Bachelor Thesis

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F3

Faculty of Electrical Engineering
Department of Electromagnetic field

Visible Light Communication for the Automotive Industry

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[1] Z. Ghassemlooy, L. Nero Alves, S. Zvanovec and M. Ali Khalighi, Visible Light Communication Systems: theory, applications and future trends, ed., CRC Press,2017.

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Declaration

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Abstract

This thesis describes visible light communications and their usage in automotive industry. It presents the required technologies for VLC and VLC's advantages and applications. Utilization of polarizers for enhancing the link quality is discussed and evaluated. There is also a description of the design and realization of printed circuit boards for diode drivers and for laser diode itself that were created as part of the project presented in this thesis. The last chapter contains results from testing and measurements of designed technologies.

Keywords: VLC, automotive industry, communication, polarizer, NLOS, laser diode, driver, PCB

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Abstrakt

Tato práce popisuje komunikace ve viditelné části elektromagnetického spektra a jejich využití v automobilovém průmyslu. Projekt prezentuje technologie pro VLC a také jejich výhody a aplikace. Využití polarizátorů pro zlepšení kvality komunikace je popsáno a ověřeno v této práci. Nachází se v ní také popis návrhu a realizace desek plošných spojů pro diodové drivery a samotnou laserovou diodu, které byly vytvořeny jako součást projektu prezentovaného v této práci. Poslední kapitolou jsou závěry z měření a testování navržených prototypů.

Klíčová slova: VLC, automobilový průmysl, komunikace, polarizátor, NLOS, laserová dioda, budič, DPS

Překlad názvu: Komunikace ve viditelném světle pro automobilový průmysl

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Chapter 1

Introduction to visible light communication

Visible light communication (VLC) is a subfield of optical wireless communication (OWC) which describes a general usage of optics for a cord less connection. Visible light communication is a term describing the usage of lighting sources operating in visible light frequency spectrum not only for lighting purposes but also for communication [1]. This combination gives a lot of advantages because light sources are widely available and affordable. This chapter describes the current state of the art and theory of VLC.

In recent years light emitting diodes (LEDs) had become very popular in many areas reaching from house lighting through automotive beam lights to special purpose lamps. LEDs are very energy efficient and they have also become cheap for normal users. As communication means, LEDs are also great because they could be switched on and off with high frequencies and they have a long life cycle [2]. Using standard lighting sources for communication requires special drivers that would switch and modulate the light to transfer the information but also to remain the character of a still light from a spectator's perspective. Therefore used frequencies must be faster than perception of the human eye [3]. Usage of lasers is escalating in the communication industry. They are used for optical cables and in recent years they have started to be used as a lighting source as well, for example in luxury cars from Audi or BMW. Therefore lasers are also a suitable technology for visible light communication. More on the topic of light sources is described in Section 1.3.

Emitted light also needs to be received and processed. There are many ways how to receive a light signal. The most common receivers are photodetectors, avalanche photodiodes or photoresistors. But there is also a possibility to use a high speed camera image sensor manufactured with complementary metal-oxide-semiconductor (CMOS) or charge-coupled device (CCD) technology. Receivers are further described in Section 1.4.

VLC is currently under development in many areas. One of them being wireless internet connections. The idea of developers is to create an alternative or supplement to Wi-Fi but using light sources with modulated communication instead of standard Wi-Fi routers and access points. This concept is referred to as Li-Fi.[1] For some special purposes where only broadcast is required VLC could be a great option. Bidirectional communication would require devices to flash light towards the unit which would need to have a detector as well. A hybrid system that uses combination of radio frequency (RF) and VLC was proposed in [4].

1.1 Standards for VLC

Many standards were developed to ensure that all contributors use the same conventions. IEEE developed *802.15.7* standard for short-range wireless optical communication using visible light as shown in [3, 5]. They mentioned 96 Mb/s communication speed but multi-gigabit-per-second can be achieved theoretically using array of LEDs with multiple-input multiple-output (MIMO) method [3]. Some modulation techniques and DC balancing methods are proposed to mitigate flickering. Also some ideas for idle patterns are discussed. A forward error correction (FEC) for VLC is shown in [5] as well as optimization for communications under optical noise sources (daylight and artificial).

The Visible Light Communications Consortium (VLCC) has proposed *CP-1221*, *CP-1222* and *CP-1223* JEITA standards which define e.g. packet frame [6]. The *ISO/IEC 17417:2011* standard also known as *ECMA-397* describes short distance visible light communication (SDVLC) in category of Telecommunications and information exchange between systems [7]. It specifies physical layer and medium access control (MAC) for a mobile-to-mobile communication. This standard also describes two use scenarios for a multi-purpose VLC:

- Lighting and communication

[1] Li-Fi is short for *light fidelity*.

- Communication and Displaying status of the communication

And authors also suggest using VLC as a replacement of near-field communication (NFC) or Infrared Data Association (IrDA) technologies.

1.2 Advantages and disadvantages of VLC

The visible light communication have some advantages but also several disadvantages. This relates to the Li-Fi example mentioned above but also to other applications of this technology. Most communication technologies nowadays operate on radio wave lengths ranging from 10^{-1} m to 10^{4} m of wavelength. These are much longer wavelengths compared to the visible light which operates in spectrum of 380 nm to 700 nm. This gives different characteristics to optical waves in visible light spectrum. One of the disadvantages against common cellular networks or Wi-Fi connections is a short range and a need for direct line of sight between communicating objects. Big advantages given by the high frequencies that visible light operates on are a large bandwidth and a possibility for high speeds.

1.2.1 Advantages

One of the key advantages of VLC is speed. It operates on frequencies that range to 10^{14} Hz. This offers a great bandwidth of approximately 300 THz and possibility to scale to many different channels maintaining great speed of the data transfer. Because the frequency spectrum is so wide VLC doesn't suffer from a spectrum congestion as opposed to the RF technologies. According to [1] another advantage over the current systems is an immunity to electromagnetic interference (EMI) as well as insignificant electromagnetic radiation.

There are usually more LEDs in the source and it is possible to dim the light, allowing to modulate the signal in many ways such as a bit angle modulation or a pulse width modulation (PWM). Using RGB LEDs enables a deployment of Color Shift Keying (CSK) which can enable speeds up to 500 Mbps. Another big advantage is security as it is difficult to eavesdrop the communication from a distant place. It is also easy to verify from what direction the light is coming and therefore filter data from different directions and eliminate possible attacks. The intrinsic cell boundary leads to a low interference and possibility to reuse carrier frequencies as discussed in [1]. In contrast to RF there is no need for license for communication bands. Installation of VLC technology is also fast. This makes VLC available and affordable to manufacturers.

One of the benefits is usage of existing infrastructure. As mentioned earlier the light sources and receptors are already widely used for lighting and other purposes. This would reduce the cost of building new complex communication systems. It is also ecologic to have one device serving two purposes (lighting and communication). As there is no need for new devices this also helps from aesthetic point of view because all electronics could be hidden in the light cover and there is no need for bulky devices with antennas. According to [1, 2] other advantages are high precision positioning, scalability, long lifetime of LEDs or laser diodes and their power efficiency.

1.2.2 Disadvantages

Also some disadvantages need to be considered. Waves with very short wave lengths are not able to travel around or through objects. Because of this characteristics VLC can only be used for a short to mid range communication and communicating devices need direct vision. This is referred to as line of sight (LOS) communication. As the signal itself is a beam of light the receiver could also catch some other light sources resulting in errors. Such ambient light interference might be produced by screens, lamps and other light sources but also by sun. Another problem mentioned in [8] might be multipath reflections or road surface reflections in vehicle to vehicle (V2V) communication, those arrive to the receiver with a delay. This must be dealt with in the software or with polarizers as explained in upcoming chapters.

Usage of VLC outdoors has many challenges to accomplish. VLC suffers from signal loss in free space due to changes of atmospheric conditions, especially fog can corrupt the connection. Many ways to improve the robustness of the outdoor channel are explained in [9]. When working with directed LOS communication[2] it is important to align transmitter and receiver properly. For moving objects, tracking must be implemented. Optical safety might be a concern and power limits should be considered but it is not a problem for short distance indoor communications. Another problems might be a saturation of the photodiode, shadowing or contribution to light pollution.

[2]Both transmitter and receiver have narrow field of view (FoV).

1.3 Optical sources

The choice of a light source is heavily dependent on the proposed application according to demanded features. As stated by [1] the main properties are wavelength, line width, numerical aperture, radiance, modulation bandwidth, life period, reliability, efficiency, size and price.

Light Emitting Diodes (LEDs) are recently spreading as a light source in numerous applications. LEDs are semiconductors that emit photons due to the recombination of electrons. The light produced by LEDs is incoherent and the wavelength they shine on is selected by the energy band-gap of their semiconductor material. This could be in UV, visible or IR spectrum. White light which is used the most is created by mixture of colors (usually using separate red, green and blue diodes) or by phosphorus conversion (blue LED is coated with phosphorus layer). Phosphorus LEDs are favored because of their lower complexity and cost. A disadvantage is that phosphorus has slow response time which cuts LED's modulation bandwidth to few megahertz. The book [1] suggests using filter to pass only the blue light at the receiver end to increase the speed up to 20 MHz. Usage of Resonant-cavity LEDs (RCLEDs) is proposed in [4]. They could theoretically enable speeds up to 500 Mbps. RCLEDs use photon quantization in microcavities to enhance spontaneous emission, directionality, intensity and they have a faster response time than traditional LEDs [10].

As stated in [11] the Lambertian radiation intensity of LED is

$$R_0(\phi) = [(m+1)/2\pi] \cdot \cos^m(\phi), \tag{1.1}$$

where m is Lambertian order and ϕ is angle of radiation. Hence the transmitter's output power is

$$P_{\mathrm{TX}} = P_{\mathrm{LED}} \cdot R_0(\phi). \tag{1.2}$$

Laser stands for light amplification by stimulated emitted radiation. They produce photons by optical oscillation. Lasers are emitting coherent light on a very narrow band of wavelengths and have a very narrow beam divergence. Lasers are more powerful, more temperature dependent and more expensive than LEDs. They are secure as they shine only in the exact direction we want them to and they are usable for longer distances. Optical safety needs to be bewared of when using powerful lasers. To create a more divergent white light, more lasers in combination with mirrors, lenses and yellow phosphorus are used.

Light sources also need to be correctly driven and also controlled to perform as communication devices. LEDs can provide constant brightness when they are driven with a current source. Commonly used LED drivers are ON/OFF digital drivers. They use MOSFET transistors because they handle high currents and are efficient as mentioned in [2]. Microcontrollers are usually used as controllers because they can modulate the signal to transmit the data.

1.4 Optical detectors

Frequently used receivers are photodetectors. They generate electrical signal proportional to received optical power. Photodetectors should have high sensitivity, wide range of wavelengths and low noise. As described in [1] there are four types of photodetectors: PIN photodiodes, avalanche photodiodes (APDs), photoconductors and metal-semiconductor-metal photodiodes.

The PIN photodiode consists of p- and n-doped regions and intrinsic (undoped) region in between. They require reverse bias voltage to deplete charge carriers from the intrinsic region. APD is more sensitive than PIN photodiode but it provides multiplication noise and it is temperature sensitive.

A high speed camera could also be used to catch the optical signal. Nowadays most personal computers and mobile phones have cameras. And even in cars cameras are becoming a standard because of security and comfort reasons. Those camera chips are able to catch light even with high frame rates when there is a proper microcontroller to process these data. Such sensors have also great resolution and that allows for all kinds of modulations of signal and even for reception of more than one stream of data at once. The transmission speed is limited to the camera's frame rate. Cameras are less sensitive and more expansive than photodetectors.

1.5 Applications and configurations

One of the most interesting applications of VLC is home networking which was already mentioned in the beginning of this chapter. Li-Fi could be a faster competitor to current technologies when outsourced computing[3] comes

[3]Streaming of computing power from a powerful server to homes

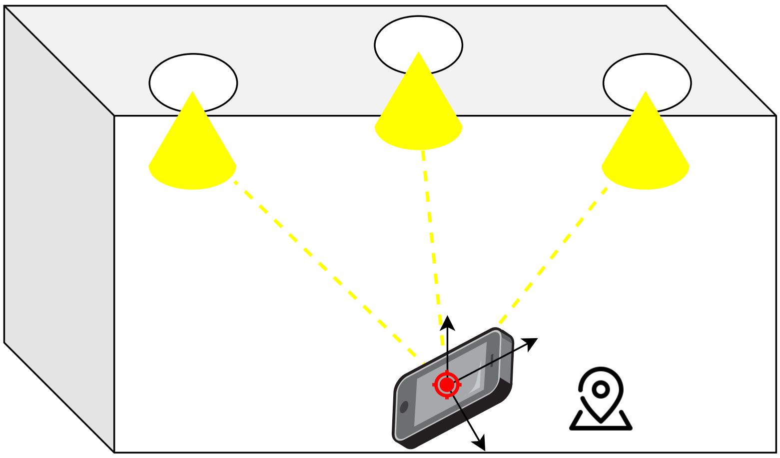

Figure 1.1: Example of using VLP to navigate people indoors via their smartphones, ceiling LED lamps represent transmitters and smartphone's front-facing camera is a receiver.

to market. Other usage scenarios include airplane networking where VLC doesn't interfere with crucial RF systems and train networking where RF is blocked by a heavy steel structure. Some medical instruments are RF sensitive and therefore using VLC in hospitals would be safer. VLC could be also used in applications where OWC links are used such as last mile connections which overcome the bandwidth bottleneck [1]. Usage of VLC for localization and for automotive industry is closely discussed in forthcoming Subsections 1.5.1 and 1.5.2, respectively.

1.5.1 Visible light positioning

Visible light positioning (VLP) is using the principles of VLC for purpose of indoor localization of objects. Indoor positioning system based on VLP could be used in shopping malls for better orientation of customers (see Figure 1.1) or in warehouses for easier logistics. VLP can be also used for indoor traffic-research system linked with client data in shops [4].

Three degrees of freedom are present for projects dealing with precise localization. The receiver needs to have LOS with at least 3 transmitters. A design with an accelerometer at the receiver side can allow for only 2 transmitters in LOS [12]. Very small amount of data needs to be sent and hence there is no need for wide bandwidth. Therefore LEDs are a perfect light source for VLP application as their critical frequency is not a limitation. There is also no need for using complicated signal modulations. Simple on-off keying (OOK) could be easily implemented. Each LED transmitter could implement a specific frequency. For the receiver to distinguish between transmitting points those frequencies need to be different from one another by a certain factor as so that also their harmonics differ. This factor could be a power of 2 to address this problem [13]. A more complicated approach could be to send some data based on previously precisely measured location of the VLP transmitter.

1.5.2 VLC for automotive industry

Automotive industry is one of the fields where visible light communication could be used. New technologies are currently in development for cars and infrastructure such as various driving assistants, autonomous or self-driving modes. Also the idea of smart cities with smart roads and signs is spreading. With demand for safer and easier to drive vehicles there is a need for communication means.

Some of the possible applications of VLC in automotive industry are:

- Vehicle to vehicle communication (V2V)
- Infrastructure[4] to vehicle (I2V)
- Vehicle to infrastructure (V2I)

Connected devices could create a chain and deliver the information to any car on the road. VLC has a potential to be used for Intelligent transportation systems (ITS) as discussed in [14].

The data to be sent are safety information, road surface condition, accident details for emergency services, traffic jam reports, closures and more. That would lead to increased road safety and more fluent traffic. Navigation system in the vehicle would be able to automatically choose the fastest way based on those data. In the future autonomous cars would be able to accommodate the correct speed to travel fluently through intersections and adapt to speed of other vehicles thanks to data received by VLC. Communication with toll gates might be another application.

The main communication transmitters for VLC in vehicles are front low beam headlights and rear lights. The receiver could be a front camera that

[4] E.g. Road sign, traffic light, street light, lights on toll gates or parking barriers

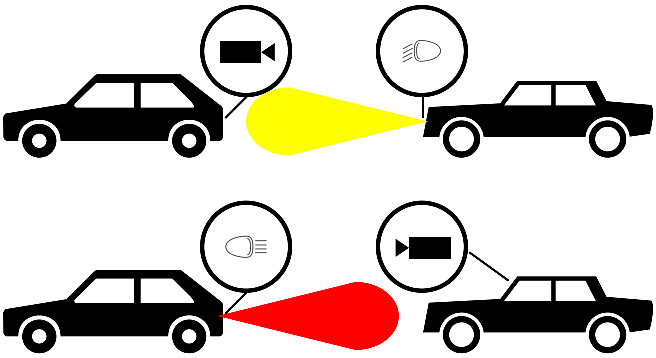

Figure 1.2: Example of V2V communication using front headlights and rear lights as transmitters together with rear parking camera and front drive-assistant camera as receivers.

could also be used for lane assist or pre-collision system or rear parking camera. Example of this V2V communication is presented on Figure 1.2. Dedicated photodiodes are also an option but usage of present technologies would keep the cost down. VLC could also be easily connected to car's controller area network (CAN) bus for flawless integration with electronic control units (ECUs) and infotainment systems as proposed in [15].

Other competing technologies in automotive industry are 4G and 5G networks and also communication on 5.9GHz dedicated band. In comparison with them has VLC some advantages like better security and less interference. Those advantages were further discussed in Chapter 1.2. Fast speed is not a main goal of VLC for automotive industry as not too many data is being sent and therefore the focus should be mainly on robustness of the link.

1.5.3 Link configurations

An information can be transmitted in different ways using the OWC transceiver link as shown on Figure 1.3. **Directed LOS** uses very narrow FoV to direct the light precisely into the receiver and hence no power is lost [1]. Special version of directed LOS link is a **tracked link** which can be applied on moving objects and uses tracking devices in cooperation with actuators to direct information from the transmitter (TX) to the receiver (RX). **Nondirected LOS** can be used for point to multipoint communication. Nondirected LOS is a great use case scenario for VLC because no extra energy is wasted when the light is also used for illumination. But this link suffers from multipath dispersion. **Diffuse link** uses non line of sight (NLOS) light and reflective surfaces to direct it to the receiver. This is not very power efficient and hard to accomplish. **Cellular links** use many TX cells (e.g. LEDs) to cover a

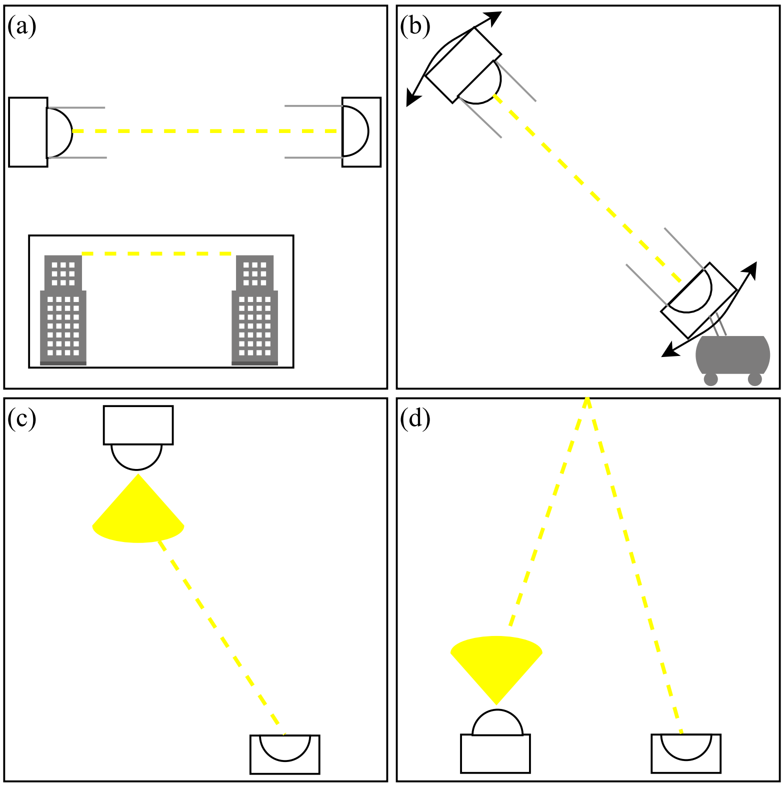

Figure 1.3: Link configurations: (a) directed LOS, (b) tracked, (c) nondirected LOS, (d) diffuse, inspired by [1, Figure 1.7].

bigger area with Nondirected LOS communication.

1.6 Polarizers

In the experimental part of this thesis a usage of polarizers is mentioned. Polarizers are based on an optical property called polarization which is a state of vibration of electric field vector in the optical signal [11]. Throughout this project only linear polarizers are used, circular and elliptical are the other possible types. When an unpolarized light passes through a linear polarizer the output is a polarized beam which means that it's electric vector is only vibrating in one plane[5] as mentioned in [16]. The intensity of light transmitted by an ideal polarizer is

$$I = \frac{I_0}{2}, \tag{1.3}$$

[5]When considering ideal polarizer. In real situations there is a very small component vibrating in the perpendicular plane.

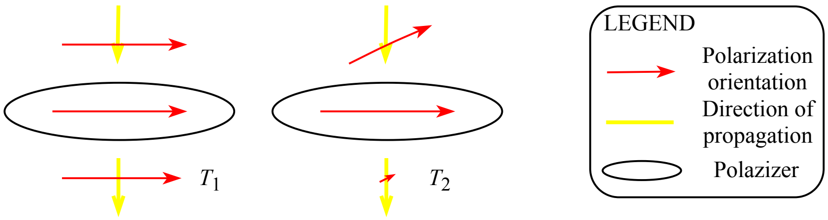

Figure 1.4: Principal transmittances of polarizer (measured for linearly polarized light passing through polarizers with collinear or perpendicular orientation of polarization).

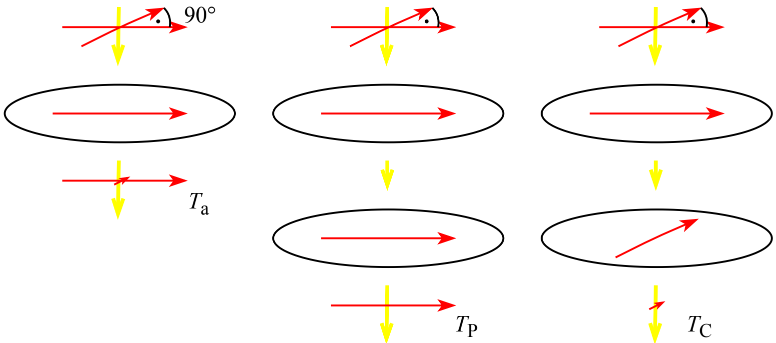

Figure 1.5: Transmission of unpolarized light through one or two polarizers (with parallel or perpendicular alignment).

where I_0 is intensity of the original unpolarized light.

Figure 1.4 shows the amount of light that passes through a polarizer for different polarizations of the input beam. T_1 and T_2 are called principal transmittances and they define properties of the polarizer as shown in following equations. Values of principal transmittances refer to the transmission of linearly polarized light through a polarizer with collinear orientation of polarization for T_1 or perpendicular orientation for T_2. The subsequent equations show transmission through one or two polarizers when unpolarized light passes through as shown in Figure 1.5:

$$T_{\mathrm{a}} = \frac{1}{2}(T_1 + T_2), \tag{1.4}$$

$$T_{\mathrm{P}} = \frac{1}{2}(T_1^2 + T_2^2), \tag{1.5}$$

$$T_{\mathrm{C}} = T_1 \cdot T_2, \tag{1.6}$$

where transmissions T_{P} and T_{C} are called Parallel and Crossed, respectively [17]. They are often mentioned in product catalogs. Parallel and Crossed transmissions were important for choice of polarizers for a part of this project as further discussed in Section 2.2.

Important polarizer's properties are a degree of polarization P and an extinction ratio ρ_p and they are defined as:

$$P = \frac{T_1 - T_2}{T_1 + T_2}, \tag{1.7}$$

$$\rho_\mathrm{p} = \frac{T_2}{T_1}. \tag{1.8}$$

Chapter 2

Design

Design ideas and their execution are shown in this chapter. Firstly printed circuit boards (PCBs) were designed for laser diode and it's drivers. In the second part a setup for optical measurements aiming at eliminating the effect of reflections on VLC is discussed.

2.1 Laser diode and drivers

As lasers are being used in headlamps of some vehicles the idea of using them for VLC as well as for lighting comes to mind. Three printed circuit boards aiming at utilizing lasers for VLC were designed as a part of this bachelor project.

- Laser diode board with Osram 450B (Laser board)
- Driver board featuring Diodes Inc. BCR421 (BCR board)
- Driver board featuring Maxim MAX3766 (MAX board)

The user can choose from two different boards for driving the laser diode. This modular design also allows to put the laser diode in different orientation against the driver board. Those boards were designed mainly for school or laboratory usage and hence they offer some adjustability with jumpers and

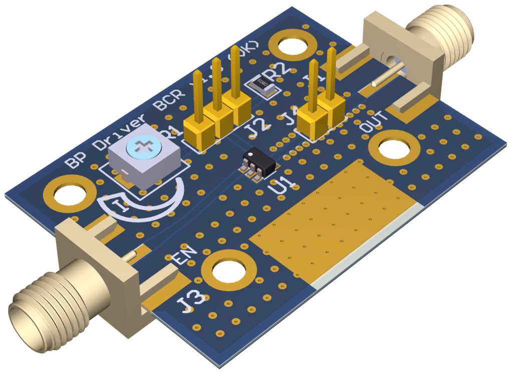

Figure 2.1: Layout for BCR driver board.

trimmers. All boards are fitted with standard SMA connectors for signal and two-pole connectors for power. 3D layouts of those boards are on Figures 2.1, 2.2 and 2.3. of ttics are in Appendix A.

2.1.1 Inputs and outputs

This section describes inputs and outputs (IO) of each board. All boards are designed with following scheme: Modulation input on the left, DC input on the top (GND is left and VCC right), Driver output on the right. IO is further shown in following tables, they include values to operate those PCBs properly.

Table 2.1: BCR driver board IO.

Input: left SMA					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Enable Current	-	1.2	-	-	mA
Enable Voltage	-	3.3	-	18	V
Output: right SMA					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Output Current	-	10	-	500	mA
Output Voltage	1.4	-	-	-	V

Note that Typical output current for BCR board is 10 mA without an external resistor (no J2 jumper) and 85 mA with external resistor of 10 Ω value (J2 jumper on the right).

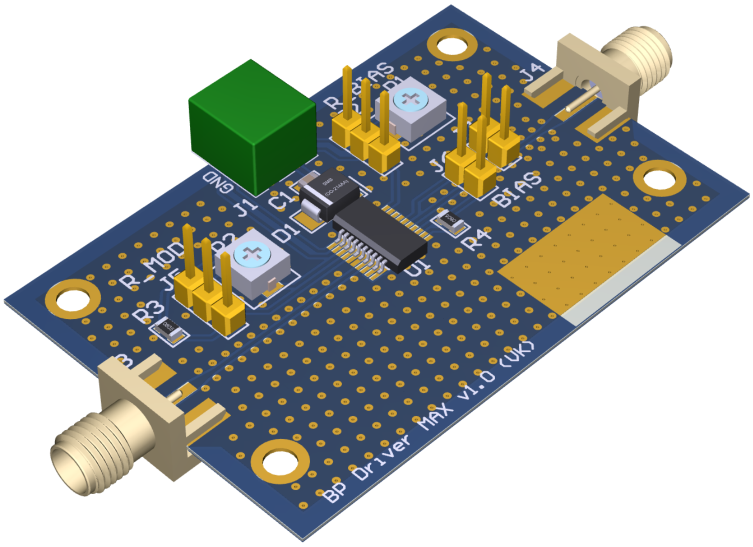

Figure 2.2: Layout for MAX driver board.

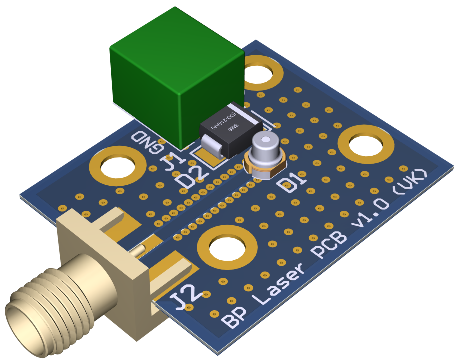

Figure 2.3: Layout for Laser diode board.

Table 2.2: MAX driver board IO.

Input: left SMA					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Enable Voltage	$V_{CC} - 1.4$	$V_{CC} - 1.3$	$V_{CC} - 1.19$	18	V
Input: two-pole connector					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Supply Current	21	25	32	-	mA
Supply Voltage	4.5	5	5.5	7	V
Output: right SMA					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Output Current	-	-	80	100	mA
Output Voltage	$V_{CC} - 2.5$	-	-	-	V

Table 2.3: Laser board IO.

Input: left SMA					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Diode Current	17	75	145	165	mA
Input: two-pole connector					
	Minimum	Typical	Maximum	Absolute maximum	Unit
Input Current	17	75	145	165	mA
Input Voltage	7.9	-	11.5	40	V

2.1.2 Features and possible improvements

Both driver boards have exposed copper on ground plane and headers on signal tracks for easy measurement as could be seen on presented figures. The ground plane is on both top and bottom. There are many via stitches on the board that connect both sides. This also provides good heat dissipation. There is a via shielding around signal tracks to allow high frequency signals. MAX driver board and laser board have Schottky diode next to the DC input connector to prevent opposite polarization.

Settings and drivers

BCR driver board has header J4 for measuring the driver output which is the diode current. Jumper J2 enables user to choose external resistor that changes the output current. Left position enables the 50Ω trimmer, right position enables 10Ω resistor which sets the current to 80 mA.

MAX driver board's jumper J2 selects maximal bias current. Upper position selects 1kΩ trimmer, lower position disables bias current. Jumper J5 selects modulation resistor. Upper position selects 1kΩ trimmer, lower position selects 100Ω resistor which sets the current to 50 mA. Jumper J6 connects bias with VCC, jumper J7 connects bias to output. Shorting the jumper J7 enables bias and shorting jumper J6 disables it.

BCR5421UW6 is a LED constant current regulator which uses NPN emitter-follower with emitter resistor to limit the current. It is limited to 25kHz input frequency. MAX3766EEP+ is a laser driver designed for fiber optic LAN transmitters and is optimized for speed 622 Mbps. It includes special safety and monitoring features along with optional bias current. It also compensates for temperature to provide stable modulation current. Another feature is smooth laser start-up.

Possible improvements for future versions:

- Installing socket for the laser diode to allow swapping the diode in case of failure and to prevent damaging the diode during soldering.
- Adding capacitors for filtering and stabilizing voltage on diode input.

2.2 Setup eliminating the influence of reflections

This thesis showcases VLC for outdoor automotive applications but also for indoor short distance use cases. In both of those scenarios unwanted reflections cause errors. NLOS light arrives to the detector later than LOS component resulting in inaccuracies between logical 1 and 0. Road surface diffuse reflection can affect V2V communication as it adds a delay to the bit stream. Reflections are also harming in an inside environment especially in offices with many surfaces with both diffuse and specular reflections. The goal of this project was utilizing polarization for resolving those problems and enhancing quality of VLC. Effect of the NLOS component on the communication link can be reduced by utilizing polarizers thanks to their properties (see Section 1.6).

For evaluating this idea a setup consisting of transmitting and receiving part was built. Simple schema of the TX part is shown in Figure 2.4. All used devices are listed in the Table 2.4.

All TX part is located on one peace of wood which is secured to the wooden structure that holds the whole setup. Most of the devices use custom 3D printed mounts for precise positioning as shown on renders and photos in Appendix B. 65 W power supply is powering the TX part. Adafruit microcontroller is programmed to modulate the signal. Linear technology LED driver drives a powerful Bridgelux LED with modulated current which could be controlled with a trimmer. This is possible due to voltage divider with 8.2kΩ resistor and 2kΩ trimmer connected to *CTRL* pin of the LED driver board. The maximal LED current is 600 mA and it was used for the measurements. Transmitter uses a signal with OOK non-return-to-zero (NRZ) modulation at frequency of 1 kHz. The polarizers are designed to withstand

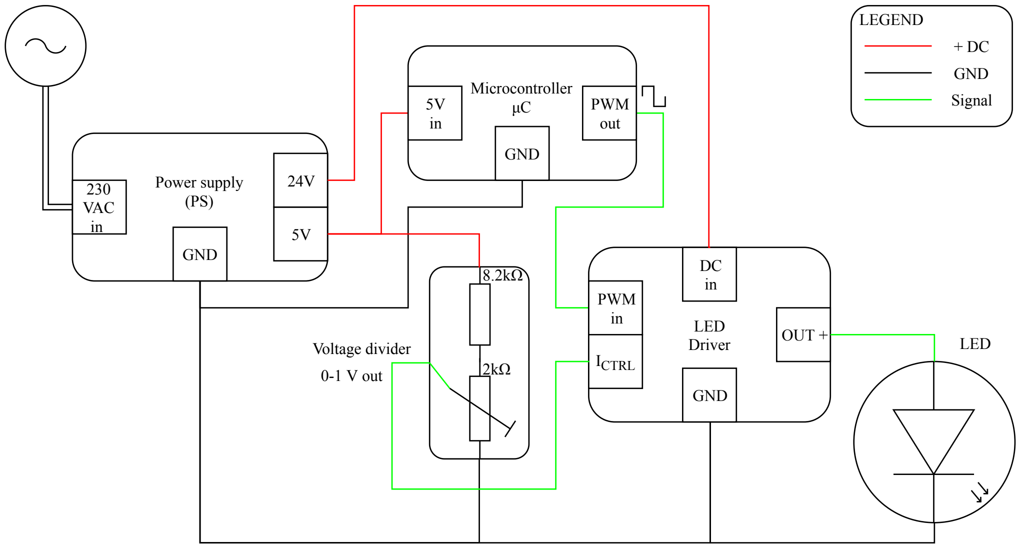

Figure 2.4: Schema of the TX part.

80°C temperatures and hence they cannot be too close to the powerful LED. Light is directed from the LED to the polarizer with a 3D printed collar to make sure that all light is polarized.

RX part consists of a polarizer and Thor Labs photodiode which is connected to the acquisition devices through a filter. Receiving photodiode's output is voltage which corresponds to the light intensity. Photodiode offers a variable gain which was set to 30 dB. A first order low pass RC filter was designed to eliminate higher frequencies and enable sampling. It was placed after the photodiode and before the acquisition device. Filter's cutoff frequency for harmonic signals is 30 kHz. As the signal for measurements was 1 kHz there shouldn't be a distortion caused by this filter although it acts as an integrator on higher frequency square waves. Sampling rate of the data acquisition device was set to more than 100 000 scans/s and MATLAB with DAQ toolbox and Digilent Waveforms were used for acquiring and processing the data.

As linearly polarized light reflects off surfaces it's polarization state changes to unpolarized. This setup uses two perfectly aligned linear dichroic polarizers on transmitter and receiver sides. This should result in LOS light component being transmitted and NLOS component being muted. This idea is pictured in Figure 2.5. As discussed in Section 1.6 polarizers transmit maximally 50 % of light. This affects the lighting performance of the setup but human eye's perception is not linear and hence 50 % of measured light corresponds to 70 % [3, Figure 1] of perceived light which shows that polarizers can be used without too noticeable results. Polarizers add additional cost[1] to the lighting

[1] 100 cm^2 of High contrast linear polarizing film costs $35.70 [17]

Table 2.4: Devices used in the polarization evaluation setup.

Transmitter	
LED	Bridgelux V15 BXRE-50C3001-D-24
LED driver board	Linear Technology DC2257A (w/ LTM8005 chip)
Polarizer	Edmund Optics, 43mm
Microcontroller	Adafruit Trinket 5V
Current control	Voltage divider
Power supply	MeanWell RT-65D
Receiver and measurement devices	
Photodiode	Thor Labs PDA100A-EC
Polarizer	Edmund Optics, 43mm
Data acquisition	National Instruments USB-6212 Digilent Analog discovery 2
Oscilloscope	Tektronix TDS 2002b
Low pass filter	RC, 1. order, cutoff: $f = 30\text{kHz}$

setup but it is acceptable compared to the price of the whole setup.

The setup enables changing a distance from the wall which is the only reflective surface nearby. This reflective wall is colored in light-gray color and is completely flat to provide a reference similar to common office environments. The setup next to the wall is pictured on Figure 2.6. The measurements were done for distances from 30 cm to 160 cm from the wall. Distance from TX to RX is 170 cm and the setup is elevated 210 cm of the floor surface. For the measurements is distance greater than 100 cm from the wall considered as being in free space because the influence of reflected signal is close to zero. It is possible to take off both polarizers to evaluate effects on the communication link.

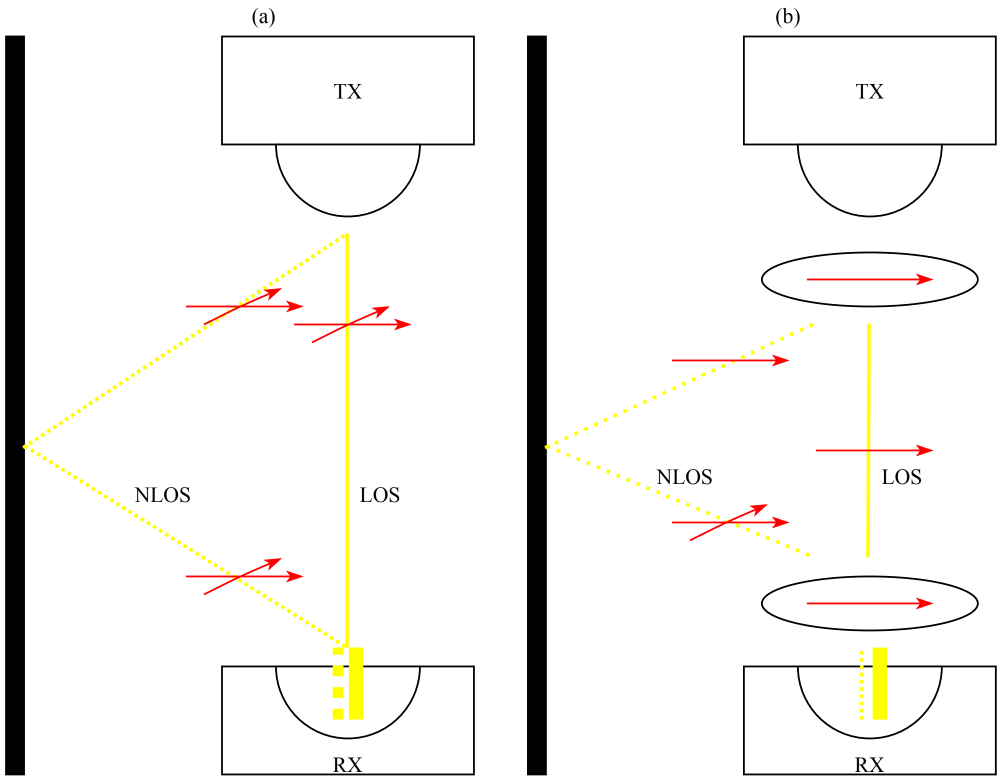

Figure 2.5: Comparison of influence of the reflected NLOS component on link: (a) without polarizers, (b) with polarizers, for legend see Figure 1.4.

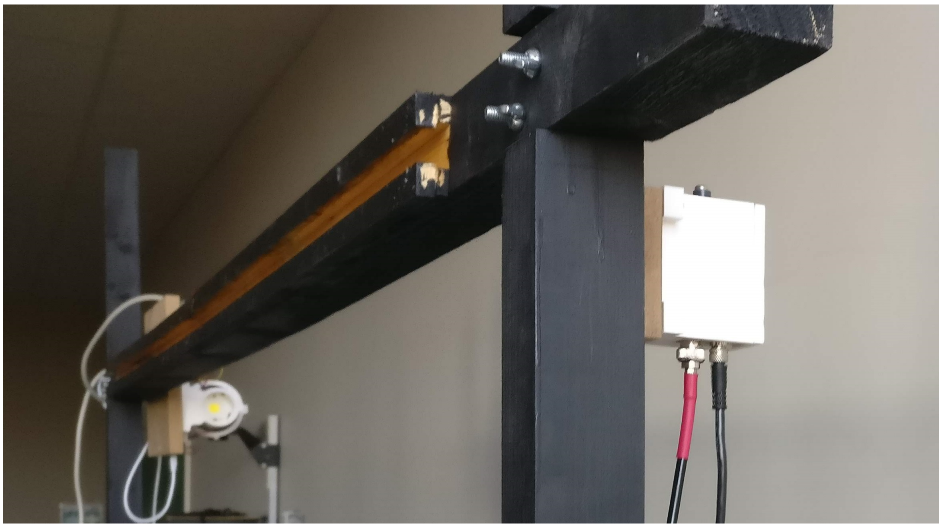

Figure 2.6: Photo of the whole setup with the TX part on the left an the RX part on the right.

Chapter 3

Testing and measurements

This chapter describes performance of the designs shown in the previous chapter. All creations were tested and the results were evaluated.

3.1 Laser diode and drivers measurements

The initial function tests of the diode and drivers showed that the laser diode and BCR driver board were working as expected. Due to some unknown reason the MAX3766 driver or the PCB was not working correctly. The fault was not found despite inspections and various adjustments. Therefore the tests continued only with the BCR421 driver and its board.

Firstly the Current-Voltage characteristics (I-V curve) of the PL 450B laser diode was tested. The graph in Figure 3.1 correlates with the data in diode's datasheet.

Then the diode board was connected to the BCR driver board and the BCR421 driver characteristics were tested. Following measurement tested the relation between output current and enable voltage. This relation varies for different values of external resistor. This measurement was done with $R_{\text{ext}} = 10\ \Omega$ which could be selected by jumper J2 on the BCR board. The resulting graph is shown on Figure 3.2.

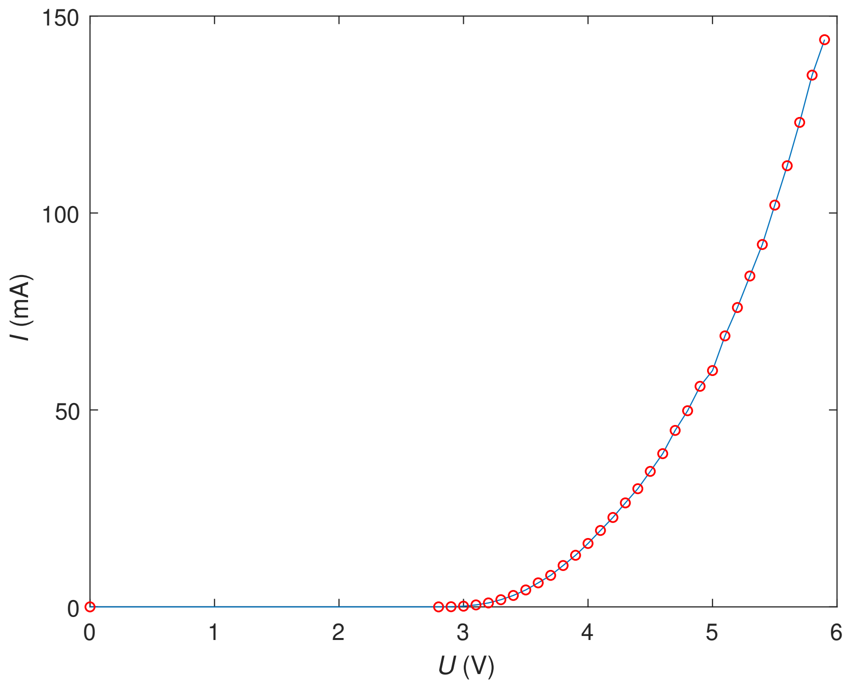

Figure 3.1: I-V characteristics of PL 450B diode, forward bias.

Lastly the relation of diode forward voltage on frequency on driver's enable pin was tested. The output current which is also a current through the diode was calculated from the diode's I-V characteristics. The Figure 3.3 shows both relations in one graph. The input was a square wave with 50% duty cycle. The driver output started to be distorted with higher input frequencies. The driver is rated for frequencies under 25 kHz. The output signal successively changed from square to a sine wave from around 100 kHz.

Further testing showed that the driver output current adjustments with trimmer R1 worked well. Also variant with permanent resistor and variant with no external resistor worked flawlessly.

3.2 Setup with polarizers

The setup and measurement devices which were listed and explained in Section 2.2 are used in this section to evaluate the application of polarizers for VLC link enhancement.

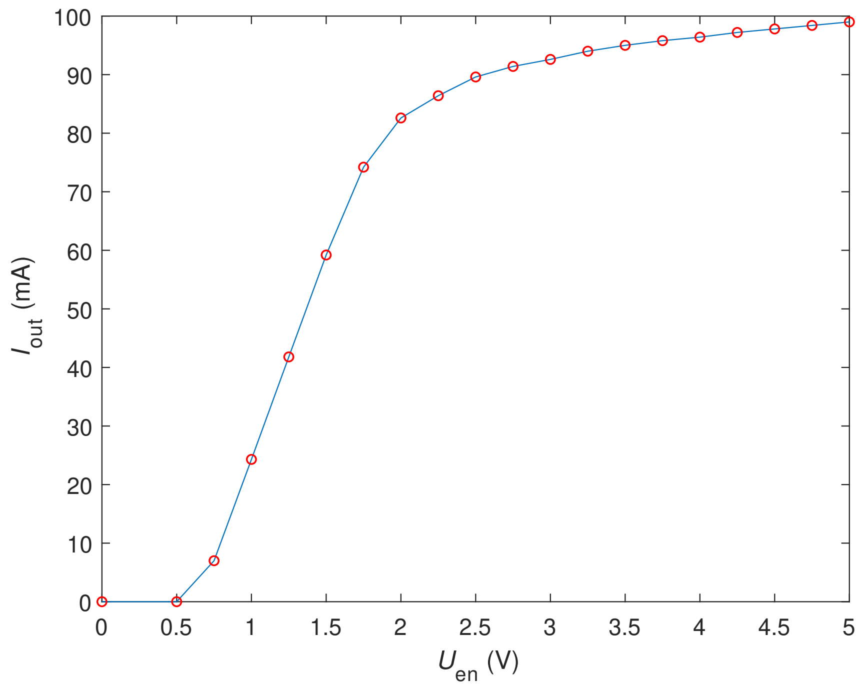

Figure 3.2: Output current against Enable voltage, BCR421, $R_{ext} = 10\ \Omega$.

Table 3.1: Edmund Optics polarizer evaluation.

	Old set	New set	
Transmission	Measured	Measured	Manufacturer
T_1 Single	0.30729	0.42222	0.42
T_P Parallel	0.16406	0.35278	0.36

Firstly the properties of polarizers were tested. All measurements were done with a same set of polarizers that replaced a previous set which wasn't performing very good, parameters of both are listed for comparison. Parameters described in Section 1.6 and shown on Figure 1.4 were measured, compared to manufacturers data and results are presented in Table 3.1. It is important to note that the orientation of TX polarizer towards LED is not important as LED's output is completely unpolarized. New polarizers are also larger and have better heat resistance which is important for the lighting application.

Final measurements with the last version of the setup with upgraded polarizers are summarized in Table 3.2 and resulting values are shown in Table 3.3. They are average of 2 measurements where each consists of 524 288 samples. Row labels *No pol (a)*, *1 pol (b)* and *2 pol (c)* refer to 3 scenarios from Figure 3.4. $U_{LOS+NLOS}$, $U_{NLOS(ii)}$ and $U_{LOS(i)}$ are measured voltage differences that were obtained according to Figure 3.5. They refer to *High-*

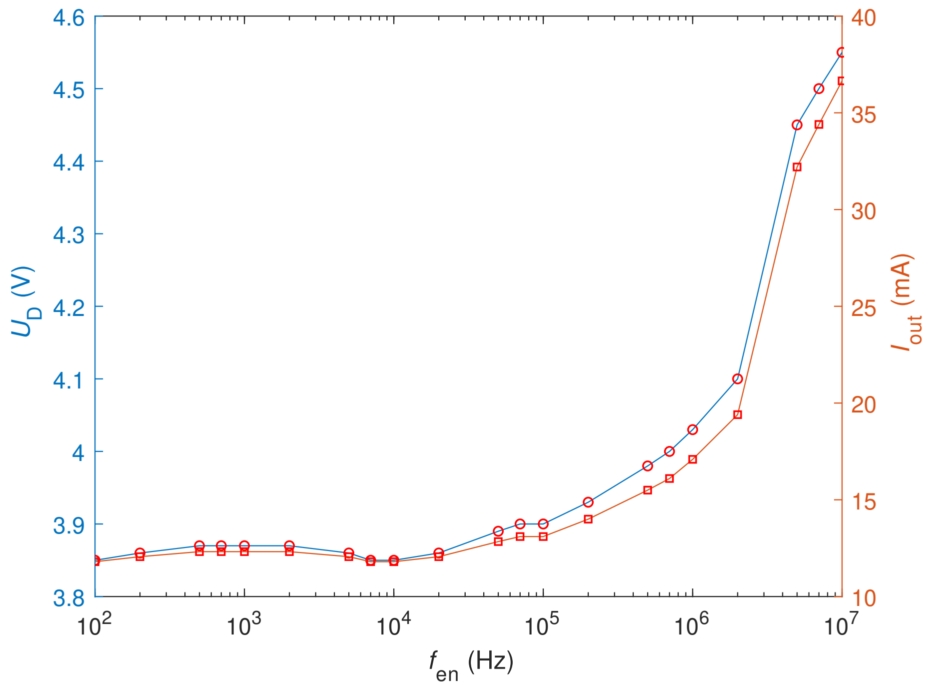

Figure 3.3: Diode voltage and current against Enable frequency, BCR421.

Low from Table 3.2 which are subtractions of logical high voltage minus logical low voltage on the filtered photodiode's output. With this approach the average of the noise is subtracted from the results leading to consistent measurements with very low noise levels. The noise was also measured separately and its value corresponded to the value of logical low as expected.

Values for $U_{\mathrm{LOS+NLOS}}$ are measured 20 cm from the reflective wall. $U_{\mathrm{LOS(i)}}$ is measured with distance of at least 100 cm from any reflective surfaces (140cm from the wall). $U_{\mathrm{NLOS(ii)}}$ is measured 20 cm from the wall with LOS component being blocked.[1] These measurement setups are shown on Figure 3.5. $U_{\mathrm{LOS(ii)}}$ and $U_{\mathrm{NLOS(i)}}$ are calculated voltages and they represent the amplitudes of LOS and NLOS components of light reaching the photodiode. Results are calculated as follows:

$$U_{\mathrm{LOS(ii)}} = U_{\mathrm{LOS+NLOS}} - U_{\mathrm{NLOS(ii)}}, \tag{3.1}$$

$$U_{\mathrm{NLOS(i)}} = U_{\mathrm{LOS+NLOS}} - U_{\mathrm{LOS(i)}}, \tag{3.2}$$

$$\alpha_{\mathrm{(x)}} = \frac{U_{\mathrm{LOS(x)}}}{U_{\mathrm{NLOS(x)}}}, \tag{3.3}$$

where α describes a ratio between LOS and NLOS light components. The higher the ratio is the more is NLOS component suppressed. Parameter α

[1] As it is not blocked entirely, it needs to be measured separately (140 cm off the wall) and subtracted.

would ideally limit to infinity.

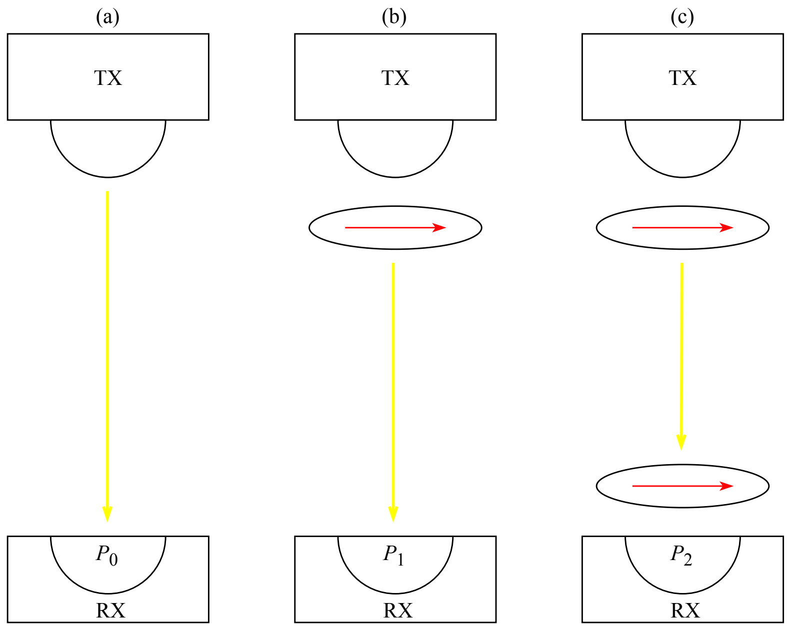

Figure 3.4: Different measurements to evaluate polarizers and the setup in free space with (a) 0, (b), 1, (c) 2 polarizers.

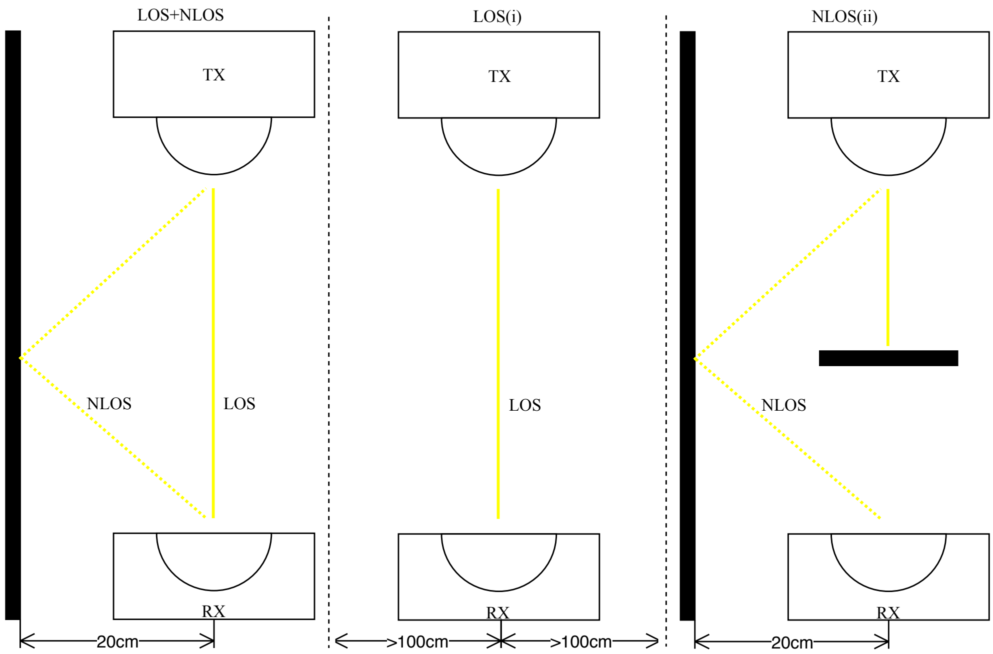

Figure 3.5: Different measurement models to capture LOS and NLOS light components.

Table 3.2: Measured values for modified setups.

		$U_{LOS+NLOS}$	$U_{LOS(i)}$	$U_{NLOS(ii)}$
No pol (a)	Low	0.0228	0.0186	0.0051
	High	3.4735	3.1629	0.2675
	High-Low	3.4507	3.1443	0.2624
1 pol (b)	Low	0.0225	0.0175	0.0027
	High	1.5043	1.3484	0.1411
	High-Low	1.4818	1.3309	0.1383
2 pol (c)	Low	0.0138	0.0111	0.0027
	High	1.2600	1.1411	0.1027
	High-Low	1.2462	1.1300	0.1000

Table 3.3: Calculated results for High-Low from Table 3.2.

	$U_{LOS(ii)}$	$U_{NLOS(i)}$	$\boldsymbol{\alpha}_{\mathbf{(i)}}$	$\boldsymbol{\alpha}_{\mathbf{(ii)}}$
No pol (a)	3.1883	0.3063	10.2888	12.1521
1 pol (b)	1.3434	0.1509	8.8199	9.7143
2 pol (c)	1.1462	0.1162	9.7386	11.4605

Results in the Table 3.3 show that using polarizers in this scenario is not very practical and it would only be useful in environments with more reflections than one wall has. Results also show that the setup attenuates the NLOS component well as parameter α is almost the same for scenarios with or without polarizers despite the loss in intensity. The setup with one polarizer at the TX side produces the worst results which proves that the concept of using two polarizers is useful. The table also shows that separating LOS and NLOS components in measurements is challenging as different measurement methods brought different results. Here is a list of some reasons why presumably the concept of utilizing polarizers for enhancing the communication link is not that advantageous in employed scenario:

- Reflections are polarized randomly and hence is their effect minimized by maximally 50 %.
- Reflective surface is usually diffuse and the reflections are unpredictable.
- Darker colors absorb light and do not reflect all of it.
- Only 42 % of light passes the TX polarizer and hence the lighting abilities of the setup are weaker.

Chapter 4

Conclusion

The task of this thesis was to analyze usage of visible light communication for automotive industry and also design and testing of technologies for VLC.

Firstly the general knowledge about visible light communication was discussed. VLC's potential in certain applications including automotive was shown in addition to it's advantages. Light sources and receivers that could be used for VLC were described in other sections.

Three printed circuit boards were designed as a part of this Bachelor thesis. One PCB incorporates laser diode that emits blue light and could be used for VLC and automotive applications. Two driver PCBs were designed to drive this laser. Those drivers are able to modulate the current output to allow communication. These boards were tested and their characteristics were measured in the last chapter. One driver board worked as designed and drives the laser diode properly. The other driver board is not working as expected.

A setup consisting of the optical transmitter, receiver and polarizers was created with a main purpose to eliminate the effect of reflections on the VLC link. Polarizers were able to reduce the NLOS component but they were not able to improve the VLC communication. This solution in presented scenario was not effective enough especially with additional cost and worse lighting ability. With higher communication speeds the influence of NLOS light on the link would increase as it would arrive delayed to the receiver and utilization of polarizers would be more useful.

VLC has a potential to be used in the automotive industry for Intelligent transportation systems. Car transport could get faster, smoother and safer with visible light communication. It has to be further examined to overcome challenges like the effect of reflections and noise on the link.

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Appendix A

Board documentation

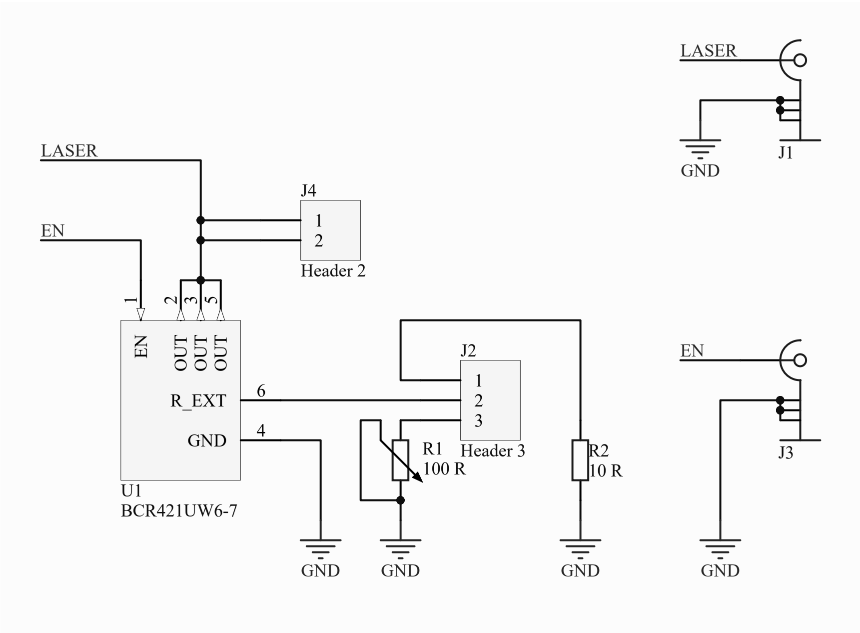

Figure A.1: Schematic for BCR driver board.

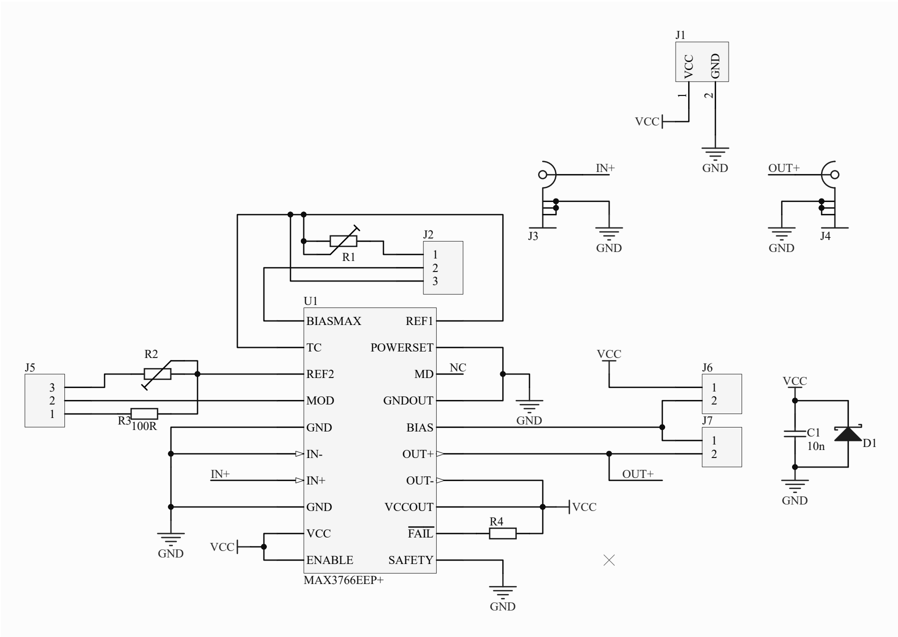

Figure A.2: Schematic for MAX driver board.

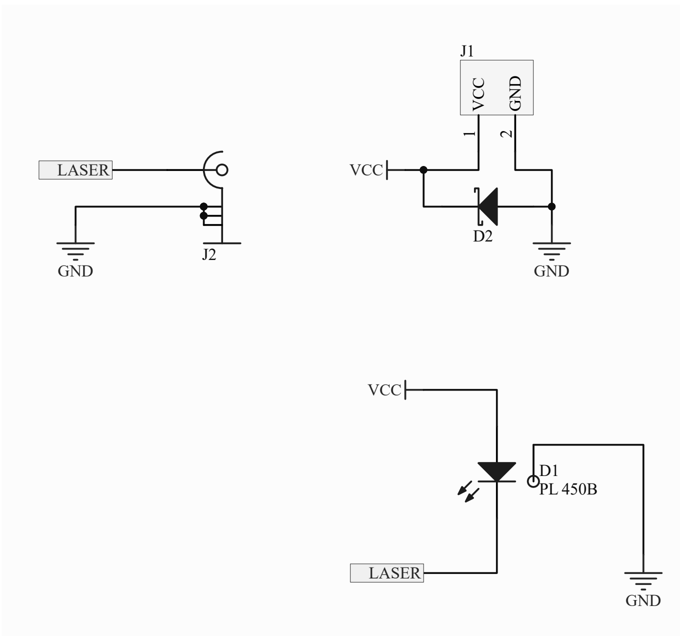

Figure A.3: Schematic for Laser diode board.

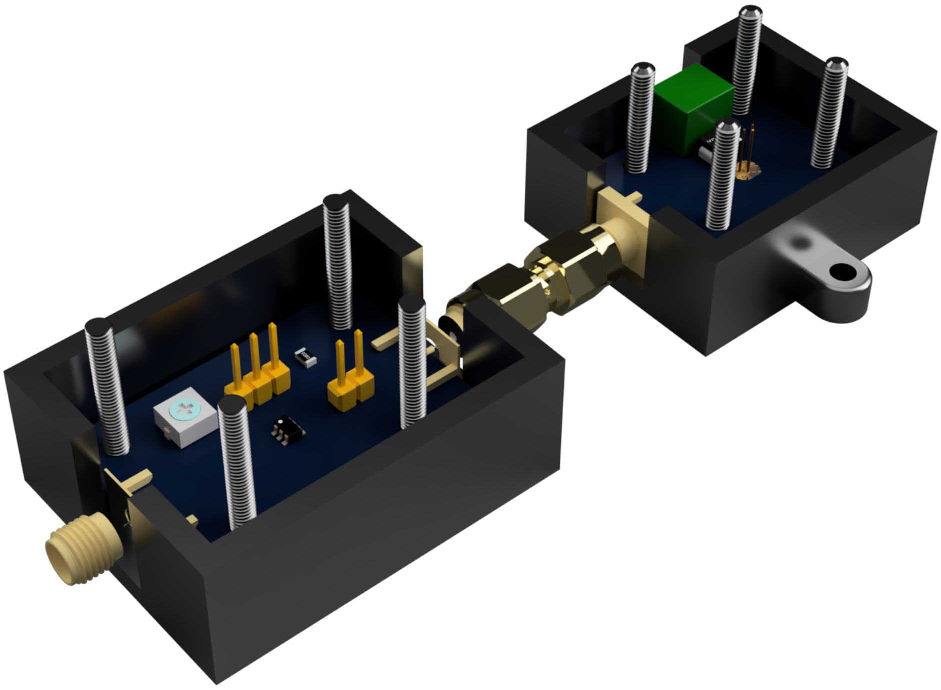

Figure A.4: 3D model of intended usage of laser diode board with BCR driver (both boards in custom 3D printable casings).

Appendix B

Setup renders and photos

Figure B.1: 3D printable mount for LED and it's heatsink.

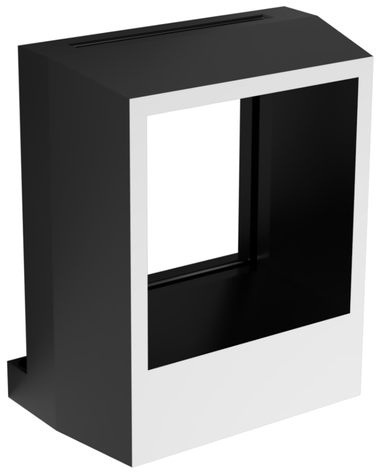

Figure B.2: 3D printable holder for polarizer, including collar guiding light from LED.

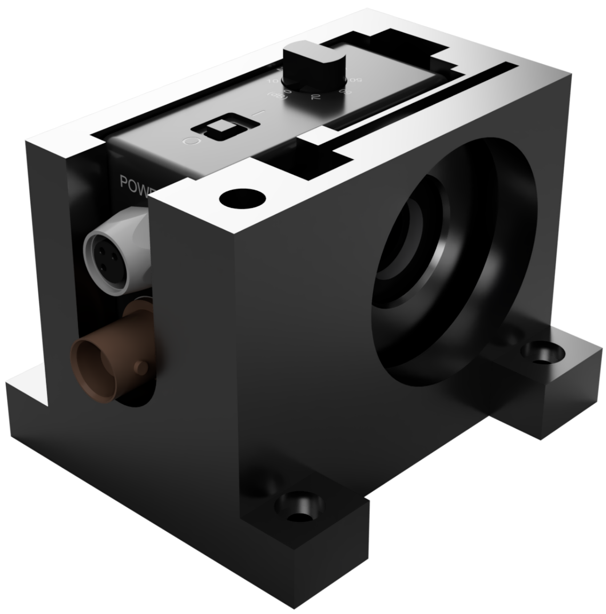

Figure B.3: Thorlabs PDA100A-EC photodiode in 3D printable housing, photodiode model by Thorlabs Inc. (2017) [18].

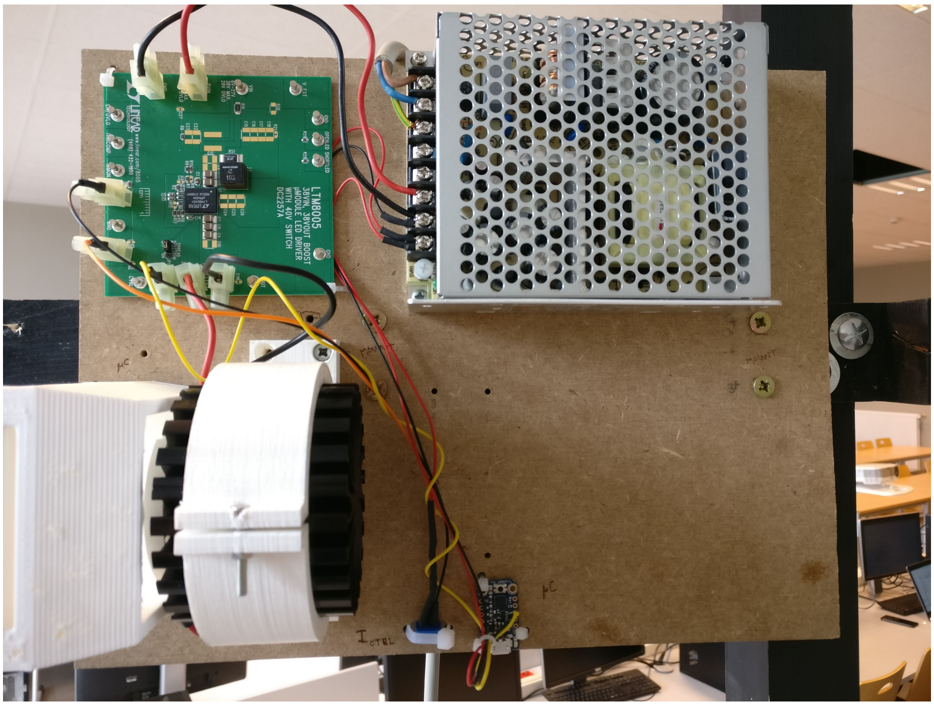

Figure B.4: Photo of the TX part of the setup.

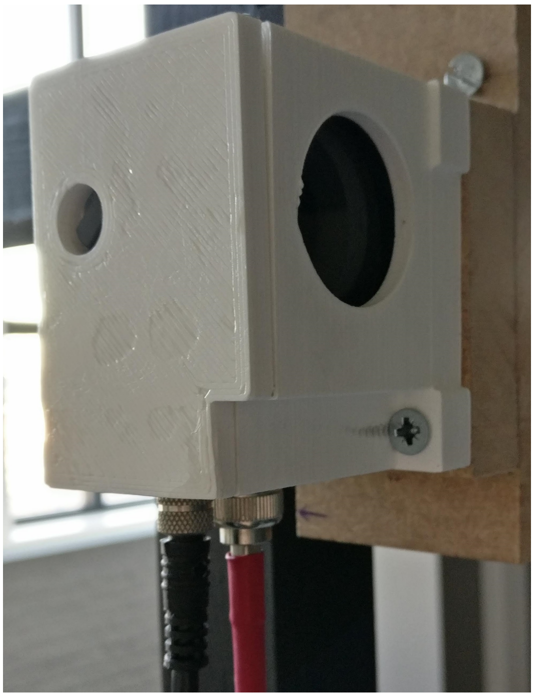

Figure B.5: Photo of the RX part.