VISIBLE LIGHT COMMUNICATION

by

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The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “VISIBLE LIGHT COMMUNICATION” by Durgesh Gujjari in partial fulfilment of the requirements for the degree of Master of Applied Science.

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To my parents Nagendra Prasad and Laxmi Rajyam

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ABSTRACT

White LEDs (Light Emitting Diodes) in Visible Light Communication (VLC) is an emerging technology that is being researched so it can eventually be used for common communications systems. LEDs have a number of advantages, one of which is long life expectancy. However, like many emerging technologies, VLC has many technical issues that need to be addressed. We proposed an optical indoor wireless communication system that used white LEDs like plug-in devices. We developed a practical implementation of VLC and demonstrated it experimentally. In particular we focused on designing a prototype of VLC that can be used without having to make major changes to the present infrastructure with two types of protocol — namely RS-232 and USB — for data transmission.

LIST OF ABBREVIATIONS AND SYMBOLS USED

VLC	Visible Light Communcaition
LED	Light Emitting Diode
RGB	Red-Green-blue
Ge	Germanium
GaN	Gallium Nitride
USB	Universal Serial Bus
UART	Universal Asynchronous Receiver/Transmitter
BPS	Bits Per Second
DTE	Data Terminal Equipment
DCE	Data Circuit Terminating Equipment
TTL	Transistor-to-Transistor Logic
DC	Direct Current
Op-Amp	Operational Amplifier
FOV	Field of View
E1	Lower energy level
E2	Higher energy level
ν	Optical frequency
W_g	Band gap of semiconductor
eV	Supplied energy (electron volt)
h	Plank's constant
λ	Wavelength
R_B	Base Resistance
I_b	Base Current
I_C	Collector Current
I_E	Emitter Current
I_{IB}	Input bias current
I_{CBO}	Collector-Base leakage current
Lx(lux)	SI unit of illuminance and luminous emittance

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

This chapter will provide the motivation for this thesis, describing the importance of visible light communication in various aspects. Finally, the objectives and organization of the thesis will be stated.

1.1 Introduction of Visible Light Communciation (VLC)

Humankind has been utilizing light as a communication medium for many years, and light continues to be of great benefit in the field of communication. Fire has been used to make smoke signals on clouds; that is a kind of visual communication. After the invention of the electric light bulb by Thomas Alva Edison in the 19th century [5], new ways were developed to use light to communicate. The invention of the electric bulb led to the invention of the Signal Lamp, a visual signalling device used for optical communication invented by Arthur C. W. Aldis. Typically, the Signal Lamp uses Morse code to give information to the observer by making shutters mounted on the front of the lamp open and close [6].

The idea of using light as a communication medium was implemented by Alexander Graham Bell in 1880 with his invention of the photophone, a device that transmitted a voice signal on a beam of light. Bell focused sunlight with a mirror and then talked into a mechanism that vibrated the mirror. The vibrating beam was picked up by the detector at the receiving end and decoded back into the voice signal, the same procedure as the phone did with electrical signals. But Bell could not generate a useful carrier frequency, nor was he able to transmit the light beam from point to point. Obstacles in nature such as fog and rain — which could interfere with the photophone — made Bell stop any future research into his invention [7]. With the invention of LED (Light Emitting Diode), the idea of using light as a communication medium has started again. VLC uses white Light Emitting Diodes (LED), which send data by flashing light at speeds undetectable to the human eye. One major advantage of VLC is that we can use the infrastructure around us without having to make any changes to it. LEDs' ability to transfer information signals over light (light which is between 400THz to 800THz of frequency and whose wavelength is between 400nm to 700nm) makes it a very good communication medium. Now the light we use in our daily life can not only be used for providing light but also for communication.

1.1.1 Applications

Why use LEDs ? LEDs have many advantages both in communication and lighting purposes. Some of them are :

- Longer life time (on average, LEDs last three to five times longer than fluorescent and 20 to 30 times longer than incandescent light) [8].
- High brightness (3watt LED can produce as much illumination as a 45watt incandescent light bulb) [9].
- Lower energy consumption (and environmentally friendly) [2].
- Fast switching (due to an LEDs' short response time, it can modulate easily for the purpose of communication. By quickly switching LEDs on and off (brighter and dimmer).
- Current adoption for traffic signals [3] [4].

1.2 Motivation and Objective

Upon detailed investigation of VLC research, it was found that not a lot of research has been done to develop this technology for commercial use. But because research into VLC is relatively new, the possibilities are wide open. A lot of research is being done to make this technology available for commercial use in various fields, including Internet access and vehicle-to-road communication using traffic signal lights. From our review of the literature, it became evident that work should be done to look into the possibility of designing a new model that could fit the present infrastructure for indoor applications. Therefore, the objectives of the research presented in this thesis can be summarized as follows:

- Develop a prototype of VLC and demonstrate its efficacy by using commercial LEDs.
- Present detailed experimental work on the prototypes and discuss the performance.
- Suggest a guideline for the design and implementation of future development of the prototypes.

1.3 Contributions

As the contributions of this thesis, the models proposed in this thesis were designed with RS-232 and USB. As a result, they can be easily integrate with the present infrastructure. The first prototype was integrated with the existing Terminal Emulation Program (Hyper-Terminal), which was already present in the computer. The second prototype is designed for simple connection to the computer USB comports; it needs Terminal v1.9b software, which is available for free. For better understanding of the commercial use of the white LEDs for lighting and transmission range, illumination distribution and power distribution of the white LEDs were then measured and plotted. These designs, when truncated further, can be used as plug-in devices for low-cost commercial usage.

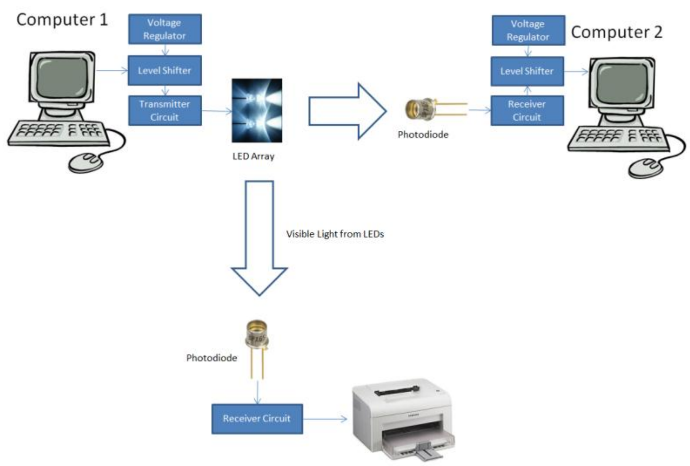


Figure 1.1: VLC Prototype Model.

The above Fig. 1.1 illustrates the basic idea of the entire model design. The basic idea is to make two computers talk with each other using free space light propagation. Two models with different interfaces were proposed, namely RS-232 and USB. Prototype 1 was designed to be compatible with RS-232 interface and Prototype 2 was designed to be compatible with the USB interface.

1.4 Organization of the Thesis

Chapter 1 of this thesis serves to provide an overview of the basic concepts and techniques in physics and engineering and also shows several designs that are required for the implementation of VLC. Chapter 2 provides the background needed for the VLC designs. Chapter 3 provides the literature review of the VLC technology. Chapters 4 and 5 provide the experimental setup and implementation of the models. Chapter 6 presents recommendations for improving the designs, as well as the conclusion with suggestions for further improvements in the work.

CHAPTER 2

BACKGROUND THEORY

This chapter will provide some background for the information that was needed for this thesis, which includes light emitting diodes, photodiodes, transistors, amplifiers, and Rs232/USB interfaces.

2.1 Light Emitting Diode (LED)

In this study, the work is concentrated on the semiconductors formed by P-type and N-type materials. Light emitting diode (LED) is a PN junction semiconductor that emits light when forward biased releases the energy in the form of photons [10]. This effect is called as electroluminescence. What makes LED different from other diodes? It is the bandgap of the LED which is designed for radiative recombination.

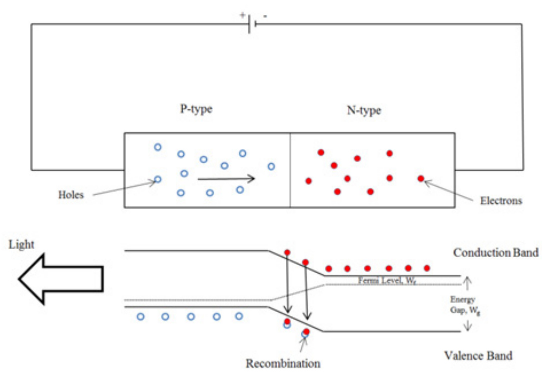


Figure 2.1: LED PN- junction biasing arrangement and the energy bands associated with the diode [10].

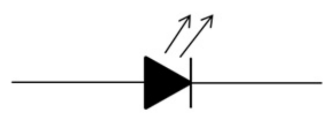


Figure 2.2: The circuit symbol representation of LED [10].

When joining the N-type and P-type materials, the Fermi levels (W_f) will be aligned and will produce an energy barrier even when there is no external voltage applied. There are two energy bands, namely the conduction band and valence band, which are separated by a forbidden region with the width of W_g. In the conduction band, electrons not bound to individual atoms are free to move [10]. In the valence band, unbound holes are mobile and have positive charge. The free electrons in the N region cannot go up the barrier without the external energy; that is the same for the holes that cannot surmount the barrier. By applying a sufficient energy (eV), a free electron crosses the barrier, falls into the lower energy level and recombines with the hole, releasing the energy in the form of photons.

2.2 White Light Emitting Diodes

Although every color can be produced by LEDs within the visible region, white light is the most desirable color for general illumination. The visible radiation detectable to the human eye is between 480nm to 750nm [29]. White light emission from an LED is by mixture of multi-color LEDs or by the combination of phosphors with blue/UV LED emission [12]. There are different types of white LEDs. Some of the important ones are:

2.2.1 Phosphor based White LEDs

The InGaN blue LED is coated with with phosphor. The wavelength converting phosphors is combined with a blue LED to emit white light [12], [13]. The chip inside the LED emits blue light when external voltage is applied. The emitted blue light passes through the yellow phosphor, yielding white light emission.

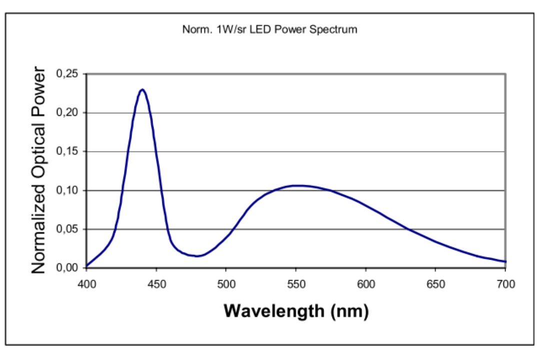


Figure 2.3: Normalized optical spectrum of a white LED [33].

From the resulting optical spectrum in Fig.2.4, the left peak is due to the blue LED, while the wider right emission corresponds to the yellow phosphor [33]

2.2.2 Ultraviolet (UV) based White LEDs

Ultraviolet LEDs were fabricated with pre-coating blue/green/red phosphors onto ultraviolet (UV) LED to emit white light [12], [13].

2.2.3 RGB (Red-Green-Blue) LEDs

An RGB (red, green, blue) 3-chip LED is a mixture combination of three colors to produce white light with little variance in the Kelvin color temperature [15]. What we see coming from the sun is white light. We know that the visible spectrum of radiation that the sun emits is actually a broad range of wavelengths, ranging from red to orange, yellow, green, blue, indigo to violet (ROYGBIV). When this broad range of colors impinges on our retina, our brain interprets it as “white”. A tri-color LED tries to mimic this effect by outputting a board range of wavelengths (red, green and blue). Note that the three dominant wavelengths of the tri-color LED are at the ends and the center of the visible spectrum, thus attempting to replicate the coverage of the range and getting close to (ROYGBIV) as possible (with minimal hardware). So, it is less of a mixing and more of an attempt to create a continuous function by using a few sampled points.

2.3 Photodiode

A photodiode converts the incident light into the current. It works on the principle called photo-conduction, whereas LED works on the principle of electro-luminance. The photodiode is a type of photodetector which converts the light to either current or voltage [10], [38].

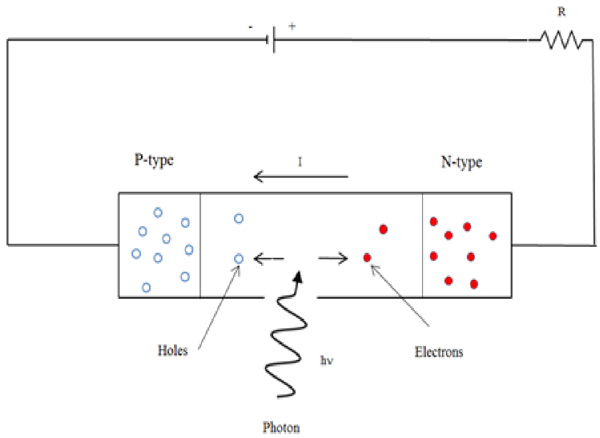


Figure 2.4: Basic biasing arrangement and construction of photodiode [10].

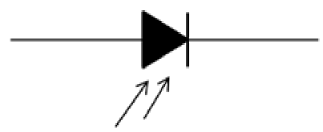


Figure 2.5: Circuit symbol representation of photodiode [10].

2.3.1 Modes of Operation

2.3.1a Photovoltaic Mode

Photovoltaic mode, also called as zero bias operation, occurs when no external voltage is given to the photodiode. The photo-current generated is fixed and also linearly dependent on the incident radiation level [10].

2.3.1b Photoconductive Mode

The diode is reverse biased (cathode positive and anode negative), which increases the depletion region width, reducing the junction capacitance. This results in faster response time. However, in this mode the effects of noise and dark currents will be more [10], [38].

2.4 Transistor

A transistor is a semiconductor device, which can be used as an amplifying or controlling and generating electrical signal. A transistor consists of three regions: collector, base and emitter. In 1947, John Bardeen and Walter Brattain invented the transistor [18]. They added another junction to a P-N junction, which controls the flow of majority carries. In 1951, William Shockley made the modern version of the transistor.

2.4.1 N-P-N and P-N-P Configuration

The transistor contains two junctions; they are formed by sandwiching with p-type and n-type semiconductors. There are two types of transistors: NPN transistor and PNP transistor.

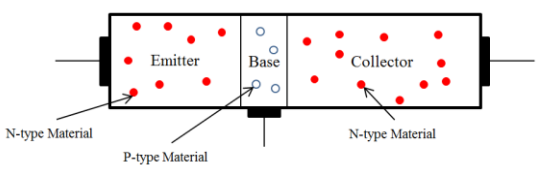


Figure 2.6: NPN transistor [19].

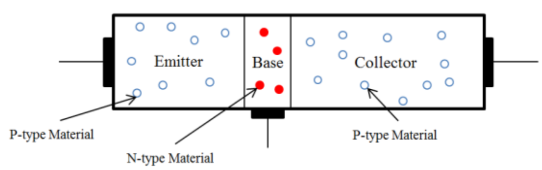


Figure 2.7: PNP transistor [19].

From the Fig. 2.7 and 2.8, the PNP transistor consists of a narrow N-region (base) in the middle while the NPN transistor has a narrow P region in the middle. The three layers are categorized as emitter (negative charge), base (positive charge) and the collector (negative charge). From Fig. 2.6, If the emitter-base junction is forward biased and collector-base junction is reverse biased. The forward bias causes the electrons in the emitter to flow towards the base. This constitutes the emitter current I_E. As the electrons flow through the P-type base, they tend to combine with holes. As the base is lightly doped , only a few electrons (less than 5%) combine with holes to constitute base current I_B. The remaining (more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector current region. The current from emitter to collector is several hundred times greater than the current from emitter to base, making a transistor a powerful amplifier [19].

2.5 Voltage Comparator

The output of the comparator depends on the differential input voltage value. If the difference of the input voltages is positive, then the output of the comparator is positive. If the difference of the voltages at the input terminals is negative, then the output is negative. The output of a comparator is a square wave.

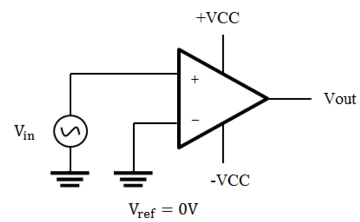


Figure 2.8: Voltage Comparator configuration [21].

2.6 RS-232 Interface

RS-232 is a single ended electronic data communication between the DTE (data terminal equipment) and DCE (data circuit terminating equipment) in computer serial ports. It supports the bit transmission rate up to 115,200 bps in serial communications [22].

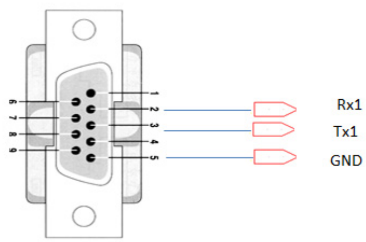


Figure 2.9: DB-9 female connector.

In this work, we only have to concentrate on the transmitter (pin 3); the receiver (pin 2) has a voltage swing of +/- 12v; also pin 5 is ground.

2.7 Universal Serial Bus (USB)

It is the replacement of serial and parallel port communications with more efficiency and ease of use that supports a data rate of 12Mbps (USB 1.0), 480Mbps (USB 2.0). The new version of USB 3.0 can run up to 5Gps. USB was designed in such a way that it can connect easily to all the computer peripheral devices. It is a hot plug and play with +5v at the source [25], [26].

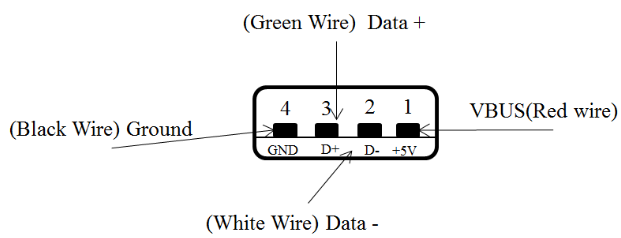


Figure 2.10: Standard USB plug A [25].

CHAPTER 3

LITERATURE REVIEW OF VISIBLE LIGHT COMMUNICATION

This chapter provides an overview of the topics that supplied the ideas for this thesis. The following sections examine the previous works which have been done on implementing Visible Light Communication technology. Finally the Avenue of the approach for the thesis.

3.1 The Visible Light Communication System Considered

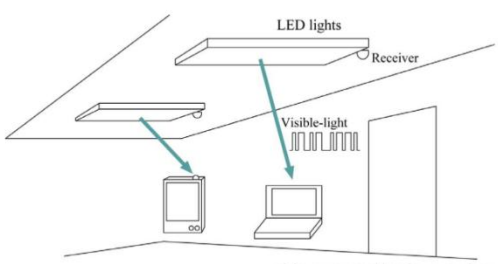


Fig 3.1: VLC model room [1].

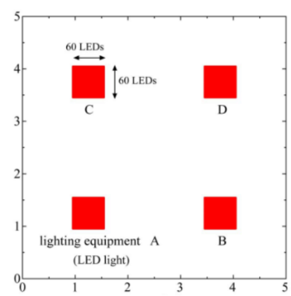


Fig 3.2: Distribution of LEDs inside model room [1].

An indoor visible light communication system using white LEDs under consideration is shown in Fig. 3.1 & 3.2 [1]. All the lights in the room are replaced by LEDs. The LEDs are not only used for illuminating the room but also for an optical wireless communication system. On-off Keying Return-to-Zero (OOK-RZ) coding is used for modulating white LEDs. Optical lighting and optical transmission of the white LEDs have been tested to evaluate the requirements of using VLC for indoor applications. The effects of the delay problems faced in the high data rate transmission have been studied and presented [1].

3.2 Visible Light Road-to-vehicle Communication Using High-Speed Camera

LEDs are already being used in traffic lights, and they can be used as the communication medium. Road-to vehicle communication using the LEDs in the traffic signal lights was proposed.

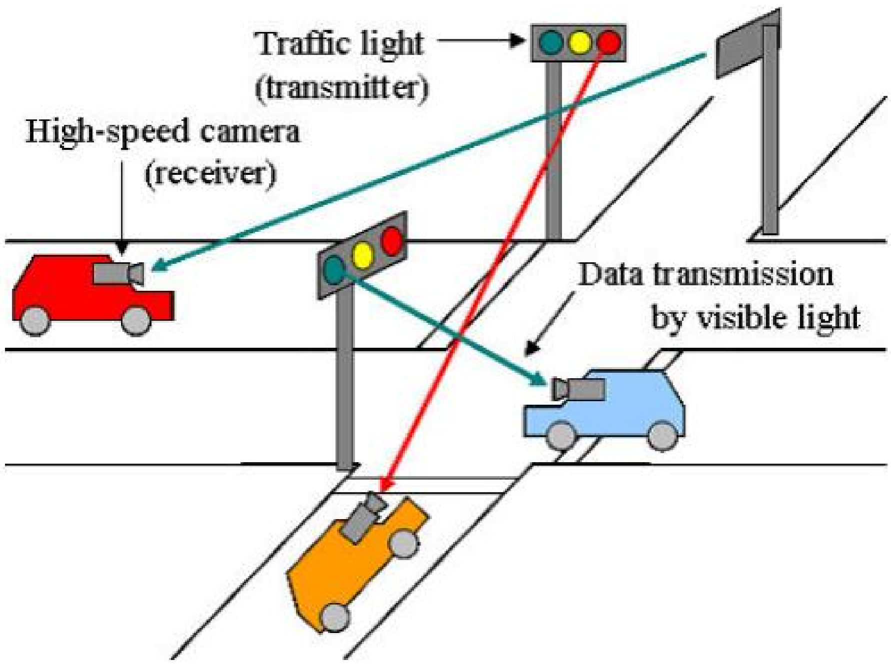


Figure 3.3: Road-to-vehicle visible light communication [17].

The above Fig. 3.3 shows the basic usage of LED as a transmitter and CAMERA as a receiver. In this model, they mounted a camera before the front end of the car. The camera is used as the information receiver from traffic signal lights. The advantage of using the camera is that multiple data can be transmitted by the LEDs and received by High-speed cameras [17].

3.3 Integrated System of White LED Visible-Light Communication and Power-Line Communication

In [2], optical communication using the existing power-line in a household is proposed as shown in Fig. 3.4 and Fig. 3.5.

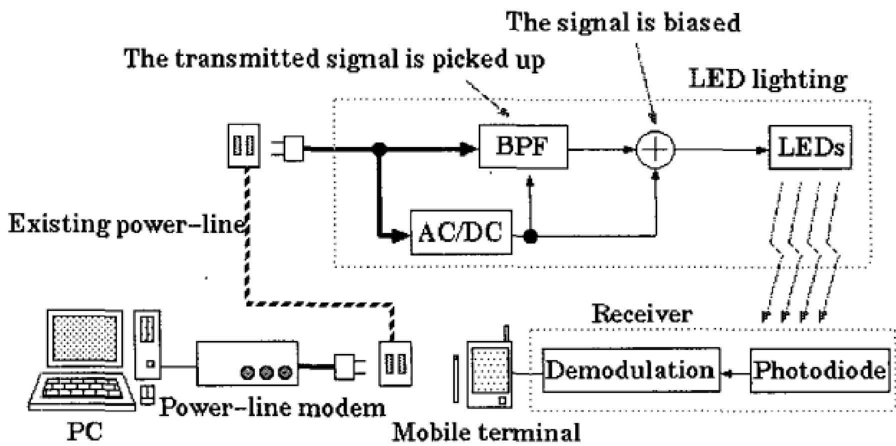


Figure 3.4: System model [2].

The power-line is used for communication between white LEDs and other fixed networks. The already installed power-lines and outlets behave as data networks and ports.

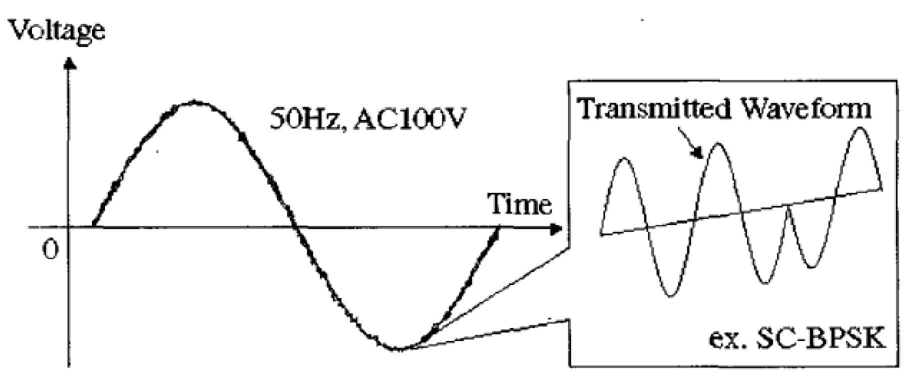


Figure 3.5: Waveform on power-line [2].

As in optical intensity modulation, the transmitted signals are added to the cyclic waveform of the alternating current (AC). The transmitter signal from the PC is picked by BPF through the power-line, and biased before sending to the LED lights. The electrical signal is then converted into an optical signal by LEDs and sends it to the photodiode, where it converts the captured optical signal to an electrical signal. The signal is demodulated according to the received level of light and then is passed to the mobile terminal [2].

3.4 Visible Light Communication for Advanced Driver Assistant Systems

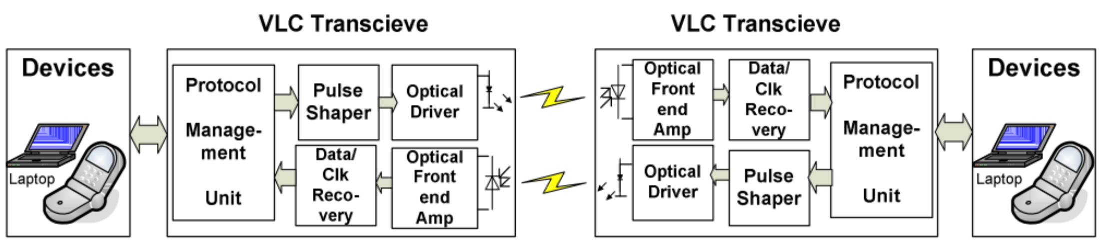


Figure 3.6: General architecture for a full duplex VLC system [4].

Optical communications for outdoor communication has been discussed and elaborated upon [4]. Devices such as laptops and mobile phones can be used for transmitting and receiving information, using transceivers, as shown in Fig. 3.6. Transceiver systems use both LEDs and photodiodes. Intensity modulation was implemented to reach the most viable modulation. Various important design parameters were optimized by using intensive investigation based on gain variation over 100m of transmission range [4].

3.5 A Dual-Use Visible Light Approach to Integrated Communication and Localization of Underwater Robots with Application to NonDestructive Nuclear Reactor Inspection

A VLC system for wireless underwater communication was proposed in [23] for robotic inspection of nuclear power plants; there the reactor exists in an underground environment as shown in Fig. 3.7. A solution for maintaining the consistent line of sight to maintain a communication link was discussed in detail in [23].

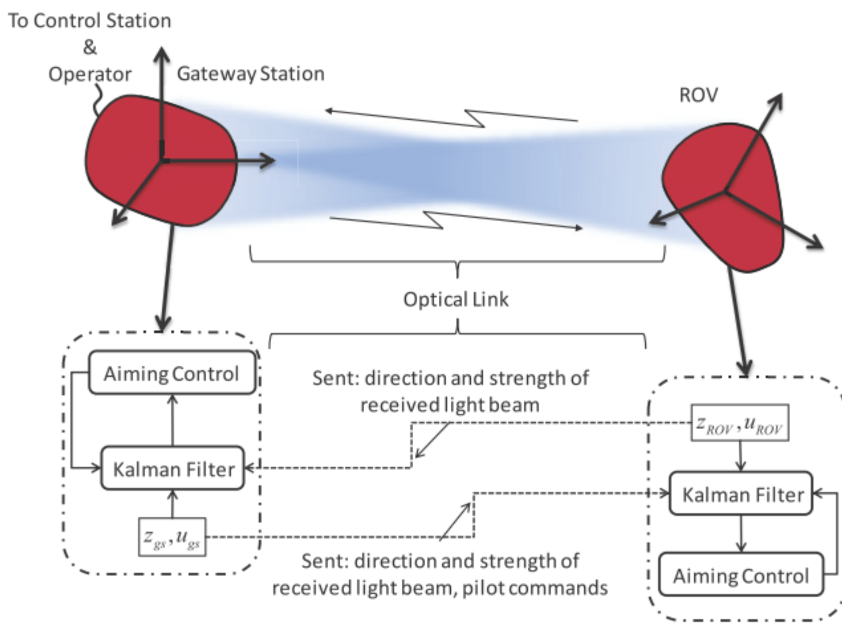


Figure 3.7: Architecture of the dual-use optical communication system [23].

An optical wireless link has been established between the Remotely Operated Vehicles (ROV) and gateway station using LEDs and Photodiodes on both sides as depicted in Fig 3.7. Underwater ROV was used to communicate with the gateway station over water to transmit control signals. Both the gateway station and ROV are capable of directing a light beam in the three-dimensional space [23].

3.6 Study of Visible Light Communication System Using RGB LED Lights

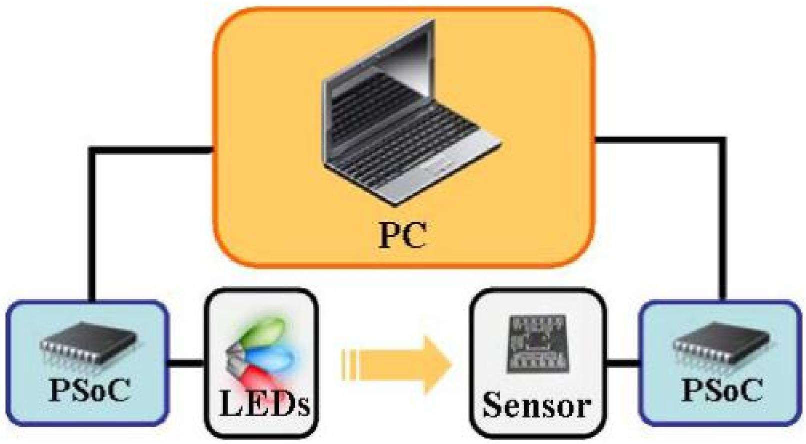


Figure 3.8: Outline of the system [24].

A prototype was designed to demonstrate wireless VLC using RGB LEDs and sensors [24]. As shown in Fig. 3.8, on the left are the RGB LEDs used as signal transmitters. The right side is the RGB sensor, which is used as a receiver. The RGB LEDs enable parallel signal communication, and a PSoC microcontroller is used to control them, thus significantly reducing the need for extra circuits. Pulse Width Modulation was used to switch RGB LEDs at high speeds. The characteristics of both the variation in color and change in intensity of each RGB LED and RGB sensor were analyzed to realize multiple-value signals communication by using RGB color [24].

3.7 Visible Light Communication Link for Audio and Video Transmission

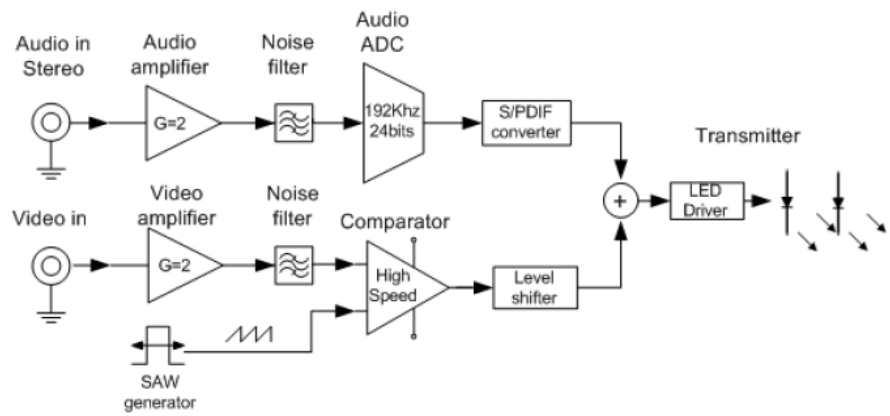


Figure 3.9: Block diagram of transmitter module [27].

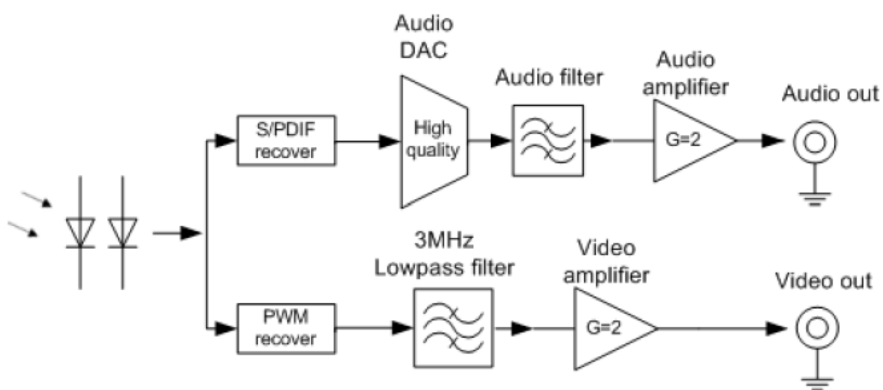


Figure 3.10: Block diagram of receiver module [27].

A VLC system to transmit high quality video and audio signal was proposed and demonstrated by using illumination LEDs in [27]. The analog video signal was modulated by using an ultra high speed comparator in the transmitter. The analog signal was converted from analog to digital. Both the video and analog signals were transmitted using the illumination LEDs in the transmitter. The photodiode at the receiver senses the optical signals from the LEDs and is converted into electrical signals. The electrical signal is then amplified to recover the digital signal and converted back to an analog signal to video/ audio out [27].

3.8 Ultra Thin Secondary Lens for Visible Light Communication Based on a White LED

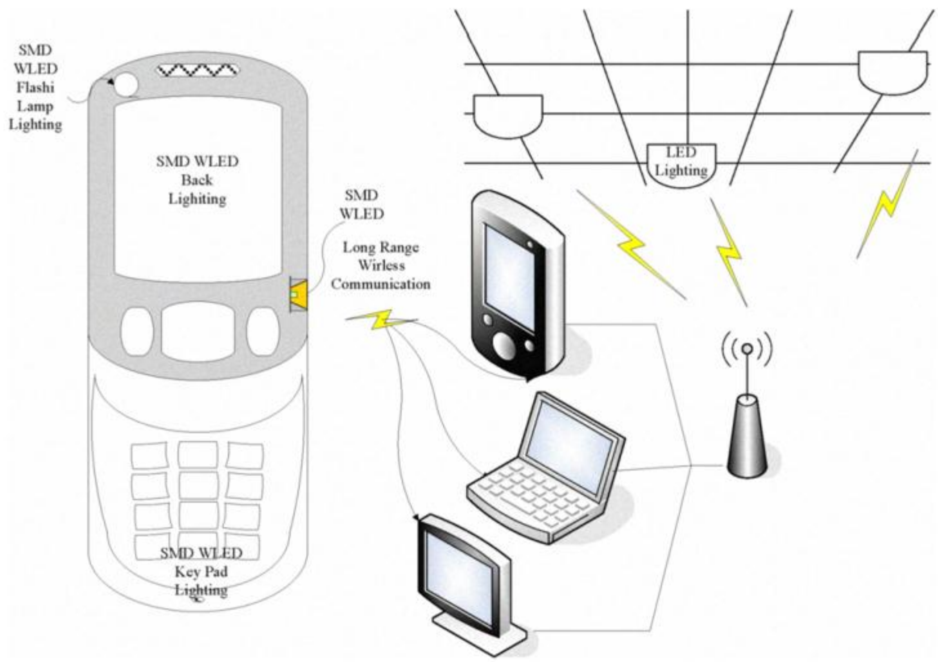


Figure 3.11: VLC system using WLED for personnel mobile telecommunication device [42].

A new design was proposed in [42] for an ultra-thin secondary lens by using white Surface Mount Device (SMD) LEDs for VLC. The GaN-based blue LEDs are used as SMD LEDs and were mounted directly on the surface of the mobile device. The SMD LEDs are used for optical transmission between mobile devices. The precise modeling of the GaN chip was analyzed and verified. The modeling data were compared with measured data to verify the proposed model.

3.9 Avenue of Approach

In future, LEDs are expected to replace all the incandescent and fluorescent lights. VLC technology focuses on utilizing the LEDs not only for lighting, but also for communication. Many models have been proposed using LEDs as communications means in various applications, for example, traffic lights for signalling [17], accessing the Internet in a room [1] and underwater communication using remotely operated vehicles (ROVs) [23]. Based on the literature review, several methods were considered for utilizing VLC technology when deciding how to proceed with the thesis. This thesis work concentrates on using LEDs for indoor usage. If all the lights in our houses and offices are replaced by LEDs, free space optical communications can then be achieved. Wireless optical communication between computers has been proposed for indoor applications. The proposed model is easy to implement, just like plug-in devices that require no additional hardware.

CHAPTER 4

EXPERIMENTAL SETUP FOR PROTOTYPE 1

4.1 Design of Prototype 1

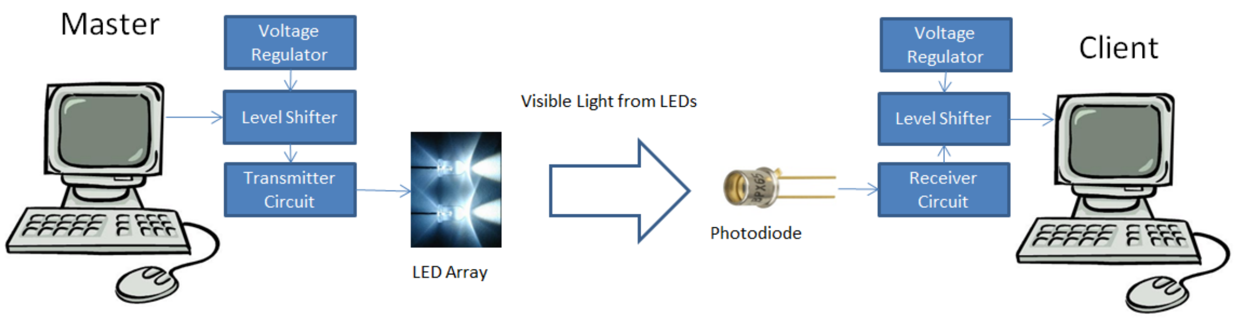


Figure 4.1: Design of prototype 1 with RS-232 interface.

The prototype was designed to demonstrate serial communication between two computers with RS-232 interface as shown in Fig. 4.1. The voltage regulator supplies constant voltage to the level shifter from the power supply by maintaining constant DC voltages and avoiding unwanted spikes in current. The level shifter helps to convert the high voltages of RS-232 (which are +/- 11V from the model computer) to transmitter and receiver circuit levels (which are 0 to +5V). The electrical data from the computer is converted into optical data using LEDs and transmitted over light, the optical data is captured by the receiver, converted into electrical data by the photodiode and sent it to the client computer. All the circuit designs in this thesis are drawn using PSPICE simulation software.

4.2 Observation of LED Performance

The performance of a single LED was tested in the laboratory to examine the limitation and the setup is shown in Fig. 4.2a with the measurements in Fig. 4.2b.

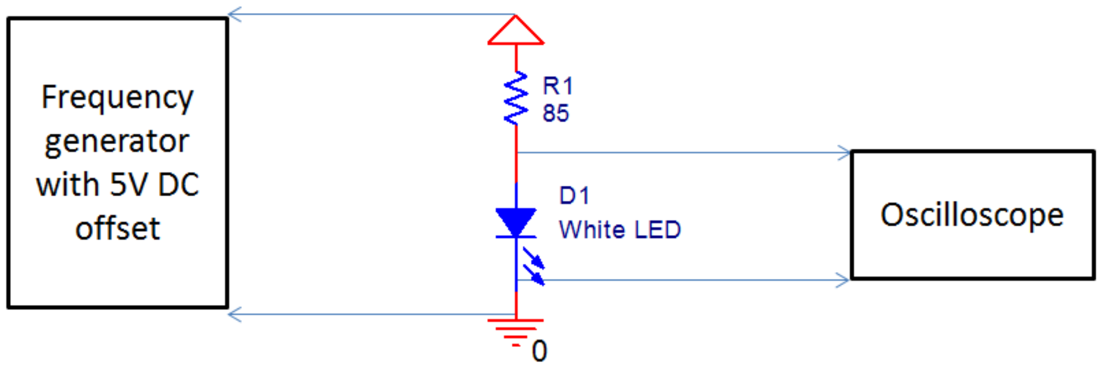


Figure 4.2a: Circuit representation of LED observation

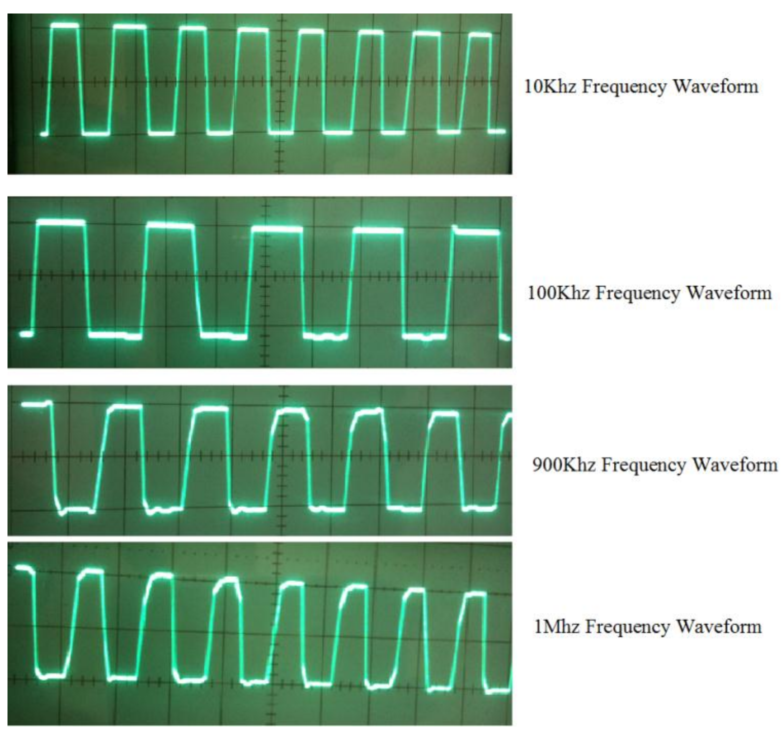
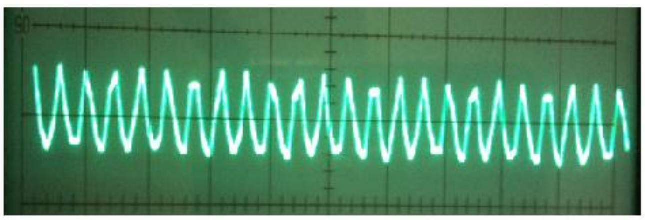


Figure 4.2b: Voltage waveforms across an LED for different frequencies (2V/DIV).

The white LED with a forward voltage of 3.3V drives 20mA of current with resistor R1 in Fig. 4.2a (DC offset of 5V from function generator). The waveforms across the white LED for different frequencies were observed using the oscilloscope in Fig. 4.2b. As seen from the waveforms shown in Fig. 4.2b of different frequencies, the waveform maintains rectangular shapes at 10kHz and 100kHz , but when compared with 1MHz frequency, the waveform is distorted, hardly managing a square shape.



After 1Mhz Frequency Waveform

Figure 4.3: Waveform across an LED at 10Mhz frequency.

The LEDs have capacitance associated with the depletion region and the minority carriers that transport the charge. As a result, the driving signal has to charge and discharge capacitance. Due to the limited charging/discharging speeds, the frequency performance is limited. The waveform at 10MHz shown in Fig. 4.3 requires the charge and discharge too fast for a capacitance to catch up with.

4.3 Photodiode Performance

MRD-500 photodiode is used for the receiver to capture the optical signal from LED at high frequencies. The response time of MRD500 photodiode is 1nS.

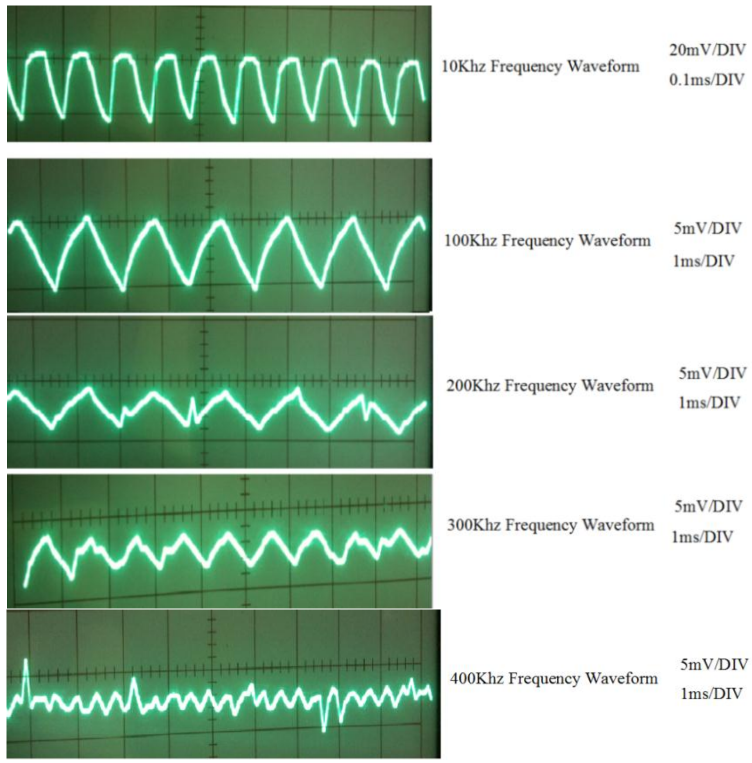


Figure 4.4: Voltage waveforms captured by MRD-500 photodiode.

Fig. 4.4 shows the voltage across the photodiode (captured from oscilloscope) looks triangular. This might be because of the slow time constants involved [46]. The photodiode, when receiving light pulses, behaves like a weak current source causing the capacitance to charge or discharge but too slowly to catch up the charge of the signals. (in our case it was the junction capacitance of the photodiode that was in parallel with the oscilloscope probe capacitance) [46]. At 400kHz frequency, the waveform has hardly managed its rectangular form. MRD500 photodiode, does not work for frequencies higher than 300kHz. After evaluating the performance of light emitting diode and photodiode, the transmitter and receiver circuit is built accordingly.

4.4 Transmitter Circuit

The Transmitter side has a voltage regulator, level shifter and the LED driver circuit.

4.4.1 Voltage Regulator

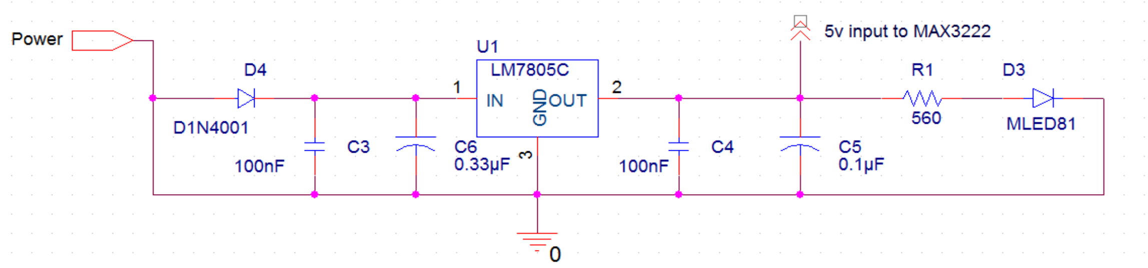


Figure 4.5: Voltage regulator.

The voltage regulator is for supplying the constant voltage to the MAX3222 chip level shifter. It is needed because the unregulated voltage coming from our electricity provider can fluctuate greatly depending on several factors, including time of day and appliances powering on and off. Using a voltage regulator compensates for all these problems and protects the MAX3222 level shifter.

According to the data sheet of LM7805c, two capacitors are enough to give a constant voltage output. However, for getting pure regulated DC output without any oscillation, additional capacitors have been added [37]. Two additional capacitors are used at the input and output terminals of the IC to smooth any oscillations which generate from the IC.

4.4.2 MAX3222 Level Shifter

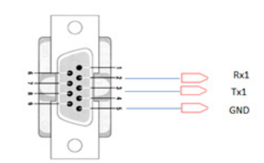


Figure 4.6: DB-9 female connector of transmitter computer.

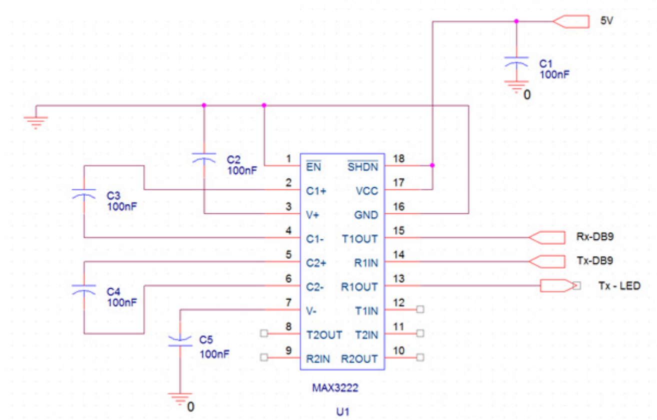


Figure 4.7: Max3222 Level shifter for transmitter circuit.

The Fig. 4.6 and 4.7, shows the connection of DB-9 connector to the MAX3222 level shifter. The MAX3222 transceiver is a level shifter which takes the +/- 12v levels of Rs-232 and converts them to 0 to 5V of TTL levels. The Rs-232 interface on the computer uses -3v to -12v logic 1 and +3 to +12v for logic 0. The transmitter circuit, however, uses VCC as a logic 1 and 0V as logic 0. MAX3222 is used to interface between the RS-232 and TTL variants. It takes +/- 12V from Rrs-232 and gives out 0 to 5V. It also protects the transmitter circuit from voltage spikes from the RS-232 interface [44].

Most computers are limited to 115kbps at RS-232 interface; MAX3222 is guaranteed to work up to 120Kbps while maintaining the RS-232 output levels. The capacitors in MAX3222 are added according to the data sheet. These capacitors, C3 and C4, are charge pump capacitors used to create either higher or lower voltage power sources, whereas C1 and C5 are the reservoir capacitors used to smooth the small, unwanted, residual periodic variation of the direct current (DC). In addition, SHDN is connected to VCC so that the chip won't be deactivated completely. Also, EN has been pulled to GND to enable the activity at the receiving end [44].

4.4.3 LED Driver Circuit

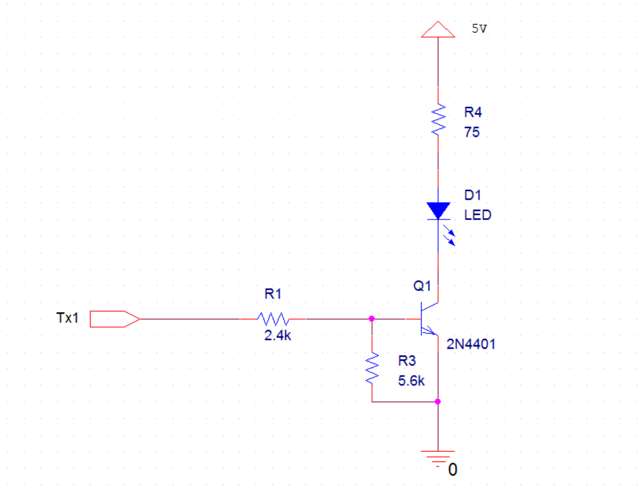


Figure 4.8: LED Driver Circuit 1.

The signal from MAX3222 is sent to the transmitter driver circuit as shown in Fig. 4.8. The transistor 2N4401 serves as a switch to control the LED to turn ON and OFF. The LED will turn ON for 5V and OFF for 0V from the PIN 13 of MAX322. An LED is a semiconductor, which behaves differently when compared to the resistor. After examining the characteristics of the 2N4401 transistor, the transistor can work in MHz frequency range. It is not a problem for this model design, since MAX3222 is designed to work up to 120Kbps which is approximately 50 kHz frequency. R_3 is introduced to divert the collector-base leakage current (I_{CBO}), which flows from the collector to the base of the transistor. If this current is not diverted, it will flow from the collector into the base-emitter junction, which will lead it to act as a base current coming from outside. This can be a problem because this base current can amplify the transistor's gain. By placing R_3 between the base to the ground, it will divert the leakage current to the ground instead of going into the base-emitter junction. The selection of the R_3 is critical. If the value is too high, it will not divert enough leakage current; if the value is too low, the normal base current is driven too much and the transistor base won't get enough base current to turn the LED ON. Consequently R_3 value should be selected such as way that it should be high enough to divert the leakage current, but it should be lower than the base current. Also, the value should be low enough such that the voltage drop across the resistor must be less than the voltage across the base-emitter (V_{BE}) due to I_{CBO}.

According to the datasheet of 2N4401, I_{CBO} = 100 nA = 0.1 μA,

The current diverted by 5.6 KΩ resistor is then derived from the following equation

$$I_{R3} = \frac{V_{BEsat}}{R_3} = \frac{0.75}{5.6*10^3} = 133\ \mu A(\text{Approximately}), \tag{3.1}$$

where $I_{R3} > I_{CBO}$. Since I_B is 1.9 mA , I_{R3} won't affect the transistor from turning ON while diverting the leakage current.

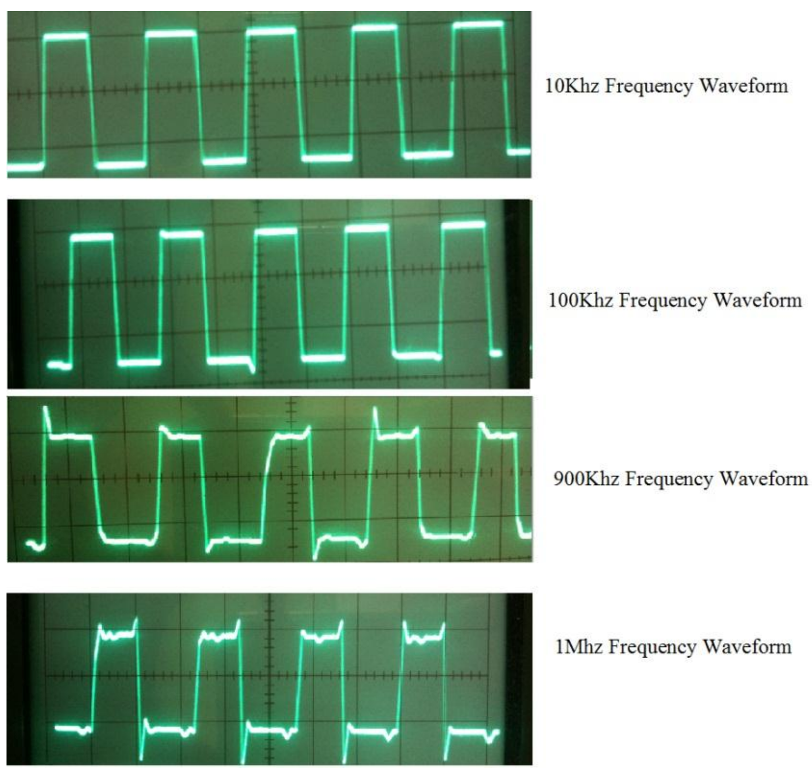


Figure 4.9: Voltage waveforms captured across the LED (2V/DIV).

Even though the waveform has distortions at 1MHz , it roughly still maintains the square shape.

4.5 Receiver Circuit

The receiver side has a voltage regulator, level shifter and the photodiode driver circuit.

4.5.1 MAX3222 Transceiver

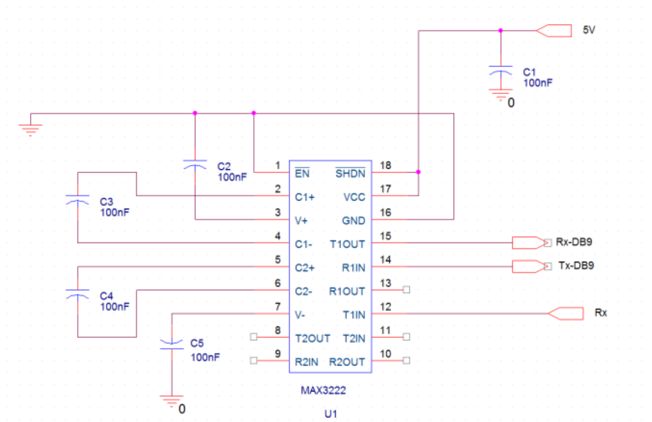


Figure 4.10: MAX3222 transceiver for receiver circuit.

The operation of the MAX3222 is similar to the operation explained in the transmitter circuit section in 4.7 with a few changes. The output of the receiver circuit is fed to the pin 12 (T1IN) and the pin 15 (T1OUT), where the voltage levels are converted from TTL TO RS-232, is fed to the DB-9 pin 2 (receiver).

4.5.2 Voltage Regulator

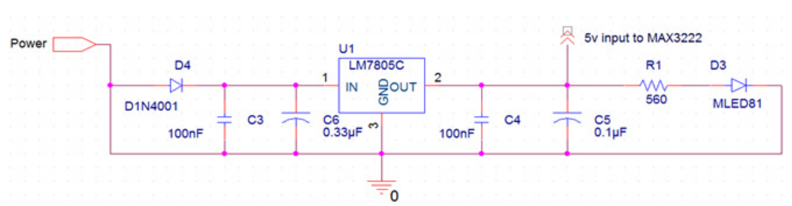


Figure 4.11: Voltage Regulator for receiver circuit.

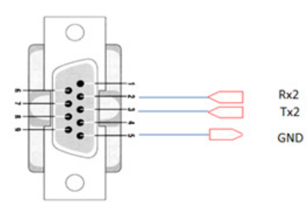


Figure 4.12: DB-9 female connector on receiver.

The function of the voltage regulator is the same as that explained at the transmitter side in 4.4.1, to provide constant voltage to the MAX3222.

4.5.3 The MRD500 Photodiode Driver Circuit

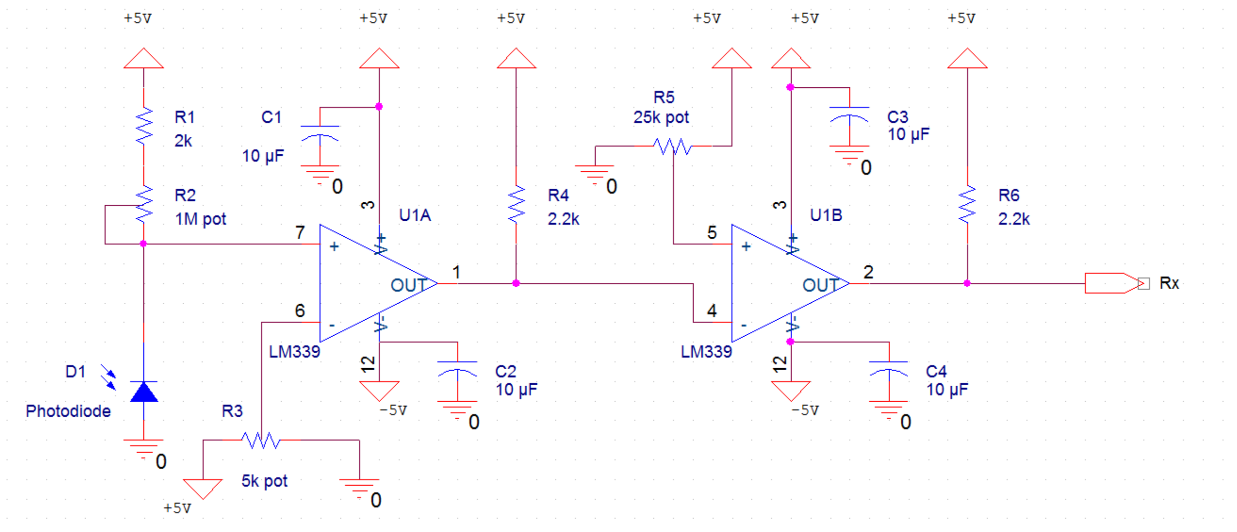


Figure 4.13: MRD500 Photodiode driving circuit.

The driver circuit is shown in Fig. 4.13. The capacitors C1, C2, C3 and C4 are the smoothing capacitors connected across the DC supply to act as a decoupling capacitor. Sometimes, the power supply supplies an AC signal superimposed (also known as noise) on the DC power line. Such a signal is undesirable for the electronic circuits because they need pure DC supplies. A decoupling capacitor prevents the AC signal by decoupling it from the power supply and giving the pure regulated power supply to the comparator. Choosing to use R4 or R6 depends on the comparator output current. According to the LM339 data sheet, the maximum current it can drive is 16mA. Therefore, R4 and R6 must be chosen so that they both won't drive more current than specified. R4 and R6 drives total of 4.4 mA of current (2.2 mA current individually). R1 is used to protect the photodiode in default when adjusting the 1M pot (R2) to a very low value. The photodiode is reverse biased with the series with R1 and R2 so that the current flow can be controlled and will not allow a large current to flow through the photodiode when exposed to intense light. R2 is regulated until the square wave is seen. The photodiode is reverse biased since it decreases diode capacitance. The photodiode voltage bias is connected to the non-inverting input pin 7 of the Quad comparator LM339. The 5K pot (R3) is introduced to the inverting pin so that the voltage can be adjusted accordingly. On the other hand, R2 value depends on the light intensity threshold. The LM339 quad comparator is designed so that it will hold at a voltage which is set by both the non-inverting pin 7 and the inverting pin 6 when the photodiode is not exposed to the LED light (in this case it is 0.54V). When the photodiode is exposed to LED light, the voltage across the photodiode changes accordingly with the LED ON and OFF switching causing the voltage change to the non-inverting pin 7. The square wave output from the pin 1 has resulted from the voltage change in the non-inverting input of LM339. The Rx pin at the output goes to the MAX3222 level shifter receiver.

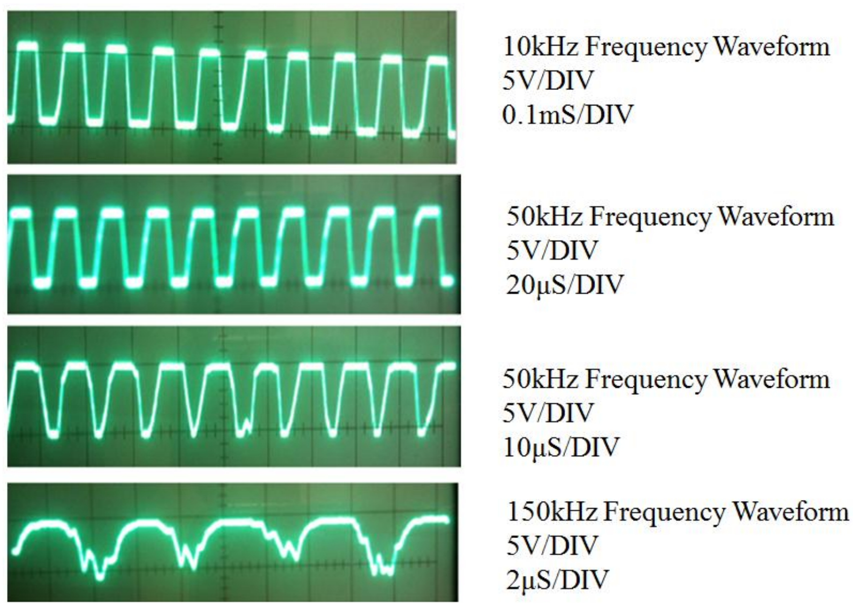


Figure 4.14: Waveform from the receiver circuit across resistor R_6.

The signal is a perfect square at 10kHz and 50 kHz frequency from LM339 comparator output. When increased more than 50 kHz frequency, the signal shape is distorted; it is improved by replacing the 2.2k resistor with lower value at the output; for higher frequency, we need a high-power output drive. But for this model, we only concentrate up to 50 kHz frequency since RS-232 interface will only work upto 115Kbps.

50Khz Frequency Waveform

5V/DIV

10µS/DIV

Figure 4.15: Output waveform from MAX3222 from Tout pin15.

4.6 Hyper-Terminal Communication Port Setting

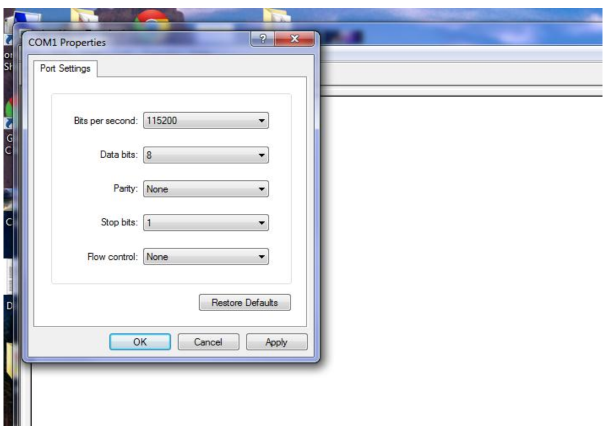


Figure 4.16: COM Port setting configuration for hyperterminal.

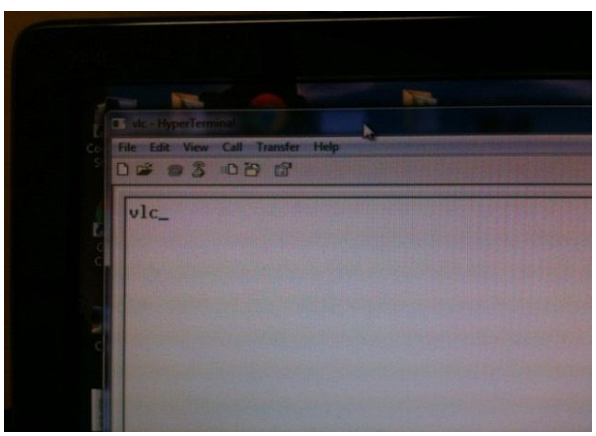


Figure 4.17: Sending symbols through hyperterminal from transmitter computer.

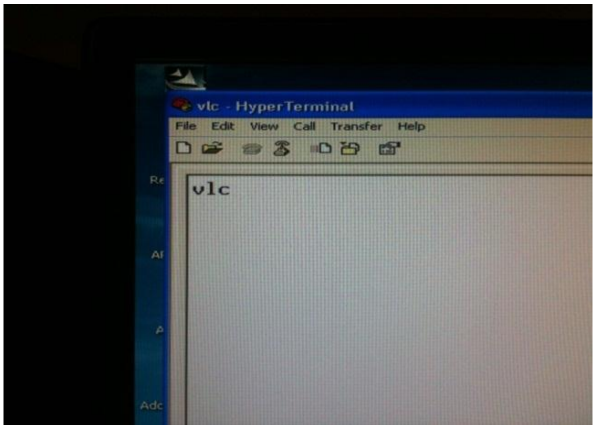


Figure 4.18: Received symbols in hyper-terminal to receiver computer.

The hyper - terminal was used for sending serial data through computer comports. Fig. 4.16 shows the comport setting configuration. Fig. 4.17 shows the symbols or characters sending from the master computer and Fig. 4.18 showing the received symbols on the client computer.

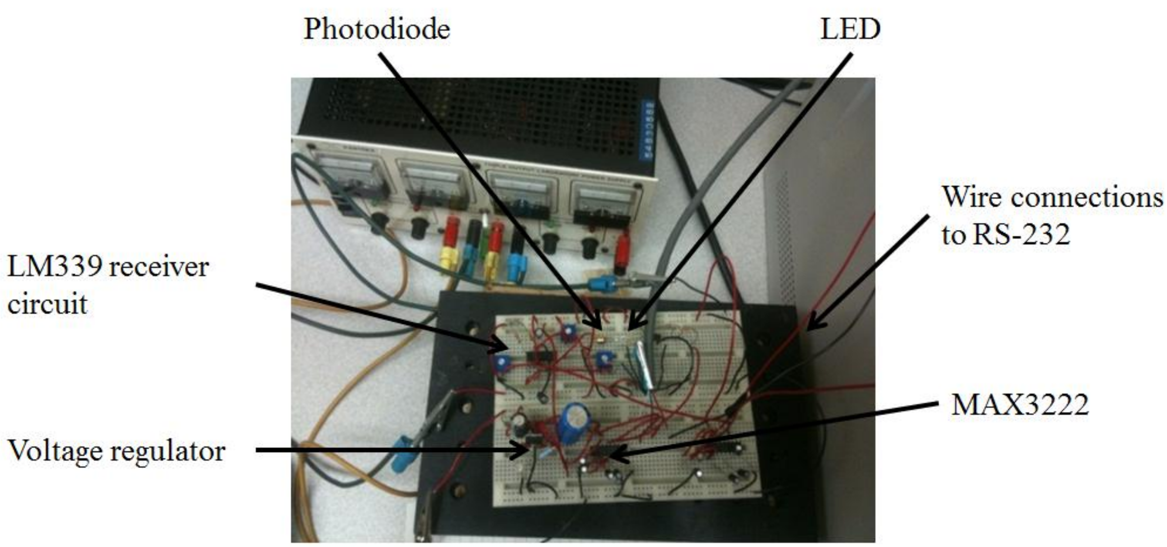


Figure 4.19: Prototype for transmitter with single LED in off state.

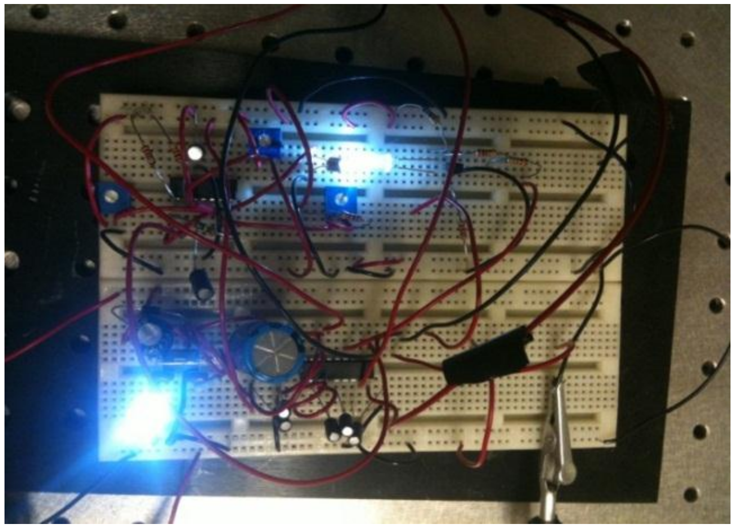


Figure 4.20: Prototype for transmitter with single LED in ON state.

The serial communication between two computers has been obtained with the maximum RS-232 configuration speed of 115200bps with 10cm distance between the LED and the photodiode. The 10cm is pretty small and is not good enough. To improve the range between the transmitter and the receiver, more LEDs have been used instead of the single LED.

4.7 The Modified LED Driver Circuit

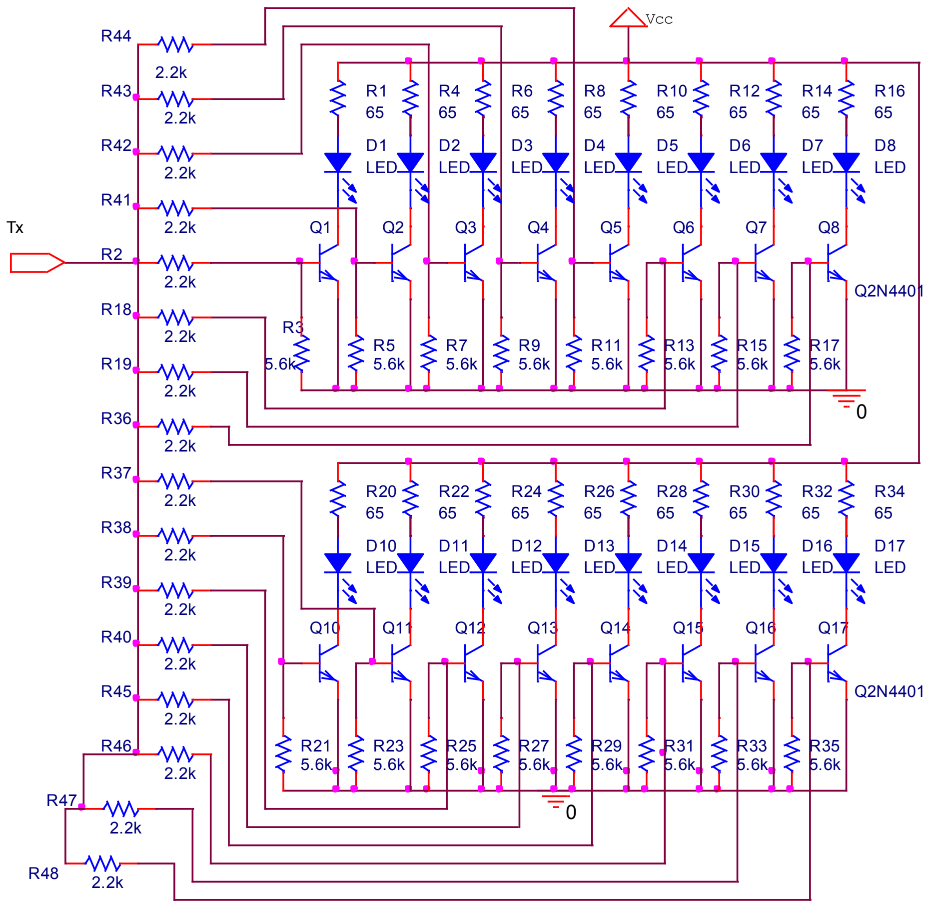


Figure 4.21: LED Driver Circuit 2 with 16 LEDs.

To use more LEDs, The transmitter driver circuit was redesigned as shown in Fig. 4.21. A set of 16 LEDs is placed each driving 20mA of current.

4.8 Illumination Distribution of 16 LEDs Versus Distance

To figure assess the performance of the transmitter LEDs, illumination distribution has been plotted with various distances as shown in Fig. 4.22, 4.23, and 4.23.

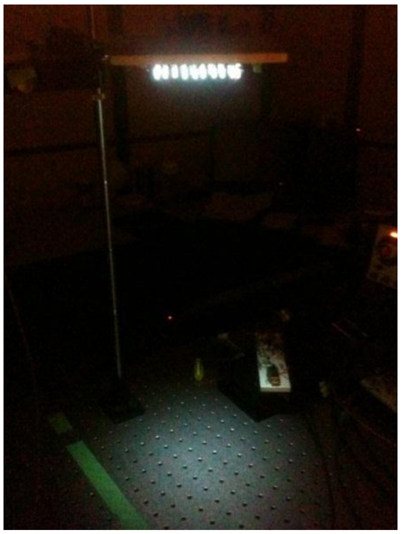


Figure 4.22: Demonstration of Transmitter with 50cm distance in dark.

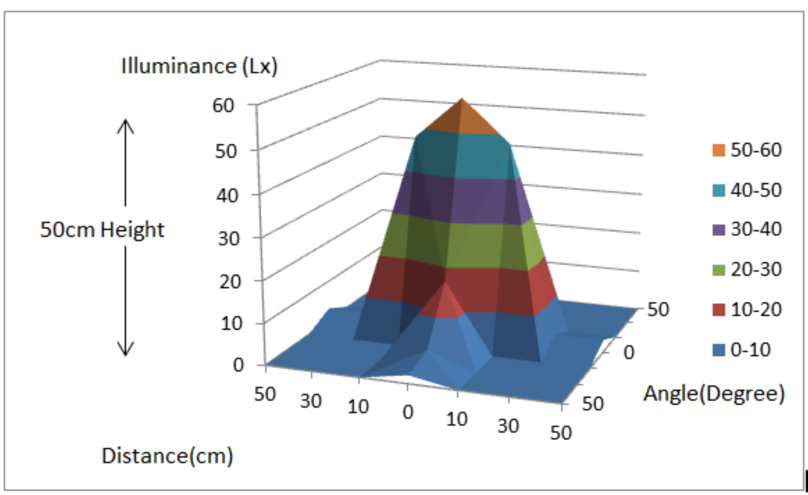


Figure 4.23: The distribution of illuminance at 50cm distance.

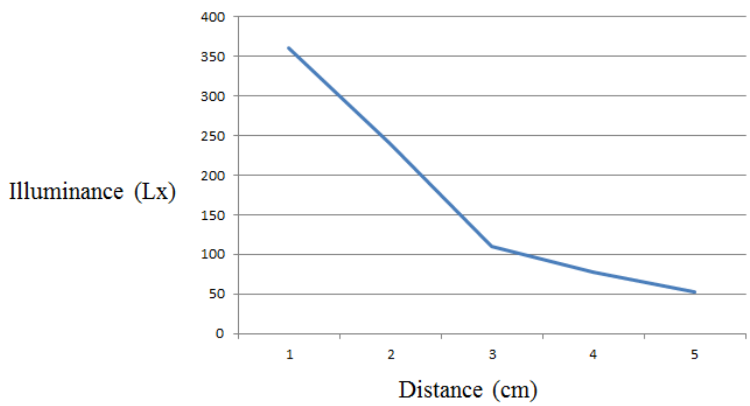


Figure 4.24: Illumination versus distance.

The maximum illuminance is 424lx and the minimum is 58lx. As the distance increased over 50cm, the LEDs are not bright enough to give sufficient light intensity to excite the photodiode. So the data transmission distance was fixed by 50cm.

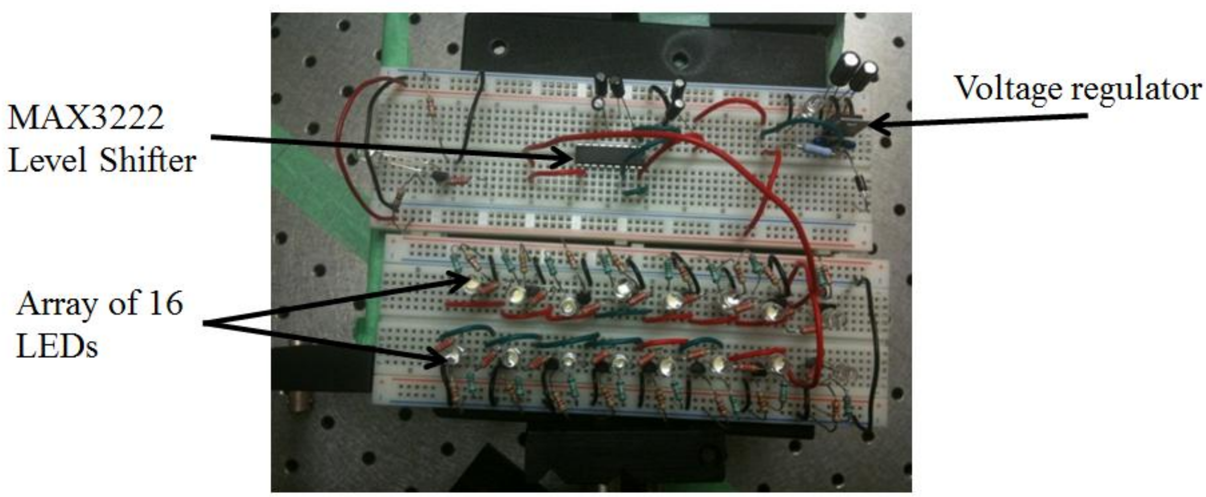


Figure 4.25: Transmitter Circuit with 16LEDs.

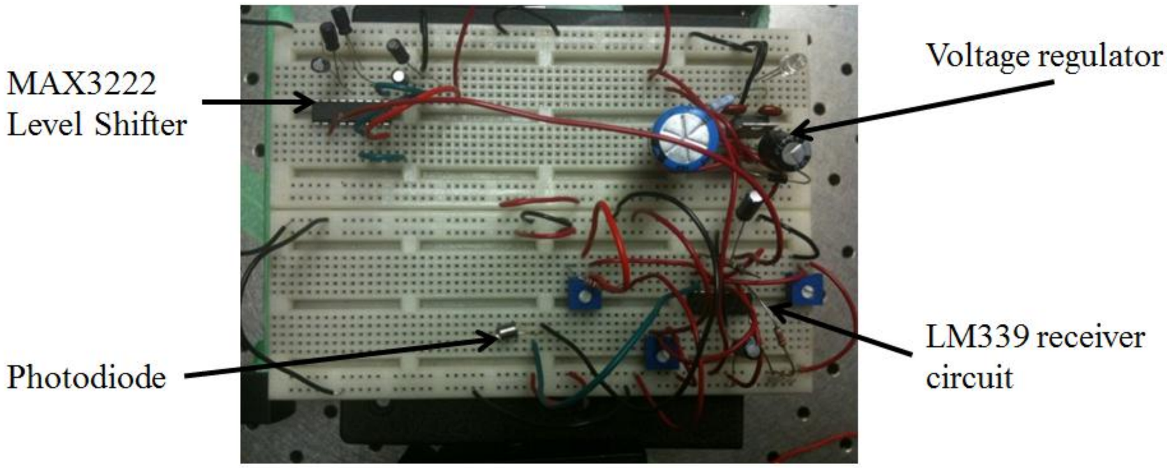


Figure 4.26: Complete Receiver Circuit.

Figures 4.25 and 4.26 show the prototypes of the transmitter and receiver.

4.9 The Test Results of Prototype 1

The prototype 1 was tested. The data transmission speeds of 115,200 bps was obtained for 10cm distance transmission. When transmission data rate was incresed to 115,200 bps, there are a lot of errors in the received data. Therefore, the limitations of in the prototype 1 are:

- The RS-232 interface that used to connect the computer comports can only work up to 115,200bps.
- The LEDs used in prototype 1 are not bright enough for long distance transmission. Even by using multiple LEDs, data transmission only achieves up to 50cm.

CHAPTER 5

EXPERIMENTAL SETUP FOR PROTOTYPE 2

Prototype 2 was proposed to overcome the limitations of prototype 1. For working with higher speeds, USB (universal interface bus) was used since its speeds are nearly 12Mbps to 480Mbps.

5.1 Design of Prototype 2

The problem faced in the prototype 1 is data transfer rate; the RS-232 interface is designed to work only up to 115200Bps. This is also the case with the MAX3222 level shifter. For getting better data transfer rates, the RS-232 interface is not suitable to work with. The prototype 2 focuses on a different type of interface which can work with higher data transfer rates, namely Universal Serial Bus (USB), with a speed of 12Mbps to 480Mbps. The configuration of prototype 2 is shown in Fig. 5.1.

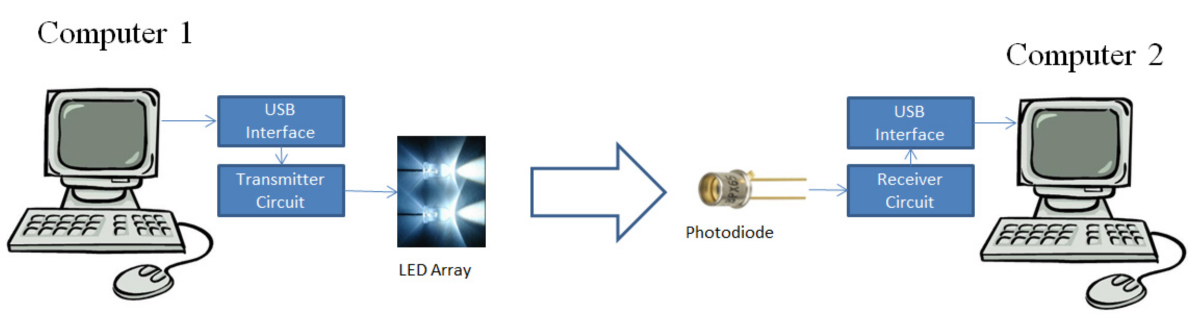


Figure 5.1: Design of prototype 2 with USB interface.

5.2 USB Protocol

The USB protocol is completely different from RS-232 protocol. For using any device attached to the computer USB interface, the device has to be recognized by the computer so that it grants permission to a COMport usage for the device to process. Granting permission needs a USB ID. USB ID also called as device descriptor, is an identification or an access permission for any device to start its operation with a computer [34], [42].

The ID is recognized through the connection, and the computer recognizes the device; then it allows the devices to operate with it. UM232R is such a device; it has a USB ID and can be used with any computer USB ports. The FT232 chip in UM232R does most of the work; it converts USB to TTL, which is needed for our transistor circuit.

Figure 5.2: UM232R USB serial UART Development Module [43].

5.3 Observation for Two Types of White LEDs

Another problem is the LEDs used in prototype 1 are not bright enough for the photodiode to capture the optical signal at long distances. So, prototype 2 is built to improve the problems faced in prototype 1. A new type of white LEDs was tested, which is brighter than the the one used before.

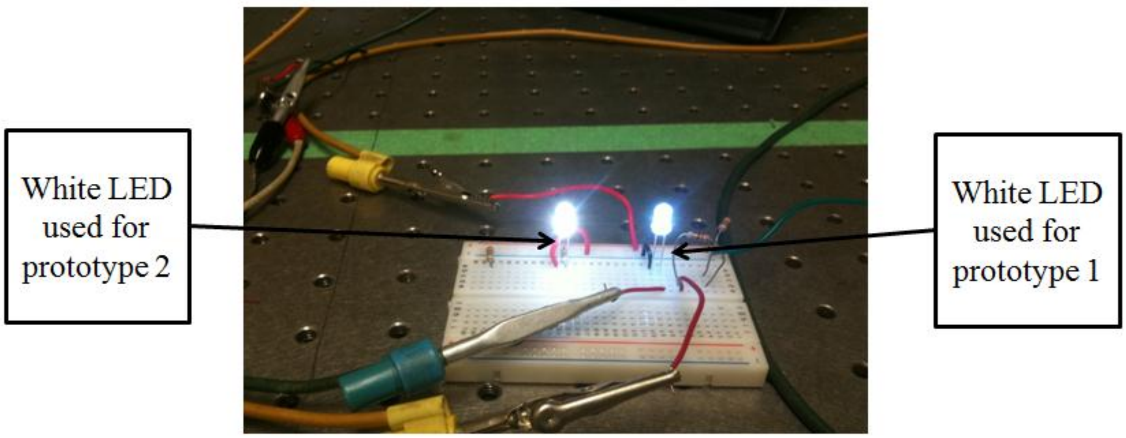


Figure 5.3a: Observation of two white LEDs (front view).

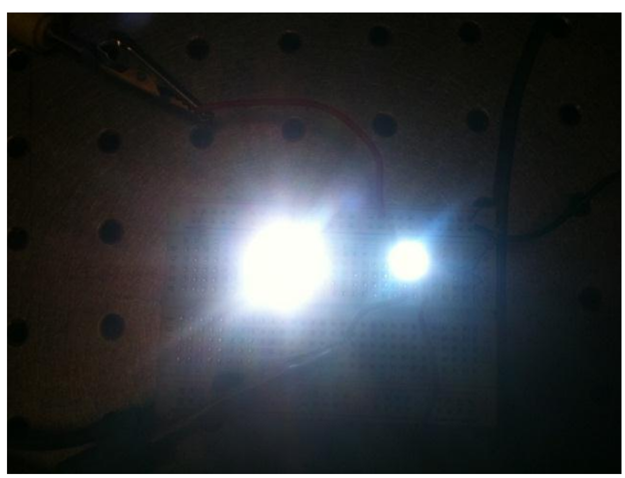


Figure 5.3b: Observation of two white LEDs (top view).

Fig. 5.3 show the differences between the two LEDs. In Fig 5.3a and 5.3b, the left LED is the new, brighter one; it has 3V of forward voltage. The right LED is the one used in prototype 1 with 3.3V of forward voltage. Both are testing @20mA current. It is clearly observed that the LED with a forward voltage of 3V is brighter than the one on the right.

5.4 LED Driver Circuit

By taking the facts from the testing of the brighter LED and 818-SL photodiode into the design, prototype 2 was developed.

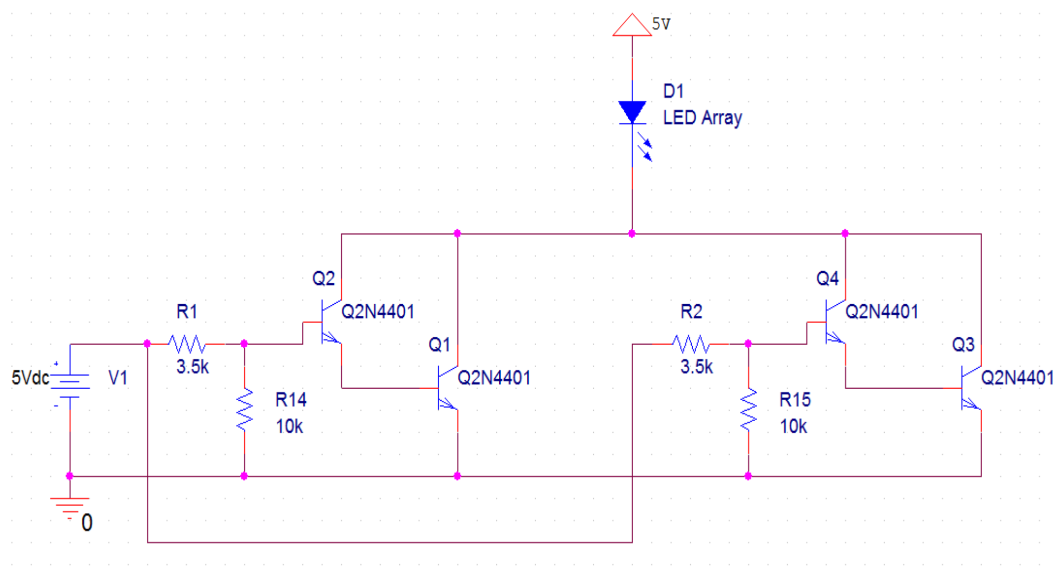


Figure 5.4: Transmitter circuit with array of 20 LEDs @ 18mA current.

Fig. 5.4 shows two cascaded Darlington configurations with common collector configurations (Q1-Q2 and Q3-Q4) [45]. Two transistors are cascaded so that they have a common collector. This will result in having a larger collector current with less base current. The circuit is designed for acquiring high gain (approximately square). The emitter of Q2 is connected to the base of the Q1, and the current amplified by Q2 is further amplified by Q1, which is similar in the case of Q3 and Q4. The Darlington transistor pair (Q1-Q2 and Q3-Q4) behaves like a single transistor with high gain.

5.4.1 Design calculations for one Darlington configuration

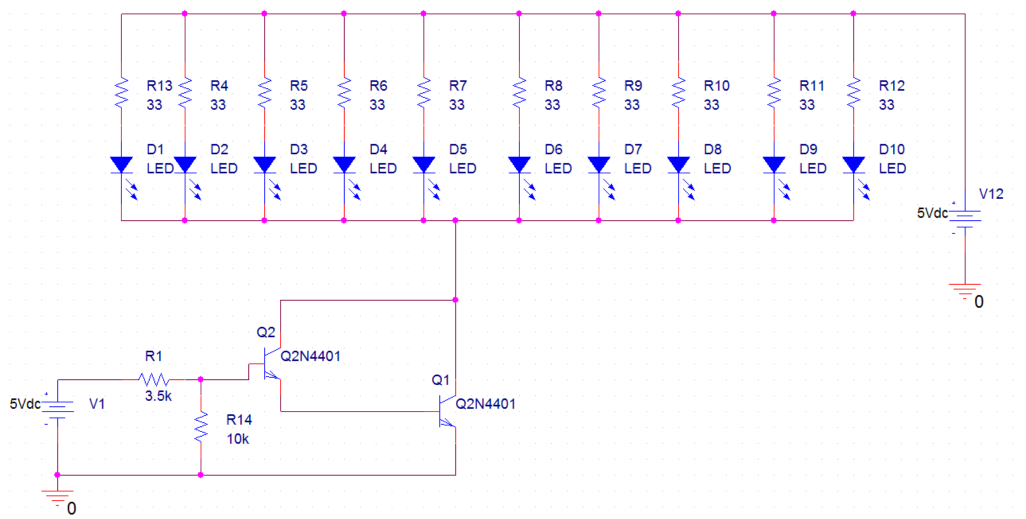


Figure 5.5: For 10 LEDs with one Darlington configuration.

According to the datasheet $V_{BE\,(SAT)}$ =0. 75V and $V_{CE\,(SAT)}$ =0. 4V for a single transistor. In the Darlington configuration, the two transistors must be seen as a single transistor.

$$V_{BE\,(Q2)} = V_{BE\,(Q2)} + V_{BE\,(Q2)} = 0.75V+0.75V = 1.5V. \qquad (4.1)$$

$$V_{CE(Q1)} = V_{CE(Q2)} + V_{BE(Q1)} = 0.4V+0.75V = 1.1V. \qquad (4.2)$$

Since β_1=10 and β_2= 20,

$$I_C = \beta_1 * \beta_2 * I_B, \qquad (4.3)$$

Then, 180mA of current is required for an array of 10 LEDs (18mA current for each LED).

For Ic of 180mA ,

$$I_B = \frac{180*10^{-3}}{10*20} = 0.9\text{mA}; R_B = \frac{V_{CC}-V_{BE(Q2)}}{I_B} = \frac{5-1.5}{0.9*10^{-3}} = 3.9\text{K}\Omega, \qquad (4.4)$$

The value R_B works fine when the internal resistance is not involved from the input voltage source and also if the I_{CBO} current is not considered too. Therefore, in this case, we have 0.1μA of I_{CBO}. R_{14} value should be such that it drives I_{CBO} through it. In addition of R_B, the total resistance at the base should be R_1=R_B-R_S.

R_S is the internal resistance of the input voltage source 5V. In this case it is zero.

$$R_B = \frac{V_{CC} - V_{BE\,(Q2)}}{\frac{I_C}{\text{Total Gain}} + \frac{V_{BE\,(Q2)}}{R_{14}}} = \frac{5-1.5}{\frac{180*10^{-3}}{10*20} + \frac{1.5}{10*10^{3}}} = 3.5K\Omega\,. \quad (4.5)$$

R_{14} is taken such that it drives a minimum of 0.1μA , in this case 150μA.

Therefore,

$$R_1 = R_B - R_S = 3.5K\Omega + 0 = 3.5K\Omega\,. \quad (4.6)$$

$$R_C = \frac{V_{CC} - V_{LED} - V_{CE(Q1)}}{I_{CL\,(\text{for each LED})}} = \frac{5-3.3-1.1}{18*10^{-3}} = 33\Omega \text{ (for each LED)}. \quad (4.7)$$

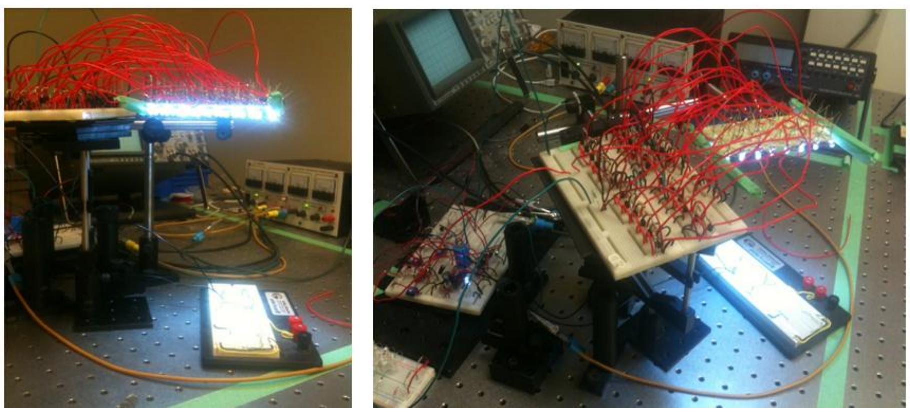
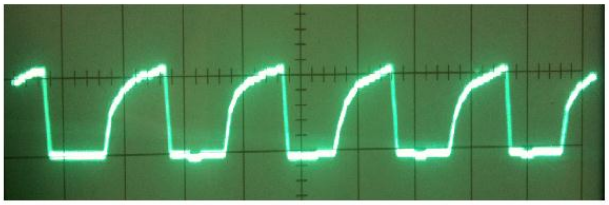


Figure 5.6: Picture of the model (front and top view).

The data transmission rate of 9600bps was achieved. Unfortunately, it could only work up to 9600bps. The possible reason could be that the Darlington configuration, has a disadvantage when it comes to fast switching. The base voltage is much less compared to the emitter voltage when the transistor is fully saturated. For a single transistor, the voltage drop across the $V_{\mathbf{CE}}$= 0.4V and the $V_{\mathbf{BE}}$ = 0.75V when fully ON. But in this case, the $V_{\mathbf{BE}}$ = 1.1v instead of 0.75V (since the base-emitter voltage drop of the Darlington configuration is the addition of two transistor base-emitter voltage drop).



10Khz Frequency

1V/DIV

50µS/DIV

Figure 5.7: Waveform captured across LED.

To improve the data rate, the circuit was re-built as described in the next section.

5.5 The Modified LED Driver Circuit

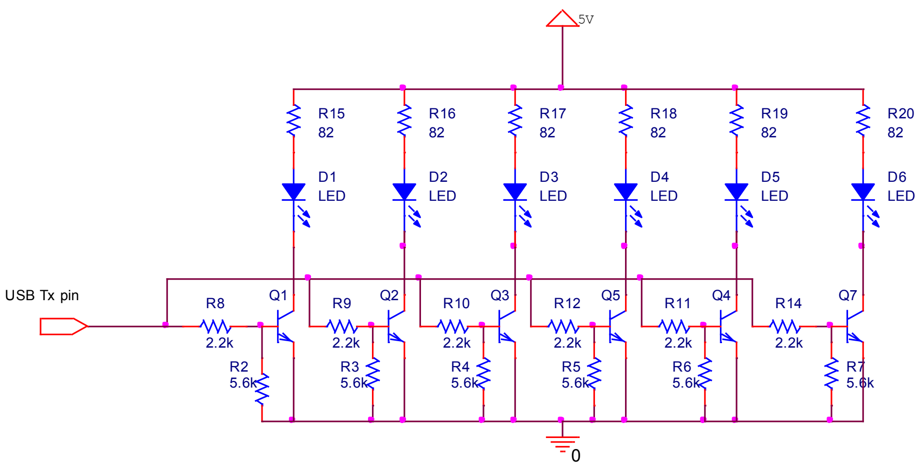


Figure 5.8: LED driver circuit.

The modified circuit is shown in Fig. 5.5. 7 LEDs are implemented with 2N4401 transistors for switching. For more LEDs, we can use more transistors. Each transistor to act as a switch for each LED.

5.6 The MRD500 Photodiode Driver Circuit

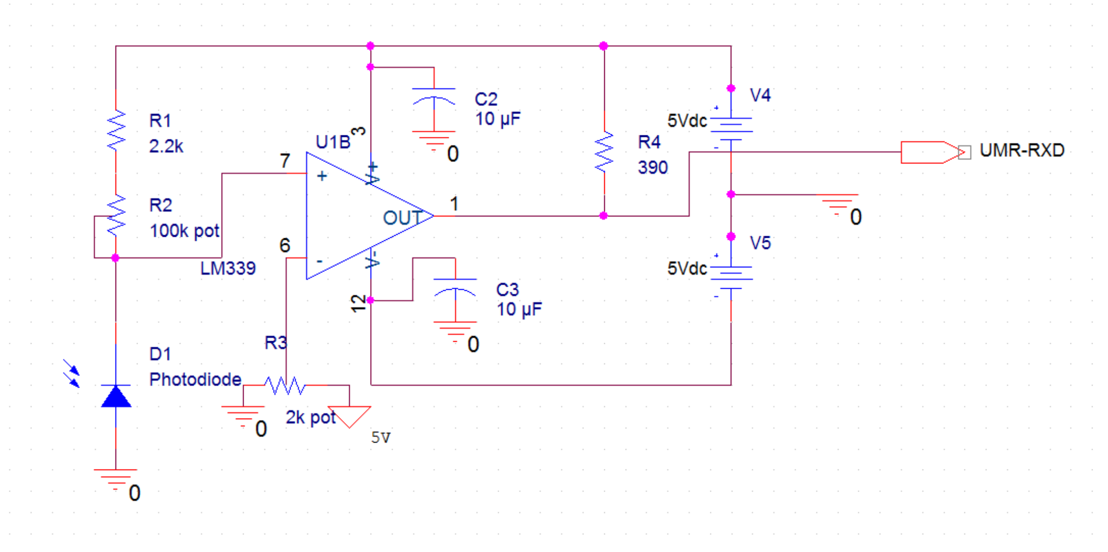


Figure 5.9: MRD500 Photodiode driving circuit.

The driver circuit for the photodiode in the receiver is shown in Fig. 5.9. 1Mohm resistor, which is placed in between the output pin 1 to inverting input pin 6, is placed there to avoid unwanted oscillations from the signal when it stays closer to reference voltage. The switching point is determined by the pin 7 (non-inverting input terminal). The light intensity on the photodiode controls the switching process of the reference voltage. The 2Kpot is used to set the input threshold voltage of any desired value by comparing the input voltage of pin 7.

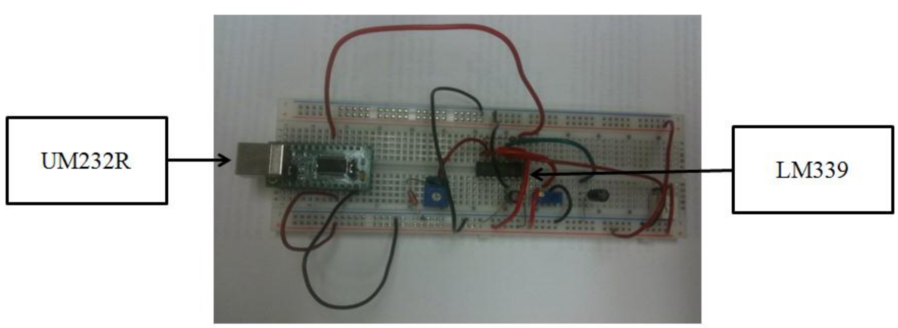


Figure 5.10: Picture of the receiver.

The experimental setup is started by the 10cm distance between the transmitter and the receiver; 256kBps speed has been obtained in the presence of ambient light.

But when increased the distance to 50cm, the electrical signal from MRD500 photodiode suffers from distortions at 50cm distance away from the transmitter. The data transmission was unable to be obtained by the receiver if the distance exceeds 40cm distance apart from the transmitter. In this case, the maximum distance is 40cm for the transmission for this VLC prototype model.

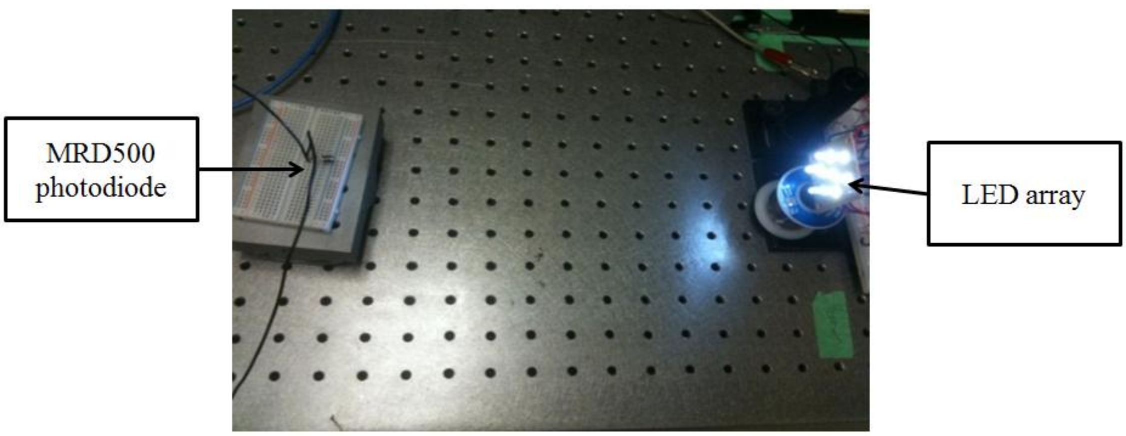


Figure 5.11: Testing the receiver performance for 50cm distance.

Figure 5.12: Waveform captured from the receiver.

Since the MRD-500 photodiode area is small, it is unable to capture the optical signal for large distances.

5.7 818-Silicon Photodetector

Figure 5.13: Picture of 818-SL photodiode.

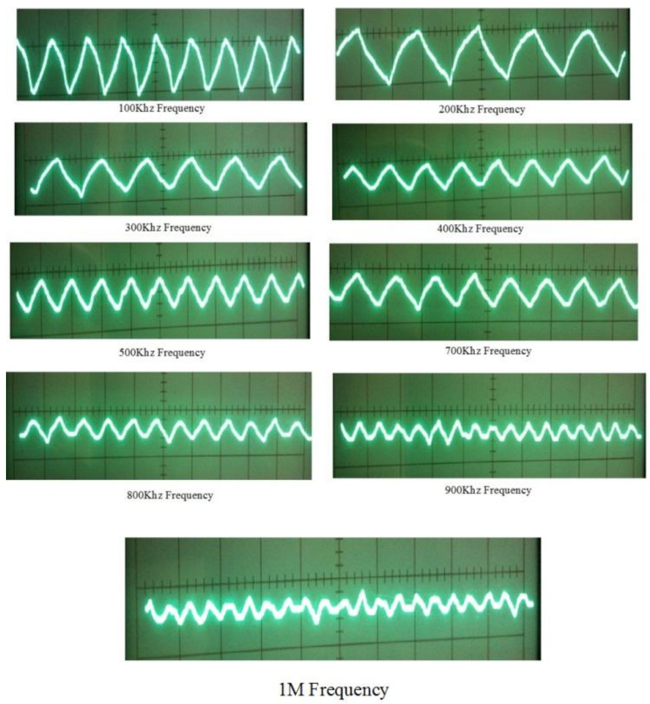


Figure 5.14: Response waveforms captured by the 818-Silicon photodiode (2mV /DIV).

To explore the potential of other photodiode, the photodetector replaced MRD500 photodiode. The 818-Silicon photodiode was selected for better performance at low power detection for longer distance. As we can see from Fig. 5.19, the waveform gradually loses its form and suffers from distortions with the increase in frequency. At 1Mhz frequency, the waveform looks like noise. The 818-SL photodiode is actually a power meter. Its response time is 2μs. Due to its large area, it can be used for transmission for larger distances.

5.8 Transmitter Power Distribution

Power distribution of the LEDs was plotted to determine the field of view (FOV) of the transmitter LEDs.

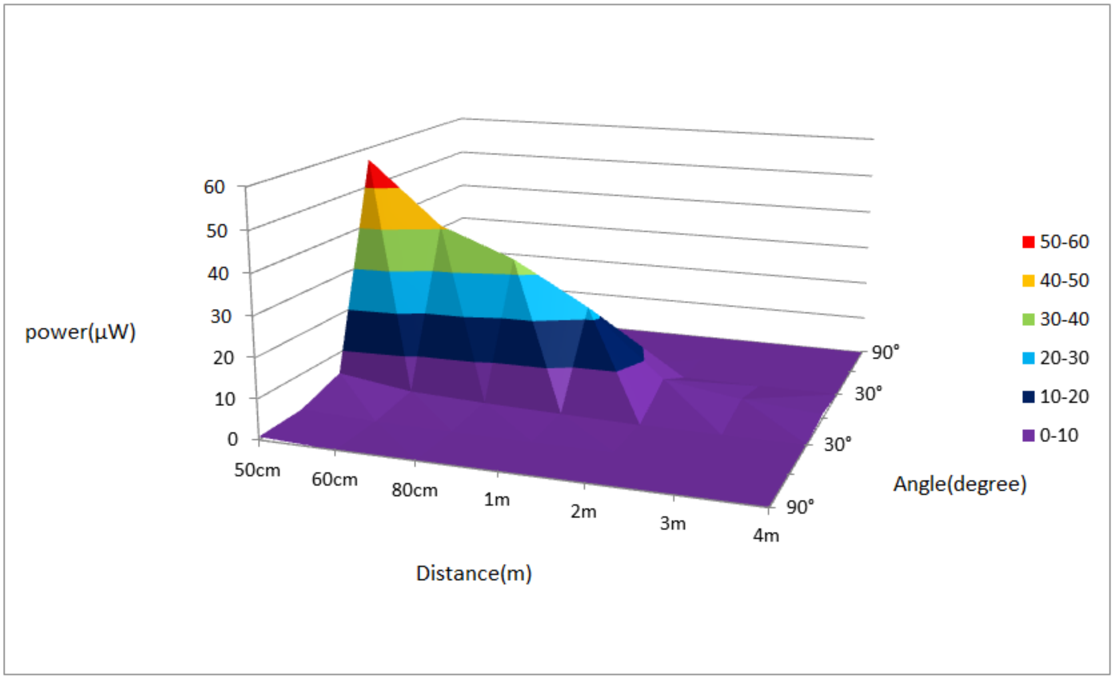


Figure 5.15: Power distribution plot.

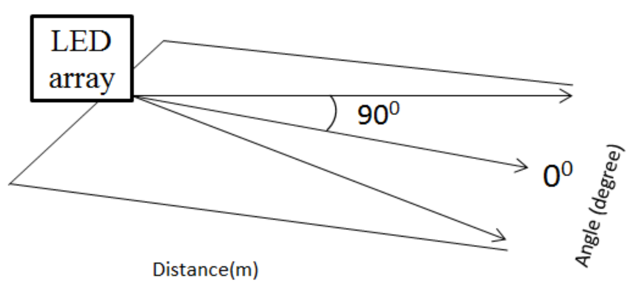


Figure 5.16: Symbol representation of LED array with distance and angle.

The field of view of the transmitter is determined by the power distribution plot. The position of the receiver can be placed according to the power distribution of the transmitter. According to the plot, power distribution is obtained upto 4 meter distance. As a result, the transmission can be possible up to 4 meter distance.

5.9 818-Silicon Photodiode Driver Circuit

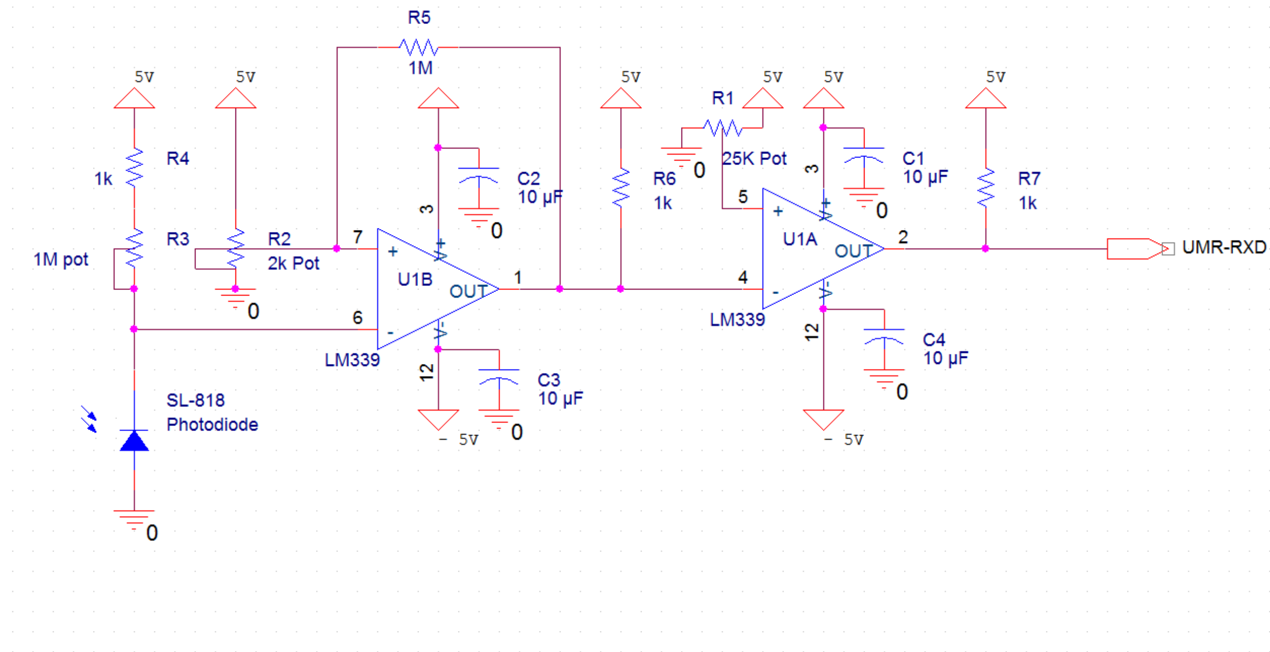


Figure 5.17: Circuit diagram of 818-Silicon photodiode driver circuit.

The 818-Silicon photodiode driver circuit was designed with an LM339 quad comparator. The first one (U1B) is in inverting arrangement, as is the second one (U1A). The leakage current increases when light falls on the photodiode, raising the inverting input pin 6 input voltage. The 2k pot at pin 7 was used to set the required voltage with reference to the input voltage at pin 6, in case the signal stayed close to the reference voltage. 1M pot was placed to avoid unwanted oscillations. The output signal from pin 1 is fed to the inverting input pin 4 to reverse the signal and to obtain the original signal from R7 resistor of pin2. The output signal of the comparator from pin2 is fed to the UMR232 receiver pin.

5.10 Testing the Transmission for One Meter Distance

The prototype 2 was tested as shown in Fig. 5.18 and Fig. 5.19.

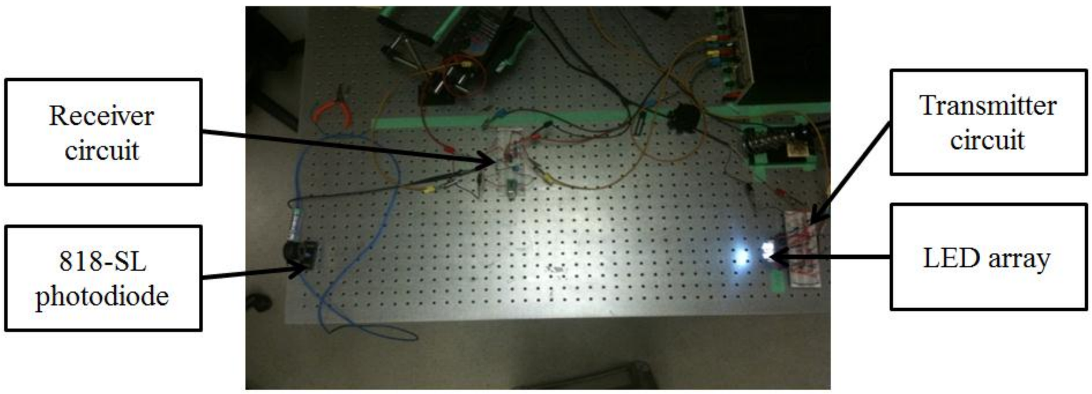


Fig 5.18: One meter distance with effect of room illumination (top view).

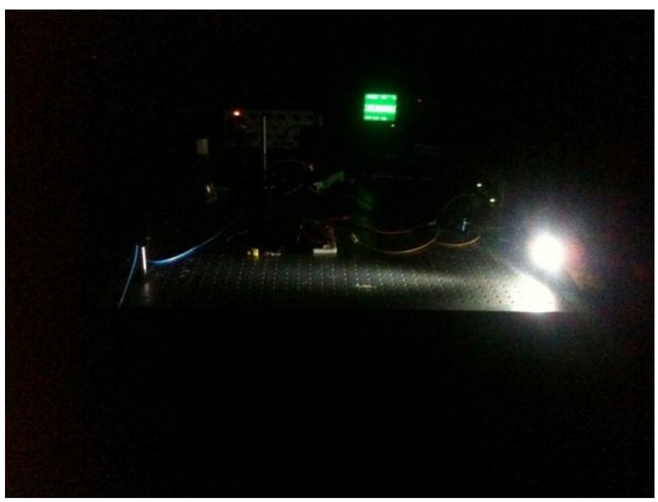


Fig 5.19: One meter distance without effect of room illumination (front view).

The distance between the transmitter and the receiver was increased to 1 meter; a transmission rate of 19200bps was obtained without symbol errors observed. When the Baud rate is increased, the errors are increased.

Figure 5.20: Data transmission at 19200bps for one meter distance.

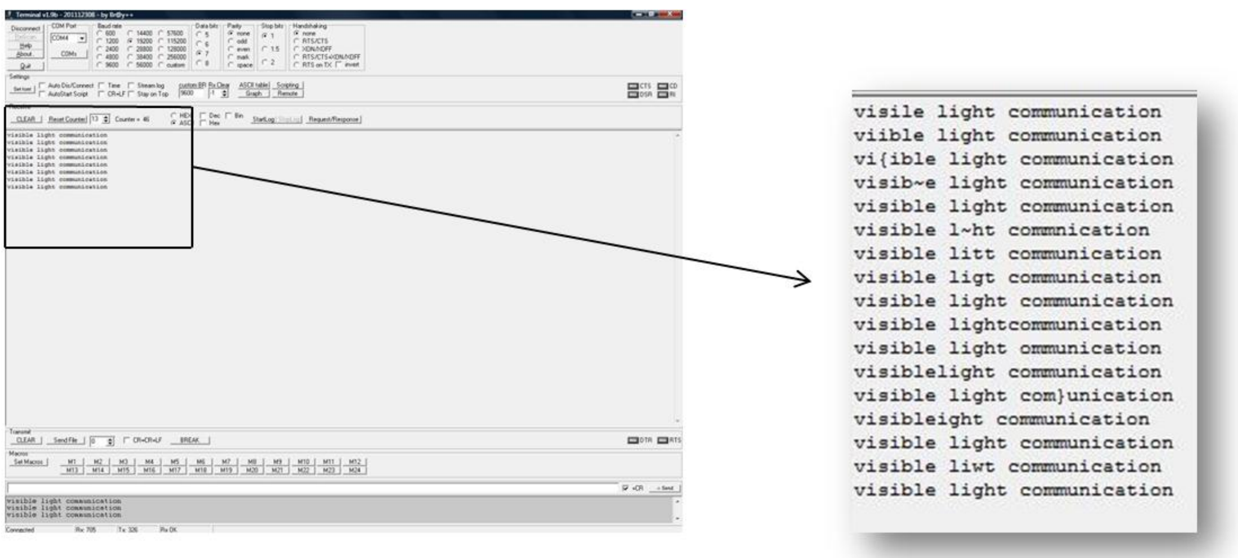


Figure 5.21: Data transmission at 28800bps for one meter distance with errors.

Figures 5.24 and 5.25 are captured using the Terminal v1. 9b software tool. We can see that in Fig. 5.24, the data transmission at one meter distance is obtained at 19200bps. When increased to 28800bps, there are errors in the received text.

5.11 Transmission Testing Using MATLAB File

For testing the transmission, 3-D plot file from Matlab is selected and sent through the Terminal v1.9b software and the received data is manually observed for the errors in the received text.

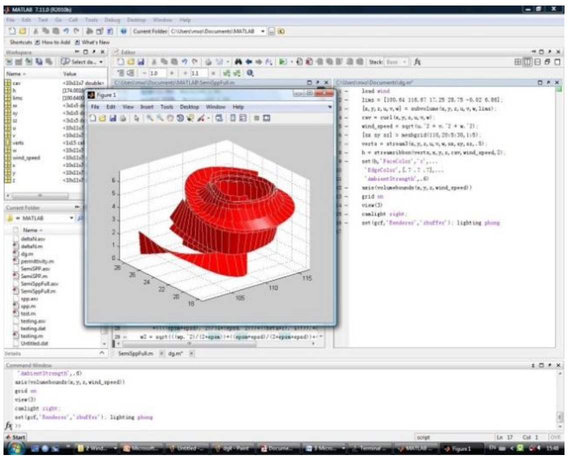


Figure 5.22: Matlab code for the 3D generated graph.

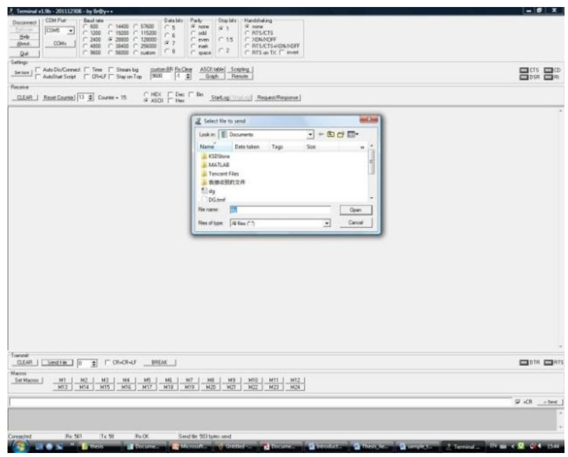


Figure 5.23: The Matlab file sent from the transmitter through terminal v1. 9b software tool.

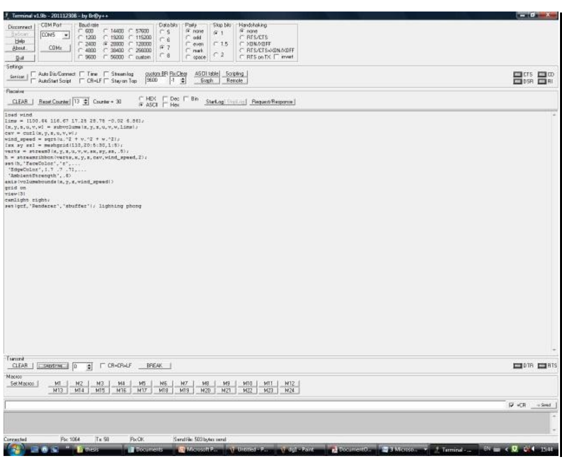


Figure 5.24: The recevied Matlab file.

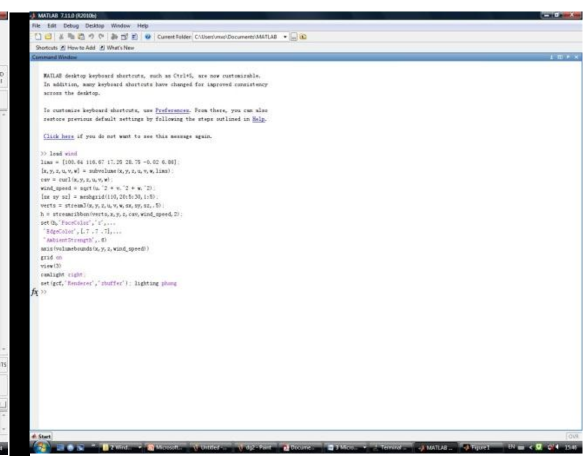


Figure 5.25: Testing the received file in the Matlab.

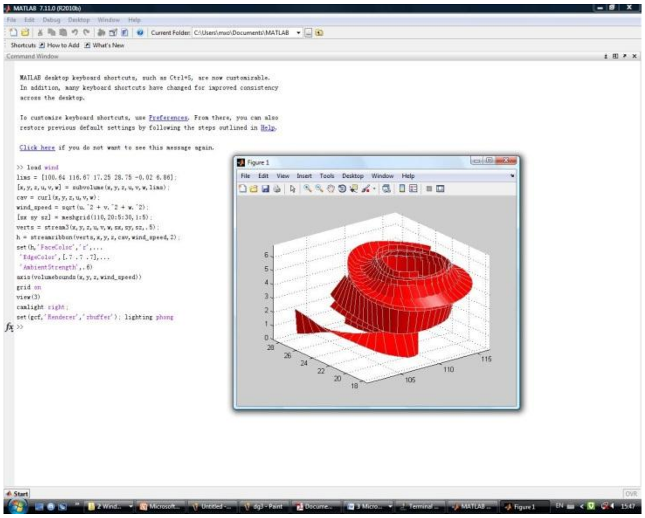


Figure 5.26: Generated 3D graph in the Matlab.

As we can see, the generated graph in fig. 5.30 is the same as the graph in Fig. 5.26. Thus the transmission is successful at one meter distance at 19200bps with no errors in the received data in the presence of room illumination and 38400bps in the dark.

5.12 Transmission Testing for Maximum Distance

Increasing to the maximum distance according to the power distribution plot in figure 5.20, 4m distance transmission was tested. The errors are drastically increased.

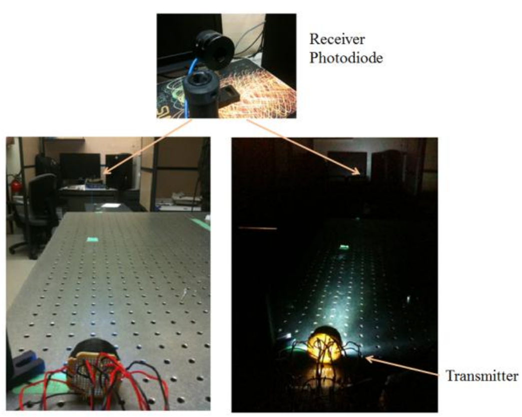


Figure 5.27: 4m distance demonstration of VLC prototype 2.

Figure 5.28: Waveform recovered at the receiver.

From the waveform above, it is seen that the signal suffers from distortions. 4.8Kbps data transmission without errors in the received data was obtained.

5.13 Data Transmission Rates Versus Distance

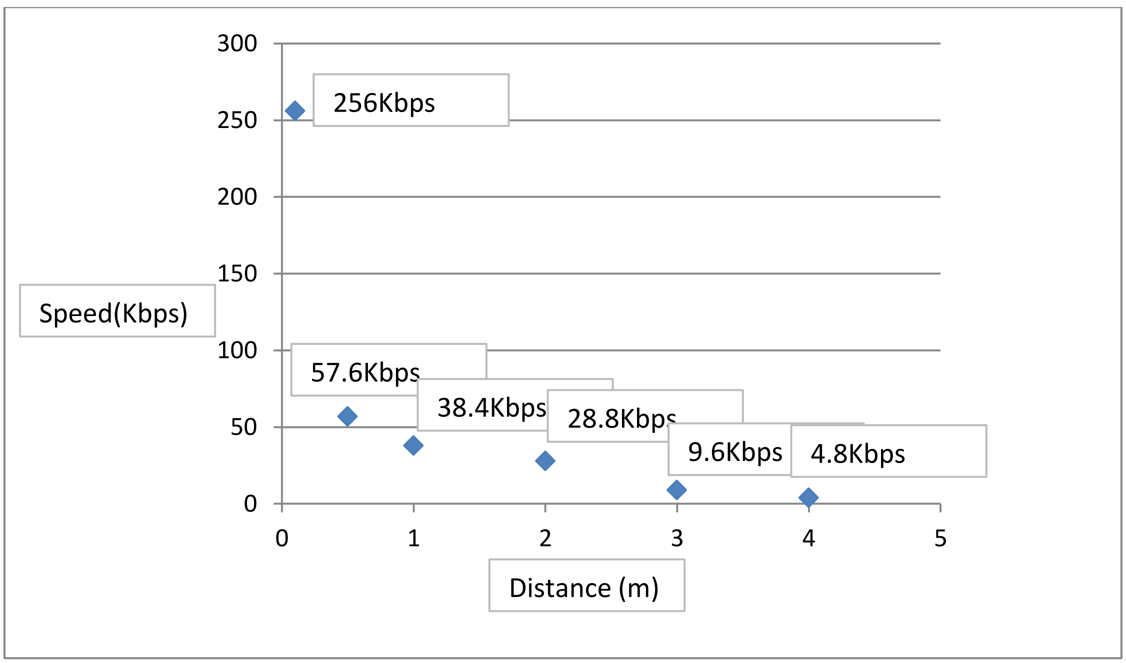


Figure 5.29: Data transmission rate without errors in the received data for several distances.

The above graph is plotted for the received data rates without errors in the received data for various distances. When tested with 256kBps data rate, the number of errors in receiving data increased significantly. The reason for this are elaborated as follows :

Data transmission is related to the Energy to Noise ratio per bit ($\frac{E_b}{N_o}$). Each bit needs sufficient energy to propagate over certain distances to reach the destination (photodiode). The energy falls off relative to distance. In order to acquire long distance, high energy is needed. The given energy is shared by the amount of bits that are set to travel. Low bit rates can have higher energy per bit when compared to higher bit rates (256KBps). In other words, by including more bits with the same amount of energy, energy will be lesser for each bit, thus resulting in higher data transmission.

5.14 Comparison of LED Illumination with Room Illumination

LEDs are expected to serve in the next generation lighting that replaces all the incandescent and florescent lights [1]. VLC must be compatible with the levels of illumination required in a room that is occupied [33].

Figure 5.30: Fluorescent lights in the Photonics Lab.

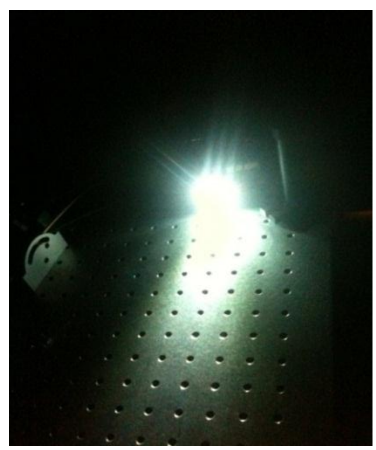


Figure 5.31: Picture of the transmitter LEDs in the dark.

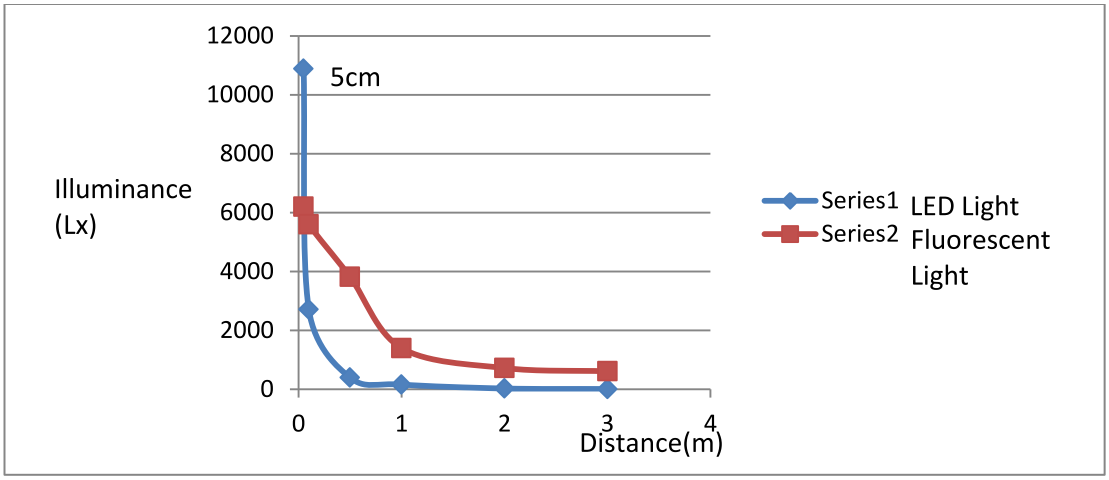


Figure 5.32: Comparison of LED illumination with room illumination.

Shown in Fig. 5.36 is the illumination of the LED when compared to the fluorescent light in the Photonics Lab. Only 7 LEDs are used for the experiment. The maximum illuminance of the fluorescent light in the room is around 6000 lx and for the LED it is around 11000 lx, which is 5000 lx higher. From the comparison we can see that there will not be a problem in lighting the room with the LEDs because LED lights are brighter than the florescent light.

The transmission can also be improved if all the lights in the room are replaced by LEDs due to the fact that the ambient light is a noise source to the VLC optical receiver. Some of the major sources include fluorescent light [36].

5.15 Test Summary for Prototype 2:

Prototype 2 obtained data transmission rates of 256,000 bps, which was the highest rate that was obtained in this work. The data transmission rate, without observed errors in receiving data for several distances, was plotted in Fig. 5.29.

CHAPTER 6

CONCLUSION

6 Summary

This thesis demonstrated a solution to the problem of integrating Visible Light Communication technology with present infrastructure, without having to make major changes to that infrastructure. The proposed system was segmented into two parts with different interface protocols and was demonstrated practically. Visible Light Communication is a rapidly growing segment of the field of communication. There are many advantages to using VLC. There are also many challenges. VLC will be able to solve many of the problems people have been facing for many years, mainly environmental and power usage issues. VLC is still in its beginning stages, but improvements are being made rapidly, and soon this technology will be able to be used in our daily lives. It is intended that this research will provide the starting steps for further study and development on USB to TTL interfaces where white LEDs can be used for data transmission. In spite of the research problems it is our belief that the VLC system will become one of the most promising technologies for the future generation in optical wireless communication.

6.1 Suggested Future Work

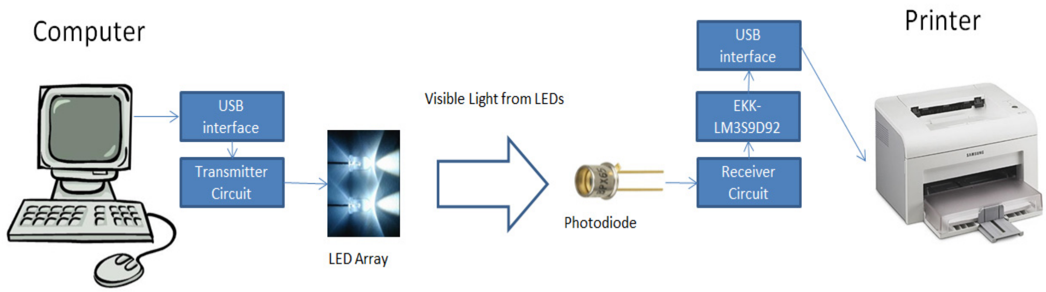


Figure 6.1: Experimental setup for prototype 3.

At the end of this work, we also started to develop the third prototype as the future work. Its objective is to enable the communication between the computer and a printer using visible light. Prototype 3 is designed to integrate with prototype 2. The transmitter and the receiver circuits are the same except the EKK- LM3S9D92 evaluation kit is added to the receiver end. The function of EKK- LM3S9D92 evaluation kit is to convert the bit speed from Kbits to USB speeds with which the printer can be worked on. Initial testing has been done with the chip but the work cannot go ahead because the needed software has yet to be developed. For the EKK- LM3S9D92 processor to work, it needs a software language to make it active so that it can be programmed to work with the receiver circuit.

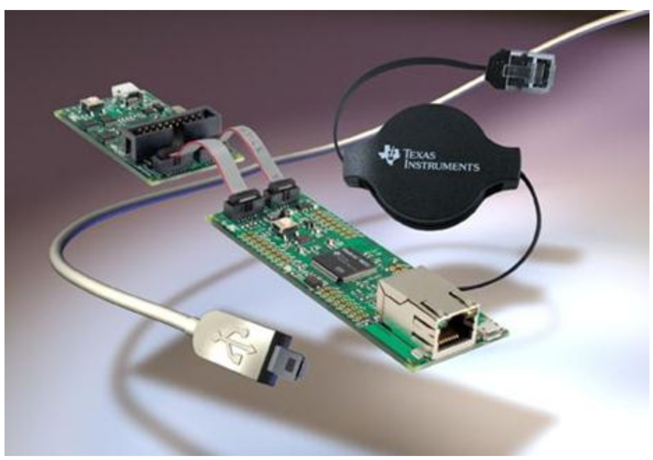


Figure 6.2: Stellaris EKK-LM3S9D92 evaluation kit [47].

EKK- LM3S9D92 evaluation kit functions as a processor for the printer (like a printer brain). It hand shakes with the computer before the data is sent. Programming is required to activate the chip (C language is preferred).

Work must be continued to develop c language coding, which can make the EKK-LM3S9D92 processor work with the prototype 3 model. That will enable the printer to take commands from the computer and print them through light.

To improve the bit transmission rate, work on different types of LEDs — namely RGB (Red-Green-Blue) LEDs — are recommended because they have the capability to work at higher frequencies than the UV/Blue, phosphor-coated white LEDs.

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