CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Design and Performance of a 1550nm Free Space Optical Communications Link

A graduate project submitted in partial fulfillment of the requirements
For the degree of Master of Science
in Electrical Engineering

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Table of Contents

Signature Page..................................................................................................................................................ii
Acknowledgement...............................................................................................................................................iii
List of tables....................................................................................................................................................ix
List of figures...................................................................................................................................................x
Abstract............................................................................................................................................................xiii

Chapter 1: Introduction ........................................................................................................................................1

Chapter 2: Background .......................................................................................................................................2

2.1 History of Optical Wireless Communications.........................................................................................2

2.2 FSO Link Configuration.............................................................................................................................3
  2.2.1 Directed LOS........................................................................................................................................4
  2.2.2 Non-directed LOS.................................................................................................................................5
  2.2.3 Diffuse Configuration.........................................................................................................................6
  2.2.4 Tracked system.....................................................................................................................................6

2.3 Comparison of RF and FSO systems .........................................................................................................7
  2.3.1 Bandwidth..........................................................................................................................................7
  2.3.2 Power Efficiency.................................................................................................................................8
  2.3.3 Multipath fading.................................................................................................................................8
  2.3.4 Signal Penetration.............................................................................................................................9
2.3.5 Performance in different atmospheric conditions ..............................................9
2.3.6 Spectrum License ..........................................................................................9
2.4 FSO Application Areas ..................................................................................9
2.5 Safety .............................................................................................................10
  2.5.1 Eye hazard ...............................................................................................10
  2.5.2 Maximum Permissible Exposure (MPE) .................................................11
  2.5.3 Accessible Emission Limit (AEL) ..........................................................11
  2.5.4 850 vs. 1550 nm lasers ........................................................................11
  2.5.5 Classification ..........................................................................................11

Chapter 3: Optical Sources and Detectors .............................................................13
  3.1 Laser Emitting Diode (LED) ........................................................................13
  3.2 LASER .........................................................................................................13
  3.3 Photodetector ...............................................................................................15
    3.3.1 Photoconductors ....................................................................................15
    3.3.2 Photodiodes ..........................................................................................16

Chapter 4: FSO Channel ......................................................................................17
  4.1 Indoor Channel .............................................................................................17
    4.1.1 Path loss ..............................................................................................17
    4.1.2 Ambient Light ......................................................................................18
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.2.1 Incandescent lamps</td>
<td>18</td>
</tr>
<tr>
<td>4.1.2.2 Fluorescent lamp</td>
<td>19</td>
</tr>
<tr>
<td>4.2 Outdoor Channel</td>
<td>20</td>
</tr>
<tr>
<td>4.2.1 Atmospheric Loss</td>
<td>21</td>
</tr>
<tr>
<td>4.2.1.1 Scintillation Loss</td>
<td>21</td>
</tr>
<tr>
<td>4.2.1.2 Absorption</td>
<td>21</td>
</tr>
<tr>
<td>4.2.1.3 Scattering</td>
<td>22</td>
</tr>
<tr>
<td>4.2.2 Pointing loss</td>
<td>24</td>
</tr>
<tr>
<td>4.2.3 Beam Divergence</td>
<td>25</td>
</tr>
<tr>
<td>4.2.4 Sunlight</td>
<td>26</td>
</tr>
<tr>
<td>4.3 Link Equation</td>
<td>26</td>
</tr>
<tr>
<td>Chapter 5: Modulation</td>
<td>28</td>
</tr>
<tr>
<td>5.1 Analogue Intensity Modulation</td>
<td>28</td>
</tr>
<tr>
<td>5.2 Digital Baseband Modulation</td>
<td>30</td>
</tr>
<tr>
<td>5.2.1 On-Off-Keying (OOK)</td>
<td>30</td>
</tr>
<tr>
<td>5.2.2 Pulse Position Modulation (PPM)</td>
<td>31</td>
</tr>
<tr>
<td>Chapter 6: Design of a 1550 nm simplex free space optical communication system</td>
<td>33</td>
</tr>
<tr>
<td>6.1 Laser diode</td>
<td>33</td>
</tr>
<tr>
<td>6.1.1 Wavelength</td>
<td>33</td>
</tr>
</tbody>
</table>
6.1.2 Safety.................................................................................................................................34
6.1.3 Laser Specification...............................................................................................................34
6.2 Laser Driver.............................................................................................................................36
6.3 Bias-T........................................................................................................................................39
6.4 Isolator......................................................................................................................................39
6.5 Collimator..................................................................................................................................40
6.6 Telescope....................................................................................................................................42
6.7 Photodetector............................................................................................................................42
  6.7.1 Responsivity.........................................................................................................................43
  6.7.2 Dark current..........................................................................................................................43
  6.7.3 Bandwidth............................................................................................................................44
  6.7.4 Noise Equivalent Power.......................................................................................................45
6.8 Modulation...............................................................................................................................45

Chapter 7: Performance, Simulation and Test Results..................................................................48
  7.1 Measuring signal under various weather conditions...............................................................50
  7.2 Loss due Beam Divergence......................................................................................................52
  7.3 Range Loss..............................................................................................................................53
  7.4 Antenna Gain..........................................................................................................................54
  7.5 Link equitation evaluation........................................................................................................55
    7.5.1 Theoretical approach.........................................................................................................55
7.5.2 Measuring received power using OptiSystem ................................................. 55

Chapter 8: Summary and Conclusion ........................................................................... 57

References ..................................................................................................................... 59
List of Tables:

Table 2-1: Different classes of laser diodes.................................................................12

Table 4-1: Atmospheric loss as a function of visibility for a 1550 nm FSO system........24

Table 6-1: LPS-PM1550-FC Specifications........................................................................34

Table 6-2: Pin-out of the LSP-PM1550-FC....................................................................35

Table 6-3: LD1100 Specification.....................................................................................36

Table 6-4: LD1100 Pin-out.............................................................................................37

Table 6-5: Feedback gain resistor setting........................................................................38

Table 6-6: IO-H1550FC Specification............................................................................40

Table 6-7: Specification of the DET01CFC....................................................................44

Table 7-1: Visibility range and attenuation coefficient at the 1550 nm wavelength..........51

Table 7-2: Power loss due to the beam divergence..........................................................52

Table 7-3: Measure power at various distances from the source; range loss is the cause of attenuation...............................................................53

Table 7-4: Transmitter and receiver antenna gain............................................................54

Table 7-5: Parameters of the test...................................................................................55
List of Figures:

Figure 2-1: Photophone invented by Alexander Graham Bell...................................................... 2
Figure 2-2: Block Diagram of a simple FSO system........................................................................3
Figure 2-3: Directed LOS System..................................................................................................4
Figure 2-4: Non-Direct LOS.................................................................................................. 5
Figure 2-5: Diffuse Configuration ..............................................................................................6
Figure 2-6: Tracked System.................................................................................................. 7
Figure 2-7: Bandwidth capability of RF and Optical communication systems.......................8
Figure 2-8: Eye diagram..................................................................................................................10
Figure 3-1: p-n Junction LED....................................................................................................13
Figure 3-2: Diagram of a simple semiconductor optical amplifier........................................14
Figure 3-4: Diagram of a typical Photocunductor......................................................................15
Figure 3-5: p-n junction photodiode.........................................................................................16
Figure 4-1: Finding the path loss in a Directed LOS system..................................................18
Figure 4-2: The relative spectral radiation of a tungsten-halogen lamp
indifferent wavelength and temperatures...............................................................................19
Figure 4-3: Spectrum of a 16 W compact fluorescent light.....................................................20
Figure 4-4: Transmittance of atmosphere in different wavelength.........................................22
Figure 4-5: Power loss due to the beam divergence.................................................................25
Figure 4-6: Intensity of solar radiation.....................................................................................26
Figure 5-1: Modulation tree.......................................................................................................28
Figure 5-2: Intensity Modulation by driving LD/LED current

Figure 5-3: IM using external modulator (Mach-Zehnder)

Figure 5-4: Symbols for a) NRZ and b) RZ

Figure 5-5: Time waveforms for OOK and PPM

Figure 6-1: Block diagram of a basic FSO system

Figure 6-2: Bottom view of LPS-PM1550-FC laser diode

Figure 6-3: Pin diagram of LPS-PM1550-FC laser diode

Figure 6-4: Styles of laser diodes

Figure 6-5: Changing pin connections of LPS-PM1550-FC

Figure 6-6: LD1100 laser driver

Figure 6-7: Feedback loop diagram

Figure 6-8: T1G board schematic

Figure 6-9: Light propagation in an isolator

Figure 6-10: Transmitting laser beam with/without using collimator

Figure 6-11: Using a telescope at the receiver to converge the light into the photodetector

Figure 6-12: Responsivity curve of DET01CFC

Figure 6-13: Determining the extinction ratio

Figure 6-14: LIV curve of LPS-PM1550-FC

Figure 6-15: Waveform to find the extinction ratio of this project

Figure 7-1: System setup of 1550 nm FSO link

Figure 7-2: System scheme of the FSO system
Figure 7-3: Determined power for different visibilities……………………………………………….52
Figure 7-4: Determined power at different distances from the source…………………………….53
Figure 7-5: Range loss of the transmitted signal…………………………………………………….54
Figure 7-6: Using OptiSystem to observe the effect of the attenuation on the transmitted signal………………………………………………………….56
ABSTRACT

Design and Performance of a 1550nm Free Space Optical communications Link

By

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Master of Science in Electrical Engineering

The demand for high-speed communications systems to transfer large amounts of data has led to the development of new technologies as well as re-visiting old ones. Although Free Space Optical systems (FSO) are not a new technology, they are attracting more attention due to the availability of large amounts of the unregulated bandwidth. The development of FSO systems has been rapid. In spite of their advantages, the performance of FSO systems is affected by weather conditions and pointing problems. Eye-safety issues must also be considered when using an FSO system.

In this project, a 1550 nm FSO system was designed using a laser diode. The advantage of the laser diode is that it provides a collimated beam with a low amount of divergence. The effect of the atmospheric and range loss are tested and observed using the OptiSystem software. In addition, the experimental issues of designing and implementing the FSO system are presented in this report.
Chapter 1: Introduction

Invention, implementation and development of wired and wireless communication systems has had a large impact on human life. Initially, communication systems were intended to be used to transfer small amounts of data (e.g. voice in telephone system) but later due to the invention and development of the Internet, the demand of transferring huge amounts of data in the fastest and most reliable way expanded rapidly. By applying laser diodes and optical fiber technology in communication systems, transferring high data rates has become achievable. However, the lack of mobility of the optical fiber technology and the need to install the cable are disadvantages of these systems.

Development of Free-Space Optical (FSO) systems is a solution to overcome some of optical fiber issues. This project studies the properties of FSO systems and describes the design, test, and simulation of an FSO communications link. Chapter 2 provides background on the history of optical wireless communications and other material on FSO systems. Chapter 3 discusses optical sources and detectors, Chapter 4 describes the FSO channel, and Chapter 5 summarizes some modulation techniques used in FSO systems. Chapter 6 details the design of an FSO link and Chapter 7 provides its test and simulation results. Chapter 8 summaries this project.
Chapter 2: Background

2.1 History of Optical Wireless Communications

“And around his head the bright goddess set a crown of a golden cloud, and kindled therefrom a blazing flame…with the going down of the sun blaze out the beacon fires in line, and high aloft rusheth up the glare for dwellers round about to behold, if apply they may come with ships to help in need”[1]. This quote from Homer’s Iliad shows one of the oldest use of free space optical communication in 800 BC where they applied fire beacons for signaling. The communication system was invented by Polybius, a Greek historian in 150 BC. Smoke signaling used by Native American tribes, flag semaphore telegraphy systems and the heliograph are other examples of using optical communications.

But probably Graham Bell’s photophone was the first optical communication system used to transmit voice over a beam of light. The carrier in this system was sunlight and Bell transmitted a modulated signal for a distance of 200m. He used a parabolic mirror and put a selenium cell at its focal point as the receiver.

Although, according to him, Bell’s invention was his most important invention, it was not practical for more than a few hundred yards. The main problem was outside interference such as clouds. In the 1960s, the discovery of the laser was a turning point in the use of FSO systems. This technology was of interest to military organizations at first but could not get into the civilian application market. In 1962 the MIT Lincoln Laboratory group used a GaAs diode to
demonstrate the optical transmission of television signals from Mount Wachusett to the roof of the Lincoln Labs facility, a distance of up to about 50 km [3].

About a year later, in 1963, a group of researchers in the North American Aviation Company implemented the first TV-over-laser demonstration. However the first commercial use of FSO occurred in 1970 when NEC, a Japanese company, implemented a full duplex link using a He-Ne laser to communicate between Tamagawa and Yokohama, a distance of 14 Km. From this time forth, FSO systems have been researched both in military areas for secure communication as well as in deep space communications by NASA and ESA. [4]

The first indoor use of FSO system was suggested by F.R. Gfeller and U. Bapst. They suggested and designed an indoor communication system using diffuse emission at 950nm-wavelength. [5]

Development of optoelectronic devices as well as enhancement in system design led to the rebirth of FSO in present day market. After years of success in military applications, FSO systems are now attracting more attention and investments in civil applications.

2.2 FSO Link Configuration

The simple block diagram of the FSO system is shown below:

![Figure 2-2: Block Diagram of a simple FSO system](image)

The four possible physical configurations of FSO systems are:

1. Directed Line-Of-Sight (LOS) links
2. Non-directed LOS links
3. Diffuse links
4. Tracked systems
2.2.1 Directed LOS

The configuration used in this project is Directed LOS. That means the transmitter and receiver are stationary, pointed and aligned together for point to point communication link. Directed LOS is mainly used in outdoor systems. Narrow beam and high power flux density at the photodetector are characteristics of this configuration.

![Directed LOS System](image)

Figure 2-3: Directed LOS System

Advantages of directed LOS:

- Low power requirement
- The highest data rate
- Immune to multipath signal distortion
- Suitable for long distance communications

Disadvantages of directed LOS:

- Small coverage in indoor usage
- Inability to support mobile users
2.2.2 Non-directed LOS

In this configuration wide beam transmitters and wide Field Of View (FOV) receivers are used to cover broader areas. They are similar to RF system and proper for point to multipoint broadcast communications and are mostly used in indoor systems.

Advantages of non-directed LOS:

- Wide area coverage
- More flexibility than other configurations
- No need of alignment and tracking
- Overcoming blocking problem

Disadvantages of non-directed LOS:

- High optical pass loss thus higher transmit power
- Multipath induced dispersion
- Limited data rate around a few Mbps
- Degraded performance due to influence of intense ambient lights
2.2.3 Diffuse Configuration

This configuration is similar to Non-Direct LOS except the transmitter points directly toward the ceiling emitting a wide beam of IR.

Advantages:

- no need for precise alignment and tracking between the transmitter and receiver
- immune to blockage of the direct transmission path
- high flexibility

Disadvantages:

- high path loss (need of higher transmit power)
- multipath dispersion
- signal attenuation due to reflections
- low bit rate

2.2.4 Tracked system

By using a tracking method, the transmitter and receiver are constantly pointed and aligned together. This topology is similar to the directed LOS but here the transmitter and receiver can be mobile. The tracking system makes sure that there is a direct line of sight between the Tx and Rx by pointing them towards each other.
Advantages:

- supports mobile transmitters and receivers
- Low power requirement
- The highest data rate
- Immune to multipath signal distortion
- suitable for long distance communications

Disadvantages:

- Small coverage in indoor usage
- higher cost

2.3 Comparison of RF and FSO systems

2.3.1 Bandwidth

The demand for very high data rates is increasing rapidly. This means there is a need for more bandwidth. Optical communications systems have 100 to 1000 times more bandwidth available than radio frequency (RF) communications systems.
2.3.2 Power Efficiency

The short wavelength of light makes FSO systems have a much smaller beam divergence than RF systems. This factor decreases power loss between the transmitter and the receiver which means that less transmitter power is required for a given bit error rate over a long distance link. This is a key feature especially when a limited power source is available like in spacecraft and satellites.

2.3.3 Multipath fading

Over multipath channels, a transmitted signal may be received from different reflective paths. In RF technology, multipath propagation leads to fluctuations in the received signal’s amplitude and phase. [6]

In an optical communication system, the small size of wavelength relative to the photodiode size eliminates multipath fading. [7]

The antenna in an FSO system is the photodiode which can be modeled as a square law device. A square law device squares the amplitude of the impinging electromagnetic signals and integrals them over a specific period of time. The amplitude fading in the received signal occurs at the points located on the order of half a wavelength apart. The large size of the antenna relative to the wavelength leads to more signals to be covered in the integration and so mitigates the fading.
2.3.4 Signal Penetration

Infrared radiation and visible light are similar in some ways. Both are absorbed by dark objects and reflected by plane surfaces. Infrared radiation is blocked by walls and other opaque barriers. On the other hand, RF waves penetrate through walls and as a result they have an advantage over optical systems. [2]

2.3.5 Performance in different atmospheric conditions

Atmospheric channel loss causes signal fading in both RF and FSO systems but the power loss due to rain, fog and snow are extreme sources of atmospheric loss. In RF technology, signal fading due to snow is much lower than for FSO systems. It is almost negligible for dry snow.

2.3.6 Spectrum License

The infrared spectrum is located above 300 GHz therefore it is unlicensed and free unlike the RF spectrum which requires a license to be used. This reduces the system cost of FSO technology.

2.4 FSO Application Areas

Some of many of application areas of FSO system are mentioned below:

- **Deep space communication:** Low power consumption, high data rate, much reduced size and weight in comparison to RF, and security are just some factors that have made FSO of interest to deep space missions.

- **Last mile access:** Fiber based systems usually can support more than 2.5 Gbps, but the final leg of system which connects the end-user to the service provider usually cannot support this rate. This is due to the low capability of copper wire or coaxial cable used in this final leg. By employing FSO technology, this bandwidth bottleneck issue can easily be overcome.

- **Temporary link:** Natural disasters, wars and other events may damage existing communication infrastructures. In this case, applying temporary FSO systems is fast and reliable. Another example is seen in the war zone where making secure and fast networks is very critical. An FSO system is the best solution for this need.
Areas with sensitive devices to RF signals: In hospital areas and airport, use of RF signals to deliver data may affect sensitive electrical devices. FSO systems do not cause interference problems.

Dense metropolitan zone: In such zones employing FSO technology saves both more time and cost than implanting optical fibers.

2.5 Safety

Human safety is the highest priority in employing any kind of technology. Laser systems which operate between 0.18 μm and 1 mm may cause biological damage to the eye and skin. IR lasers are located in this window so applying them in FSO systems should be followed by safety considerations.

2.5.1 Eye hazard

Our eye is a complex system that is more sensitive than skin and as a result is more susceptible to laser hazards.

Figure 2-8 shows the eye diagram. The light passes through cornea and then is focused on retina.

Focused light at the retina has irradiance of 100,000 times greater than the irradiance before entering the eye. This huge optical gain causes the entering beam from laser to be dangerous.
2.5.2 Maximum Permissible Exposure (MPE)

MPE is the level of laser radiation that is considered safe for an unprotected human eye. Its unit is either W/cm$^2$ or J/cm$^2$ and is measured at the cornea of the human eye. MPE value depends on the exposure duration of the laser beam to the eye and it decreases as the exposure time increases.

2.5.3 Accessible Emission Limit (AEL)

The accessible emission limit is a metric used in laser classifications. It’s the corresponding power at which the maximum emission level lies in a particular hazard class and its unit is Watts. Point sources AEL can be found by multiplying the area of limiting aperture by the MPE value.

2.5.4 850 vs. 1550 nm lasers

There are two major laser types that are used in FSO systems. For a specific amount of exposure time, the 1550 nm laser has a much higher MPE than 850 nm. This is due to the fact that most of the beam energy at the 1550 nm wavelength is absorbed by the cornea before being focused on the retina. This means a higher laser power can be used to transmit data with 1550 nm than with 850 nm without exceeding the safety limit.

2.5.5 Classification

There are various organizations which provide laser safety standards. For this project, the safety standard provided by the Laser Institute of America is used.

Lasers, depending on their characteristics, fall in one of the following classes:
<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Safe in all conditions</td>
</tr>
<tr>
<td>1M</td>
<td>Safe all the time except when using optical instruments like telescope</td>
</tr>
<tr>
<td>2</td>
<td>Low power lasers with visible portion of spectrum (0.4 to 0.7 μm) are usually safe due to aversion response and blinking of eye</td>
</tr>
<tr>
<td>2M</td>
<td>Similar to class 2 but may cause eye damage if used with optical aids</td>
</tr>
<tr>
<td>3R</td>
<td>Direct or reflected beam may cause injury if the eye is stable and focused</td>
</tr>
<tr>
<td>3B</td>
<td>Direct or reflected beam may cause injury</td>
</tr>
<tr>
<td>4</td>
<td>Dangerous to the eye or skin and may cause fire</td>
</tr>
</tbody>
</table>

Table 2-1: Different classes of laser diodes
Chapter 3: Optical Sources and Detectors

3.1 Light Emitting Diode (LED)

The LED is a semiconductor device and an optical source which radiates an optical beam when a forward bias voltage is applied to it. The mechanism of the LED is based on a p-n junction. Applying direct voltage to the LED terminals makes a flow of electrons from the n-side (anode) to the p-side (cathode). Each electron, by reaching the hole on the p-side releases energy in the form of a photon. The wavelength of the radiated photon depends on the energy gap between semiconductor materials. A basic LED diagram is shown in Figure 3-1.

LEDs are low cost devices. LEDs belong to the class of low power devices and also because of their high beam divergence and non-coherent beam characteristics, they are considered to be eye safe light sources.

3.2 LASER

LASER is the acronym for Light Amplification by Stimulated Emission of Radiation. Stimulated emission is a process in which the incident photon causes the excited electron to go to a lower energy level and during this transition radiates a photon with same phase and frequency of the incident photon.
The basic diagram of a semiconductor optical amplifier, which is the main concept used in LASER technology is shown in Figure 3-2.

![Diagram of a simple semiconductor optical amplifier](image)

Figure 3-2: Diagram of a simple semiconductor optical amplifier

To produce a coherent beam of photons, direct bias voltage is applied to the diode. This causes the flow of electrons towards the p-type region and holes into the n-type region and as a result, an electron-hole pair is generated; in laser applications this is called pumping. In this case, emission of a photon leads to the recombination of electron-hole pairs. The result of this recombination is the production of an additional photon with the same frequency and phase as the first photon.

These photons, the input photon and the generated one, can be guided out of the semiconductor or can also be used to generate more photons. One usual way to reach this goal is by using two mirrors, one perfect mirror which reflects all incident photons and another partial mirror which reflects just a portion of the photons and transmits the rest. Trapped photons can be used to stimulate more electrons and therefore more generation of photons. Those photons which pass through the partial mirror are the laser beam output.
3.3 Photodetector

There are two kinds of devices that can be used to detect the light photons:

- photoconductive detectors

- photodiode detectors

Both are based on a phenomenon called the photoelectric effect. Electrons in a material become excited due to photon absorption and transit from the valence band to the higher level of energy in the conduction band. This process makes electron-hole pairs. The output voltage source can be used to create an electric field that forces electrons to move in the opposite direction of the field and force holes to move in the direction of the electric field, causing a current flow.

3.3.1 Photoconductors

A typical photoconductor is made of a semiconductor. Absorption of a photon generates an electron-hole pair that creates a current by applying external voltage. The basic diagram is shown in Figure 3-4.

Figure 3-3: Diagram of a typical Photoconductor
3.3.2 Photodiodes

As it can be deduced from its name, photodiodes detectors are based on both a diode structure and the photoelectric effect. In p-n junction diodes, absorption of a photon by the depletion layer produces an electron-hole pair. The generated electron-hole pair can be transported by means of the external reversed biased voltage creating a current flow. Photons can also be absorbed in the p-side or n-side of the diode and produce an electron-hole pair. Even in the presence of external reversed bias voltage and the resulting electrical field, they move in a random direction and do not have an effect on the external current. Only those who can reach the depletion layer randomly contribute a signal to the external circuit. Figure 3-5 shows the diagram of p-n junction photodiode.

Photodiodes are much faster than photoconductors and as a result are mainly used in optical communication systems.

![Figure 3-4: p-n junction photodiode](image)
Chapter 4: FSO Channel

Eye safety and other issues make LEDs more useful than the LD in indoor FSO systems. On the other hand, lasers are the main sources used in outdoor point to point FSO systems.

Implementing a practical system cannot be done without the knowledge of a communication channel. This chapter discusses indoor and outdoor channels, as well as their key factors.

4.1 Indoor Channel

FSO link configuration models are described in section 2.2. In this project, the Directed LOS configuration is used. One of the most important factors in a communication system is to accurately deliver the transmitted signal power to the receiver. FSO systems, like other wireless communication systems, are subject to path loss. Providing enough power at the receiver is not the only issue in these systems. Ambient light that generates photocurrent shot noise is another major problem in directed LOS systems.

4.1.1 Path loss

Indoor communication systems normally cover short distances; the path loss is approximately [2]:

\[ A_{pl} = 20 \log_{10} \left( \frac{2 \theta d}{D_{Rx}} \right) \]

where:

- \( \theta \) is the half-angle beam width
- \( d \) is the distance between the transmitter and the receiver
- \( D_{Rx} \) is the diameter of the receiver capture surface
4.1.2 Ambient Light

The receiver in FSO systems not only collects the transmitted optical beam, but it also obtains intense ambient light from natural and artificial sources. Any collected light, other than the transmitted one, is considered as noise. Three major sources of optical noise are sunlight, fluorescent lamps and incandescent lamps.

The shot noise from an ambient light source can be represented as a white Gaussian noise. The power spectral density (PSD) of this noise is given by [9]:

\[ N_0 = 2qI_b \]

where \( I_b \) is the total DC photocurrent due to light noise sources and \( q \) is the charge of one electron.

4.1.2.1 Incandescent lamps

An incandescent lamp produces light by electrically heating a wire filament. Tungsten is a common chemical element used in incandescent lamps as the wire filament, and a tungsten light bulb acts as a blackbody radiator. This type of electromagnetic radiation has a continuous blackbody Planck spectrum and the intensity of its radiation at any frequency depends solely on the temperature of the body.
Figure 4-2 shows the intensity of a tungsten-halogen lamp for different wavelengths and temperatures. The figure shows that the highest intensity occurs at around 870 nm for the 3300 K lamp. This means that most of the energy of this kind of lamp radiates in the invisible spectrum.

![Figure 4-2: The relative spectral radiation of a tungsten-halogen lamp in different wavelength and temperatures [12]](image)

A tungsten lamp has an optical spectrum at both 850 nm and 1550 nm wavelengths, which are used in most free space optical communication systems. This interference causes degradation in the performance of FSO systems.

### 4.1.2.2 Fluorescent lamp

Another source of noise in indoor wireless optical communications is a fluorescent lamp. A fluorescent lamp is a sealed glass tube containing low-pressure mercury vapor and an inert gas, which is typically argon. The inner surface of the tube is coated with phosphor powder, which is a fluorescent material. Fluorescent means it emits visible light by absorbing light at other wavelengths. An electric discharge in the tube excites mercury electrons and they transit to higher level of energy. In the process of returning to the lower level of energy, electrons radiate photons in the ultraviolet wavelength range that cannot be detected by the human eye. The phosphor absorbs the ultraviolet light and radiates visible light.
There are two major types of fluorescent tubes: the low frequency and high frequency tube. The word frequency refers to the frequency of the electronic ballast, which is a key part in fluorescent tubes. A low frequency fluorescent tube includes a visible spectrum up to 1500 nm. The spectrum range for high frequency tube, which is used mostly in United States and Japan, is between 600 and 1100nm.

The spectrum of a typical fluorescent lamp is shown in Figure 4-3.

![Figure 4-3: Spectrum of a 16 W compact fluorescent light](image)

According to Figure 4-3, fluorescent lamps have peak intensity in wavelengths below 800 nm. That means interference of fluorescent lamps in optical communication systems working at 1550 nm wavelengths, which is the case for this project, is less than incandescent lamps. Nevertheless fluorescent lamps are an important source of noise for 850 nm FSO systems.

**4.2 Outdoor Channel**

FSO systems are mostly used in outdoor applications, but they encounter more problems than indoor systems. There are several factors in outdoor wireless communications such as atmospheric loss, pointing loss, beam divergence, and sunlight that degrade system performance.
4.2.1 Atmospheric Loss

Atmospheric loss can be due to scintillation loss, absorption, and scattering. These types of losses are inevitable.

4.2.1.1 Scintillation Loss

Any small turbulence in the atmosphere forms an inhomogeneous gas in regards to the refracting index. A beam of light that travels in this inhomogeneous space faces different refraction indexes, and some photons might refract from the line of sight and cannot reach the receiver. An example of this effect is the twinkling of stars. Lower wavelengths are refracted more than the higher wavelengths so scintillation loss in lower wavelengths is more than higher wavelength. For small distances (less than 1 Km), this effect is negligible. However, in long distances, scintillation is a severe problem that can cause degradation in communication system.

4.2.1.2 Absorption

The transmitted light photons in FSO systems may collide with molecules that are present in an atmosphere and be absorbed by them. An absorbed photon excites the atom of the molecule, which means that the atom moves to the higher unstable level of energy. The de-excitation of an atom happens in two ways: emitting a photon or releasing energy as heat. The latter case is called absorption and all the energy of the absorbed photon converts to heat. In the first case, the excited atom returns to the stable level and releases a photon. The emitted photon usually has lower wavelength and hence a lower energy than the absorbed one. The difference in energy of the absorbed photon and the emitted one usually appears as a vibration (heat). Absorption yields to energy loss of the transmitted beam.

The only solution to mitigate absorption loss is to find a window (range of wavelength with minimal loss for wavelength used). Figure 4-4 shows the atmospheric transmittance at different wavelengths.
Atmospheric transmission windows (wavelength ranges with low atmospheric attenuation) are [2]:

- Visible to Near IR 0.4 to 1.4 μm
- Near IR 1.4 to 1.9 and 1.9 to 2.7 μm
- Mean IR 2.7 to 4.3 and 4.5 to 5.2 μm
- Far IR 8 to 14 μm
- Extreme IR 16 to 28 μm

In addition to the safety issue, which is explained in section 2.5, low attenuation of light at 1550 nm is another reason to choose 1550 nm for this project.

4.2.1.3 Scattering

There is a probability that the radiated photon from the excited atom, which is mentioned in the previous section, is at the same wavelength as the absorbed one. However, it travels in a different direction and because of this it will not reach the receiver; this is one type of scattering.

Figure 4-4: Transmittance of atmosphere in different wavelength [2]
Another type of scattering is caused by weather conditions like rain, snow and fog. This kind of attenuation is a function of wavelength and visibility. Visibility is a meteorological term and is the greatest distance at which a black object of suitable dimensions, situated near the ground, is visible and recognized when observed against a bright background [14].

Fog has the most severe effect among atmospheric conditions and highly degraded FSO systems. The scattering coefficient resulting from fog is [15]:

$$\beta_n = \frac{13}{V} \left(\frac{\lambda_{nm}}{550}\right)^{-Q}$$

where:

- $V$ is the visibility in Km.
- $\lambda_{nm}$ is the wavelength in nanometers.
- $Q$ is the constant parameter related to particle size distribution.

$$Q = \begin{cases} 
1.6 & \text{if } V > 50 \\
1.3 & \text{if } 6 < V \leq 50 \\
0.16V + 0.34 & \text{if } 1 < V \leq 6 \\
V - 0.5 & \text{if } 0.5 < V \leq 1 \\
0 & \text{if } V < 0.5
\end{cases}$$

Table 4-1 shows values of attenuation at a 1550 nm wavelength using the above formula.
### Table 4-1: Atmospheric loss as a function of visibility for a 1550 nm FSO system

<table>
<thead>
<tr>
<th>Atmospheric Condition</th>
<th>Weather Constituents (mm/h)</th>
<th>Visibility (m)</th>
<th>Attenuation (dB/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense fog</td>
<td></td>
<td>50</td>
<td>260</td>
</tr>
<tr>
<td>Thick fog</td>
<td></td>
<td>200</td>
<td>65</td>
</tr>
<tr>
<td>Moderate fog</td>
<td></td>
<td>500</td>
<td>26</td>
</tr>
<tr>
<td>Light fog</td>
<td>Storm</td>
<td>100</td>
<td>770</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Very light fog</td>
<td>Strong Rain</td>
<td>25</td>
<td>1900</td>
</tr>
<tr>
<td>Light mist</td>
<td></td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Average Rain</td>
<td>12.5</td>
<td>2800</td>
</tr>
<tr>
<td>Very light mist</td>
<td></td>
<td></td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>Light Rain</td>
<td>2.5</td>
<td>5900</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10,000</td>
</tr>
<tr>
<td>Clear air</td>
<td>Drizzle</td>
<td>0.25</td>
<td>18,100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20,000</td>
</tr>
<tr>
<td>Very clear air</td>
<td></td>
<td></td>
<td>23,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50,000</td>
</tr>
</tbody>
</table>

The system margin should be chosen to compensate for signal attenuation to reduce the effect of atmospheric loss. That means more power should be used in some weather conditions or increase the receiver aperture size, which increases receiver gain.

**4.2.2 Pointing loss**

Any small amount of misalignment or partial alignment of the transmitter and receiver causes signal loss. Pointing loss is negligible for short-range stationary FSO systems (less than 1 Km), but it is a significant factor in long-distance links. In long link ranges, even a small movement of a building can affect the system performance. For links between mobile systems, the pointing and alignment is even more important. This issue is overcome by using a tracking system to align and maintain alignment between transmitter and receiver at all times.
4.2.3 Beam Divergence

Lasers produce a collimated narrow beam but the beam spreads out as it travels in space. The proper type of collimator can be used to overcome this issue. A collimator reduces beam divergence but cannot remove it completely. For long distances (e.g. deep space communication), beam divergence introduces signal loss as a part of the transmitted signal that is collected by the receiver.

![Diagram showing beam divergence](image)

Figure 4-5: Power loss due to the beam divergence

Figure 4-5 shows a transmitter with the beam divergence of $\theta$. $D_t$ and $D_r$ are the transmitter and receiver aperture diameter, respectively.

The beam size at the distance $L$ of the transmitter is:

$$d = D_t + 2(L \times \tan(\theta/2))$$

for small angles $\tan\alpha \approx \alpha$ so:

$$d = D_t + L\theta$$

The ratio of the received optical power to the transmitted power indicates amount of power loss due to the beam divergence [2]:

$$L_{\text{div}} = \frac{P_r}{P_t} = \frac{A_r}{A_t} = \frac{D_r^2}{(D_t+L\theta)^2}$$
4.2.4 Sunlight

In outdoor communication systems the receiver collects not just the transmitted light but also the background light such as sunlight. The sun is a black body just as an incandescent lamp and it emits incoherent light. Figure 4-6 displays its spectrum below.

![Intensity of solar radiation](image)

Figure 4-6: Intensity of solar radiation [2]

Interference from the sun spectrum and the transmitted beam degrades performance of such systems.

4.3 Link Equation

Two types of channels, indoor and outdoor, and different elements that affect FSO systems are described in the previous sections. Now the link equation can be introduced considering all those factors [16]:

\[ P_{rx} = P_t G_t G_r L_a L_R \eta_p \eta_t \eta_r \]

- \( P_{rx} \) Average signal power received
- \( P_t \) Transmitted power
- \( G_t, G_r \) Transmit and Receive aperture gain
- \( L_a \) Atmospheric loss
- \( L_R \) Range Loss
\( \eta_{pt} \quad \text{Pointing efficiency} \)

\( \eta_t, \eta_r \quad \text{Transmitter and Receiver efficiency} \)

The antenna (aperture) gain at the transmitter and receiver is:
\[
G = \frac{4\pi A}{\lambda^2} = \left(\frac{\pi D}{\lambda}\right)^2
\]

where \( A \) is the transmitter/receiver aperture and \( \lambda \) is the wavelength and \( D \) is the diameter of the aperture.

The Range Loss is:
\[
L_R = \left(\frac{\lambda}{4\pi R}\right)^2
\]

where \( R \) is the distance between the transmitter and receiver. As it can be seen from the formula, the larger wavelength causes more signal loss.
Chapter 5: Modulation

Modulation techniques developed for RF channels are not popular in FSO systems. In fact, eye and skin safety issues require the average optical transmit power not to exceed a specific maximum limit. That means a large number of pulse shapes with limited bandwidth like sinc pulses cannot be used.

Figure 5-1 shows the different types of modulation which can be used in optical communication systems.

**Figure 5-1: Modulation tree [4]**

Internal (also called direct) modulation varies the characteristics of the transmitted signal before exiting the LD/LED. External modulation changes the characteristics of the light beam after it emits from LD.

### 5.1 Analogue Intensity Modulation

This type of modulation codes analogue signals (data) or a pre-modulated RF signal on light by varying the LD/LED intensity of the beam which can be done in two ways:

1. Using a current driver as a modulator, to vary the LD/LED current, accordance with data.
Advantages of intensity modulation by varying the laser diode current:

- Low cost modulation system
- Simple scheme
- Low cost detection using non-coherent (direct) detection at the receiver

Disadvantages:

- Not suitable for high frequency applications due to limited bandwidth of the optical source

2. Using an external optical modulator to put the analogue signal onto the light beam emitted from the laser. External modulation provides the capability of using AM, QAM, PAM and SCM modulations.

In Figure 5-3 MZM represents a Mach-Zehnder modulator. MZM modulates the light beam by changing the signal intensity. This is done by dividing the light into two equal beams and making a phase shift in one of them according to the message (modulating signal). The summation of the signal with phase shift and the original one results variation in intensity of the output light.
Advantages:

- Capable of high frequency modulation
- Simple scheme
- FSO link is transparent to the modulation format of RF signal

Disadvantages:

- High cost of external modulators, ex. Mach-Zehnder modulator (MZM)
- Costly detecting due to using coherent detection at the receiver
- Requires high drive voltages
- Shows nonlinearity at high power levels which leads to intermodulation distortion

5.2 Digital Baseband Modulation

There are several techniques to modulate data in digital format. On-Off-Keying and Pulse Position Modulation are two major techniques, which are discussed in this section.

5.2.1 On-Off-Keying (OOK)

The simplest form of digital IM/DD modulation is OOK. To represent each bit, 0 or 1, two discrete forms of signal are needed. An optical pulse can represent a bit 1 and the absence of the optical pulse can be assigned for a bit 0. Modulation schemes like RTZ and NRZ or return-to-zero-inverted can be applied. The intensity of light (power of light), is always equal or bigger than zero and therefore any kind of bipolar coding cannot be applied.

The transmitted pulse shape, \( p(t) \), for NRZ and RZ (with half duty cycle) On-Off-Keying are:

\[
p_{\text{NRZ}}(t) = \begin{cases} 
2P_{\text{avg}} & t \in [0,T_b] \\
0 & \text{elsewhere} 
\end{cases} \quad p_{\text{RZ}}(t) = \begin{cases} 
4P_{\text{avg}} & t \in [0,T_b/2] \\
0 & \text{elsewhere} 
\end{cases}
\]

\( P_{\text{avg}} \): average power
\( T_b \): bit duration

These symbols are shown in Figure 5-4.
5.2.2 Pulse Position Modulation (PPM)

In PPM, M bits can be transmitted by a single pulse, occupying one slot of the total L (=2^M) slots.

The transmitted pulse shape, p(t), for PPM is [17]:

\[
p(t) = \begin{cases} 
1 & t \in \left[ \frac{k-1}{L} T, \frac{k}{L} T \right] \\
0 & \text{elsewhere}
\end{cases}
\]

where:

\[T = T_b M/L\]

\[k \in \{1, 2, \ldots, L\}\]

The ppm waveform is shown in Figure 5-5.

In the matter of power consumption, PPM waveforms need less power than OOK but pay the price of needing more bandwidth. Average power efficiency is a key factor in FSO systems with regards to eye safety issues. Occupying more bandwidth is not a serious issue in FSO systems as
the available bandwidth is not limited. Another issue is the synchronization of the received signal to the local clock in order to detect each symbol properly. Various types of synchronization techniques can be used to demodulate the received signal properly. The differential-pulse-position-modulation (DPPM) is a technique that improves bandwidth efficiency by eliminating the empty slots after each pulse in one symbol. In addition, DPPM modulation technique eliminates the need of synchronization. However detecting a single slot in error results multiple symbols to be detected in error. For this reason, higher power is needed at the transmitter. Another price of using PPM waveforms is greater complexity of the transmitter and receiver.
Chapter 6: Design of a 1550 nm simplex free space optical communication system

In this chapter, the design of a free space optical communication system is described. The provided system is simplex which means the communication occurs in one direction, from the transmitter to receiver only.

The system block diagram is shown in Figure 6-1.

![Figure 6-1: Block diagram of a basic FSO system](image)

In following sections, design, selecting and specification of each component is described.

6.1 Laser diode

Introduction to the laser diode and safety issues were provided in chapter 2, Section 2.5 and Chapter 3, section 3.1. In this section the process of selecting 1.5 mW, 1550 nm pigtailed laser diode is shown.

6.1.1 Wavelength

The atmospheric loss degrades the performance of FSO systems which was the subject of chapter 4, section 4.2.1. On way to reduce effect of atmospheric loss is choosing the proper wavelength at which the power attenuation due to atmospheric loss is low. Two major wavelengths that are widely used in FSO systems are 850 nm and 1550 nm. These wavelengths are located in a
window with low atmospheric loss. Comparing these two wavelengths, the 1550 nm suffers less atmospheric loss than 850 nm and therefore is preferred.

6.1.2 Safety

The American National Standard for Safe Use of Lasers is the reference standard source for this project. Due to the book copyright, no formula or tables used to determine the laser safety could be provided in this writing.

As described in chapter 2, class-I lasers are considered safe and do not need any eye protection to work with. Regarding the ANSI standard, 1550 nm lasers with optical output power less than 9.6 mW are considered as class-I. In other word, AEL for class-I lasers with wavelength 1550 nm, is 9.6 mw.

For lasers with wavelength of 850 nm, AEL for class-I is 0.77 mW.

6.1.3 Laser Specification

Considering factors mentioned above, safety and atmospheric loss issues, a 1550 nm laser with maximum output power of 1.8 mW is chosen to be used in this project. As the maximum output power of this laser is less than the AEL for class-I lasers, it does not require eye protection. The 1550 nm wavelength also suffers less attenuation due to atmospheric loss.

<table>
<thead>
<tr>
<th>LPS-PM1550-FC Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
</tr>
<tr>
<td>1520 nm</td>
</tr>
<tr>
<td>1550 nm</td>
</tr>
<tr>
<td>1580 nm</td>
</tr>
</tbody>
</table>

*Temperature = 25 °C

Table 6-1: LPS-PM1550-FC Specifications
In Figure 6-3, the PD abbreviation stands for photodiode. The job of a photodiode is monitoring the optical output power of LD and providing a control signal to the LD that guarantees the constant output optical power.

Lasers are manufactured in different pin code styles. These styles are shown below.

As shown in Figure 6-4, LPS-PM1550-FC laser diode has the style D pin configurations.

<table>
<thead>
<tr>
<th>Pin Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LD Cathode</td>
</tr>
<tr>
<td>2</td>
<td>PD Anode</td>
</tr>
<tr>
<td>3</td>
<td>LD Anode</td>
</tr>
<tr>
<td>4</td>
<td>PD Cathode</td>
</tr>
</tbody>
</table>

Table 6-2: Pin-out of the LSP-PM1550-FC
6.2 Laser Driver

To maintain constant output power of LD, a laser diode driver is used. The LD driver uses the signal of the monitor photodiode, which is implemented internally, as a feedback signal. LD driver uses a feedback circuit to adjust the laser current in order to reach and maintain the desired output power.

Referring to the LPS-PM1550-FC laser diode specifications, the maximum operational current is 50 mA. The LD1100 laser driver, which provides current up to 250 mA, is chosen to drive LPS-PM1550-FC laser diode. Specifications of LD1100 laser driver are shown in table 6-3.

<table>
<thead>
<tr>
<th>Performance Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Mode</td>
</tr>
<tr>
<td>Output Current</td>
</tr>
<tr>
<td>Output Control</td>
</tr>
<tr>
<td>Output Stability</td>
</tr>
<tr>
<td>Output Noise</td>
</tr>
<tr>
<td>Feedback Gain</td>
</tr>
<tr>
<td>Monitor Current Range</td>
</tr>
<tr>
<td>Operating Voltage</td>
</tr>
<tr>
<td>Quiescent Current</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
<tr>
<td>ESD Protection</td>
</tr>
</tbody>
</table>

Table 6-3: LD1100 Specification [18]

LD1100 supports Style A and Style B laser pin configurations. Four pin laser diodes (Style D and Style F) can be connected to the LD100 to match either Style A or Style B configuration. To change pin connections of PM1550-FC laser diode from style D to Style A, the pin number 3 (laser anode) should be connected to the pin number 4 (Photodiode cathode). This is shown in Figure 6-5.

![Figure 6-5: Changing pin connections of LPS-PM1550-FC laser diode from style D to Style A](image)
Figure 6-6 and table 6-4 show LD1100 board schematic and pin-out of the LD1100 laser driver respectively.

![Figure 6-6: LD1100 laser driver [18]](image)

The pin-programmable feedback gain in the LD1100 accommodates variation of the photodiode monitor current range from 0.01 mA to 3.62 mA. To have proper operation of the LD, the feedback gain in LD1100 should be set according to the monitor current of the photodiode.

Feedback gain of monitor photodiode is set in LD1100 using three steps:

Step 1: Determining the laser monitor photodiode feedback current from the laser specification.

Step 2: Finding the resistor combination that matches photodiode current from table 6-5.

Step 3: Applying the combination on the LD1100 J1 pins: to enable each resistor, the corresponding pin should be connected to the power supply common (pin2).

![Table 6-4: LD1100 Pin-out [18]](image)
Based on the LD specification in table 6-3, the monitor current ($I_{\text{mon}}$) is 1 mA. Using table 6-5, the resistor $RD$ should be turned on; this can be done by connecting pin 10 to pin 2 (common).

### Table 6-5: Feedback gain resistor setting [18]

<table>
<thead>
<tr>
<th>Max $I_{\text{mon}}$ (mA)</th>
<th>RA 1000 kΩ</th>
<th>RB 33 kΩ</th>
<th>RC 10 kΩ</th>
<th>RD 3.3 kΩ</th>
<th>RE 1 kΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.035</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.085</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.110</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.260</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.285</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.335</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.360</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>0.767</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>0.792</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>0.843</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>0.868</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>1.017</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>1.042</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>1.093</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>1.118</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>2.610</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2.635</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2.686</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2.610</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2.760</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2.785</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2.835</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>2.860</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>3.267</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>3.292</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>3.343</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>3.368</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>3.517</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>3.542</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>3.593</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>3.62</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
</tbody>
</table>

Figure 6-7: Feedback loop diagram
6.3 Bias-T

LD1100 laser driver provides a dc current to the laser so the output power of the laser is approximately constant. The DC signal does not contain any information and to convey data, alternation of signal is needed. To achieve this goal a bias-T can be used to superimpose a modulation current onto the DC current. A Bias-T is a three port network to insert DC power into an AC signal.

6.4 Isolator

One of the issues that a laser driver faces is back reflection of the transmitted light beam. Back reflection can cause intensity fluctuation, frequency shift and damage to the laser diode. To prevent this effect, an optical isolator is used. The optical isolator, also called a Faraday isolator, passes light in only one direction (forward direction) and prevents light from being transmitted in the reverse direction. The operation of the isolator is shown in Figure 6-9.
The isolator used in this project is IO-H-1550FC and its specifications is shown in Table 6-6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>1535-1565</td>
<td>nm</td>
</tr>
<tr>
<td>Peak Isolation</td>
<td>36.46</td>
<td>dB</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>0.58</td>
<td>dB</td>
</tr>
<tr>
<td>Return Loss (Input/Output)</td>
<td>&gt;60/50</td>
<td>dB</td>
</tr>
<tr>
<td>CW Power</td>
<td>300</td>
<td>mW</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20 ~+60</td>
<td>°C</td>
</tr>
</tbody>
</table>

Table 6-6: IO-H1550FC Specification

6.5 Collimator

Laser diodes produce collimated narrow beam. However, the divergence of the beam exiting the LD is not zero. Due to the beam divergence, the longer the beam travels, the wider the beam size becomes. For example if a laser with the beam divergence of 15° is used, as is the case for this project, the beam radius after a 100 meters is about 26.8 cm.

To overcome this problem, a device called collimator is used. A basic collimator is a convex lens in which when a beam of light passes through its focal point and hits the lens, the output is a parallel beam to the lens principal axis.
Using a laser diode with/without a collimator is shown in Figure 6-10.

In Figure 6-10 a point source (LD) with a beam divergence of 15° transmits a light beam in two cases. Without using a collimator, Figure 6-10(a), the beam radius after traveling a distance of 100 m is about 26.8 cm. The collimator in Figure 6-10(b) reduces the divergence to about 0.05°. The beam radius after traveling 100 m is:

\[ d = 100 \cdot \tan(0.05°) = 87.3 \text{ mm} \]

New beam radius = \( r + d = 88.91 \text{ mm} \)

The difference between the beam diameter after 100 m using the collimator and without using any collimator shows the benefit of applying a collimator. This means that a smaller antenna at the receiver is needed to recover most of the transmitted signal energy.

The collimator used in this project is TC06FC-1550 with the focal length of 6.18 mm and the full angle divergence equals to 0.101°. The effective aperture of this collimator is 4.5 mm.
6.6 Telescope

Due to the divergence effect mentioned in the section 6.5, the beam arriving at the receiver has a larger diameter than the transmitted beam. The beam diameter at the receiver is usually bigger than the aperture of the photodetector. To converge the arriving beam to the photodetector, a telescope is used. The telescope has the same structure as a collimator and they usually use a convex lens to collimate or converge light. Beams parallel to the principal axis of a convex lens converge at its focal point.

![Figure 6-11: Using a telescope at the receiver to converge the light into the photodetector](image)

When the received beam diameter is bigger than the receiver aperture size, increasing the collection aperture diameter results more signals to be guided to the detector and the receiver gain increases subsequently. This gain was shown in section 4.3 as part of the link equation. However, a telescope with larger aperture captures more unwanted light (noise) too. The telescope used in this project is F810FC-1550 with the effective diameter of 7 mm.

6.7 Photodetector

In order to detect and convert the received optical signal to an electrical signal a device called a photodetector is used. A photodetector consists of a photo diode which is reverse-biased. Two type of photodiodes used in optical communication systems are: PIN and Avalanche Photodiode (APD). The PIN photodiode is manufactured by using p-type and n-type semiconductors separated by lightly doped intrinsic region.
An APD photo diode offers a higher sensitivity than the PIN type but they are more sensitive to the noise and changing in the temperature. APD photodiodes also consume high amount of power comparing to PIN types.

Responsivity, dark current, bandwidth and noise-equivalent power are key factors in choosing a photodetector. These factors are described briefly in following sections.

6.7.1 Responsivity

The ratio of the generated current to the amount of incident power to the aperture of the detector is called responsivity.

Responsivity is wavelength dependent and has the peak value at the specific wavelength. The photodetector which is used in this project is the DET01CFC with the peak responsivity equal to 0.95 A/W at the 1550 nm wavelength. This is an InGaAs PIN photodiode. The responsivity curve of DET01CFC is shown in Figure 6-12.

![Spectral Response](image)

Figure 6-12: Responsivity curve of DET01CFC

6.7.2 Dark current

Dark current is the amount of current that the photodiode produces by applying the bias voltage without applying an optical source. This leakage current is temperature dependent and it also depends on the amount of applied voltage to the photodiode.
DET01CFC has a dark current of 0.25 nA at T=25 °C and V_{bias} of 12 v.

6.7.3 Bandwidth

The bandwidth of a photodetector is dependent on the load and junction capacitance of the photodetector. It can be expressed as:

\[ f_{BW} = \frac{1}{2\pi R_L C_j} \]

where \( R_L \) is the load of the photodetector and \( C_j \) is the junction capacitance.

The bandwidth of the photodetector applied in this project is 1.2 GHz.

The complete specification of the DET01CFC is shown in Table 6-7.

<table>
<thead>
<tr>
<th>Electrical Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
</tr>
<tr>
<td>Active Area Diameter</td>
</tr>
<tr>
<td>Wavelength Range</td>
</tr>
<tr>
<td>Peak Wavelength</td>
</tr>
<tr>
<td>Peak Response(^2)</td>
</tr>
<tr>
<td>Diode Capacitance (12V)</td>
</tr>
<tr>
<td>Bandwidth (-3 dB)(^2)</td>
</tr>
<tr>
<td>Rise Time, Measured(^2,3)</td>
</tr>
<tr>
<td>Rise Time, Theoretical(^3,3)</td>
</tr>
<tr>
<td>NEP ((\lambda_p))</td>
</tr>
<tr>
<td>Saturation Power (CW)</td>
</tr>
<tr>
<td>Damage Threshold</td>
</tr>
<tr>
<td>Bias Voltage</td>
</tr>
<tr>
<td>Dark Current(^{4}(\text{with 10 M(\Omega) Load}) )</td>
</tr>
<tr>
<td>Output Voltage</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

### General

<table>
<thead>
<tr>
<th>Input</th>
<th>FC/PC Fiber Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>SMA (DC Coupled)</td>
</tr>
<tr>
<td>Package Size</td>
<td>2.21” x 1.40” x 0.80”</td>
</tr>
<tr>
<td></td>
<td>(56.1 mm x 35.6 mm x 20.3 mm)</td>
</tr>
<tr>
<td>Ball Lens Diameter</td>
<td>0.059” (1.50 mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>0.18 kg</td>
</tr>
<tr>
<td>Storage Temp</td>
<td>0 to 40 °C</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>0 to 40 °C</td>
</tr>
<tr>
<td>Battery</td>
<td>A23, 12 V(_{DC}), 40 mAh</td>
</tr>
<tr>
<td>Replacement Battery</td>
<td>Energizer No. A23</td>
</tr>
</tbody>
</table>

Table 6-7: Specification of the DET01CFC
6.7.4 Noise Equivalent Power

The Noise Equivalent Power (NEP) is amount of optical power that produces a signal to noise ratio (SNR) of 1.

The noise has a continuous spectrum over all frequencies. The amount of the noise affects the received signal is directly related to the bandwidth of the detector. To be able to compare detectors with different bandwidths, the unit of the NEP is defined as \( \frac{W}{Hz^{1/2}} \). A lower amount of NEP indicates a better detector.

The NEP of the detector used in this project is \( 4.50 \times 10^{-15} \frac{W}{Hz^{1/2}} \). The bandwidth of this photodetector is 1.2 GHz so the smallest amount of power that can be detected is:

\[
4.50 \times 10^{-15} \frac{W}{Hz^{1/2}} \times (1.2 \times 10^9 \text{ Hz})^{1/2} = 1.559 \times 10^{-10} \text{ W} = 155.9 \text{ pW} \approx -98.07 \text{ dBm}
\]

6.8 Modulation

The focus of this project is first to build a short-range operative FSO system and second to observe the effect of atmospheric and range losses and the effect of the artificial and natural sources of light on the performance of the system by measuring the amount of the received power in various situations (e.g. under shade and under direct sunlight). Modulation techniques are not included in this study. The signal used as data in this project is a square wave with 50% duty cycle. The frequency of the square wave varies between 10 to 20 MHz.

One important parameter of modulation in an optical communication system is the extinction ratio. The extinction ratio is the ratio of the amount of power that indicates a 1 bit to the amount of power that indicates 0 bit. The extinction ratio is usually shown in dB.

![Figure 6-13: Determining the extinction ratio; a and b indicates the transmitted power representing bit 1 and bit 0 respectively](image-url)
In figure 6-13 the extinction ratio is a/b. A large value of extinction ratio is desirable. This is because it means more of a difference in the optical power representing a 1 bit and a 0 bit. Therefore, in a noisy channel where the signal is attenuated, the receiver can distinguish between bit 1 and bit 0 with less error. Ideally, the largest amount of extinction ratio can be obtained by representing bit 0 with no power (turning off the laser). However, crossing the laser threshold current (the current at which LD starts producing collimated beam) causes signal overshoot/undershoot and ringing at the transmitter which degrades the system performance and increases the bit error ratio. Hence, the laser output power should not be lower than a specific amount.

In this project, the laser diode produces a continuous 1.5 mw optical beam. Figure 6-14 shows the Light intensity, Current, Voltage (LIV) curve for LPS-PM-1550-FC laser diode.

![Figure 6-14: LIV curve of LPS-PM1550-FC](image)

The amount of threshold current for this is indicated as 12 mA in the test data sheet provided by the manufacturer. From the figure 6-14 it can be seen that the amount of power at 12 mA is less than 0.2 mW. That means by choosing 0.2 mW as the floor of the laser power, the laser diode current will not drop below the laser threshold current. Finally, the maximum extinction ratio can be determined:

\[
\text{Extinction ratio} = 10 \log \frac{1.5 \times 10^{-3}}{0.2 \times 10^{-3}} = 8.75 \text{ dB}
\]
Figure 6-15: Waveform to find the Extinction ratio of this project
Chapter 7: Performance, Simulation and Test Results

In this chapter, the performance of the system is discussed and analyzed. Figure 7-1 shows the system setup of a 1550 nm FSO system using components and the design described in chapter 6.

Figure 7-1: System setup of 1550 nm FSO link
The transmitter and the receiver were pointed directly towards each other and the distance between them was about 70 cm. The signal generator provided the 20 MHz square wave. The extinction ratio, as was calculated in the section 6.8, should be 8.75 dB. That means the average power of the laser output should be 0.85 mW and the peak of the signal should be 1.5 mW. This was done by adjusting the potentiometer such that the laser produced 0.75 mW and then the amplitude of the signal generator was adjusted to have the peak at 1.5 mW.

The system was tested for proper operation and passed some initial tests but despite all cautions and following safety protocols, unfortunately, the laser diode was damaged. The high cost of LPS-PM1550-FC laser diode led to the impossibility of obtaining any replacement. The project was continued as it was planned by using optical communication system design software called OptiSystem.

OptiSystem is software mostly used to design and simulate fiber optic communication networks but it has two components for the FSO link. One of the outstanding benefits of OptiSystem program is that it can communicate with the MATLAB program to do the co-simulation. All parameters of the real components were used in the simulation.

Figure 7-2: System scheme of the FSO system
7.1 Measuring signal under various weather conditions

To find the attenuation of the signal due to atmospheric loss and specifically due to scattering (mentioned in section 4.2.1.3), a MATLAB program was written. This program is as follow:

```matlab
% This program simulates the attenuation due to the scattering
% Input parameter - Wavelength, Visibility, Length

OutputPort1 = InputPort1;

wavl=Wavelength;
V=Visibility;
L=Length;

if (V>=50)
    q=1.6;
elseif (V>=6) && (V<50)
    q=1.3;
elseif (V>=1) && (V<6)
    q= (0.16*V) + 0.34 ;
elseif (V>=0.5) && (V<1)
    q= V-0.5;
else
    q=0;
end

Attenuation=((13*L)/V) * ((wavl/550) ^ -q);
f=10^(-Attenuation/10);

if(InputPort1.TypeSignal == 'Optical')
    [Is, cs] = size(InputPort1.Sampled);
    if( Is > 0 )
        for counter1=1:cs
            OutputPort1.Sampled(1, counter1).Signal =((InputPort1.Sampled(1, counter1).Signal) * sqrt(f));
        end
    end
end
```

%
The value of the wavelength, as mentioned in the LD test data sheet, is 1548.4 nm and the range on which the effect of different weather conditioned were test was chosen as 10 m. The amount of transmitted signal power is 850 μ.

Table 7-1: Visibility range and attenuation coefficient at the 1550 nm wavelength

<table>
<thead>
<tr>
<th>Atmospheric Condition</th>
<th>Weather Constituents (mm/h)</th>
<th>Visibility (m)</th>
<th>Determined Power(mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense fog</td>
<td></td>
<td>50</td>
<td>0.4121</td>
</tr>
<tr>
<td>Thick fog</td>
<td></td>
<td>200</td>
<td>0.6457</td>
</tr>
<tr>
<td>Moderate fog</td>
<td></td>
<td>500</td>
<td>0.7064</td>
</tr>
<tr>
<td>Light fog</td>
<td>Snow</td>
<td>100</td>
<td>770</td>
</tr>
<tr>
<td></td>
<td>Storm</td>
<td>1000</td>
<td>0.7367</td>
</tr>
<tr>
<td></td>
<td>Strong Rain</td>
<td>25</td>
<td>1900</td>
</tr>
<tr>
<td>Light mist</td>
<td></td>
<td>2000</td>
<td>0.7443</td>
</tr>
<tr>
<td></td>
<td>Average Rain</td>
<td>12.5</td>
<td>2800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4000</td>
<td>0.7479</td>
</tr>
<tr>
<td>Very light fog</td>
<td>Light Rain</td>
<td>2.5</td>
<td>5900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10,000</td>
<td>0.7494</td>
</tr>
<tr>
<td></td>
<td>Drizzle</td>
<td>0.25</td>
<td>18,100</td>
</tr>
<tr>
<td>Clear air</td>
<td></td>
<td>20,000</td>
<td>0.7497</td>
</tr>
<tr>
<td>Very clear air</td>
<td></td>
<td>23,000</td>
<td>0.7497</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50,000</td>
<td>0.7499</td>
</tr>
</tbody>
</table>
Figure 7-3: Determined power for different visibilities; the distance of the receiver and transmitter is 10 m and the average transmitted power equals to 850 μW

7.2 Loss due Beam Divergence

The beam exiting the collimator has the beam divergence equals to 0.101 degrees or 1.76 mrad. The power loss due to the beam divergence is determined in this section.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Determined Power (μW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4.29</td>
</tr>
<tr>
<td>100</td>
<td>1.128</td>
</tr>
<tr>
<td>200</td>
<td>0.289</td>
</tr>
<tr>
<td>300</td>
<td>0.130</td>
</tr>
<tr>
<td>400</td>
<td>0.073</td>
</tr>
<tr>
<td>600</td>
<td>0.032</td>
</tr>
<tr>
<td>800</td>
<td>0.018</td>
</tr>
<tr>
<td>1000</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Table 7-2: Power loss due to the beam divergence
7.3 Range Loss

The equation to find the range loss was introduced in section 4.3. This type of loss is determined in the current section. The transmitted power equals to 850 μW.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Determined Power</th>
<th>dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.14 E-15</td>
<td>-149.43</td>
</tr>
<tr>
<td>2</td>
<td>2.85E-18</td>
<td>-175.45</td>
</tr>
<tr>
<td>30</td>
<td>1.27E-20</td>
<td>-198.96</td>
</tr>
<tr>
<td>400</td>
<td>7.12E-23</td>
<td>-221.47</td>
</tr>
<tr>
<td>1000</td>
<td>1.14E-23</td>
<td>-229.43</td>
</tr>
</tbody>
</table>

Table 7-3: Measure power at various distances from the source; range loss is the cause of attenuation
The smallest amount of power that can be detected was calculated in section 6.7.4 which equals to -98 dB. As it can be seen from figure 7-5, the received signal is much less than -98 dB and therefore cannot be detected. Fortunately, as it will be seen in next section, the transmitter and receiver antenna gain partially compensates this loss.

### 7.4 Antenna Gain

The formula for the antenna gain was shown in section 4.3. Here the effect of this type of gain is shown. The transmitter signal power is 850 μW.

<table>
<thead>
<tr>
<th>Transmitter Diameter (mm)</th>
<th>Receiver Diameter (mm)</th>
<th>Transmitted Power</th>
<th>Determined Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 mm</td>
<td>7</td>
<td>$7.5 \times 10^{-6}$</td>
<td>$12.611 \times 10^{12}$</td>
</tr>
</tbody>
</table>

Table 7-4: Transmitter and receiver antenna gain

![Figure 7-5: Range loss of the transmitted signal](image)
Table 7-4 shows huge amount of gain which is related to the diameter of the transmitter and receiver as well as the wavelength of the signal.

7.5 Link equation evaluation

The link equation was introduced in section 4.3. Now the amount of the received power will be calculated using both theoretical and practical (using simulation) ways.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1548.4</td>
</tr>
<tr>
<td>Transmitted Power (mw)</td>
<td>0.85</td>
</tr>
<tr>
<td>Beam Divergence (mrad)</td>
<td>1.76</td>
</tr>
<tr>
<td>Pointing, transmitter and receiver efficiency</td>
<td>1</td>
</tr>
<tr>
<td>Transmitter diameter (mm)</td>
<td>4.5</td>
</tr>
<tr>
<td>Receiver diameter (mm)</td>
<td>7</td>
</tr>
<tr>
<td>Visibility (m)</td>
<td>50,000</td>
</tr>
<tr>
<td>Length (m)</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 7-5: Parameters of the test

7.5.1 Theoretical approach

\[
P_{rx} = P_t G_t G_r L_0 L_R \eta_t \eta_r \eta_{pt} \eta_{pr}
\]

\[
P_{rx} = 850 \times 10^{-6} \times \left(\frac{4.5 \times 10^{-3}}{1548.4 \times 10^{-9}}\right)^2 \times \left(\frac{7 \times 10^{-3}}{1548.4 \times 10^{-9}}\right)^2 \times 10^{\log\left(\frac{13 \times 0.7 \times 10^{-3}}{500}\right)} \times \left(1 - \frac{7 \times 10^{-3}}{4.5 \times 10^{-3} + 0.7 \times 10^{-1} \times 10^{-9}}\right)^2 \times \left(\frac{1548.4 \times 10^{-9}}{4 \times 10^{-7}}\right)^2 = 652.9473 \text{ mW}
\]

7.5.2 Determining received power using OptiSystem

To measure the amount of received power and the observing the effect of all types of attenuation together, OptiSystem was used. All parameters were set to the specified test values and the achieved amount of power received at the receiver is shown in figure 7-6. This amount is the same as the amount was calculated using theoretical link equation.
Figure 7-6: Using OptiSystem to observe the effect of the attenuation on the transmitted signal; the left side optical power meter shows the transmitted power and the right side optical power meter indicates the received power.
Chapter 8: Summary and Conclusion

The goal of this project was to design and implement a basic FSO system and observing various issues like safety, signal loss and practical barriers. The transmitter selected was a 1.5 mW laser diode with wavelength of 1550 nm. The distance between the transmitter and receiver was 70 cm and the maximum desired data rate was 20 Mbps.

To choose the wavelength and power of the laser diode, eye safety was the main consideration. The 1.5 mW LD with a wavelength of 1550 nm is a class I laser and can be used without eye protection goggles. However, the low amount of power limited the range of applying this FSO system due to link attenuation and detector sensitivity. An isolator was used to prevent the back-reflection to the laser diode, which causes damage to the LD. To decrease the divergence of the LD, a collimator used with the aperture diameter of 4.5 mm. The beam divergence of the output of the collimator is 0.101 degrees. At the receiver, a telescope with the aperture diameter of 7 mm used to capture the transmitted signal. The photodetector used in this project was PIN type InGaAs biased detector.

System setup was performed successfully but unfortunately, the laser diode was damaged and could not be used anymore. The reasons for the damage could be either overcurrent or electrostatic discharge (ESD). As an ESD protection wristband was worn all the time, the most probable cause of damage is passing overcurrent through the laser. The cause of overcurrent could be merely applying high amplitude using the signal generator. Therefore, a high level of caution should be applied when dealing with laser diodes.

The remainder of project was performed using the OptiSystem software. All parameters of the components were applied in the software and the effect on the link of the transmitted signal was observed. It was seen that the most degradation occurs due to the range loss. The effect of different weather conditions on the transmitted signal was another purpose of this project. It was seen that the system performance degraded during poor weather conditions (low visibility). With respect to the transmitter and receiver aperture size, a huge amount of gain was observed.

After applying all of the expected attenuation factors into the system, the evaluation of the link equation of this FSO system corresponded to the result obtained in the simulation.
Modulation aspects, using a source with the different wavelength, changing the diameter of the receiver and applying tracking system are some factors that can be considered to develop this FSO system further.
References:


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[14] International Civil Aviation Organization, Annex 3 to the Convention on International Civil Aviation


[17] Yangyu Fan, Roger J. Green, Comparison of pulse position modulation and pulse width modulation for application in optical communications

[18] Thorlabs, LD1100 constant power laser driver user guide