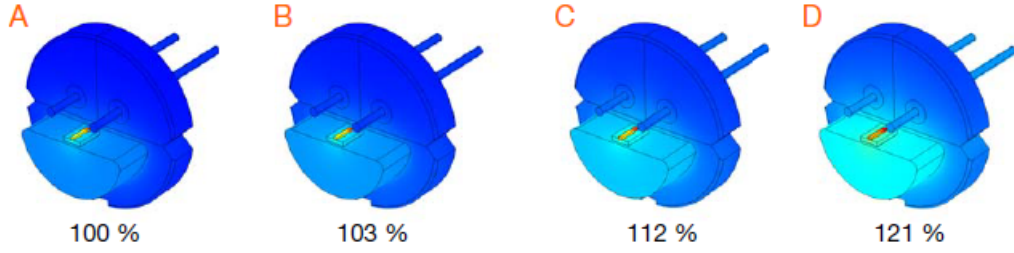U is operating voltage of laser diode,

Fig. 3.10: Various configurations of thermal connection. [32]

I is recommended operating current, and

P_{opt} is the optical output power.

Knowing the case temperature and ambient temperature is necessary to calculate the heat sink thermal resistance using equation 3.3: [33]

$$R_{\mathrm{HS}} = \frac{T_{\mathrm{case}} - T_{\mathrm{ambient}}}{P}, \tag{3.3}$$

where [33]

R_{HS} is heat sink thermal resistance,

T_{case} is case temperature,

T_{ambient} is ambient temperature, and

P is dissipation power.

Now junction temperature will be calculated using the equation 3.1 mentioned before.

Knowing the junction temperature and ambient temperature, total thermal resistance can be calculated using following equation 3.4: [33]

$$R_{\mathrm{total}} = \frac{T_{\mathrm{junction}} - T_{\mathrm{ambient}}}{P}, \tag{3.4}$$

where [33]

R_{total} is total thermal resistance,

T_{junction} is junction temperature,

T_{ambient} is ambient temperature, and

P is power dissipation.

The heat sink thermal resistance can be checked using equation 3.5: [33]

$$R_{\mathrm{HS}} = R_{\mathrm{total}} - R_{\mathrm{th}} - R_{\mathrm{cc}}, \tag{3.5}$$

where [33]

R_{HS} is heat sink thermal resistance,

R_{total} is total thermal resistance,

R_{th} is the thermal resistance (junction to case), and R_{CC} is case-cooler thermal resistance which is mentioned in table 3.1.

Tab. 3.1: Thermal resistance case-cooler depending on the mounting [34]

Mounting	R_{ths} [KW^{-1}]
directly	0.2 to 0.4
directly, silicone grease	0.1 to 0.2
mica pad	0.5 to 0.8
mica pad, silicone grease	0.4 to 0.6
teflon pad	1.0 to 1.6
teflon pad, silicone grease	0.7 to 1.1

4 Laser safety

4.1 Issues of laser radiation

Laser beam/light is generated with a laser device with wavelength from 180 nm to 1 mm. Such light has some very special properties. It is delivered in a form of laser beam which means that it propagates dominantly in a well-defined direction with moderate beam divergence (increase of beam diameter with distance). It has high degree of spatial coherence. the light is coherent if the waves (or photons) at any two points selected at random on the plane maintain a constant phase difference over time. The reason why a laser beam can propagate over long distances without spreading much is this coherence. Therefore it can be focused to very small spots. The degree of coherence is proportional to the range of wavelengths in the light beam, or the beam's monochromaticity. Spatial coherence is characterized by coherence length. There also exists temporal coherence which is the ability of light to maintain a constant phase at one point in space at two different times, separated by delay τ. Temporal coherence characterizes how well a wave can interfere with itself at two different times and increases as a source becomes more monochromatic. [17, 18]

Due to high directivity and low divergence the laser beam has high optical intensity after propagating over relatively long distance. Even when intensity at the entrance of eyes is moderate, eye can focus it to a small spot on retina. The amount of light the eye can tolerate depends on many circumstances such as intensity, wavelength and pulse duration. [35]

To give some guidance on adequate handling and required precautions, laser devices are assigned to different safety classes, with class 1 being the least dangerous and class 4 the most hazardous one. [35]

The classification of the lasers for the Europe is described in technical norm ČSN EN 60825-1 (367750), which defines the usage and output power of safety classes of lasers and defines the procedure of measuring parameters of the device which will determine the safety class.

4.2 Safety classes

This norm defines safety of the device depending on the safety class. The classification was developed to help the user to evaluate risks of the laser and to establish necessary management precautions. The classification of lasers corresponds to potential danger of accessible laser beam considering skin damage and eye damage. It does not deal with electrical, mechanical, or chemical risks, or any risk caused

by secondary radiation. Potential risks can be limited using additional protective precautions including additional technical measures (cover, case). [36]

Class 1. Laser devices which are safe when using them. It is safe even for long-term direct watching of laser beam, when using optical supplies (magnifying glass and binoculars). This class includes high-power lasers which are completely covered so no potentially dangerous radiations is accessible when using the device (encapsulated laser devices). Glance at the laser beam of class 1 can cause glare especially on low level of ambient lighting. Term 'safe for eye' can be used only for laser devices from class 1. Term 'laser safe for eye' should not be used for description of a laser based only on the fact, that wavelength of the output is larger than 1400 nm. Laser of all wavelengths can cause injury when having sufficient output power. Typical accesible emission limit for continuous wave lasers is 40 μW for blue. [36, 37]

Class 1M. Laser devices which are safe when using them, including long-term direct watching of laser beam with unprotected eyes. Eye damage can be caused by irradiation when watching laser beam using optical supplies (binocular) for collimated beam having diameter bigger than 7 mm for radiation of wavelength 400 to 1400 nm. For lasers of class 1M the range of wavelengths is limited to spectral region in which most of the glass optical materials used in optical device can significantly transfer the radiation. It is for wavelengths from 302.5 nm to 4000 nm. Glance at the laser beam of class 1M which produce visible radiation can cause glare especially on low level of ambient lighting. Typical accesible emission limit is same as for class 1. [36, 37]

Class 1C. Laser devices which are designed for direct application of laser radiation on skin or internal tissue for medical, therapeutic, or cosmetic procedures. Even if the output radiation can reach the level for class 3R, 3B, or 4, irradiation of eye is eliminated by using one or more technical resources. The level of irradiance of skin is dependent on the application. Therefore, this aspect is modified in superior norms. This class was introduced at this norm because these devices currently exist on the market and the measures commonly specified for classes 3B and 4 are inadequate for these devices. [36]

Class 2. Laser devices which have at the output visible radiation in the range of wavelengths from 400 nm to 700 nm and are safe for momentary irradiation but can be dangerous for intentional look into the beam. The time base 0.25 seconds is basic for the class definition and assumption is very low risk of damage for momentary irradiation that are slightly longer. Natural aversion against the irradiation of bright light is one of the factors which contribute to limitations of injury under unpredictable conditions. For class 2 using optical supplies does not increase danger of eye damage. However, beam of laser of class 2 can cause glare, flash blindness and persistent visual perceptions especially on low level of ambient lighting. This

can have general safety consequences because of temporary impairment of vision or frightening reactions. Users are informed by warning label not to fixedly look at the beam, instead using active protective reactions (head movement, closing eyes) and prevent continuous look at the beam. The limit of output power of class 2 laser is 1 mW. [36, 38]

Class 2M. Laser devices emitting visible laser beam which are safe for short-term irradiation of eyes without optical instruments which is the difference when compared with class 2. Designation of class 2M device warns against exposing users with optical instruments to irradiation. Accessible emission limit is same as for class 2. [36, 37]

Class 3R. Laser devices emitting radiation which can exceed maximum permissible exposure when watching the beam directly, but risk of damage is relatively small in most cases. Because of the smaller risk, there are less requirements on manufacturer and less precautions for user than for class 3B. Although class 3R device is not considered really/truly dangerous, the risk is limited because unintentional irradiation is rarely under the worst conditions (large pupil in one axis with beam, the worst possible accommodation with total energy of the beam falling into the eye), and because natural aversion against irradiation with bright light in case of visible light, and reaction on warming of the cornea on case of infrared radiation. The risk of injury is increasing with duration of irradiation and irradiation can be dangerous for eye under adverse conditions or watching the beam intentionally. Usability of specific measures for user should be described in operating instructions. Lasers 2 can cause glare, flash blindness and persistent visual perceptions especially on low level of ambient lighting which can have general safety consequences. Laser devices of class 3R should be used at places where direct view to beam is not probable. Accessible emission limit is 5 time the limit of class one for ultra violet and infrared, and 5 mW for visible radiation. [36, 37]

Class 3B. Laser devices which are dangerous when looking into the beam including random short-term irradiation. Watching diffuse reflection is commonly safe. Lasers of class 3B reaching accessible emission limit of this class can cause slight skin damage or can even ignite flammable materials, but only when the beam is focused, or it have small diameter. Accessible emission limits for continuous-wave laser cannot exceed 500 mW for wavelengths in range 315 nm to far infrared. Pulsed lasers cannot exceed 30 millijoules if the wavelength is in the range 400-700 nm. Accessible emission limit for this class is 500 mW. [36, 37, 38]

Class 4. Laser devices, where looking into the beam, or irradiation of the skin is dangerous and for which watching diffuse reflection can be dangerous. There is a risk of causing fire. Lasers from this class can be used for cutting, marking, welding, and cleaning. This class has no limit for accessible emission limit. [36, 37, 38]

Table 4.1 shows examples of maximum permissible radiation values for laser safety classes. Classes mentioned in table 4.1 U.S. FDA laser classification which is equivalent to ANSI and IEC laser classification with only slight differences. ANSi and IEC class 1 is equivalent for U.S. FDA class I. It is same for class 2 and class II, class 3B and IIIb, and class 4 and class IV. There is no special FDA class for class 1M and 2M. The definition od class IIIa is different compared with 3R but results are similar. [39, 40]

Tab. 4.1: Examples of maximum permissible radiation values [39]

Class	Wavelength [nm]	Duration [s]	Power/Energy
I.	630 (He-Ne)	$10 < \tau < 10^4$	$P = 3.10^{-7}$ W
			$E = 3.10^{-3}$ J
II.	514.5 (argon)	t $> 2.5.10^{-1}$	$P = 1.10^{-3}$ W
	630 (He-Ne)	continuous	$P = 1.10^{-3}$ W
III.a	630 (He-Ne)	continuous	$1.10^{-3} < P < 5.10^{-3}$
III.b	530 (Nd:YAG,2harm.)	1.10^{-4}	$E = 0.6$ J
		1.10^{-8}	$E = 3.10^{-2}$ J
	694 (ruby)	1.10^{-3}	$E = 1.2$ J
		1.10^{-8}	$E = 3.10^{-2}$ J
	1060 (Nd:YAG)	1.10^{-4}	$E = 12$ J
		1.10^{-8}	$E = 1.10^{-2}$ J
IV.	Above the values for class III.b		

Using table 4.1, it is evident that output power limit for class 2 laser is 1 mW for visible light (400-700 nm). Human eye's night-adapted pupil s diameter of d =7 mm. [39, 41] Surface of the pupil can be calculated using equation 4.1:

$$S = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot 7^2}{4} \approx 38.5 \text{ mm}^2 = 0.385 \text{ cm}^2. \tag{4.1}$$

Having limit 1 mW/0.385 cm^2 we can calculate limit of the output power per 1 cm^2 for laser class 2 assuming natural aversion of human against bright light and active protection by blinking and head movements. This limit is approximately 2.5 mW per cm^2. This limit will be used for construction of laser deterrent system.

When working with laser which has greater value of output power, it is necessary to use safety glasses.

5 Optics

5.1 Lenses

Lens is an optical component which is designed to focus or diverge light. There exists simple lens which is a piece of transparent material grounded into curved surface. Glass and plastic are the most common materials. Both surfaces of the lens are usually spherical, but lens are not necessarily symmetric and can have one of the surfaces planar. There also exist compound lenses which behave in more complex way. It is a combination of two or more simpler lenses (convex and concave). Compound lenses are used in telescopes, microscopes, and cameras. [42, 43, 44, 45]

The principle of the lens is refraction. The rays of the light passing through the lens are bended so they can change the direction. As a result, the rays seem to come from point which is closer or further from their origin. This makes the objects smaller or bigger than they are when seeing them through lens. [44]

Two precisely regular opposite surfaces create a single simple lens. One type is a convex lens (sometimes called a positive lens or converging lens). The surfaces of the lens bulge outwards in the centre creating classic lentil-lie shape. Other type of lens is concave lens which is the exact opposite. The outer surface is curved inwards. There exist symmetric lenses having the same shape of both outer surfaces or asymmetric when each surface has different shape (convex, concave, or planar). [44, 45]

Lenses can be classified according to their surfaces. Biconvex where both surfaces are convex (symmetrical lens). Plano-convex where one surface is planar and the other one is convex (asymmetric lens). Concavo-convex (converging meniscus), convexo-concave (diverging meniscus) where having one surface concave and other convex (asymmetric lens). This lens can be positive or negative depending on the curvature of both surfaces. Having steep concave surface, the lens is negative. Having steeper convex surface, the lens is positive. The light is neither converging nor diverging when both surfaces have equal curvature. Biconcave where both surfaces are concave (symmetrical lens). Plano-concave where one surface is planar and the other one is concave (asymmetric lens). [44, 45, 46]

Depending on the type of the lens, an entire beam of parallel rays when passing through the lens can be caused to converge on, or to appear to diverge from a single point on the optical axis which is called focal point. The focal point of positive and negatives lenses are depicted in figures 5.3 and 5.4, respectively. The distance between this focal point and the lens is called focal length. The focal length of convex lens is positive while the focal length of concave lens is negative. [45, 46] Focal length is shown at figure 5.2.
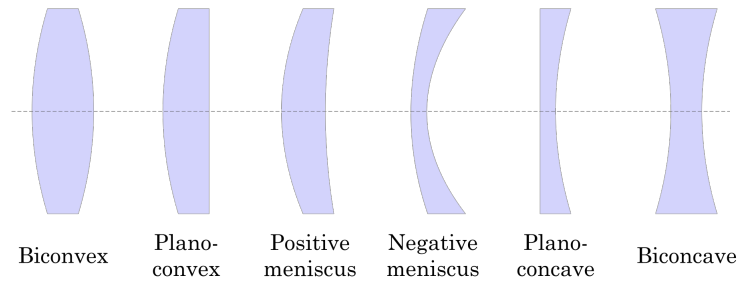
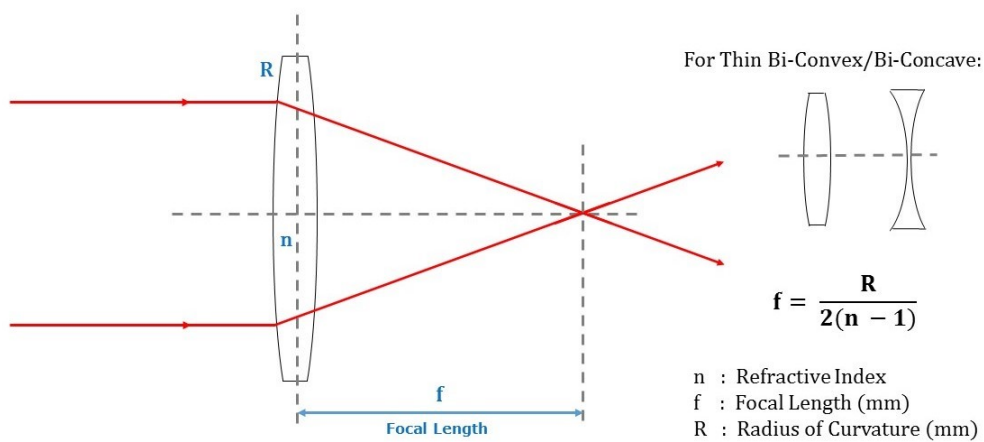Fig. 5.1: Types of lenses. [48]

Fig. 5.2: Focal length [47]

If a collimated beam of light (beam travels parallel to the lens axis) passes through biconvex or plano-convex lens, the beam converges or focuses on a spot behind the lens. [44, 46]

If a collimated beam of light passes through biconcave or plano-concave lens, the beam is diverged and spread – because of this the lens is called negative or diverging. [44, 46]

Special type is a Fresnel lens. It is a thin, lightweight plastic sheets and is created by a series of concentric grooves etched into plastic. This series of concentric grooves replaces the curved surface of a conventional optical lens. Each of this contour acts as individual refracting surface which results to bending collimated beam to a common focal length. This makes a Fresnel lens capable of focusing light similarly as a conventional optical lens while being physically narrow in profile. This brings several advantages in comparison to a thicker counterpart. This is
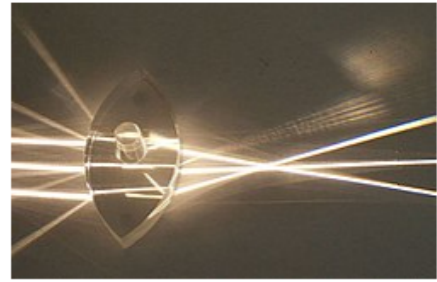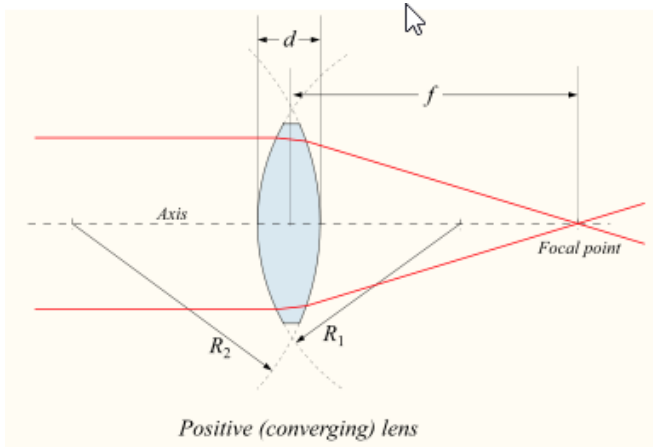
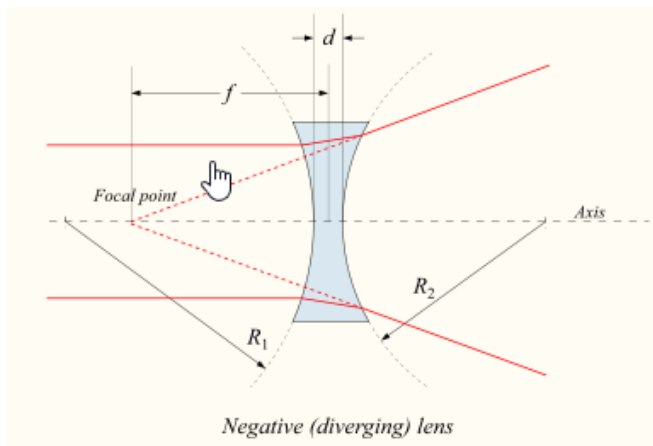Fig. 5.3: Biconvex lens [49, 50]

Fig. 5.4: Biconcave lens. [51, 52]

principle the direction of propagation of light does not change within medium but is deviated at the surface of the medium. Fresnel lens can be used for collimation of the beam or for light collection. For light collection, the overall area of the lens determines the amount of collected light. Their thin, lightweight construction, availability in various sizes, and wonderful light gathering ability make the lenses useful in a variety of applications (projection TVs, traffic lights, concentrating solar power, and lighthouses). [46, 53, 54] Comparison of side profile of plano-convex and Fresnel lens is shown at picture 5.5.

All lenses mentioned above were spherical. Lenses with larger diameter will gather more light. However, lenses with larger diameter are usually thicker when compared with lenses o smaller diameter. Greater thickness makes it more likely to create aberration. Lenses with spherical surfaces are not able to converge rays
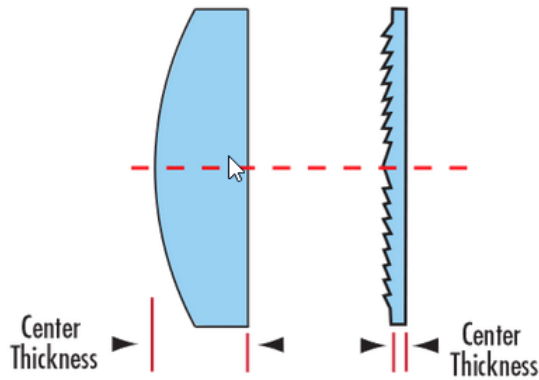
Fig. 5.5: Plano-convex vs Fresnel lens. [55]

which are parallel to the optic axis but at different distances from the optic axis to the same point. [56]

Another type of lens is aspheric. This term includes any lens having surfaces which are not portions of a sphere. One subset of aspheres are lenses which are rotationally symmetric with radius of curvature varying radially from the centre of the lens. [57] Comparison of aspherical lens from this subset and spherical lens is at figure 5.6.
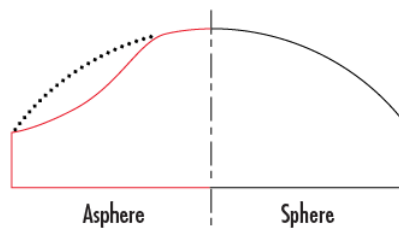

Fig. 5.6: Comparison of spherical and aspherical lens. [58]

5.2   Beam expander

"Beam expansion or reduction is a common application requirement in most labs using lasers or light sources and optics. There are many ready-made beam expanders available on the market, but often they are not available in the required expansion ratio or spectral range." [59] Besides, ready-made beam expanders are not suitable for those who do not want to spend much money on their optical solution. It is easy to build own beam expander using the "off-the shelf" components. The resulting quality of the beam expander depends only on input beam and used optics. [59]

"Simple beam expanders, sometimes referred to as telescopes, in their most basic forms generally consist of two lenses. The first lens should have a diameter larger than the maximum expected input diameter of the incoming light source. For example, if the diameter of the incoming beam is 10 mm, a 12 mm diameter lens will do a nice job with a little room to spare. The input beam is assumed to be collimated. The diameter of the output lens should be larger than the desired exit beam diameter. For a 3x expansion ratio with a 10 mm maximum input beam diameter, an output lens of greater than 30mm in diameter is required. The useable diameter of a lens is usually specified at 80% of the actual lens diameter, a minimum lens diameter of 37.5 mm would be required. If you are using off-the-shelf lenses, this will translate to 38-50.8 mm in diameter. The magnification of a 2-lens system is equal to the ratio of the focal lengths of the lenses, which is also equal to the ratio of the radii of curvatures of the lenses." [59]
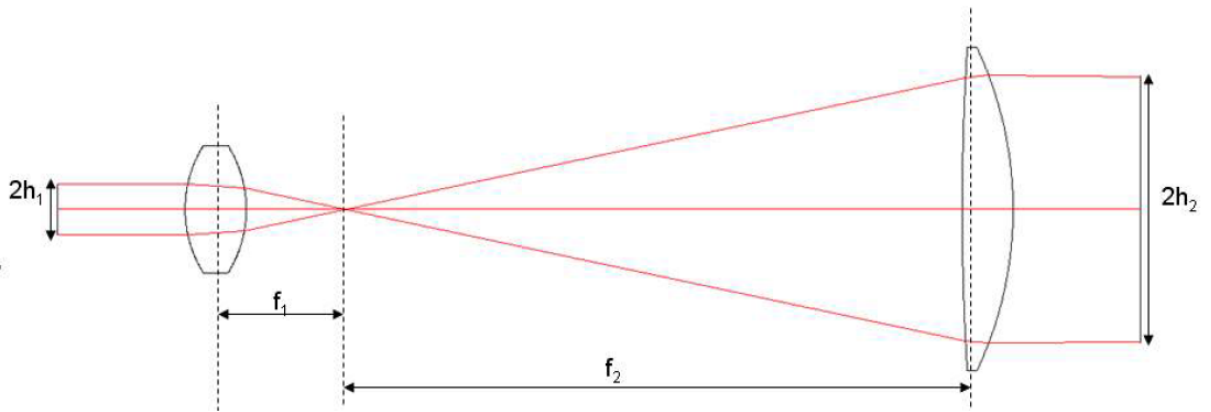

Fig. 5.7: Beam expander. [59]

Equation 5.1 defining the magnification of a 2-lens system follows: [59]

$$M = f_2/f_1 = R_2/R_1 = h_2/h_1, \tag{5.1}$$

where [59],

M = the magnification of the beam expander,
f_2 = effective focal length of exit lens,
f_1 = effective focal length of entry lens,
R_2 = radius of curvature of exit lens,
R_1 = radius of curvature of entry lens,
h_2 = radius of exit spot (image height),
h_1 = radius of entry spot (object height).

"The spacing t, between two lenses will be equal to the sum of the focal length of the lenses" [59] given by equation 5.2: [59]

$$t = f_1 + f_2. \tag{5.2}$$

"A beam expander can be used in reverse, with the larger diameter lens as the input and the smaller diameter lens as the output, in order to reduce the diameter of the input beam." [59]

Keplerian beam expander. This one is easy to build. In this model both lenses will have positive focal length. The distance between the lenses is equal to the addition of the focal lengths and a focal point in the gap between the lenses is created at the point where two focal lengths meet. This focused spot at the focal point causes high power density between the lenses, as a result, it is not recommended to use Keplerian beam expander with lasers with high pulse energies – high pulse energy density can at the focal point can cause the air to arc. [59]
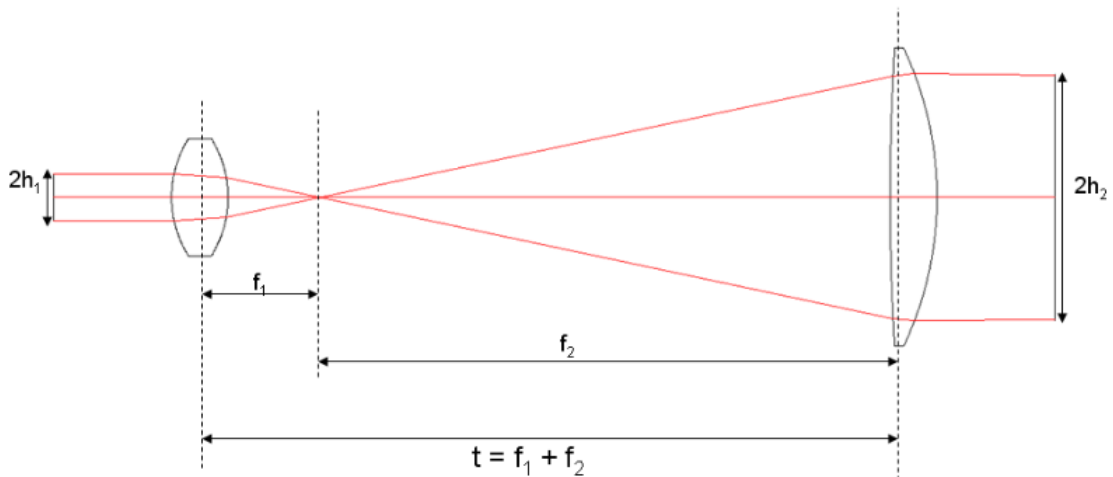

Fig. 5.8: Keplerian beam expander. [59]

If the beam expander is used in imaging applications adding a third lens (relay lens) may be desirable to correct the image orientation, otherwise the image will be inverted and reverted at the output. A biconvex lens inserted between the input and output lenses of the beam expander in a way that the distance between the input lens and the relay lens is: [59]

$$t_{r1} = f_1 + 2f_{r1}. \tag{5.3}$$

And the distance between the relay lens and the output lens is: [59]

$$t_{r2} = f_2 + 2f_{r2}, \tag{5.4}$$

f_{r1} and f_{r12} are relay lens focal lengths. The sum of the focal lengths of the relay lens will increase the overall length of the beam expander. [59]
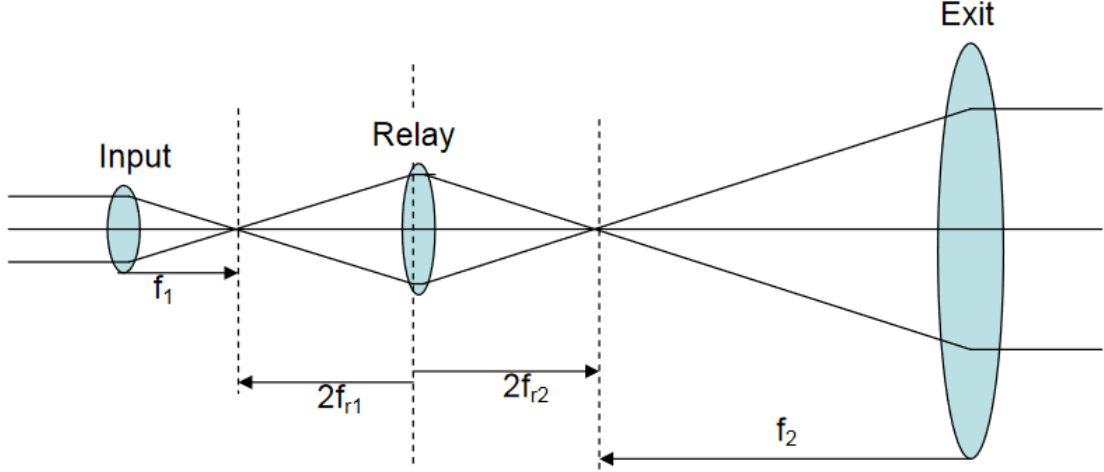

Fig. 5.9: Keplerian beam expander with relay lens. [59]

The product of the magnification of the relay lens and the magnification of the original Keplerian beam expander is the magnification of the modified beam expander given by equation 5.5. [59]

$$M_{\text{system}} = M_{\text{Keplerian}} \cdot M_{\text{relay}}, \tag{5.5}$$

where [59]

$M_{\text{Keplerian}} = f_2/f_1 =$ magnification of Keplerian beam expander,
$M_{\text{relay}} = f_{r1}/f_{r2} =$ magnification of relay lens.

Making the ratio of focal lengths be unity, the relay lens magnification will be equal to one which will preserve the magnification of the original beam expander before insertion of the relay lens. [59]

Another type of beam expander is simple Galilean which also consists of 2 lenses. The difference considering the Keplerian model is that one of the lenses has positive focal length while the other one has negative focal length. Different signs of the focal lengths results in no focal point between the lenses which makes this beam expander suitable even for the lasers with high pulse energies. Also the distance between the lenses is shorter which allows more compact design. Without focal point between the lenses, the image won't be inverted and will not require a correction lens. [59]
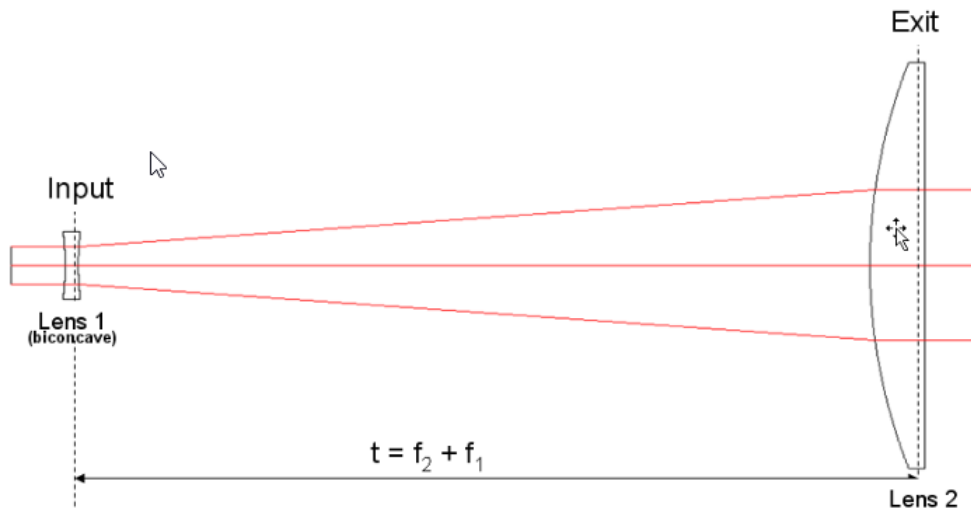
Fig. 5.10: Galilean beam expander. [59]

Following equation 5.6 gives the magnification of the Galilean system: [59]

$$M = -f_2/f_1, \qquad (5.6)$$

where [59]

f_1 = focal length of lens 1 and is a negative value (input lens),
f_2 = focal length of lens 2 (exit lens).

Choosing the proper substrate material and anti-reflection coating is important for the application. [59]

6 Collimation and modulation of laser beam

6.1 Collimation of laser beam

A collimated beam means that every ray of the beam is parallel to every other ray, having same diameter for significant distance. Production of the collimated light can be done by placing an infinitesimally small source exactly one focal length away from optical system with a positive focal length or the point source can be observed from infinitely far away. This is not possible in real world. [60]

Diode laser beam features high astigmatism because the divergence in the so-called fast axis is much higher than divergence in the so-called slow axis. There are various techniques which can be used to collimate such an astigmatic beam. Several objectives are important. Reduction of the beam divergence is the primary goal. Second goal is to eliminate astigmatism as much as possible if it is necessary for the application. Using single aspheric lens is the most simple and popular way. Aspheric lenses do not produce spherical aberration and are used when the diameter of collimated laser beam is between one and five millimetres and can also reduce astigmatism. The diameter after collimation will be larger if a lens with larger focal length is used. [61, 62]

It is necessary to know the divergence angle of source which is used and the desired output diameter when choosing a collimation lens. Choice of the right collimation lens is shown for laser diode L780P010 from Thorlabs. The typical parallel and perpendicular full width at half maximum beam divergences are 10° and 30°, respectively. As a result of divergence, the beam will be elliptical. The larger of these two divergence angles should be considered in any calculations to collect as much light as possible during the collimation process. The divergence angle equal to 30° will be used. To determine the appropriate focal length of the aspheric lens, thin lens approximation will be used since we assumed that the width of the lens is negligible compared to the radius of curvature. [62] The focal length for desired output diameter of 3mm will be calculated using following equation 6.1: [62]

$$f = \frac{1.5\text{mm}}{tan15°},\tag{6.1}$$

where

f is a focal length,

1.5 mm is output radius of the beam, and

tan 15° is tangent function of half of the beam divergence angle.

In some applications, a rounded beam cross-section is desired instead of elliptical which is caused by different divergence angles in fast and slow axis. One of the ideas
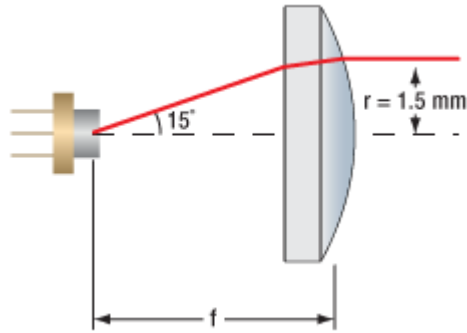
Fig. 6.1: Collimation of laser beam. [63]

to circularize the beam is to use two orthogonally positioned cylindrical lenses. [61] "One lens is placed to collimate the beam in the fast axis direction, another – in the slow axis direction. The ratio of focal lengths of both lenses is related to the ratio of laser beam divergence in fast and slow axes." [61] In reality, acylindrical lenses should be used to avoid spherical aberrations. Or anamorphic prism pair, which magnifies one axis of the beam can be used. [61, 62]

When we use spherical lens for collimation of laser beam using plano-convex lens is the best option. Asymmetry of the lens reduces the spherical aberration locating the object and the image different distances from the lens. Compared with biconvex lens it is also more economic. [64]

6.2 Laser beam modulation

Generally, modulation is a process when data are converted into radio waves by adding information to an electronic or optical carrier signal.[65] "A carrier signal is one with a steady waveform – constant height, or amplitude, and frequency." [65] There are roughly four types of modulation techniques: analog modulation, digital modulation, pulse modulation and spread spectrum modulation. [66]

When using laser whether with continuous wave or Q-switched output, it is possible, that user will need to control laser's behavior in some way. Depending on the applications of lasers, it is sometimes necessary to modulate laser beam. For laser material processing or microscopy, it is necessary to control position of the laser beam or the laser power. Control of on/off operation and the angle is required for laser light shows and projection systems. Highly stabilised lasers and active noise reduction is required for CD mastering. Modulation of the laser beam polarization improving signal to noise ratio and sensitivity in polarisation-based measurements. If it is necessary pulsing or triggering the laser, or dynamically

controlling the output power, some form of modulation is needed. There are some controllable laser parameters like angle, power, phase polarisation and others. [67, 68]

Intensity or optical power of light can be modulated by changing the value of current through laser diode. Intensity modulation is required for many applications in optical data transmission and, in laser printers. [69]

There also exist several technologies and modulators available in the market which allow us to change parameters of laser beam, all having its pros and cons. [67, 68] Some of these will be described.

Embedded electronic modulation means that electronic modulation is built into the driver circuit. This kind of modulation requires little additional equipment. Only modulation signal is needed. This circuit controls power which is delivered to the laser diode resulting in direct turning on and off of laser diode. [67]

Acousto-optic device is based on a crystal which behaves like an electronically controlled grating when exposed to an ultrasonic wave. This deflects a laser beam passing through the device. [68]

Electro-optic modulators employ a transparent crystal with electrically controlled index of refraction, changing a rotation of the polarisation of the beam passing through the device. [68]

Optical choppers are usually rotating discs with holes or slits. Rotation of the disc results in periodical blocking of the beam and pulsing laser at fixed frequency. [67]

7 Driver circuits

In most applications of laser diode, a current source and temperature controller will be needy. The need of current source is because a voltage source does not allow careful control of its current, which makes the current to change quickly and therefore putting the laser diode at risk. This can cause immediate and permanent damage (burning diode)or shorten diode life span. [21, 70]

This current source is called driver circuit. It limits appropriately amount of current which is fed into the laser diode, so that the diode functions correctly. These complex drive circuits involves feedback loops measuring output optical power, temperature, voltage and input current. When application does not require high accuracy, simple circuit using LM317 voltage regulator IC can be utilized in configuration to function as a constant current source. [24, 70, 71] Example of this circuit driver is at figure 7.1. This simple driver circuit does only limits the current through laser diode set by the serial combination of resistor R1 and R2. Resistor R1 limits maximal current which will flow through laser diode so that it is not damaged, while using trimmer the operating current of laser diode is set. The 47 uF capacitor absorbs any battery voltage spikes. There is no monitoring part in the circuit which would keep the output power of laser diode constant. [24]
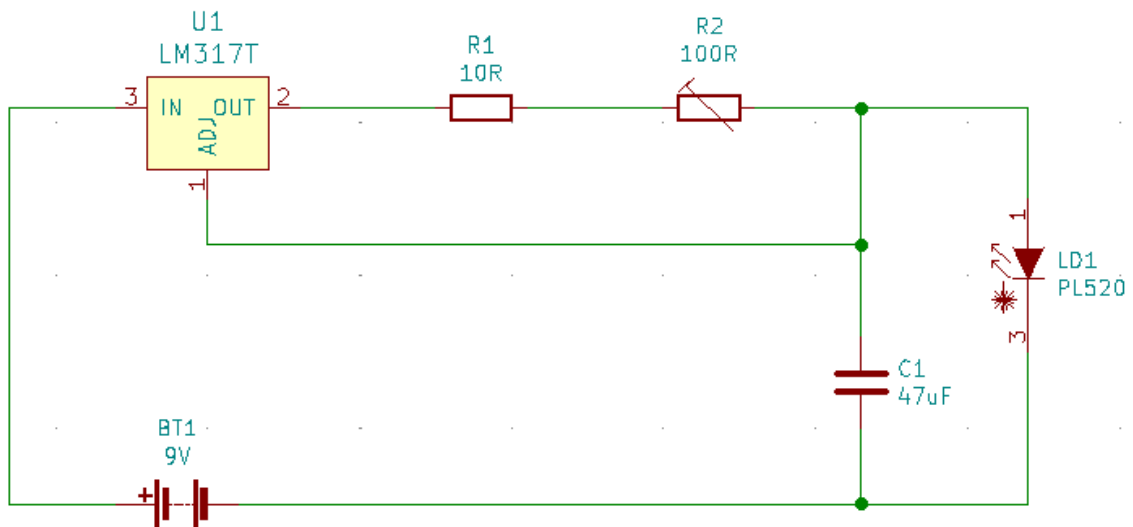

Fig. 7.1: Laser diode driver scheme using LM317. [24]

7.1   Discrete vs integrated driver circuit

When considering using discrete driver circuit it is a design challenge.The most expensive part of laser module is usually the laser diode so its protection is considered as a good investment even with higher cost of components for the circuits. [72]

Typical discrete APC (automatic power control) driver solution for supply voltage range of 6 to 12 V in constinous wave mode is shown at figure 7.2. This concrete circuit contains universal OPAMP (operational amplifier) LM358, one Zener diode, one transistor and 17 passive components requiring approximately 6 cm^2 of board space. This circuit has no reverse-polarity or failure protection. [72]
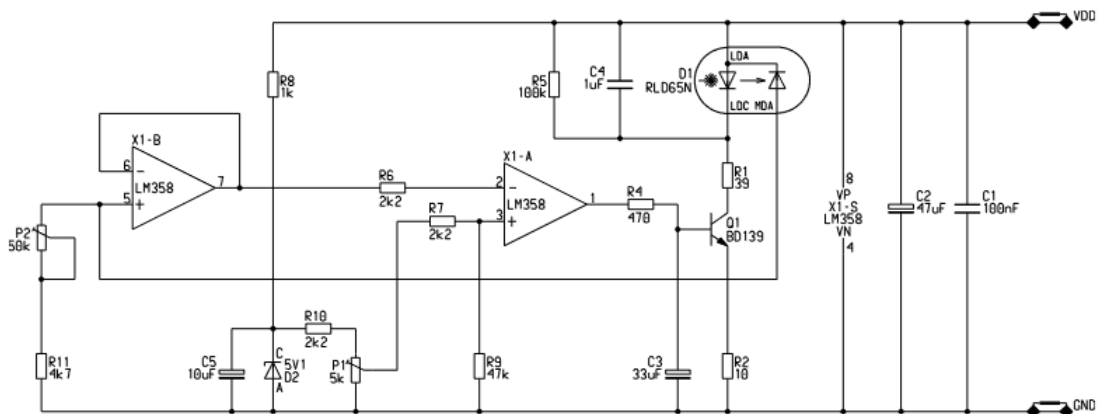

Fig. 7.2: Discrete laser diode driver circuit. [72]

In comparison with integrated driver circuit iC-WKN for continuous wave operation up to 300 mA from 2.4 to 15 V supply voltage. Only four passive components are needed for a complete driver requiring approximately 1.25 cm^2 board space. [72] "It has a reverse-polarity protection, over-current and over-temperature (of the IC) shut-down build in, as well as a fast soft start. It also protects the laser diode against transients and keeps the output power stable over a wide supply voltage range." [72]

Output power for discrete solution is approximately 10 % while integrated circuit solution has variation lower than 1.5 %. Discrete circuit has 46 solder joints while integrated circuit has only 17. Higher number of solder joints and components have a direct impact on the MTBF (mean time between failure) of discrete circuit. [72] "Consideration must also be given to the higher suscep-tibility of field failure in the discrete solution due to theincreased part count, number of solder joints and thereplacement or repair cost." [72]

8 Thesis Results

This thesis discuss source of laser radiation suitable for scaring starlings from vineyard and it is a part of the project Systém plašení špačků založený na pasivním optickém lokátoru (TJ04000441). [73] The block diagram representing integration of laser radiation source into the project is shown at figure 8.1.
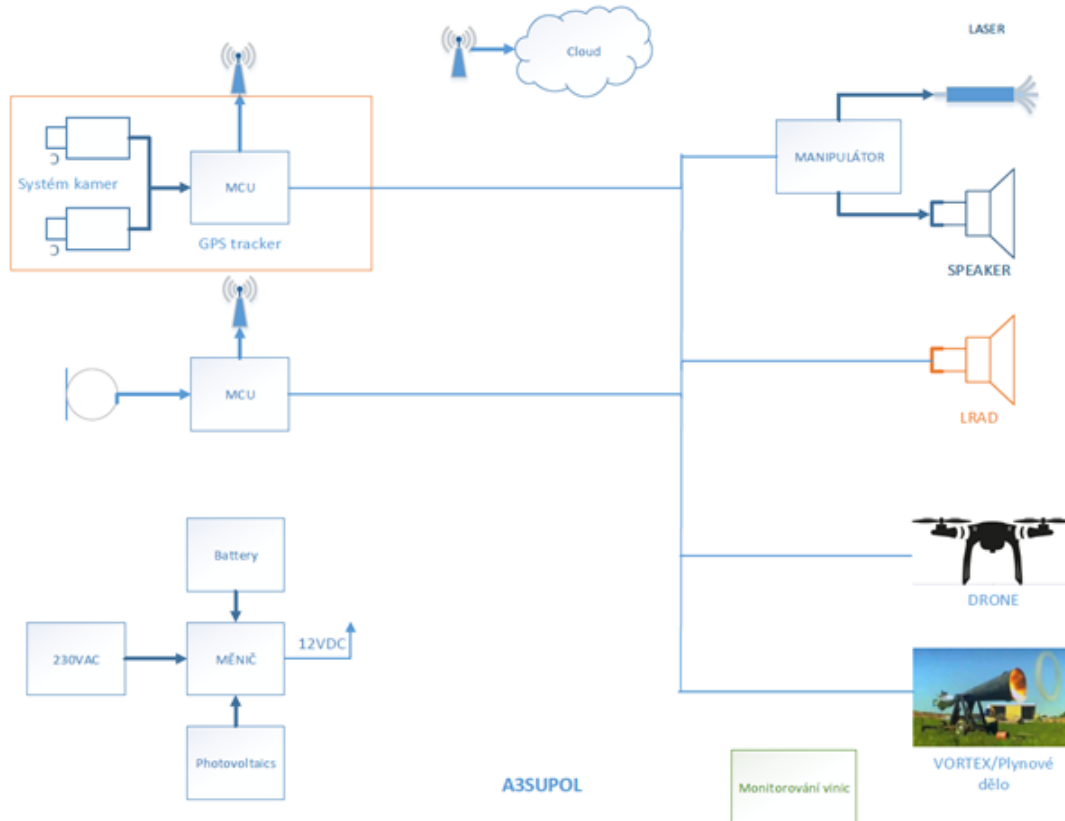

Fig. 8.1: Block diagram representing integration of laser radiation source into the project.

In a block diagram, SPEAKER is directional speaker and LRAD (Long Range Acoustic Device) is a technique using directional speakers for transmission of sound only in defined area. In orange frame is passive optical detector. The block diagram and description of individual block were provided by project researchers. [73]

8.1 Bird species and scaring technique

The birds which should be scared away are starlings. They occur on vineyard where they eat yield which is a complication for winegrowers because of financial damage which they cause.

The main reason why are starlings at vineyard - food - cannot be eliminated because it is a subsistence for people. Therefore an appropriate humane scaring technique must be chosen.

Starlings are birds active mainly during the dawn and dusk while during the direct sun they are hidden in shadows and do not occur on vineyard. Because of this lasers are suitable humane scaring technique without any disturbing noises and not being fully static birds will not habituate to the scaring technique so quickly. In addition, the whole construction will be placed on moveable arm which allows the laser to scan the whole area of vineyard according to set boundaries. The laser beam will be pointed towards the ground so there is no risk to accidentally glare pilots of airplanes which is the reason why people should not shine with the laser pointer towards the sky. Laser will be activated only when birds appear based on the detector which under development to minimize the probability that birds will habituate the the deterrent technique quickly.

For the laser deterrent will be used laser diode PLT5 520 from OSRAM which has the peak output power of 50 mW and typical emission wavelength 520 nm. This diode has package TO56 with photo diode. Typical operating current is 115 mA and typical operating voltage is 6.0 V. [74]

As mentioned optical output power is affected by forward voltage and temperature. The optical output characteristic is shown at figure 8.2. The proper cooler must be chosen.

When working with laser diode with such high output power it is necessary to protect eyes and use proper protective equipment such as protective glasses.

Using modification of equation 6.1 the radius of the beam of laser diode at distance of 1 cm can be calculated:

$$r = 1 \cdot tan 12.5° = 0.2217 \text{ cm}. \tag{8.1}$$

Knowing the radius of the beam, its surface can be determined using equation 8.2:

$$S = \pi \cdot r^2 = \pi \cdot 0.2217^2 = 0.1544 \text{ cm}^2. \tag{8.2}$$

The output power per 1 cm^2 of the laser diode at distance of 1 cm is:

$$\frac{P}{S} = \frac{0.05 \text{ W}}{0,1544 \cdot 10^{-4} \text{m}^2} \approx 324 \text{ W/m}^2. \tag{8.3}$$

Thorlabs provide safety glasses when working with sources of visible light with high output intensity. Table 8.1 shows available safety glasses.
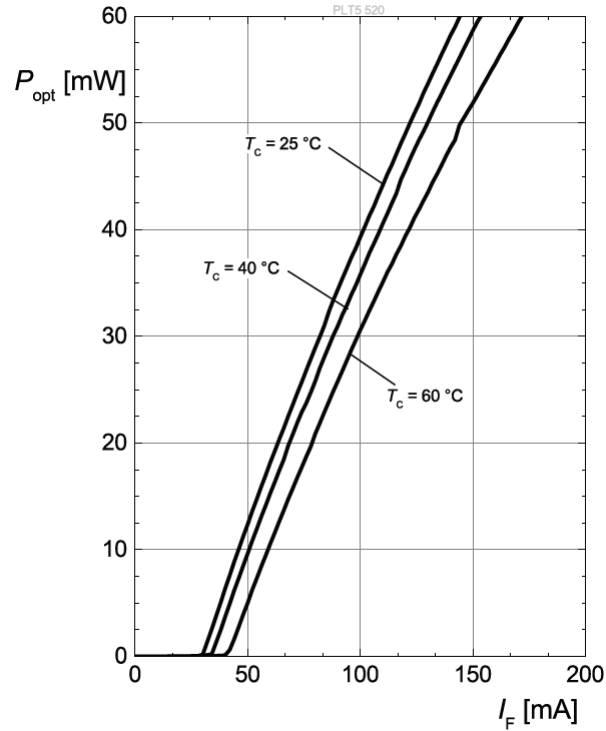
Fig. 8.2: Optical output power of laser diode PLT5 520. [74]

Tab. 8.1: Overview of laser safety glasses. [75]

OD	LBn	Maximum power density [W/m^2]	Visible light transmission
7+	LB6	10,000,000	48 %
7+	LB5	1,000,000	35 %
7+	LB5	1,000,000	11 %

OD in the table 8.1 means optical density, which can be used to determine if glasses meet the ANSI Z136 standards of laser safety protection. OD and LB-rating can be used to indicate the level of protection provided for specific wavelength ranges. Glasses with OD 7+, maximum power density of 1,000,000 W/m^2, and 10% visible light transmission.[75] Having appropriate eye protection, person can work with laser diode.

8.2   Cooler

Diode has recommended operating current equal to 115 mA and maximal operating voltage 6 V and optical output power of 50 mW for temperature range between -20

to 40 °C. Using equation 3.2, the maximal power dissipation for this laser diode is:

$$P = (6 \cdot 0.115) - 0.05 = 0.64 \text{ W}. \tag{8.4}$$

To have some reserve the dissipation power of 1 W will be considered for further calculations.Case temperature is 60 °C and assumed ambient temperature is 40 °C. Using the equation 3.3 heat sink thermal resistance can be calculated:

$$R_{\text{HS}} = \frac{60 - 40}{1} = 20 \text{ K/W}. \tag{8.5}$$

Now the junction temperature will be calculated using equation 3.1:

$$T_{\text{junction}} = 1 \cdot 34 + 60 = 94 \text{ °C}. \tag{8.6}$$

Using equation 8.7 total thermal resistance can be calculated:

$$R_{\text{total}} = \frac{94 - 40}{1} = 54 \text{ K/W}, \tag{8.7}$$

Direct mounting on a cooler is assumed, which results in thermal resistance case-cooler equal to 0.4 K/W when using value from table 3.1. Knowing all necessary value heat sink thermal resistance can be recalculated using equation 3.5:

$$R_{\text{HS}} = 54 - 34 - 0,4 = 19.6 \text{ K/W}, \tag{8.8}$$

having just slight deviation from value calculated in equation 8.5.

The cooler thermal resistance was calculates and is equal to 19.6 K/W, the cooler having lower or equal thermal resistance is needed. Assuming the diameter of heat sing equal to 6.9 cm, the surface of the heat sink must be calculate in equation 8.9:

$$S_{\text{HS}} = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot 6.9^2}{4} = 37.39 \text{ cm}^2. \tag{8.9}$$

Then the heat sink thermal resistance can be calculated using equation 8.10: [33]

$$R_{\text{HS}} = \frac{3.3}{\sqrt{\lambda \cdot d}} \cdot C^0.25 + \frac{650}{A} \cdot C, \tag{8.10}$$

where [33]
R_{HS} is heat sink thermal resistance,
λ is thermal conductivity of material,
d is thickness of heat sink [mm],
C is correction factor, and
A is surface of the heat sink [cm^2].

Using this equation 8.10 heat sink thermal resistance of the designed heat sink is 8.11: [33]

$$R_{\text{HS}} = \frac{3.3}{\sqrt{2.1 \cdot 20}} \cdot 0.85^0.25 + \frac{650}{37.39} \cdot 0.85 = 15.27 \text{ K/W} \tag{8.11}$$

Value of heat sink thermal resistance 15.27 K/W from equation 8.11 is lower than limiting value 19.6 calculated in equation 3.5. The designed heat sink fulfills the condition for thermal resistance.

The heat sink has circular shape with diameter of 75 mm on one side and turned on the other side to 69 mm diameter. On the side with smaller diameter will be mounted a laser diode using circular fixture. The laser diode will be put in excavation of 2 mm depth with 3.5 mm diameter. Cooler diagram with circular fixture are shown at appendix A.1 and A.2, respectively.

8.3   Expanding and beam collimation

As mentioned before, the output power of 50 mW is too high to use diode just as it is. Moreover, the beam of laser diode is divergent and has to be collimated. Angle of beam divergence parallel to pn-junction is at maximum 10 ° and perpendicular to pn-junction is 25 °. To reach the level of output power of 2.5 mW cm^2, it is necessary to know the surface/area of the beam which will result in the limiting of 2.5 mW cm^2 with output power of 50 mW. Using equation 8.12, the necessary surface of laser beam can be calculated:

$$S_{\text{beam}} = \frac{50 \text{ mW} \cdot 1 \text{ cm}^2}{2.5 \text{ mW}} = 20 \text{ cm}^2. \tag{8.12}$$

Having the necessary using simple calculation, the radius therefore the diameter of the beam which will be needed to decrease the output power of the beam can be calculated using simple equation 8.12:

$$r_{\text{beam}} = \sqrt{\frac{S_{\text{beam}}}{\pi}} = \sqrt{\frac{20}{\pi}} = 2.53 \text{ cm}. \tag{8.13}$$

Then the radius of the beam will be 5.046 cm. When doing the backward check, the surface of the beam will be slightly under 20 cm^2, so the diameter of the beam will be increased at 5.1 cm to have some reserve and have a laser device from class 2M.

$$S_{\text{beam}} = \frac{\pi \cdot d^2}{4} = 20 \text{ cm}^2 = \frac{\pi \cdot 5.046^2}{4} = 19.998 \text{ cm}^2, \tag{8.14}$$

$$S_{\text{beam}} = \frac{\pi \cdot d^2}{4} = 20 \text{ cm}^2 = \frac{\pi \cdot 5.1^2}{4} = 20.428 \text{ cm}^2. \tag{8.15}$$

Laser diode PLT5 520 can be easily replaced by laser diode L520P50 from Thorlabs. This diode can reach output power of 70 mW with appropriate cooling. The cooler was designed to suit both diodes. But assuming the usage of this diode with higher output power, the surface of laser beam has to be recalculated as shown at equation 8.16.

$$S_{\text{beam}} = \frac{70 \text{ mW} \cdot 1 \text{ cm}^2}{2.5 \text{ mW}} = 28 \text{ cm}^2. \tag{8.16}$$

Then the new radius of the beam will be:

$$r_{\text{beam}} = \sqrt{\frac{S_{\text{beam}}}{\pi}} = \sqrt{\frac{28}{\pi}} = 3 \text{ cm}. \tag{8.17}$$

The diameter of the beam of PLT5 520 laser diode is then 6 cm. When checking the resulting surface of the beam which is 28.274 cm, the diameter of the laser beam will be enough.

To have a possibility to switch the diodes, the higher value of the beam will be assumed for following calculations. Now collimation and beam expansion must be done.

Expansion of the beam can be done using beam expander. But the condition to use it is collimated beam. This would result into a system of three lenses, when first lens would collimate the beam and the other two lenses in layout of Galilean beam expander would increase the beam diameter. This solution is possible, but it would result in more complex solution. In this case one lens, which will be calculated using principle from section 6.1 Collimation of laser beam, knowing the divergent angle and diameter of the beam which is required, the focal length of lens needed can be calculated. Both laser diodes have same angle of divergence of 25 °. Assuming the diameter of laser beam being 6 cm therefore radius is 3 cm = 30 mm, the focal length of the required lens will be calculated in equation 8.18:

$$f = \frac{30}{tan12°} = 141.1475 \text{ mm}. \tag{8.18}$$

Other criterion of the lens which will be used is its diameter. The usable are is about 80 % of the lens' surface. Assuming, that required 60 mm diameter corresponds to 80 % of the lens diameter, the diameter corresponding to 100 % will be:

$$d_{\text{lens}} = \frac{60 \cdot 100}{80} = 75 \text{ mm.} \tag{8.19}$$

For collimation and expansion of laser beam, lens with diameter of 75 mm and focal length of 141.14 mm will be needed. The lens which has the exact parameters needed, does not exist. Lenses with diameter of 75 mm are common, but the focal length 141.14 mm is not common value, the lens with focal length equal or bigger is needed. This requirements are fulfilled when using plano-convex lens from Thorlabs with diameter of 75 mm and focal length equal to 150 mm.

Simulation of this scenario was done in OpticalRayTracer 9.6. It is shown at figure 8.3
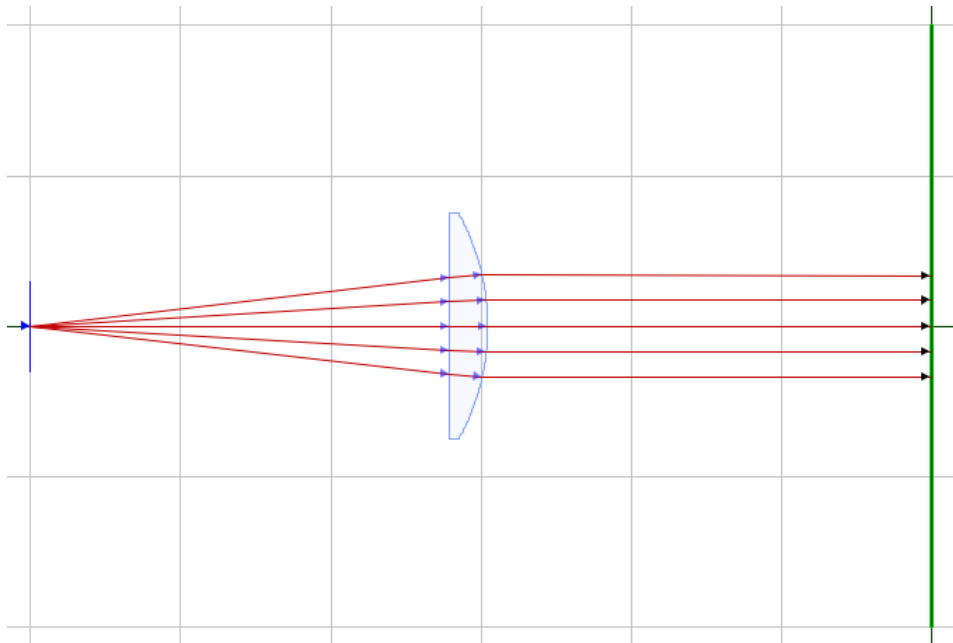
Fig. 8.3: Simulation of beam collimation and expansion.

Lens' parameters were set according to the information given for the used lens on Thorlabs web. [76] The specification of lens is given at figure 8.4.

Parameters are given at cm. The lens is plano-convex. The radius is 3.75 cm which corresponds to the diameter of 7.5 cm = 75 mm of used lens. Edge thickness is specified at the web of producer [76]. Effective thickness is calculated automatically by the program as well as center thickness. The optical axis is passing through point [0,0] (horizontal axis is x and vertical axis is y). Therefore the position of lens is Y = 0 cm, and X = -15.9 cm which is because the source of the light is at position [-30, 0] and placing the lens at distance of 14.1 cm from the source, the position at

Fig. 8.4: Specifications of lens.

axis x will be -15.9 cm. Simulation shows that collimation using specified lens is possible.

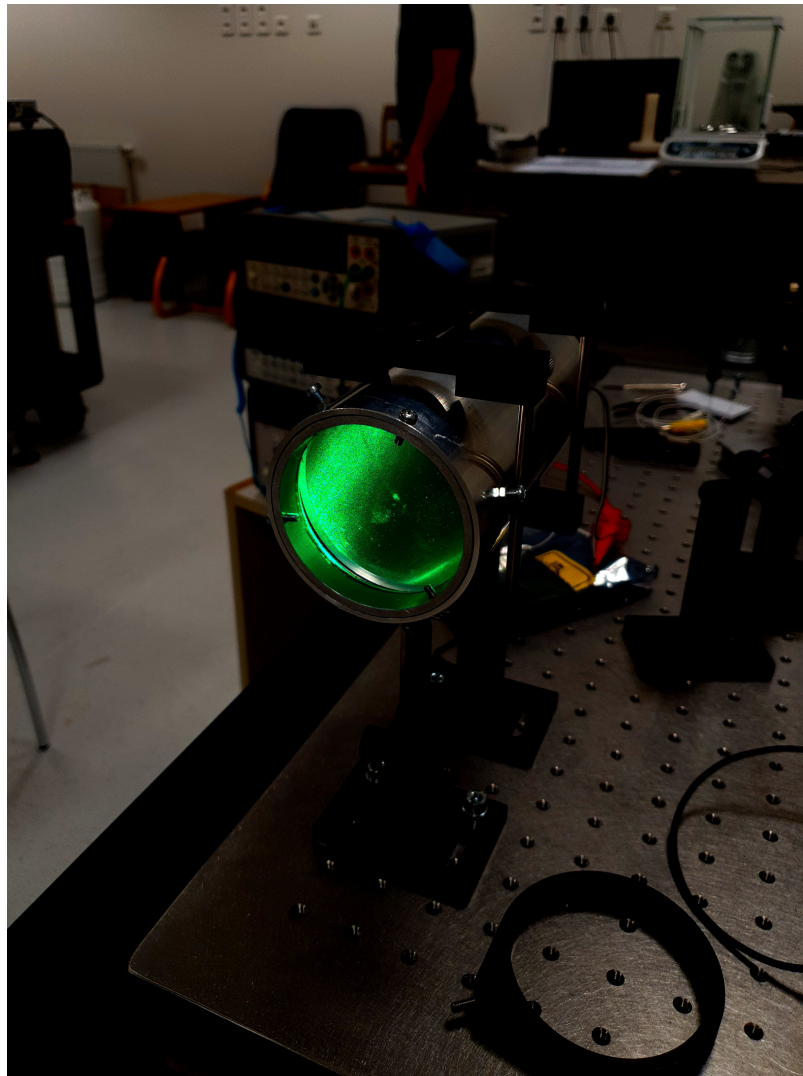The design of optics were tested, results are shown on following photos:

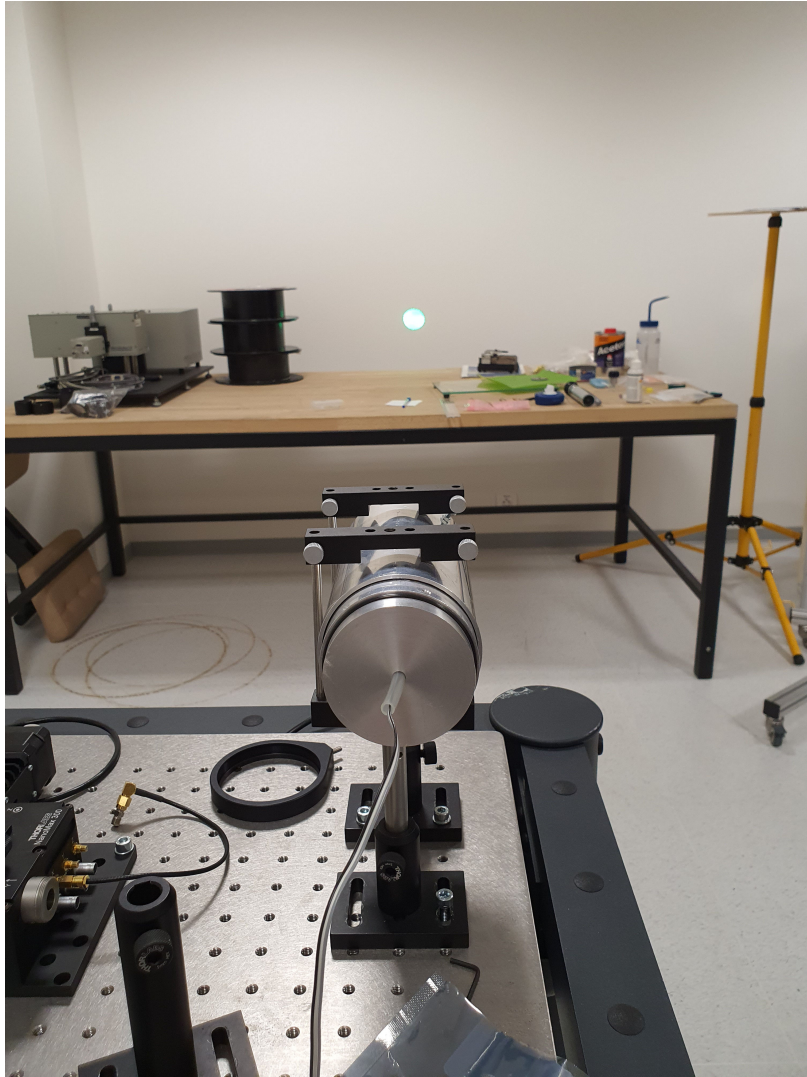Fig. 8.5: Front view of the laser.

Fig. 8.6: Rear view of the laser.

Fig. 8.7: Usage of spray to make propagation of beam visible.

A simple beam range of the laser distance test was performed shown at figure 8.8.

Fig. 8.8: Length rage of laser.

The construction could be also done using combination of laser diode with higher output power of 900 mW and Fresnel lens which is light even if it has larger diameter, but is also more expensive. This combination would have beam diameter of 22 cm and its surface would be 360 cm^2. Fresnel lens with diameter of approximately 28 cm and focal length of at least 51.75 cm would be needed. This solution would increase the price of the device as well as its dimensions.That is the reason why the laser diode with 50 mW output power and plano-convex lens with 75 mm diameter and 150 mm focal length will be used.

8.4   Monitoring diode and ESD

The package TO-56 of the laser diode contains a monitoring diode. It is necessary to know the monitor current to set correctly the output power of the laser diode. It is usually set at driver circuit by suitable value of resistor. The value of monitor current for typical output power is listed in data sheet. Problem is, that the position of the monitoring diode is not the same for every single laser diode from producer and therefore the monitor current can be a bit different for every laser diode. Hence, it is necessary to measure the monitor current for particular laser diode.

The typical monitor current of PLT5 520 laser diode listed in data sheet is 90 μA. The real measure value for operating current 115 mA is 53 μA. This value will be needed for further design. The dependence of monitor current (photo diode current) on the laser diode current, and dependence of laser diode voltage on laser diode current for PLT5 520 laser diode are shown at figures 8.9 and 8.10, respectively.
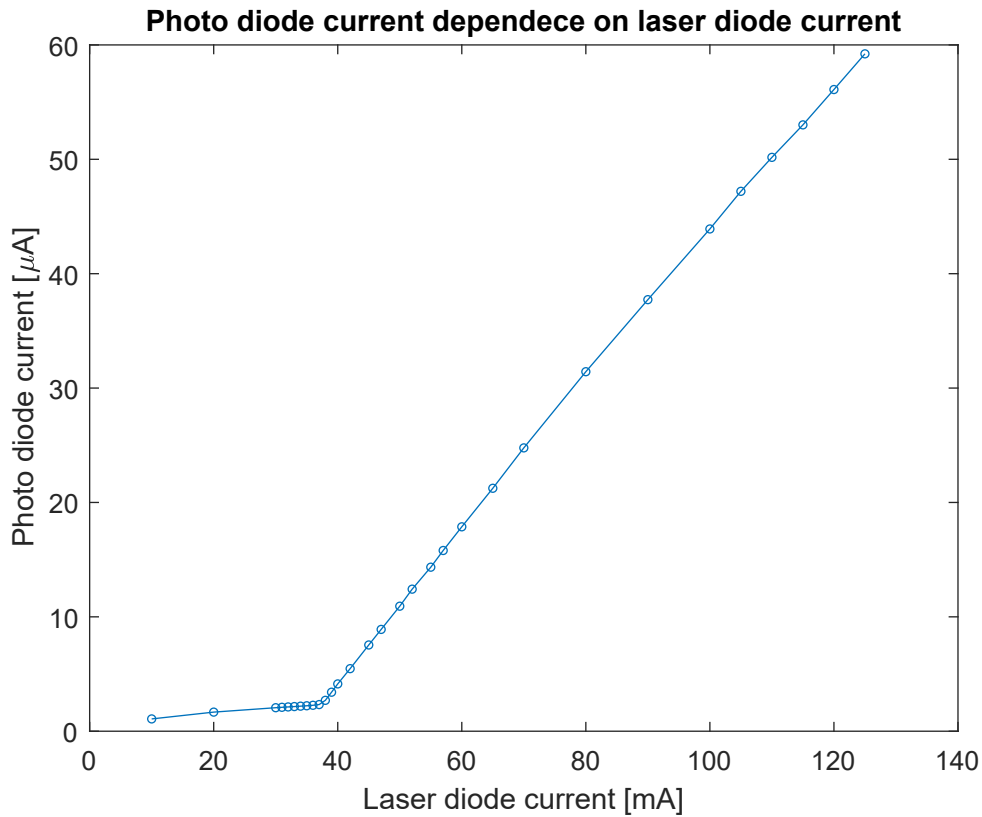

Fig. 8.9: Photo diode current dependence on laser diode current.

Laser diode is very sensitive to ESD (electrostatic discharge) and can be exposed to soldering temperature for just 10 μs. Therefore it is practically not possible to
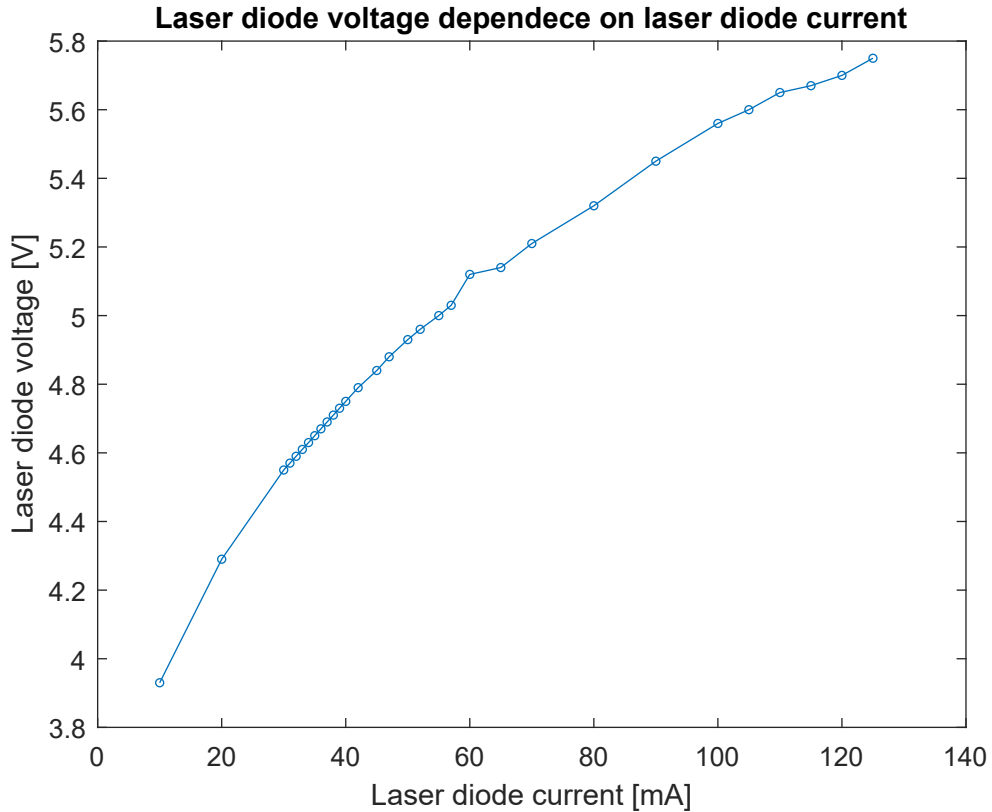
Fig. 8.10: Laser diode voltage dependence on laser diode current.

solder laser diode directly, and it is necessary to use socket. For laser diode PLT5 520 with TO-56 package, the laser socket S7060R from Thorlabs will be used.

8.5 Driver

The used driver is iC-WKN. It fulfills requirements for operating voltage and operating current since it is designed for continuous wave operation up to 300 mA with supply voltage from 2.4 V to 15 V. It has rapid soft start and also filters lase diode power supply for transients, integrated reverse polarity protection for the iC and laser diode. It also includes integrated circuity protection against destruction by ESD, excessive temperature and over-current. Using pin MDK of the iC-WKN an analogue modulation (from DC to a few kHz) can be done. Resistor RM between pins MDA and AGND sets the output power of the laser diode. [77] All integrated protections make this driver suitable for laser diode.

8.6 Microcontroller

Current drawing from pin MDK can dim the laser power. For this regulation a digital-to-analog converter in combination with resistor can be used. Because of this simple microcontroller ESP32 (module ESP32-WROOM-32D and ESP32-DEVKITC-32U) was chosen. It has SPI, I^{2}S, I^{2}C, and UART. It also has Wi-Fi which can be used for controlling the module, variant with external antenna allows to close the module into shielded case and using the Wi-Fi if needed for the application.

Combination of digital-to-analog converter resistor between ESP32 module/devkit pin 25 and iC-WKN pin MDK is used to modulate the power of the laser diode.

This module/devkit is very common, a large number of examples of code exist, people are familiar with it. Moreover, the project uses ESP-Now protocol which allows simple and fast communication between ESP8266/ESP32 which is what makes it a suitable microcontroller especially if the device is under development and testing of its possibilities is appropriate. [78]

8.7 Other components of driver circuit

There are two equivalent driver circuits, one using ESP32-DEVKITC-32U and one using the module ESP32-WROOM-32D. The driver circuit with devkit will be used for the driver debugging for laser diode. The possibility of simple plugging of whole devkit, preference of internal vs external antenna can be tested. The other board with module will be used for testing of the optics and laser diode as a source of laser radiation for bird scaring.

Driver circuit is compound from DC-to-DC converter AMSRI-7809-NZ, which converts input voltage of 12 V to 9 V which powers the driver iC-WKN. There is also DC-to-DC converter from 12 V to 5 V R-78E5.0-0.5 which powers ESP32 devkit or USB-to-UART converter FT260S-U (depending on the version of PCB). DC-to-DC converter from 5 V to 3.3 V is used to power the ESP32 module, it is not on the board with devkit. The ready solution of DC-to-DC converters were used because it is compact and the design of the converter is complex.

For programming of ESP32 module can be used UART and it is the most common way. Therefore USB connector with ESD protection and USB-to-UART converter is used on board with module. After activating Wi-Fi, the control of the module can be wireless.

Diagram of laser diode driver with ESP32 Devkit and with ESP32 module are given at appendix B.1 and C.1 to C.5, respectively.

8.8   PCB

PCB (printed circuit board) was designed in program KiCad 5.99. When using the ESP32 module with integrated antenna, it is necessary to omit a ground plane under the antenna and it is recommended to omit it even under the integrated antenna when using devkit.

To effectively cool down the iC-WKN driver, the package is soldered to thermal pad on the board. The thermal pad also contains via holes for easier heat dissipation and using these via holes it is also connected to the ground plane.

2-layer layout of the PCB was used for better heat dissipation and and due to the layout of the pins on the components.

8.9   Mounting of laser diode and lens

Laser diode located in a heat sink and lens are mounted in concentric tubes which allows to change the distance between the lens and the laser diode. The concentric tubes are made of aluminium which is light, durable and solid and therefore it is suitable material for the mounting, and laser diode and lens will be fixed even if the construction will move. Photo of the construction is shown at figures 8.11, 8.12, 8.13, and 8.14.
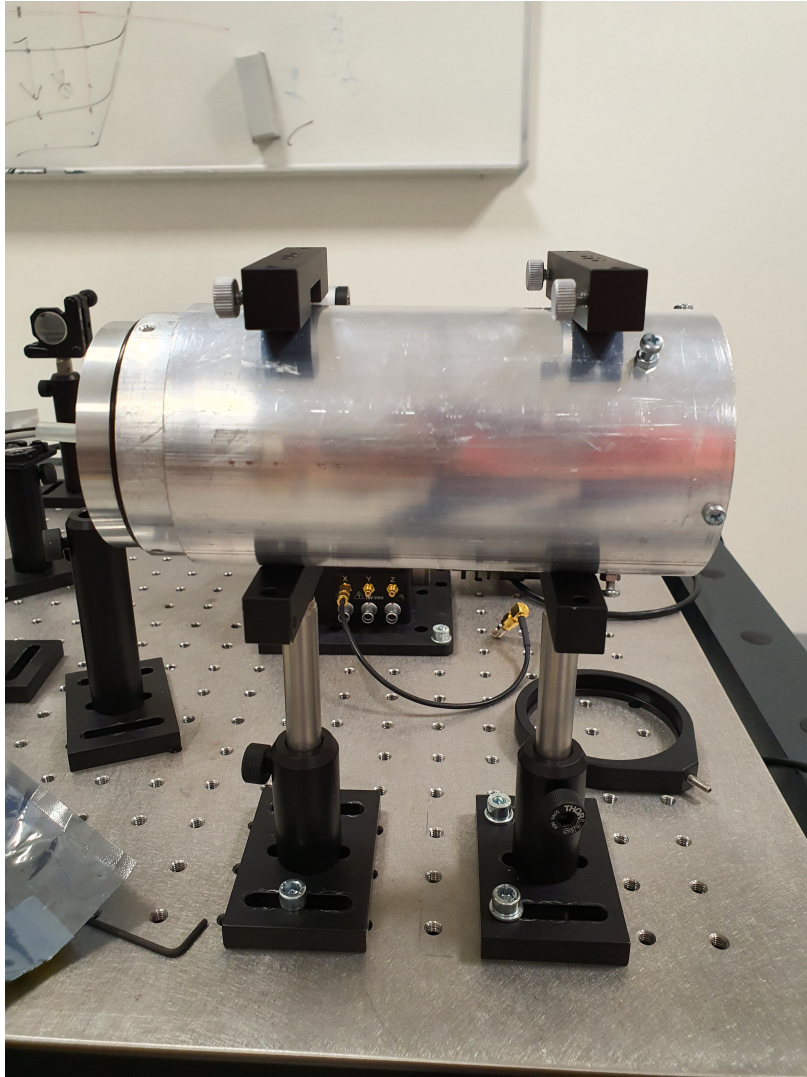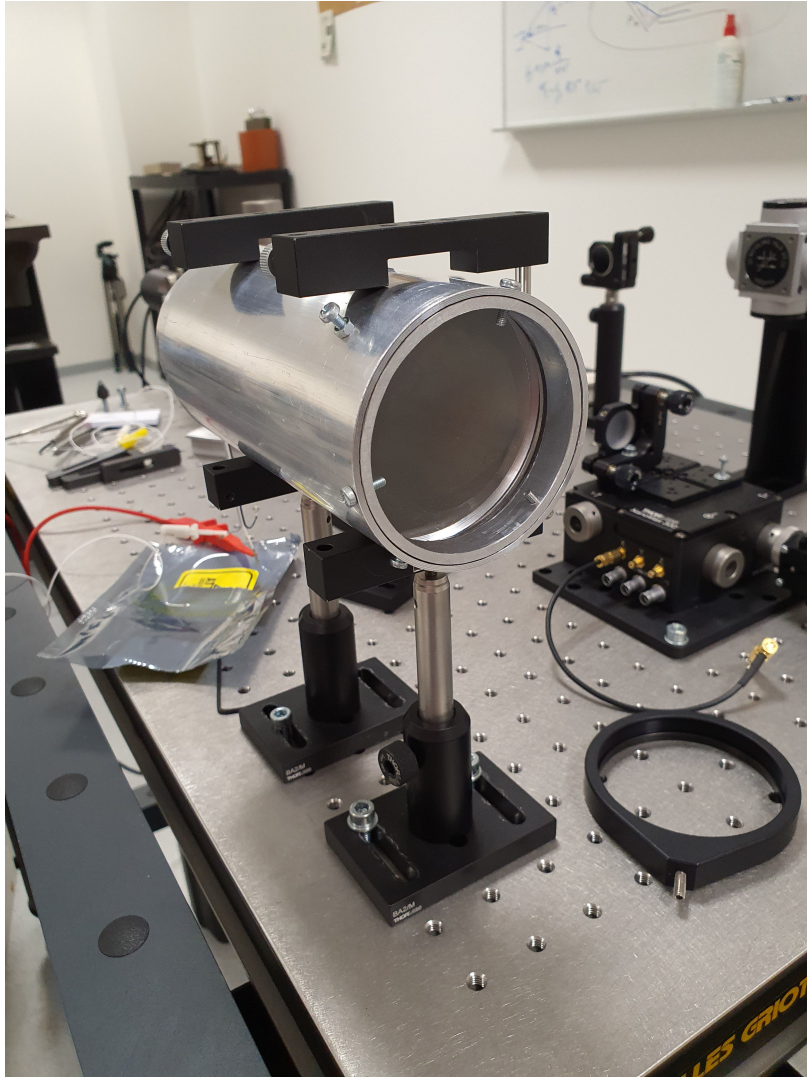
Fig. 8.11: Side view of construction.
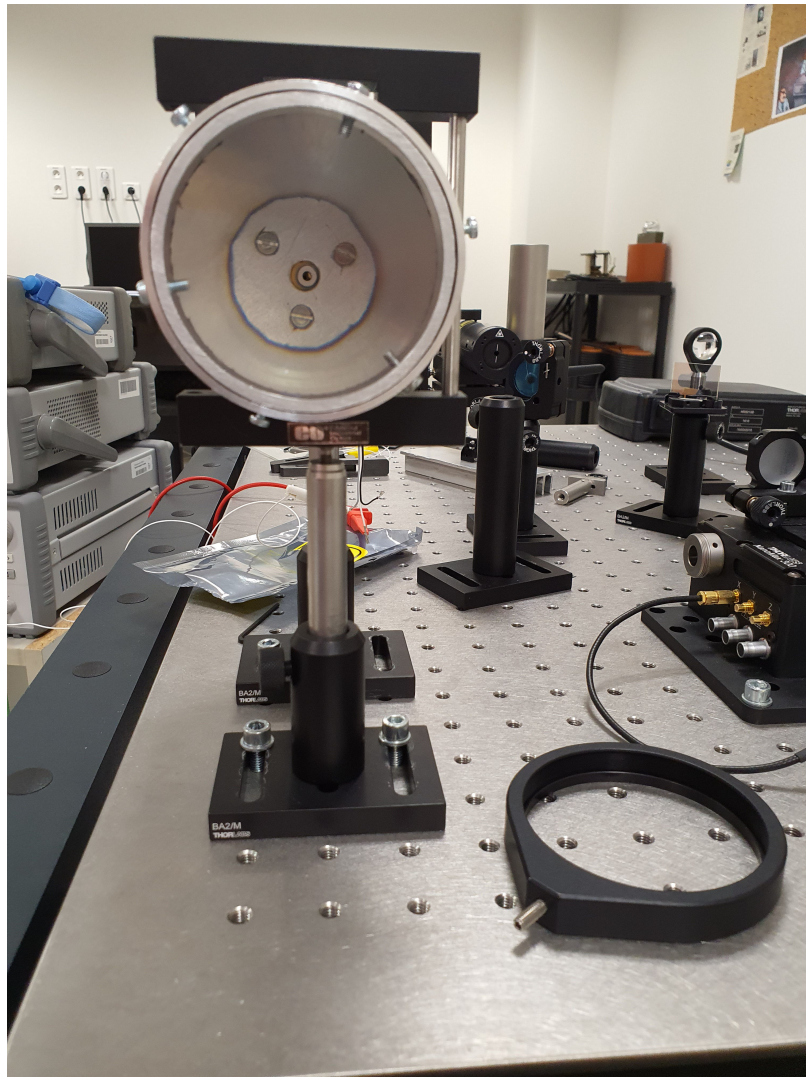
Fig. 8.12: Front view.
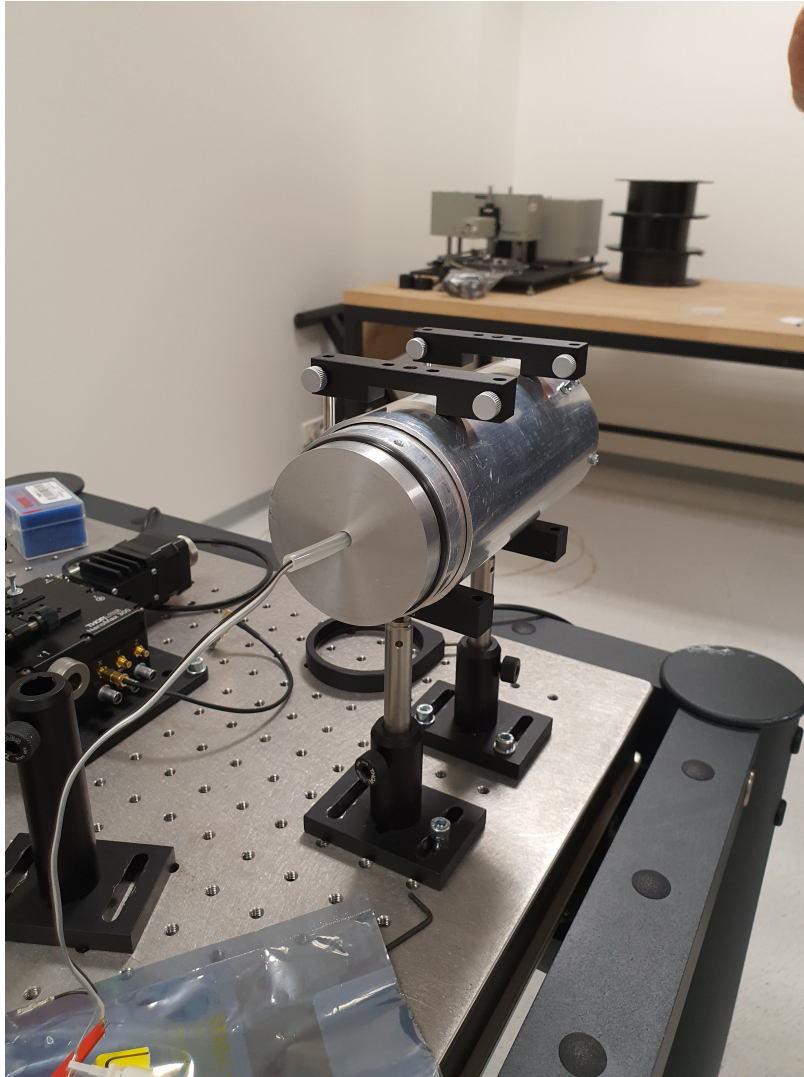
Fig. 8.13: Front view - laser diode.

Fig. 8.14: Rear view.

Laser diode placed in a heat sink must be isolated from the construction, otherwise the tubes would be at the voltage potential of anode of the laser diode.

For testing, PCB will be placed in a case, and in a final version will be integrated into the detection and scaring system and it will be mounted according to the requirements of the complete manipulator system.

8.10 PCB mounting and testing

Unfortunately due to the actual situation in the world, shortage of components, and outages in the supply, their delivery was delayed.

It started with mounting and testing the power supply on the PCB, which is functional and there were corresponding values on all pins where it was fed. The

mounting continued with passive components and integrated circuits. Regrettably, problem with integrated circuit has occurred. The problem could not be fixed before submission of the thesis due to the few day delay. Therefore the complete design of the source of laser radiation for scaring birds could not been tested. It is not a serious problem and the provided solution will be functional to the day of thesis defense.

Two figures of PCB with ESP32 devkit are shown. One with devkit with integrated antenna 8.15 and one with external antenna 8.16. And PCB with ESP32 module is shown at figure 8.17
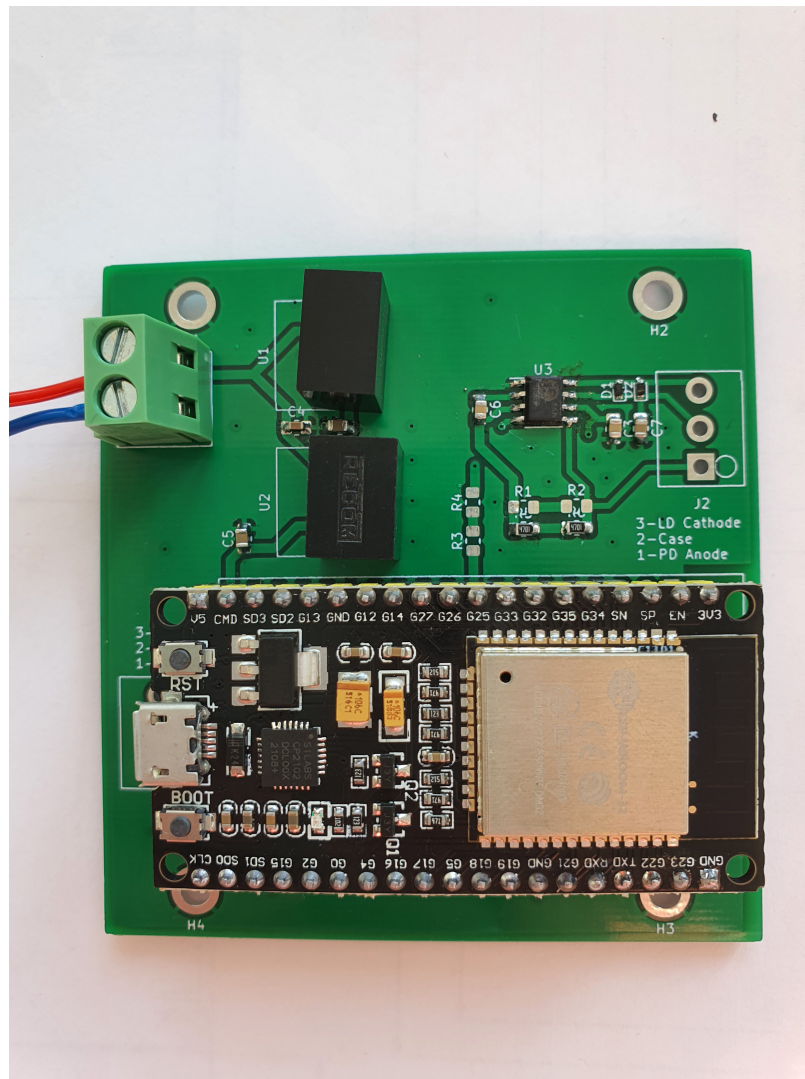

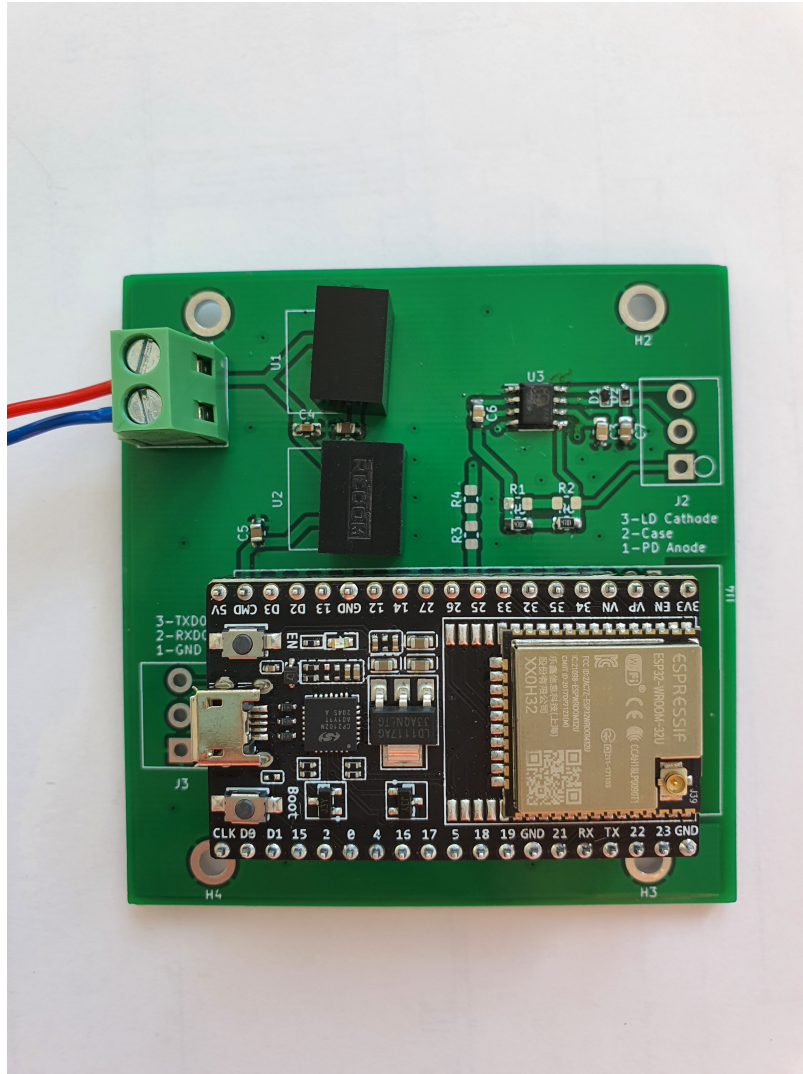Fig. 8.15: PCB with ESP32 devkit with integrated antenna.

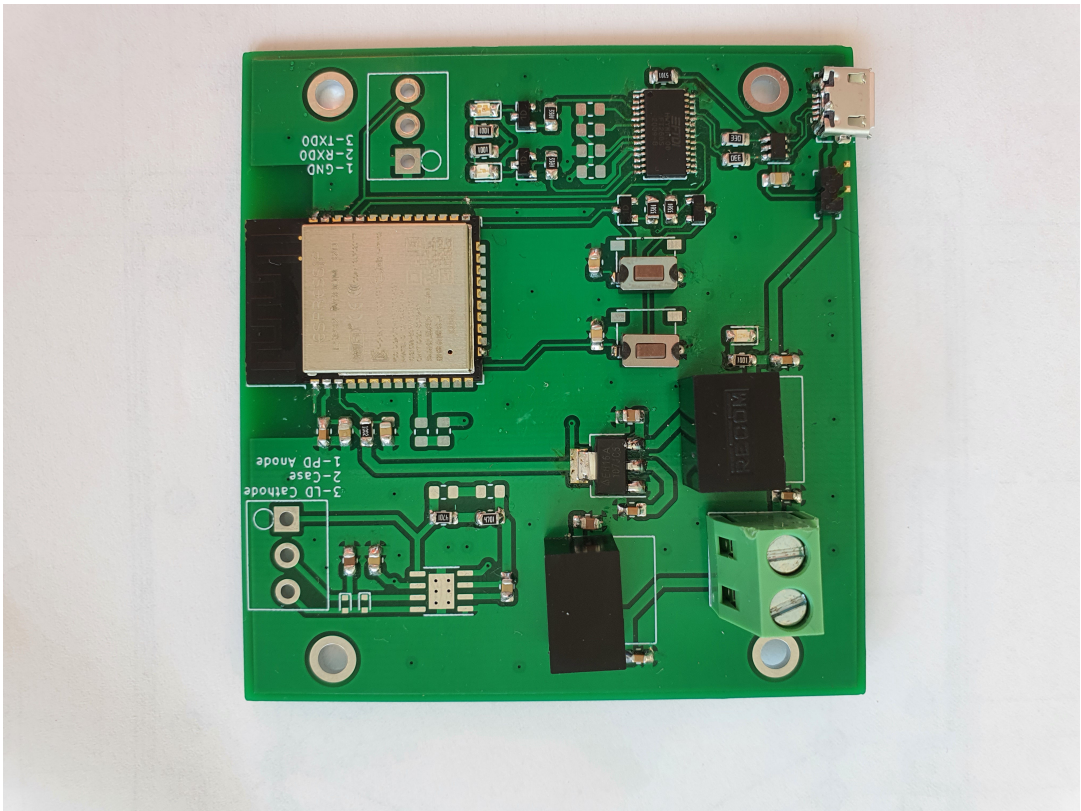Fig. 8.16: PCB with ESP32 devkit with external antenna.

Fig. 8.17: PCB with ESP32 module.

Conclusion

In thesis was discussed the importance of bird control and several scaring methods were mentioned. Statical methods of scaring such as scare crow are ineffective because the birds will habituate to them very quickly since they do not perceive any danger when they are around. Therefore it is recommended to use "active" scaring - changing position of plastic predators. More effective is to use the scaring device only when the birds appear to prolong the time interval during which they will habituate to the technique. Most effective is combination of several scaring techniques.

Briefly, bird vision and their sensitivity to colours, which is similar to human vision, have been described, with the difference that birds are able to see more colour shades due to their ability to perceive ultraviolet light.

The basic principle of the laser based on stimulated emission, the structure of the laser were described and the basic properties of laser beam were mentioned. Some types of laser diodes, their typical packages, and basic characteristics were described. The importance of cooling for the proper function of the laser diode and its lifespan was also mentioned.

Level of output power of laser safety classes were mentioned as well as importance of safety when working with laser devices. Optics used for collimation and beam expansion was presented. Brief comparison of advantages and disadvantages of discrete and integrated laser diode drivers were mentioned, when integrated drivers usually contains protection circuits to save diode from damaging.

Based on the theoretical knowledge about bird vision and their colour perception, green laser diode was chosen as a source of laser radiation. Its output power is 50 mW which exceeds the limit of output power level for safety class 2M. Safety glasses which protects eyes against an injury when working with lasers with higher output power. Because of the divergence, it is necessary to collimate the laser beam at required beam diameter. It was done by using plano-convex lens, which collimates the beam and enlarges its diameter to specific value so that the limit of output power for safety class 2M is not exceeded. Functionality of the designed optics was tested.

The heat sink for laser diode was designed.

Integrated driver circuit iC-WKN was chosen because of its built-in protections, soft-start, and possibility to modulate the output power of laser diode. Microcontroller ESP32 was chosen because a project uses ESP-Now protocol and because of its prevalence.

Two designs of PCBs were made, one with ESP32-DEVKITC-32U and one with module ESP32-WROOM-32D. The PCS with devkit provide possibility of simple

exchange of variants with internal and external antenna. Therefore, the suitability of the antenna designed and can be easily tested.

Unfortunately, because of the actual situation in the world, shortage of components and outages in the supply, the delivery of the components was delayed for few days. More difficult possibilities for personal consultations and presence in laboratory caused delays during the whole solution of the diploma thesis.

During the mounting of the components a problem appeared so it was not possible to finish the solution and testing of the device design in time. But the problem is simple, and the solution will be functional to the day of diploma thesis defense.

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Symbols and abbreviations

Laser   Light Amplification by Stimulated Emission of Radiation

DFB   distributed feed back

QWL   quantum well laser

APC   automatic power control

OPAMP   operational amplifier

MTBF   mean time between failure

LRAD   Long Range Acoustic Device

ESD   electrostatic discharge

PCB   printed circuit board

List of appendices

A Cooler diagram

Fig. A.1: Cooler diagram.

Fig. A.2: Diagram of handle for laser diode and heat sink.

B Diagram of laser diode driver circuit with ESP32 Devkit
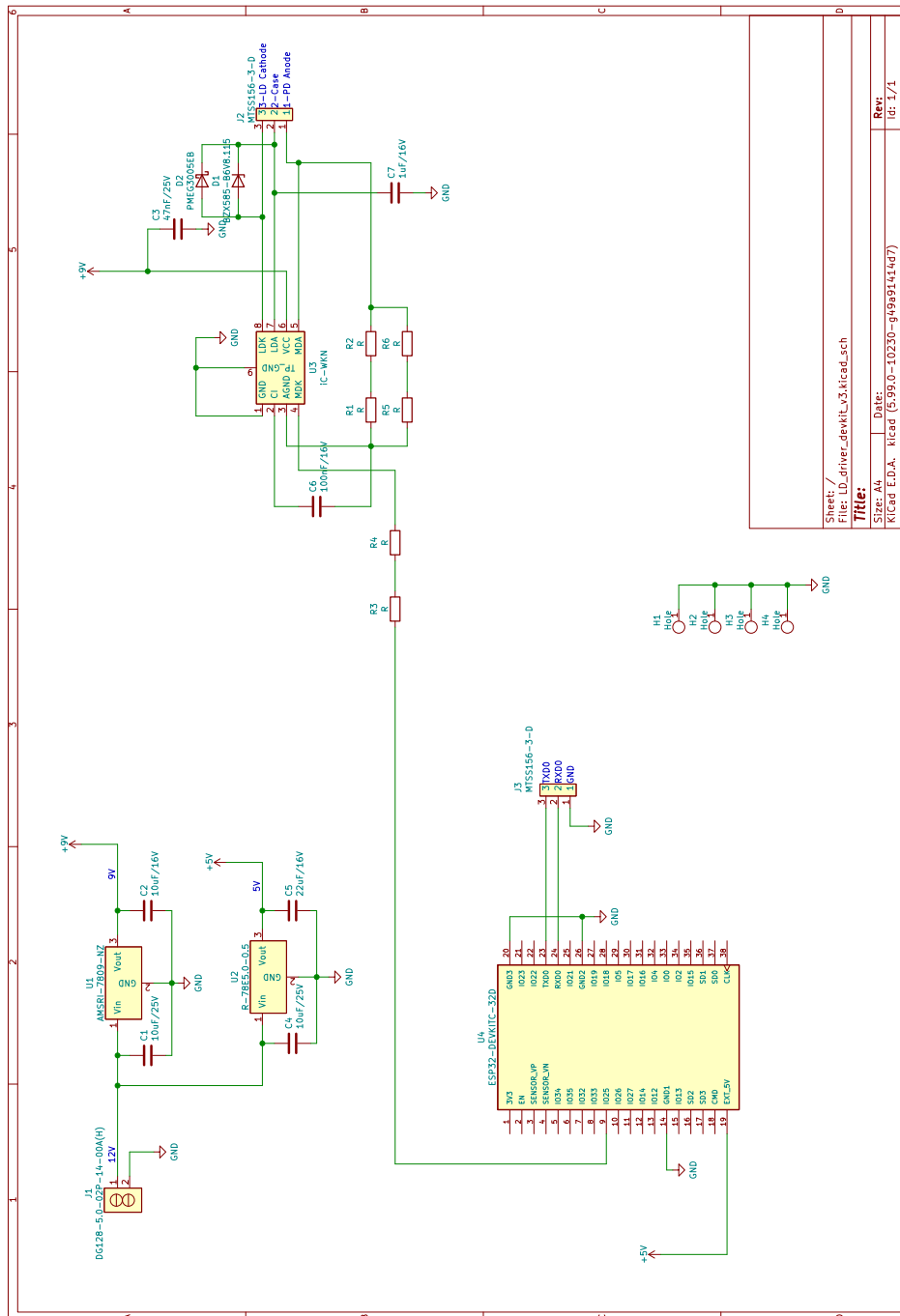
Fig. B.1: Diagram of laser diode driver circuit with ESP32 Devkit.

C   Diagram of laser diode driver circuit with ESP32 Module
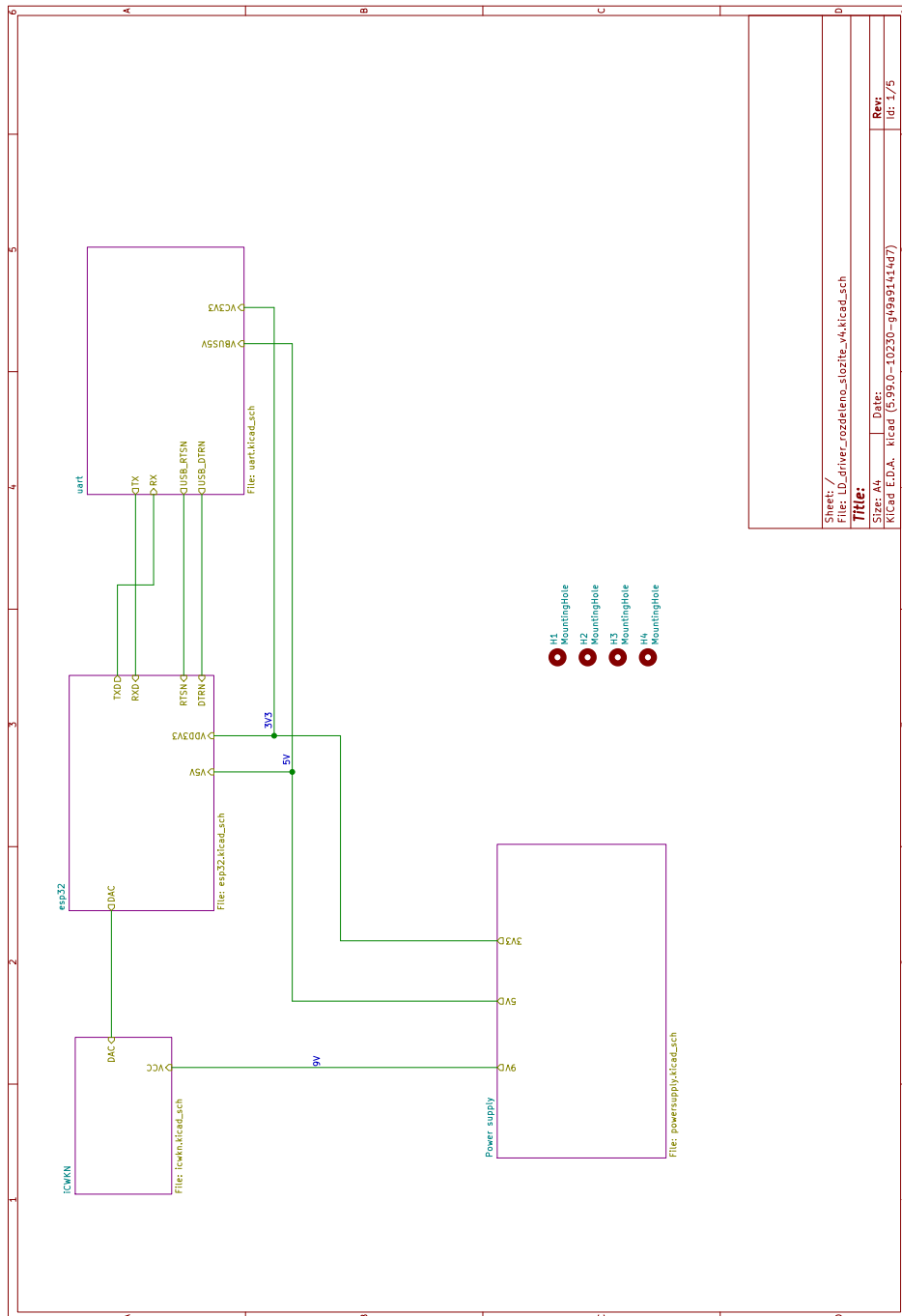
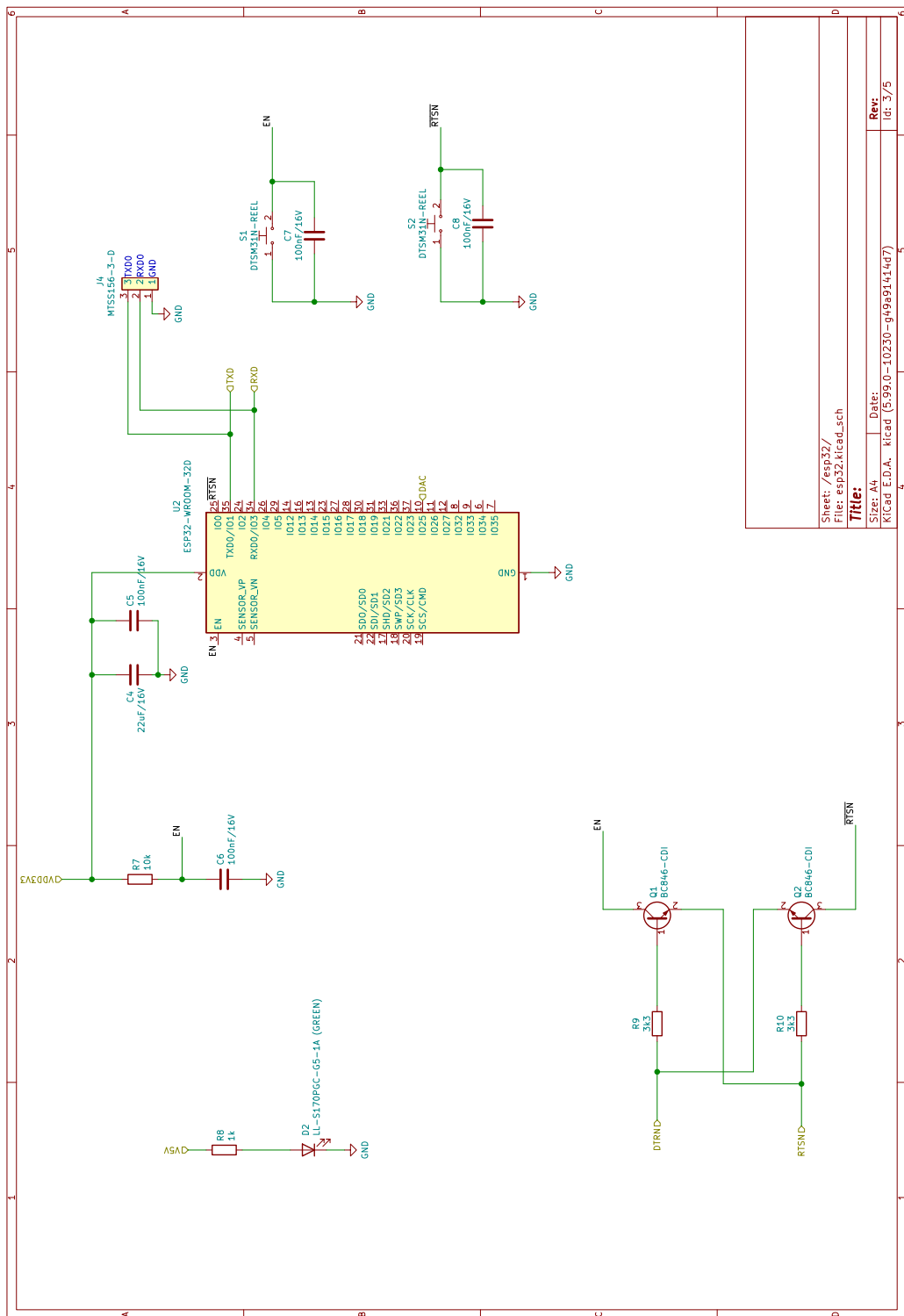Fig. C.1: Block diagram of laser diode driver circuit with ESP32 Module.
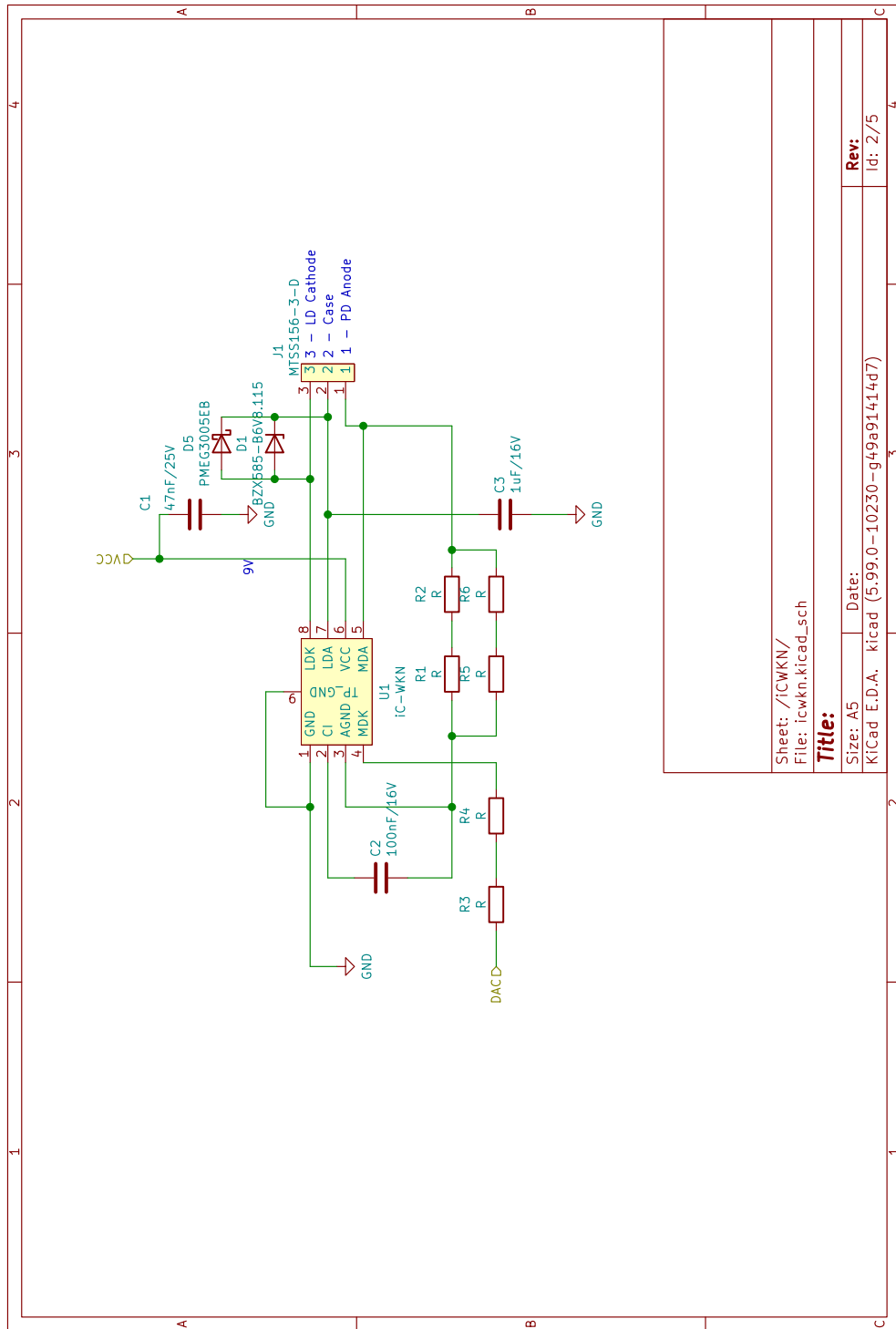
Fig. C.2: Diagram of iC-WKN block.

Fig. C.3: Diagram of ESP32-WROOM-32D block.
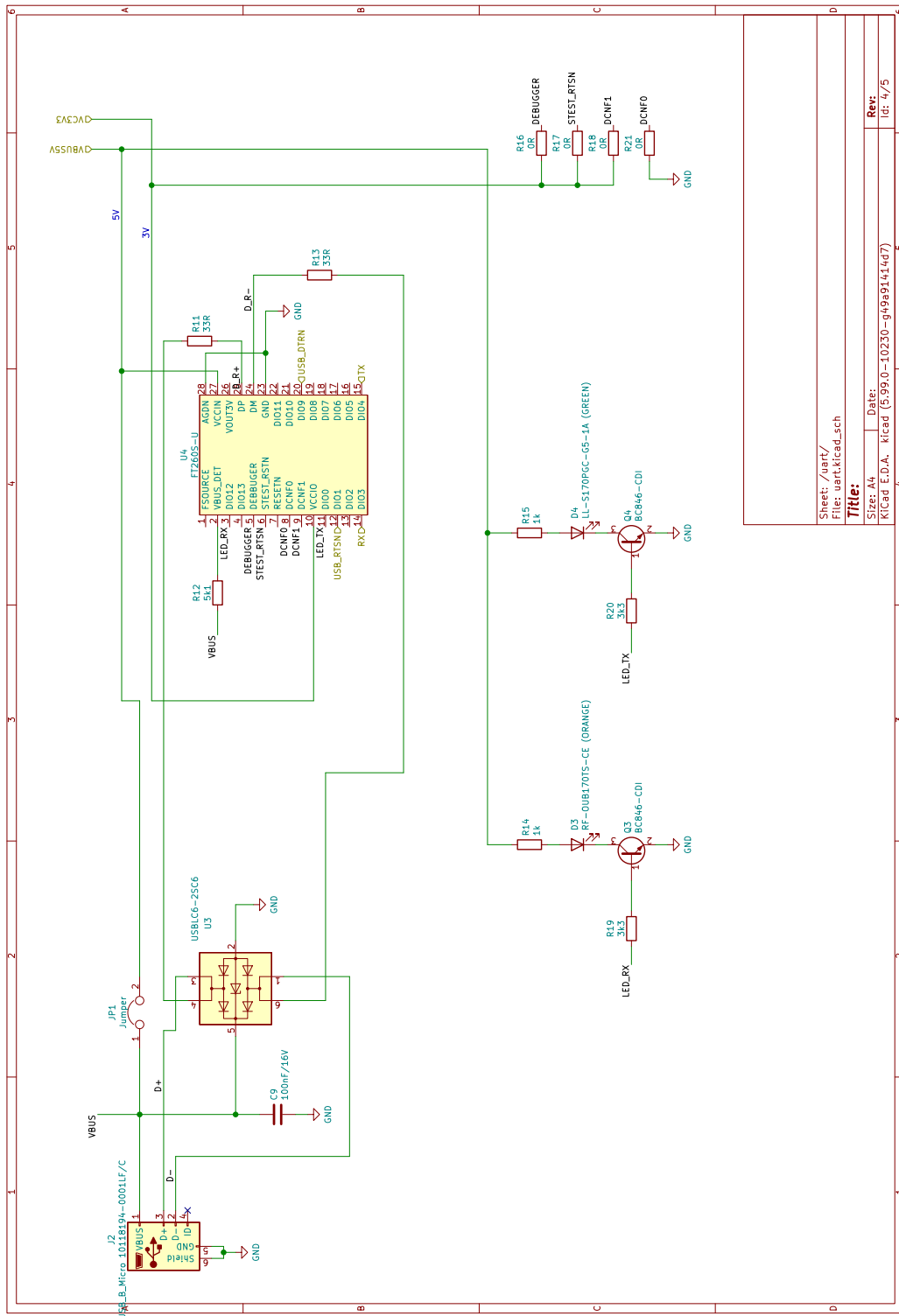
Fig. C.4: Diagram of USB-to-UART converter block.
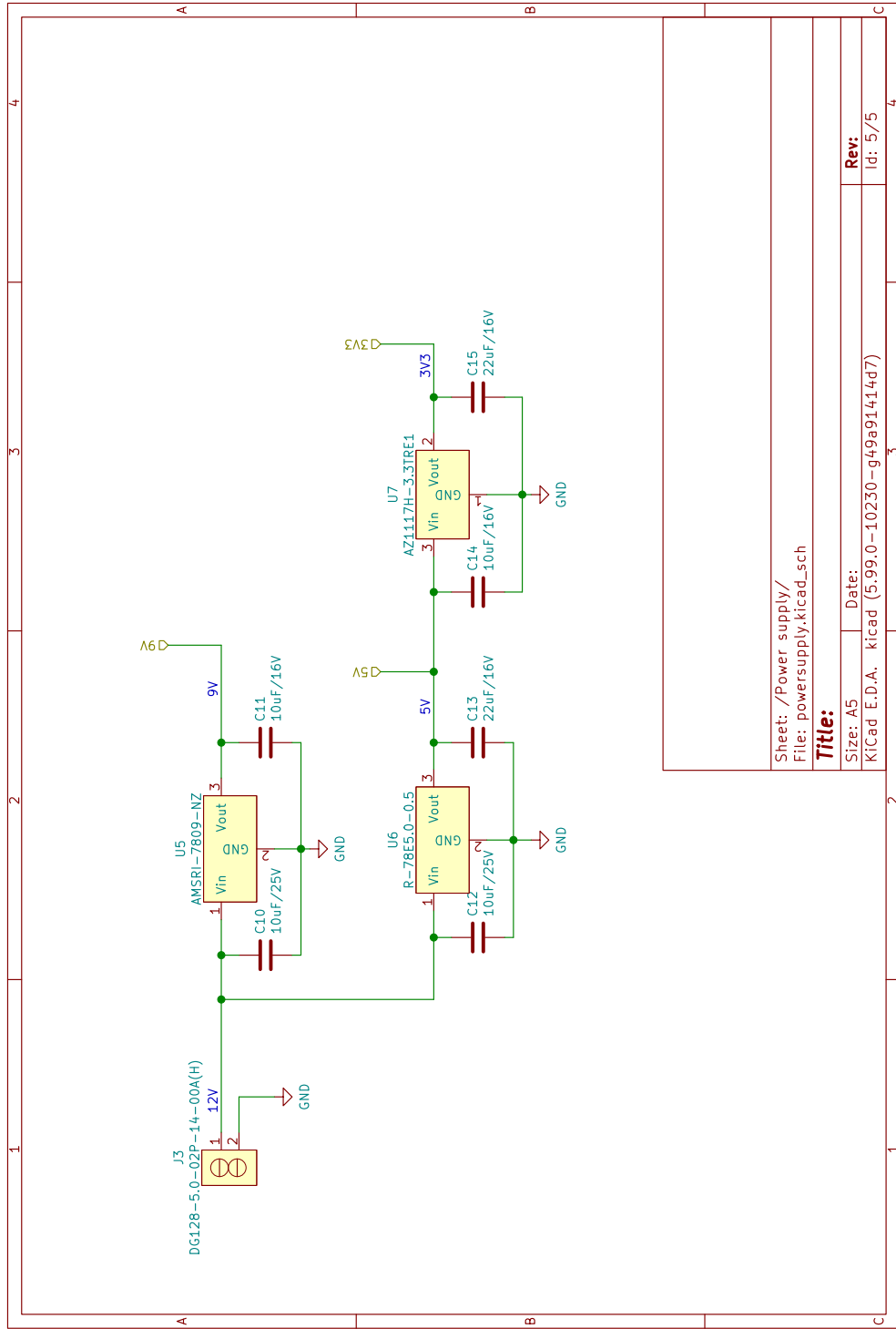
Fig. C.5: Diagram of supply voltage block.