Point to Point Free Space Optical Communication link

A Project Report

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **Point to Point Free Space Optical communication link**, submitted by **Rohan Rajasekaran**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the project work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Free Space Optical (FSO) communications is an extremely efficient and cost effective way of establishing a high speed point to point link. In this report we present the various challenges involved in setting up a point to point FSO communication link. The first part of this report gives a brief overview of FSO communications including its advantages and disadvantages. This is followed by a description of the factors affecting propagation, loss mechanisms and a description of the various components in the link.

Further we discuss the results of various experiments conducted towards establishing a FSO point to point link. This includes design,characterization of the Transmitter and receiver blocks.Finally we describe the successful implementation of a fully duplex FSO point to point link with which transmission and reception of Internet packets between a Host and a Client is demonstrated.

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ABBREVIATIONS

APD	Avalanche Photo-Diode
PD	Photo-Diode
PPM	Pulse Position Modulation
SNR	Signal-to-Noise Ratio
UV	Ultra-Violet
VCSEL	Vertical-Cavity Surface-Emitting Laser
BER	Bit-Error-Rate
FSO	Free Space Optics/Optical
IM/DD	Intensity-Modulation Direct-Detection
IR	Infra-Red
ISI	Inter-Symbol Interference
LD	Laser Diode
LED	Light Emitting Diode
RI	Refractive Index
OOK	On-Off Keying
PRBS	Psuedo Random Bit Source
RF	Radio Frequency
IRDA	Infra-Red Development association
dB	Decibel
dBm	Decibel milli-watt
OSNR	Optical signal to noise ratio
LNA	Low noise amplifier
PER	Packet error rate
TTL	Transistor Transistor Logic
LVTTL	Low Voltage - TTL
CW	Continous Wave
UART	Universal Asynchronous Receive Transmit
GRIN	Gradient Index

NOTATIONS

$\alpha_{(dB)}$	Total atmospheric loss coefficient
β_{abs}	Atmospheric Attenuation coefficient
β_{scat}	Atmospheric scattering coefficient
L	Total link length
V	Visibility in Km
λ	Transmission wavelength
θ	Full divergence angle
L_g	Geometrical loss
R	Reflectance
n	Refractive index

CHAPTER 1

INTRODUCTION

1.1 Motivation

In the previous few decades there has been a proliferation in the communications and networking industry. Today Internet bandwidth has become a need rather than a luxury. Most modern communications happen on wireless cellular services encompassing technologies like GSM,CDMA,EDGE,GPRS and more recently 3G/4G.

When we hear wireless we tend to think only about RF based technologies. The RF band of the spectrum is however limited and expensive (needs licensing), we are also fast approaching the limits of RF bandwidth. The demand for spectrum is more than the supply. Free Space Optical (FSO) communications is the way forward to fulfill this requirement.

FSO Communication refers to the transmission of data through an unguided propagation media like air or water as opposed to a guided propagation media like a fiber optic cable. The wavelength used can be a part of the visible,UV or the IR band. In comparison to traditional RF systems FSO systems have an inherently high available bandwidth which translates into high data rates. One key advantage of a FSO system is that they require no licensing which dramatically reduces cost. Some of the areas where a FSO system can be used are : Last Mile connectivity, Video surveillance and monitoring,Back Haul for existing systems,Temporary Redundant links,Broadcasting etc. The use of FSO technology has been hampered by its rather disappointing link reliability due to atmospheric turbulence and fading and sensitivity to weather conditions. Implementing an FSO link is therefore an extremely interesting and engaging engineering problem for an M.Tech Project.

1.2 Overview Of FSO Communication

Throughout history there have been several examples where light has been used as a means of communication. Ancient greeks and Romans used their polished shields to reflect sunlight during battle. The Heliograph was invented by Carl Frederick Gauss in 1810. This instrument involved a pair of mirrors to direct a controlled beam of sunlight to a distant station. Claude Chappe implemented a semaphore system which spanned all of France in 1792. This was used to transmit messages encoded in symbols. In 1880 the Photo Phone was invented by Alexander Graham Bell. It was based on the fact that human speech caused vibration on a receiver diaphragm which had an attached mirror. The vibrations were reflected and projected by sunlight and transformed back into voice at the receiver by a detector circuit. These ancient methods off optical communication had several limitations which led to the adoption of metallic wire based Technologies for communication.

Research on free space optical networks was initially limited to covert military applications and satellite communications . In the past decade there has been only one wireless optical Communication Technology which became popular namely the IRDA. However as IRDA worked only at short ranges and at low speed it was replaced by better technology like Blue-tooth and WiFi which offered speeds up-to a few megabits per second and range of a few meters.The RF spectrum however is fundamentally limited by its channel capacity and Bandwidth. RF bands are also exclusively licensed by the government and therefore any communication technology which uses RF spectrum is inherently costly because the licensing fee is passed on to the end user. More importantly there is an ever growing popularity and demand for data heavy communication. The demand for RF spectrum has started outstripping supply. In order to fulfill with demand we have to consider using part of the electromagnetic spectrum for wireless data transmission. Free space optical communication is one such technique where we use frequencies above 300 GHz for communications

1.3 Advantages and Applications of FSO communication

1.3.1 Advantages

FSO systems can be used for high speed data communication between two points over distances of several kilometers. In comparison to an RF connection an FSO link will allow much higher data rate (Gb/s). FSO systems also use very narrow laser beams. This spectral confinement provides a higher reuse factor,and an inherent security and robustness to electromagnetic interference . FSO systems can be easily deployed at a fraction of the cost of traditional fiber optic based high speed communications system. The fact that no licensing is required for the spectrum used also contributes to the lower cost of an FSO link compared to an RF link. FSO systems are also attracting attention due to their capability off serving as last mile link between the end user and already existing high speed network backbone.

1.3.2 Applications

A few interesting applications of FSO communications technology are enumerated below:

1. **Enterprise connectivity:** Today the campuses of corporations and colleges utilize heterogeneous network traffic (i.e. voice, data, fax, multimedia) which can overwhelm a traditional connection. FSO communication links can be used to connect multiple buildings and establish high speed communication

2. **Back-haul for cellular systems:** In a typical mobile cellular system wire-line communications such as T1/E1 leased lines or microwave links are used to connect the base station to the mobile switching center. FSO links can be used instead to connect the base station to the switching center. FSO links will also allow for a much higher throughput.

3. **Link Redundancy/Disaster Recovery :** Natural calamities or terrorist attacks may cause large scale disruption in connectivity. At such times temporary FSO links can be deployed quickly. After the 9/11 attacks in the US temporary FSO links were rapidly deployed for financial corporations which were left out with no land-line systems

4. **Security :** Today information security is mostly provided by encryption by computers, this is within the limits of conventional computing power. However if we use optical communications (Fiber optics or FSO links) then we can implement a radically different solution for information security based on quantum cryptography which can provide unconditional security.

5. **Broadcasting :** Temporary communications link are needed for broadcasting of live events like sports tournaments,award ceremonies etc. FSO links can provide the required high quality transmission between several temporary studios locations. During the 2010 FIFA world cup the BBC had deployed FSO links for Ethernet based transport of high definition video links between temporary studios located in Cape town, South Africa.

CHAPTER 2

LITERATURE REVIEW

2.1 Wavelength Selection

The factors which determine the operating wavelength of a FSO communication link are enumerated below.

1. **Eye Safety :** Free space optical links operate on a wavelength of either 850 nm or 1550 nm. Both of these wavelengths are invisible to the human eye. However the biophysical characteristics of the human eye is such that a collimated beam at visible and near infrared radiation (400-1400 nm) striking the eye is focused on a tiny spot on the retina. Since the retina of the eye is devoid of any pain receptors this invisible light will not trigger a blink reflex and therefore the person will lose his vision before he is aware that hazardous illumination has occurred. In contrast a laser beam operating at 1550 nm is absorbed by the cornea and does not focus on to the retina.

(a) Visible & Near IR wavelengths

(b) Mid, far-IR & mid-UV wavelengths

Figure 2.1: Light absorption and transmission characteristics of the human eye

   This property legally allows us to transmit 50 times the optical power when operating at 1550 nm compared to 850 nm. This additional power will ensure that the laser beam will travel for a longer distance and also the optical signal to noise ratio at the receiver will be much better. The maximum permissible exposure limit when using a wavelength of 850 nm is 1 to 2 mW/cm^2 and 100 mW/cm^2 when using a wavelength of 1550 nm.

2. **Atmospheric attenuation**:The attenuation of optical power that occurs in the atmosphere is strongly wavelength dependent. The two processes that cause attenuation are scattering and absorption by the atmospheric particles. Rayleigh scattering occurs when the size of the scatterer is much smaller compared to the wavelength of the light whereas Mie scattering occurs when the side of the scatterer is comparable to the wavelength of the light.

   The attenuation from the scattering process is much greater for shorter wavelength and varies inversely as the fourth power of the wavelength. The loss due to Rayleigh scattering is not significant. The greatest lost mechanism is from Mie scattering from fog particles. This is a resonant process and it is the greatest when the particle size is of the order of the wavelength.

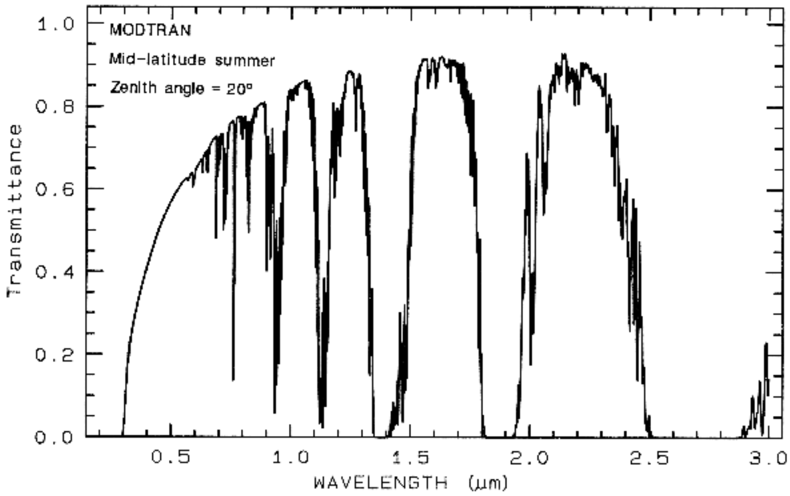


Figure 2.2: MODTRAN simulations for atmospheric transmission window

3. **Optics designs:**The physics of diffraction ensures that for the same medium and transmitting aperture size the beam spreading due to diffraction is linearly proportional to the transmitter wavelength. This means that a 850 nm beam will result in a 6 dB higher intensity at the receiver when compared to a 1550 nm beam. However, this advantage is never realized practically because the beam is almost always spread out well beyond the diffraction limit. This beam spreading may be used to an advantage as it allows relaxation in the pointing tolerance at the receiver.

4. **Detection:** High quality photo-diodes having good responsivities are available at both 850 nm and 1550 nm. A certain minimum number of photoelectrons is required to detect an optical pulse. A 1550 nm photon has half the energy of a 850 nm photon for the same preamplifier noise and therefore an optical pulse at 1550 nm can be detected with a 3 dB less noise.

5. **Commercial considerations:** Most Terrestrial fiber based optical communication systems operate at the wavelength of 1550 nm . So the supporting technical infrastructure in this wavelength range is readily available at a competitive cost.

2.2 FSO Transceiver

2.2.1 The FSO Transmitter :

The FSO transceiver consists of an Optical Source, a Modulator, an Optical amplifier (optional) and beam forming optics to collimate the transmitted FSO laser beam. Data from an Information source is modulated either internally or externally using an Electro Optic Modulator (EOM) or Acousto Optic Modulator (AOM).

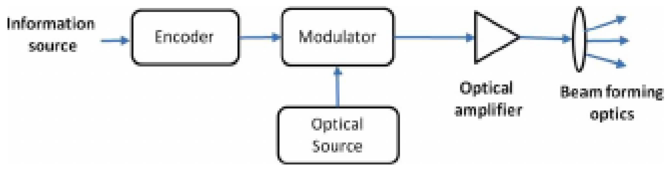


Figure 2.3: A generic FSO link Transmission Block

The modulated Laser beam from the optical source may then be passed through an Optical amplifier stage to boost the signal power.The light beam is collected and collimated by appropriately designed beam forming optics and transmitted onto Free Space. The whole transmitter may be built in a chassis that allows easy mounting and alignment of the module to achieve optimum performance. The typical source in a FSO link is a semiconductor laser diode although high power LED's may be used if the required data rate and the link distance is small. The optical source used should be capable of delivering a relatively high and stable output optical power over a wide range of temperature conditions. It should have a low MTBF (mean time between failures) and also have a low power consumption. If the chosen operating wavelength is 850 nm then VCSEL (Vertical Cavity Surface Emitting Laser) are used. If choose operating wavelength is 1550 nm then either a FP (Fabry Perot) or Distributed Feedback (DFB) lasers are used.If the FSO link is in an area where there is a possibility of it causing damage then it is better to use an operating wavelength of 1550 nm. The transmitted signal may have noise due to instability of the optical power caused by small fluctuation in the input current.

2.2.2 The FSO Receiver :

An FSO receiver can either work on coherent or non-coherent. A coherent system we can use a mixture of amplitude,frequency and phase modulation. At the receiver the received optical signal is mixed with a local oscillator before photo detection. However this technique is not preferred due to the additional system complexity and cost. Another important reason is that local atmospheric changes introduce phase fluctuations in the transmitted beam which destroys the coherence, resulting in ISI and degraded system performance. In a non-coherent system the information is encoded in the intensity of light. Changes in the intensity are detected at the receiver. This is known as intensity Modulation and direct (IM/DD) detection.

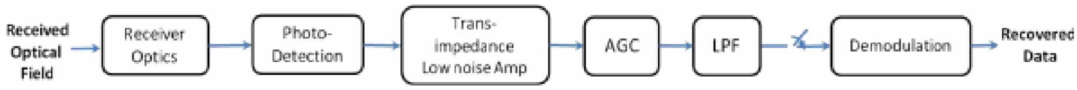


Figure 2.4: A generic FSO link Receiver block

The front end of a FSO receiver system may consist of an optical band pass filter this blocks the out of band noise sources. This is followed by a lens which collects the light and focuses it onto the photo diode. Depending on the amount of optical intensity falling on it the photo-diode can generate a small amount of photo-current. Current to voltage converter in the form of a trans-impedance amplifier is used to amplify the signal. The gain of the low noise Trans-Impedance amplifier is determined by the data required and the dynamic range (OSNR) at the receiver.The output of the low noise amplifier can be low pass filtered in order to limit the thermal and background noise. We also have to take care of Impedance Matching in case we want to use subsequent amplification stages. The photo-diodes used can be PIN photo-diodes or and APDs (Avalanche Photo Diodes). PIN diodes are used for a FSO system at ranges of a few hundred meters. For long distance link APDs are mostly used which provides a higher responsivity (>1) due to the process of impact ionization. This may cause excess noise at the output due to which the LNA gain is usually optimized with respect to the received signal power in order to maximize the signal to noise ratio.If the link operating wavelength is 850 nm then a silicon photo-diode is used in case of a link operating at the wavelength of 1550 nm InGaAs photo-diode is used. Additional circuitry to perform tasks like automatic gain control and dynamic thresholding at the receiver are often used. A PIN diode based receiver is thermal noise limited and and APD based receiver is shot noise limited.

2.3 Losses in FSO Communication

2.3.1 Atmospheric Propagation losses

The atmospheric attenuation is described by Beer Lamberts law.

$$\alpha_{(dB)} = e^{-(\beta_{abs}+\beta_{scat})L} \tag{2.1}$$

where α is the total Loss Coefficient in dB, β_{abs} is the Atmospheric Absorption Coefficient, β_{scat} denotes Atmospheric scattering coefficient & L is the total link length. The atmospheric window is affected by absorption by atmospheric gases such a CO_2 and H_2O. Scattering is due to small particulates in the transmission path of electromagnetic waves.

The loss due to attenuation is determined by the *Kruse* relation which relates the attenuation to the visibility.

$$\beta_{scat} = \frac{3.91}{V}\left[\frac{\lambda}{550}\right]^{-q} \tag{2.2}$$

where

V = Visibility in kilometer; λ :Wavelength in nanometers; q is a parameter determined empirically relating to the size of the scatterer. Typical values are

1.6 for high visibility (V $>$ 50 km), 1.3 for average visibility (6 km $<$ V $<$ 50 km), $0.585V^{1/3}$ for low visibility (V $<$ 6 km). Typical values of calculated losses relating to various weather conditions as determined by the *Kruse* relation are tabulated below.

Weather	**Attenuation (dB/km)**
Clear	0-3
Light Rain	3-6
Heavy Rain	6-17
Snow	6-26
Light Fog	20-30
Heavy Fog	50-100
Clouds	300-400

Table 2.1: Relation between weather conditions and Attenuation

2.3.2 Geometrical Losses

The Geometrical Loss arises due to the Divergence of the laser beam as it propagates through the atmosphere. If the beam diameter at the receiver is larger than the diameter of the receiver optics then only a fraction of the optical power in the beam finally is focused on the photodiode.

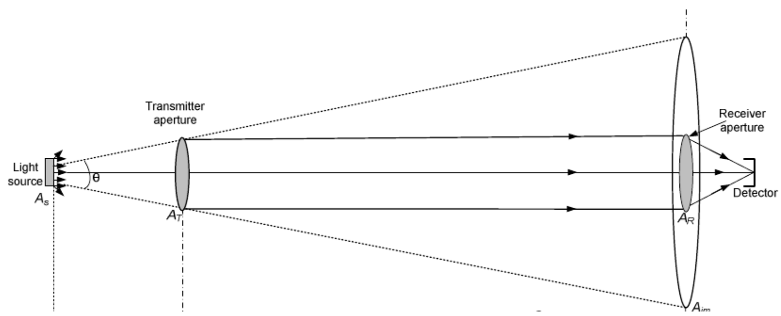


Figure 2.5: Beam Divergence induced losses in a FSO link

Quantifying Geometrical Losses

$$\frac{P_r}{P_t} = \frac{A_d}{A_i m} = \frac{(d_r)^2}{(d_T+\theta L)^2} \tag{2.3}$$

$$L_g = -20\log\left[\frac{d_r}{d_T+\theta L}\right] \tag{2.4}$$

where,

P_r is the power received at the receiver,; P_t is the transmitted power; d_r is receiver optics diameter; d_T is the transmit optics diameter; θ is the full divergence angle; L is the total Link lenght; L_g is the total geometric loss.

2.3.3 Turbulence and Scintillation

As table 2.1 above shows the atmospheric attenuation in the case of clear weather is negligible. The inhomogeneities in the atmosphere caused by slightly different temperature and pressure in adjacent layers of atmosphere cause slight variations in the refractive index along the path of the transmitted laser beam. This phenomenon is given the name of Beam wander or scintillations.

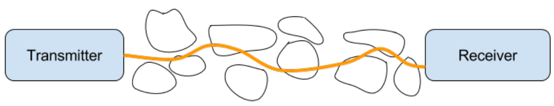


Figure 2.6: 'Beam Wander' caused by air pockets larger than the wavelength

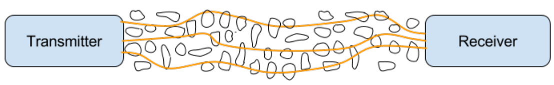


Figure 2.7: 'Scintillation' caused by air pockets smaller than the wavelength

The atmospheric turbulence caused by scintillations and beam wander result in random fluctuations in both the intensity and phase of the received optical signal.This is known as fading and it degrades the system performance by lowering the Optical signal to noise ratio (OSNR) at the receiver. This effect is high near walls and therefore we must ensure that the FSO Transmitter and Receiver must be at-least at a distance of 1m away from any walls. There are techniques which to combat atmospheric turbulence induced fading, they include having a spatial diversity in the receiver, Adaptive Optics / Tracking mechanisms or introducing a fade margin of 3 dB in the link budget.

2.3.4 Background Radiation

In addition to the desired optical signal the receiver optics also collects unwanted background radiations. This may consist of direct sunlight, reflected sunlight or scattered sunlight. The amount of background noise will be proportional to the receiver diameter.Experimental measurements indicate that while the received optical signal power is typically about tens to hundreds of μW, the background radiation power is in the range of 1-5 μW for scattered sunlight by clouds or fog, about 50-100 μW for reflected & focused sunlight . The FSO link can be in such a position that there is a possibility of reflected sunlight from a distant building facade being focused by the receiver optics onto the receiver photo-diode this may saturate the receiver and cause a link outage.

The most common ways of preventing background radiation from decreasing the SNR at the receiver is to use a band pass filter before photo-detection. The construction of the chassis that holds the receiver also has suitable baffles that block stray sunlight from falling on the photo-diode

2.3.5 Optical Losses

In every case of glass-to-air or air-to-glass transitions, there are losses due to Fresnel Reflection.It is caused by the reflection of a portion of the incident light at an interface between two media having different refractive indices. For a normal wave, the fraction of reflected incident power is given by the equation :

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \tag{2.5}$$

For normal incidence we have a 4% loss. Using anti-reflection coated materials the losses can be reduced to 0.1%. However such optical components are very costly and they can be avoided if system is not severely affected by background radiation.

2.4 Modulation schemes for FSO communication

Modulation is one of the most important factors in any communication link as it determines how the data is encoded. The chief factors to be considered when deciding on the modulation scheme are: Data-rate desired, receiver Sensitivity, Coherent/Non-Coherent detection, Synchronous vs Asynchronous systems, Spectral Efficiency. The experiments in this report are conducted with the OOK (On-Off keying) modulation scheme.When using OOK it is necessary to do dynamic thresholding at the receiver. The various modulation formats and their properties are tabulated below. The OSNR at the receiver may vary due to various effects described

Scheme	**Remarks**
OOK	Needs Dynamic Thresholding at the Receiver
PPM	Optimal in terms of Energy Efficiency
DPPM	Improved Spectral Efficiency as compared to PPM
PWM	Needs lower Peak Power, better spectral efficiency, more resistant to ISI than PPM
DPIM	No symbol synchronization, more BW efficient than PPM and PWM
PAM	Higher BW efficiency than PPM, but requires dynamic thresholding at the receiver

Table 2.2: Different Modulation formats for FSO communications

in section 2.3.3 and 2.3.4 above. This means that we have to set a decision threshold (reference voltage) at the receiver which gives us the best BER/PER performance. This is known as dynamic thresholding.

CHAPTER 3

Description & Characterization of Experimental Apparatus

3.1 FSO Transmitter Block

3.1.1 Transmitter Laser

The Star-Opto Laser module is used as the source laser. It is powered by a 5 Volt source. The data to be transmitted (OOK modulation) is applied to the $Td+$ (Transmit Data) pin. It is compatible to both TTL (5V) and LVTTL (3.3V).The laser operating wavelength is 1550 nm (+/- 10 nm). The absolute maximum power when operated in a continuous wave mode is about -1.3 dBm (0.7mW).It supports a maximum data rate of 52 Mb/s. The source laser was characterized before using. Since we can modulate the laser by using either TTL/LVTTL an experiment was done to measure if there is any change in the laser operation with respect to the maximum optical power transmitted when using different logic levels. As the final part of the experiment involves a duplex optical link two similar modules was used. The experimental setup and the results are indicated in the following figure. The Laser module draws a maximum current of 30 mA while operating in the CW mode.

Characterizing the Transmitter Laser

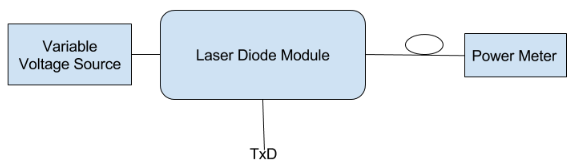
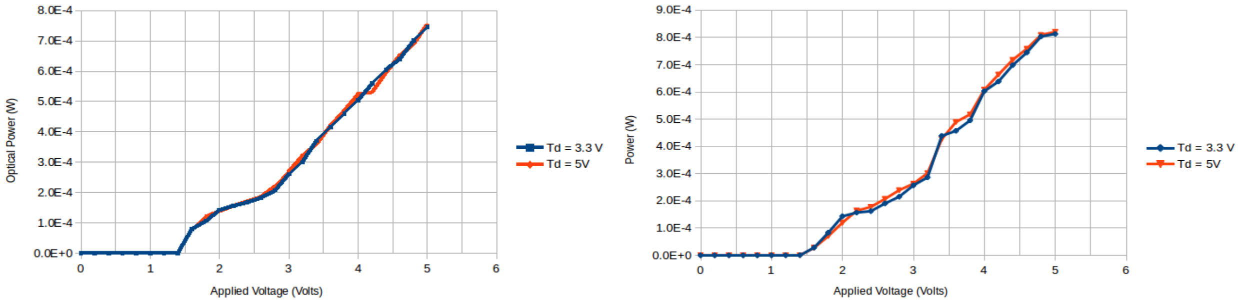


Figure 3.1: Setup to characterize the Laser Transmitter

Laser Transmitter Characteristics :



(a) Optical Power v/s Applied voltage for Laser Transmitter No.1

(b) Optical Power v/s Applied voltage for Laser Transmitter No.2

Figure 3.2: Laser Transmitter Characteristics

3.1.2 Information Source and Protocol

Information Source

The Raspberry Pi is used as the data source and detector in these experiments. It is a credit-card sized single-board computer.It runs on a 900 MHz Cortex A7-CPU and 1 Gb of Ram. Other features include 4 USB ports,40 GPIO pins,HDMI Port,Ethernet port and a Micro SD card slot. The operating system is the Raspbian OS which is Linux based. The Serial port i.e the Universal Asynchronous Receive and Transmit (UART) is used for data transmission and reception.

The UART Protocol

The UART module on the Raspberry Pi takes data and transmits it sequentially bit by bit. It has a dedicated shift register on both the Transmit and Receive pins. This shift register is instrumental in converting the data from the parallel to serial form at both the transmitter and the receiver. UART allows us to establish a link which is either simplex (unidirectional i.e one transmitter and receiver) or duplex (bi-directional i.e two transmitter and receiver pairs). Every UART operation is controlled by and independent clock which is typically 16 times the UART baud rate desired. This allows the receiver to sample the incoming signal with a 1/16 granularity providing some immunity towards error caused by timing jitters. The idle state is logic HIGH and a transition from the HIGH to the LOW state indicates the arrival of the start bit. The subsequent bits in the packet are transmitted sequentially, starting from the least significant bit (LSB). The data is typically sampled at the middle of the bit slot. This is possible as the baud rate is already known. Each UART data frame has a start bit followed by 5-8 data bits. We can have an optional parity and stop bit. The transmitting and receiving UART port must be set to the same baud rate, character length, parity and stop bits for proper operation.

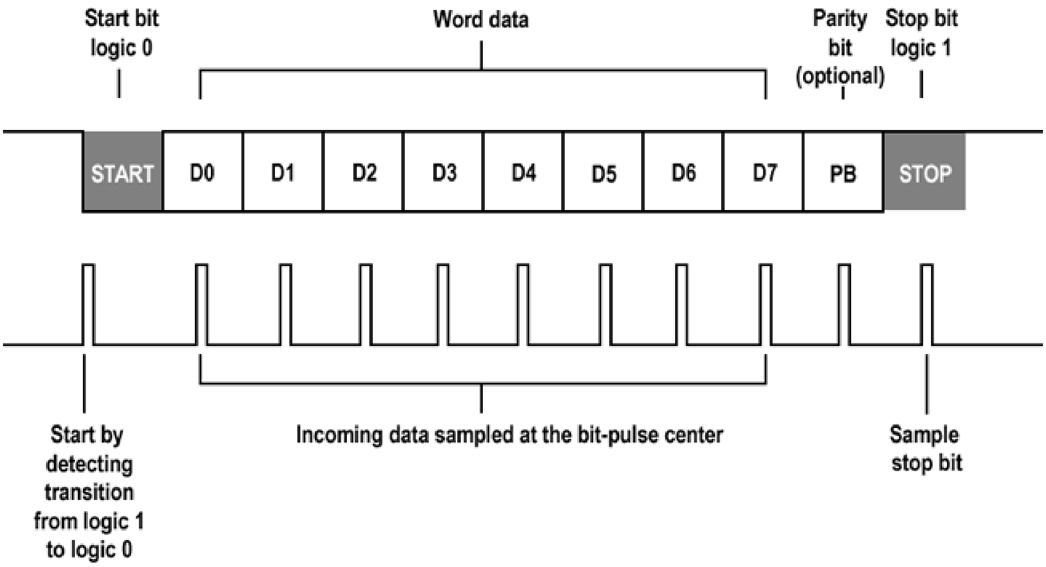


Figure 3.3: UART Data Frame

3.1.3 Transmitter Optics

A GRIN lens collimator is used as the Transmit Optics.

GRIN lens collimator: The transmit laser in the Star-Opto laser module is fiber coupled and terminated with an SC connector. It is necessary to transform the light output from the optical fiber into a free space collimated beam. Although in theory this can easily be achieved by placing the optical fiber at the focal length offer simple convex lens, the fiber and in this case has to be set at a distance from the lens which is exactly equal to the focal length of the lens, this is difficult to do. A Fiber coupled GRIN lens is used to collimate the output of the fiber.

Working principle of a GRIN lens collimator: The term GRIN stands for Graded Index.In a GRIN lens refractive effects are produced by a gradual variation of the refractive index of the GRIN lens material. This gradient can be spherical, axial, radial or parabolic. The variation can be used to produce lenses with surfaces that are flat, & lenses that do not suffer from typical problems of spherical and chromatic aberration. More details are given in Appendix A.

Characterizing the GRIN lens performance

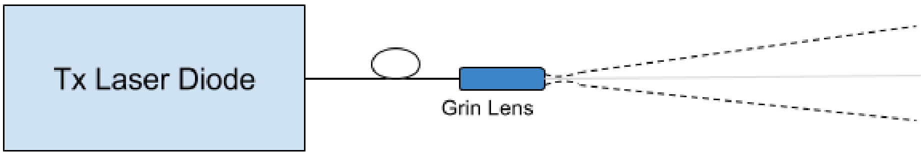


Figure 3.4: Setup to characterize the GRIN lens performance

Characterization of the GRIN lens collimator

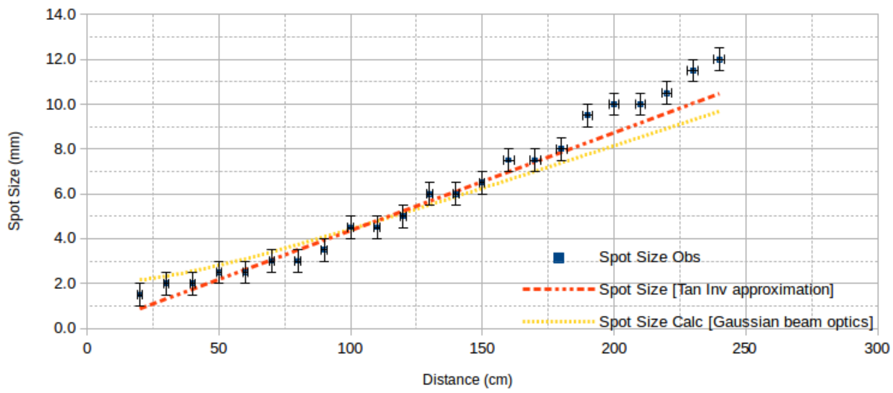


Figure 3.5: GRIN lens collimator : Spot size v/s Distance

3.2 FSO Receiver Block

3.2.1 Receiver Optics

A simple bi-convex lens was used as the receiver optics to collimate light on the photo-diode. The diameter of the lens its 75 mm and its focal length is 22 centimeters. The focal length was determined by the projection method. An image of a distant object(a window) was projected on the screen. The distance between the lens and the screen was adjusted so that a sharp image of the window may be obtained on the screen. The distance between the lens and the screen will be the focal length of the lens.

3.3 Photodiode:

An InGaAs (Indium, Gallium, Arsenide) PIN photo-diode is used at the receiver to convert the optical signal to electric current. To avoid noise no reverse bias voltage is applied. The photo-diode has a responsivity of 0.9 at a wavelength of 1550 nm and a parasitic capacitance of 60 pf.

3.4 Receiver Electronics Simulation and Design

The receiver electronics performs important function of converting the received optical signal into an appropriate electrical signal (Voltage). It is important to note that when the purpose of the optical link is to perform communications i.e. send and receive packets it is important to have sufficient gain so as to generate an output voltage high enough to trigger the receiver. This voltage is applied to the receive pin of the Raspberry Pi's UART. The receiver electronics board is a low noise amplifier which is designed using the operational amplifier op amp OPA 657U in the trans-impedance configuration. We assume a requires receiver sensitivity of -30 dBm therefore the low noise amplifier stage should provide a high gain at the same time however the system must also have sufficiently high bandwidth so that high speed communication is possible. The OPA 657U is well suited for this purpose. An additional circuit for dynamic thresholding based on the LM311 high speed comparator was implemented. The dynamic thresholding circuit is supposed to improve the PER performance for the link

3.4.1 Design and Simulation of the Trans-impedance Stage

As a photo-diode model cannot be directly inserted in the simulation schematic we have to model one by using a current source, shunt resistance and appropriate capacitance.A bias voltage may be applied if needed. The photo-current generated can be calculated by assuming a receiver sensitivity and responsivity. We can also set the modulation frequency as desired at the current source.The simulations are performed for the AC characteristics (to determine the Band Width) and the Transient Response (to observe the output signal of the LNA stage).We assume that the receiver sensitivity should at-least be -30 dBm. Through calculations and simulations a value of 1 MΩ has been determined for the Trans-impedance gain. The simulation shows a 3 dB gain bandwidth of 2.5 MHz

Simulation Schematic for the LNA

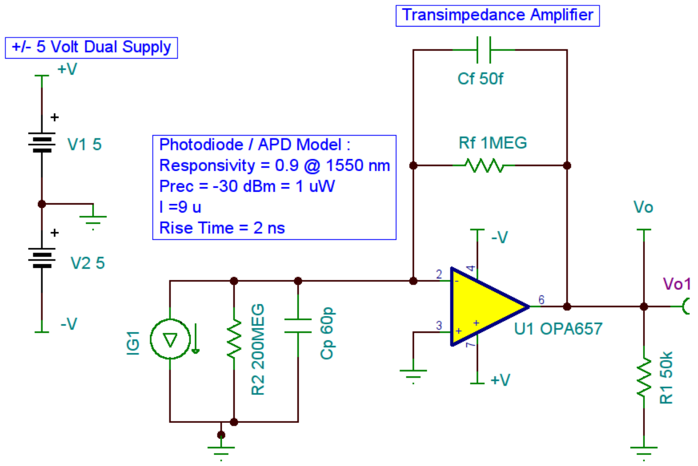


Figure 3.6: Simulation Schematic for the LNA illustrating design parameters

3.4.2 Design and Simulation of the High Speed Comparator

The Op-Amp LM311P is used in the dynamic thresholding circuit. The design circuit for the same is obtained in the application notes provided by Texas Instruments. The circuit is simulated in TI-TINA. As in the case of the trans-impedance circuit simulations are performed for the AC characteristics (to determine the Band Width) and the Transient Response (to observe the output signal when different threshold voltages are applied). The 3 db bandwidth is determined to be 2 MHz by simulations.

Simulation Schematic for the High Speed Comparator

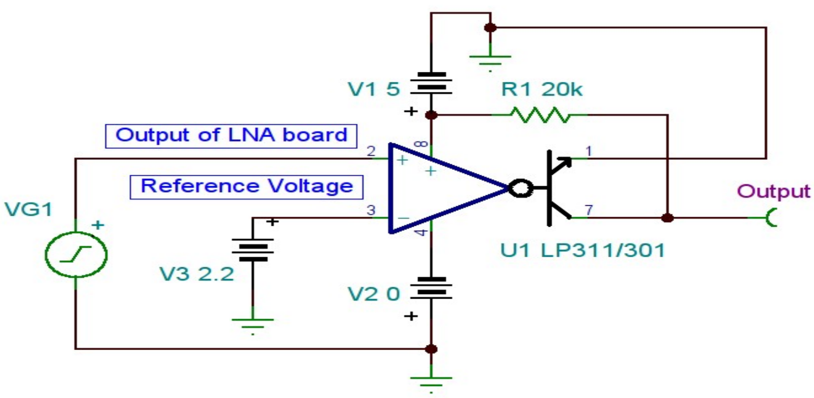


Figure 3.7: Simulation Schematic of the high speed comparator circuit

CHAPTER 4

Experimental Work

The objective was to setup a 15 m duplex Free Space Optical Link. As a part of this experiments were conducted to determine the bandwidth of the LNA board,the High Speed comparator and check the the Packet Error Rate (PER) by transmitting ASCII characters (8 bits) as packets.

Initially a 3.5 meter link was setup to experimentally characterize the performance of the receiver electronics.

4.1 Characterization of the Receiver Electronics

4.1.1 Experimental Setup

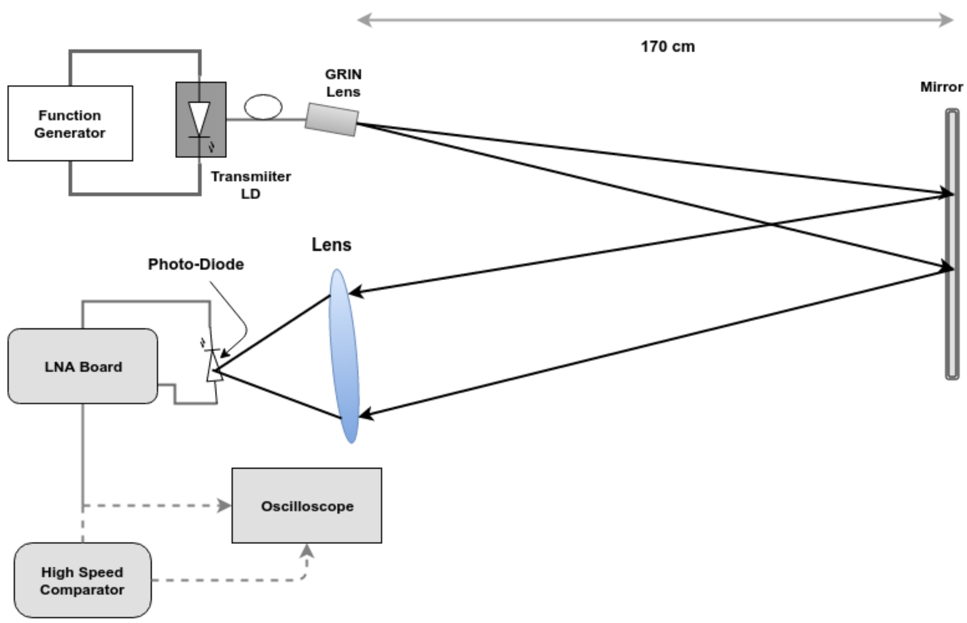


Figure 4.1: Experimental Setup used to characterize the receiver electronics

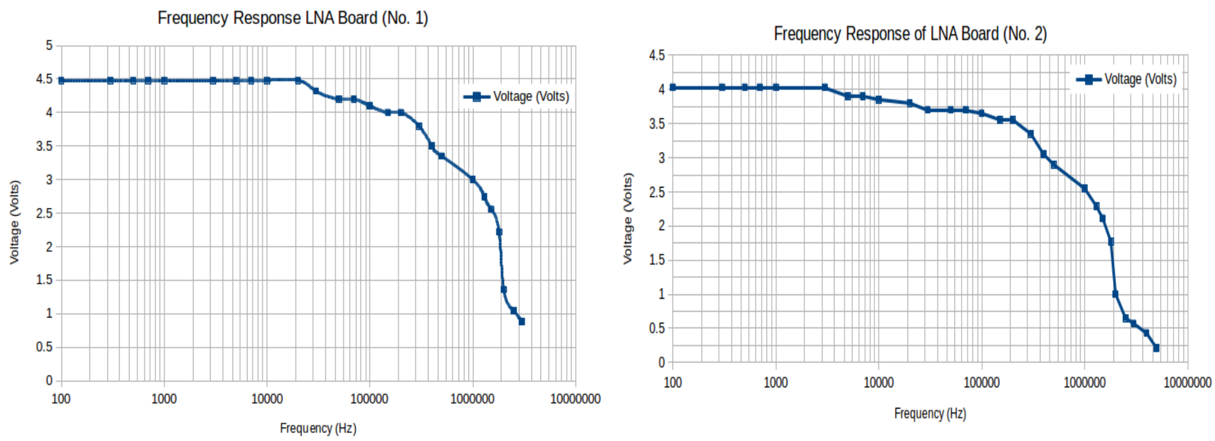
The whole setup is on an optical bench.The transmitter laser is modulated via a 5 MHz function generator. The collimated light from the GRIN lens collimator is reflected from a mirror situated on the far end of the optical bench 1.7 meters away. The reflected beam is then focused on the photo-diode by the receiver lens. The output is observed on a Oscilloscope. There is a provision to either observe the output directly from the LNA board or after passing it through the comparator.

Once a single pair consisting of the LNA board and the Comparator circuit was characterized the process was repeated for the other pair of the planned duplex link.

4.1.2 System Bandwidth

The simulated results are in Appendix B

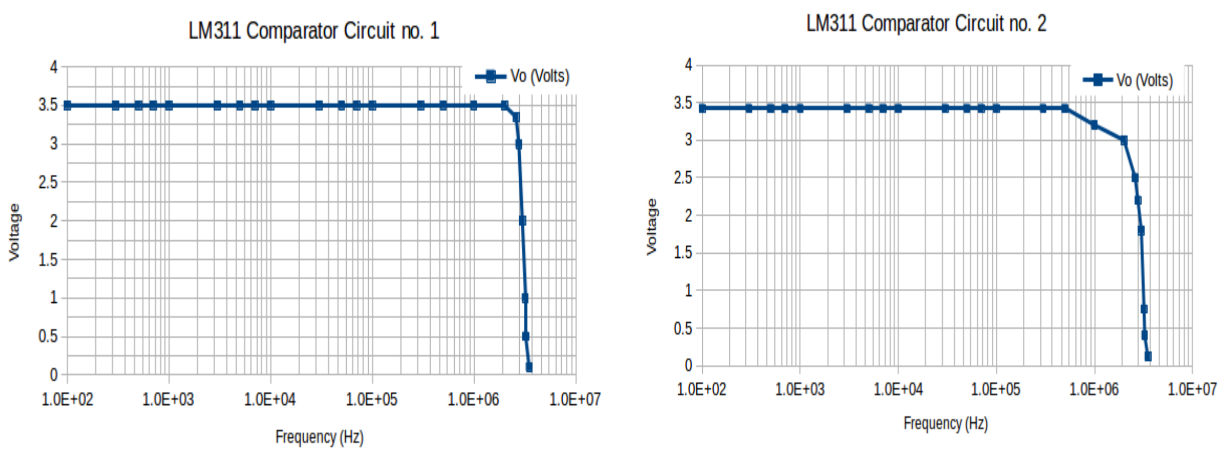
Measured LNA Board Bandwidths



(a) 3dB bandwith of LNA board no.1 is 1.8 MHz (b) 3dB bandwith of LNA board no.2 is 1.5 MHz

Figure 4.2: Bandwidth measurements for both the LNA Boards

High Speed Comparator Bandwidths :



(a) Frequency response of Comparator No.1 (b) Frequency response of Comparator No.2

Figure 4.3: Bandwidth measurements for both the Comparator Circuits

4.1.3 Experiments to determine the PER

Once the system was characterized experiments were done to measure the packet error rate of a simplex link with the help of a Python program which consisted of a PRBS generator to send packets over the serial link and compare the recieved packet to the sent. We can see that as the data-rate approaches the system bandwidth limit the PER starts increasing. The introduction of the comparator circuit improves the system performance. It is observed that as expected we

Speed (Baud Rate)	Packets in Error	Total Sent Packets	PER (%)
9600	65	125000	0.052
14400	84	125000	0.0672
19200	110	125000	0.088
38400	94	125000	0.0752
57600	88	125000	0.0704
115200	102	125000	0.0816
128000	89	125000	0.0712
256000	152	125000	0.12
512000	197	125000	0.15
921600	16875	125000	13.5
1843200	97895	125000	78.3

Table 4.1: Observed PER without the Comparator circuit

Speed (Baud Rate)	Packets in Error	Total Sent Packets	PER (%)
9600	25	125000	0.002
14400	42	125000	0.003
19200	68	125000	0.005
38400	52	125000	0.075
57600	157	125000	0.04
115200	105	125000	0.0816
128000	96	125000	0.08
256000	85	125000	0.12
512000	97	125000	0.06
921600	7658	125000	6.2
1843200	24578	125000	19.6

Table 4.2: Observed PER after introducing the Comparator circuit

see a marked improvement in PER when the High Speed Comparator circuit is employed.

4.1.4 Demonstration a full Duplex FSO Link

Description

This experiment is a Proof of Concept (POC) of Ethernet connection between two network nodes using a Free Space Optical Communication Link. The network nodes are emulated by two Raspberry Pi Boards. One Raspberry Pi acts as the Host which is connected to to the Internet Router via an Ethernet cable and the other Raspberry Pi acts as the Client on which access to the Internet is desired. The Serial Port (UART) on the Raspberry Pi's was used to setup the link via a PPP (Point to Point Protocol) connection. The data rate was set to 1843200 Baud (1.8 Mbps) which is a UART standard.The experimental setup and the steps involved in establishing the PPP link on the Raspberry Pi's are described in the appendix.

Experimental Setup :

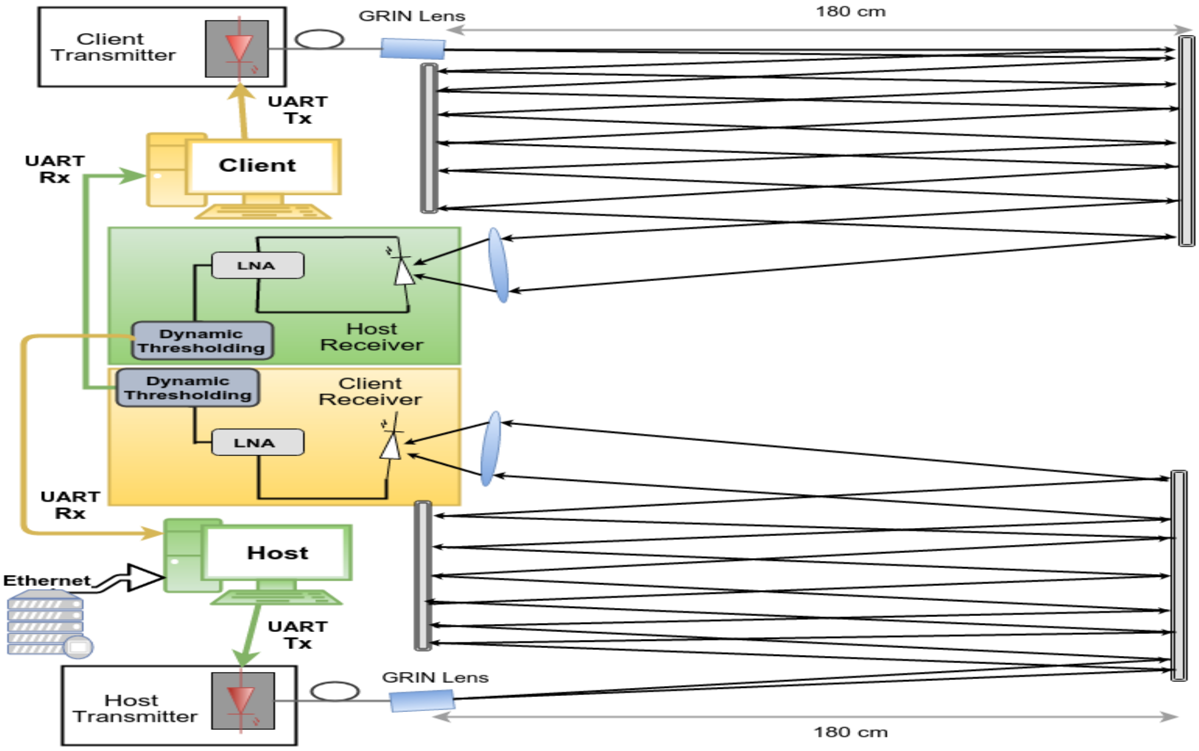


Figure 4.4: Experimental Setup for a 15 meter full duplex FSO communication link

The Host Raspberry Pi is connected to the Internet through a router. Data is transmitted via the Tx pin on the UART of the host Raspberry Pi which is connected to the data transmit pin of the Star-Opto Laser Transmitter module. The GRIN lens collimator is used as the transmit optics. The laser beam travels a distance of 15 meters by means of a two mirror arrangement before falling on the Receiver lens which focuses the beam on the Photo-diode. This is followed by the Receiver electronics circuitry, the output of which is connected to the Rx pin on the UART of the client Raspberry Pi.This constitutes a simplex link between the Host and Client. Transmission of Ethernet packets involves 'handshaking' between the Host and the Client which needs a duplex link. An additional Transmitter and Receiver pair is needed for this purpose. To achieve this we have one more simplex FSO link with the Transmitter laser connected to the UART

Tx pin of the Client Raspberry Pi and the received signal after being processed by the receiver electronics is connected to the UART Rx pin of the Host Raspberry Pi. The duplex FSO link is now established. We have to appropriately configure the Host and Client Raspberry Pi's and establish a PPP link before we are able to access the Internet on the Client.

Establishing the PPP link:

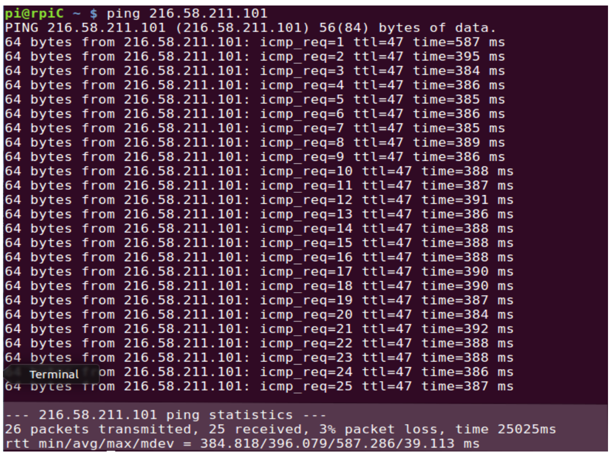
The steps to be followed to establish the Point to Point link are enumerated below.

1. Determine the Host IP address and select a available IP address for the client.
2. Ensure that no other process is using the serial port.
3. Enter the appropriate PPPD (Point to Point Protocol Daemon) commands for the Host and client where parameters such as the Baud Rate, Host and Client IP addresses & the authentication protocol is set.
4. Run the commands entered and wait for the handshaking process to complete between the Host and the Client. The IP configuration file on both the Host and the client will show the assigned IP addresses and the interface as ppp0.
5. Enable IP forwarding on the Host.
6. Set the Internet 'gateway' on the client to the host's IP address.

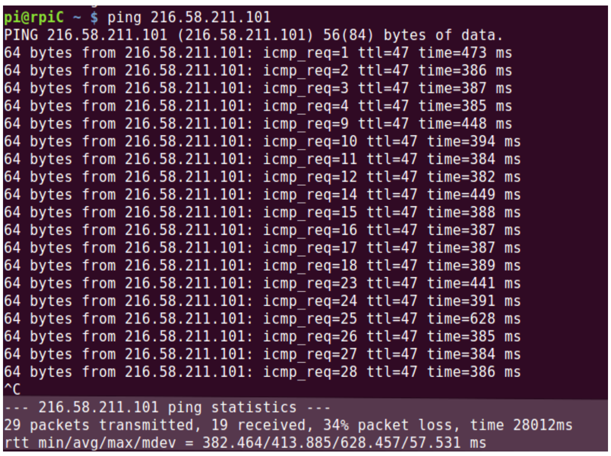
The detailed procedures with commands are listed in appendix D

Demonstration of the Internet connection on the Client

Now that the PPP connection through the FSO link has been successfully established between the Host and the Client. We can try pinging an Internet server as a demonstration. In the following case we have chosen to ping Google's server. The IP is determined to be 216.58.211.101



(a) The Ping statistics show a packet loss of 3% when the FSO beam is uninterrupted



(b) The Ping statistics show a packet loss of 34% when we interrupt the FSO beam temporarily

Figure 4.5: The Packet Transmission Statistics for the 15 m duplex FSO link

CHAPTER 5

Conclusion

Design of novel and efficient wireless systems is the need of the hour for the purpose of building communication networks that support a wide range of traffic patterns with ever increasing demand for bandwidth. With their large optical bandwidth FSO systems can be used to bridge critical gaps in existing communication networks.

5.1 Scope for Future Work

This project report ends with a in-lab demonstration of 15 meter full duplex FSO communication link at 2 Mbps. The scope for future work is enumerated below :

1. **Fiber Media Converters :** A fiber media converter is a network device that enables conversion between two dissimilar media formats. They are used in interconnecting existing copper wire systems with fiber optic based cabling systems.These can be used to connect the FSO link with already existing Ethernet cabling.

2. **Transmit Laser Power :** Media converters essentially come with fiber coupled sources whose maximum power may be in fractions of mW's. We need an Optical amplifier to increase the transmitted optical power if we are to construct a practical FSO link for a distance of several hundred meters or few Kilometers.

3. **FSO beam fiber coupling :** A efficient and cost effective way of coupling a FSO beam into a fiber should be devised. This will make a FSO communication link completely inter-operable with any existing fiber optic interface.

4. **Adaptive Optics and Beam Tracking :** Phenomenon like beam wander, scintillations, building sway, high wind may cause temporary performance degradation of the FSO link. Technology like adaptive optics and beam tracking will allow us to continuously make small adjustments to the receiver chassis and optics positioning which will help to maintain optimum link performance.

5. **Spatial Diversity in the Transmitter and Receiver.**

6. **Advanced Modulation formats :** Literature indicates that D-PPM (Differential Pulse Position Modulation) is the best format for a FSO link. Suitable modulating and demodulating circuits should be devised for a D-PPM based FSO link.

7. **Implement Hybrid RF/FSO systems :** In a hybrid RF/FSO system the RF link will act as a back-up in case weather effects like Fog, heavy Rain or snowfall completely disrupt the FSO link. Such a hybrid system will ensure a link availability approaching 100%.

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APPENDIX A

The GRIN lens

In the GRIN lens the the refractive index has a gradient which varies perpendicularly to the direction perpendicular to the Optical axis. This is expressed by the following equation:

$$N = N_0[1 - (\tfrac{k}{2})r^2] \tag{A.1}$$

where,

N_0 is the base index at the center of the lens, k is the Gradient constant, r is the variable radius in mm.

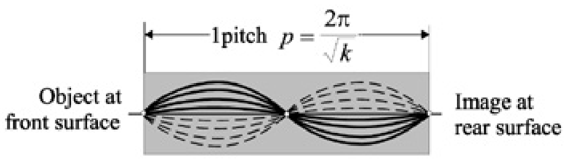


Figure A.1: A GRIN rod lens one pitch long

To make a fiber coupled FSO collimator we need to shorten the rod to a length of 1/4 pitch.

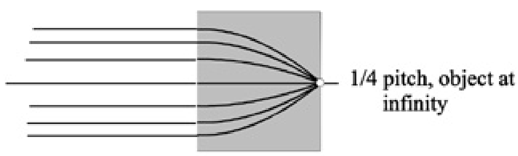


Figure A.2: A GRIN lens to collimate the light from a Fiber coupled source

Shortening the rod to a length of 1/4 pitch forms a lens with a focal length of

$$f = \frac{1}{N_0\sqrt{k}} \tag{A.2}$$

APPENDIX B

Parameters of Components Used

B.1 OPA 657U

- High Gain Bandwidth Product: 1.6 GHz
- Slew Rate 700 V/μs
- Low-Input Offset Voltage: 250 μV
- Low-Input Bias Current: 2 pA
- Low-Input Voltage Noise: 4.8 nV/$\sqrt{Hz}$
- High-Output Current: 70 mA

B.2 LM311

The LM311 devices is a single high-speed voltage comparators.

- Fast Response Time: 165 ns
- Maximum Input Bias Current: 300 nA
- Maximum Input Offset Current: 70 nA
- Can Operate From Single 5-V Supply

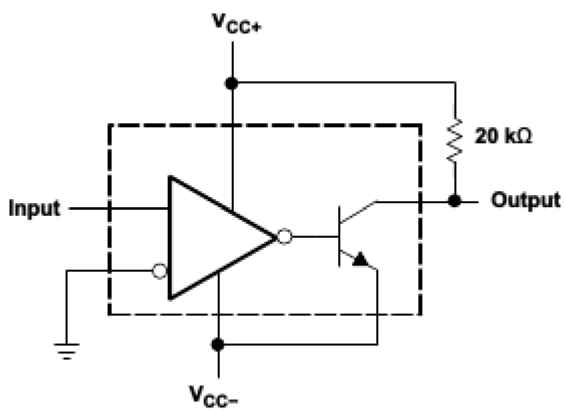
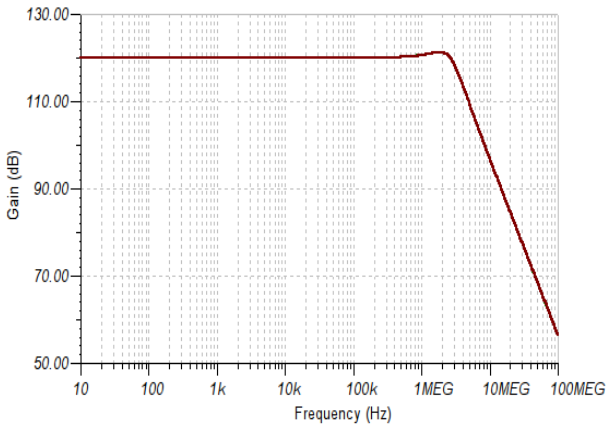


Figure B.1: A LM311 configured as comparator with the reference voltage at zero volts

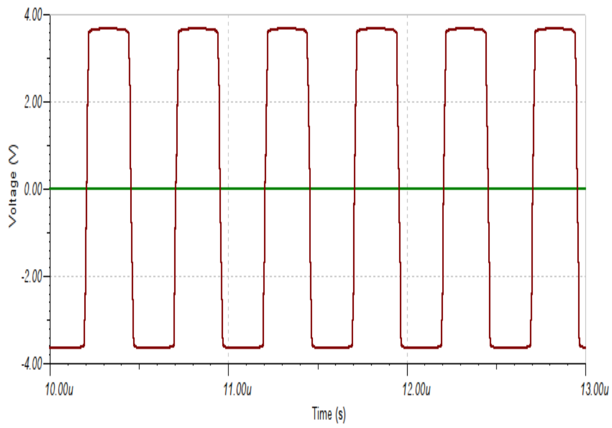
APPENDIX C

Reciever Electronics Simulation Results

C.1 Simulation Results for the TIA



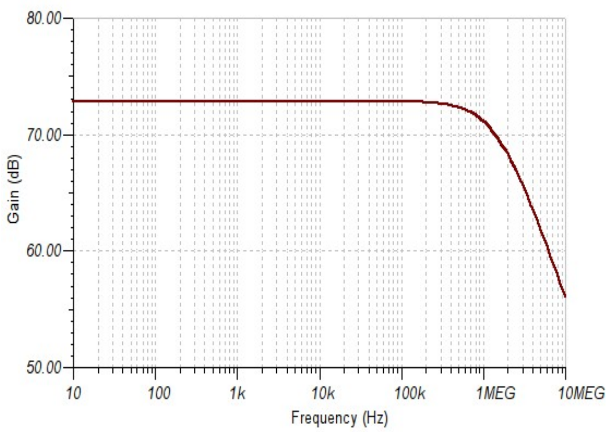
(a) AC Characteristics 3dB cutoff at 2.5 MHz



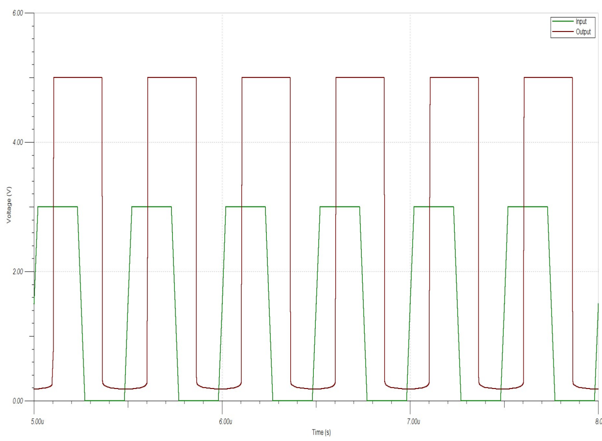
(b) Transient Response at a frequency of 2 MHz

Figure C.1: TIA simulation results

C.2 Simulation Results for the Comparator



(a) AC Characteristics 3dB cutoff at 1.9 MHz



(b) Transient Response at a frequency of 1.5 MHz

Figure C.2: Comparator simulation results

APPENDIX D

Procedures and Commands to establish PPP link

Before setting up the PPP connection it is important to first know the (Internet Protocol) IP address of the Host and also determine an unallocated IP address that can be then allocated to the Client. In our case the Host IP is determined to be 10.21.0.148 and we have chosen an IP 10.21.1.250 for the Client.

1. Settings on the Host :
   - Ensure that the serial port is free by the following command :

     ```
     stty -F /dev/ttyAMA0 raw
     ```

   - Set up the PPP connection and begin the 'handshaking' process :

     ```
     sudo pppd /dev/ttyAMA0 9600
         ↪ 10.21.0.148:10.21.1.250 proxyarp local
         ↪ noauth debug nodetach dump nocrtscts
     passive persist maxfail 0 holdoff 1
     ```

     Note that here 10.21.0.148 denotes the Host IP and 10.21.1.250 denotes the IP we want our client to have

2. Settings on the Client :
   - Ensure that the serial port is free by the following command :

     ```
     stty -F /dev/ttyAMA0 raw
     ```

   - Set up the PPP connection and begin the 'handshaking' process :

     ```
     sudo pppd /dev/ttyAMA0 9600 10.21.1.250:10.21.0.148
       ↪ noauth local debug dump defaultroute nocrtscts
     ```

     Note that here 10.21.1.250 denotes the Client IP and 10.21.0.148 denotes the Host IP.

   These two procedures are to be done simultaneously which will complete the Handshaking Process and ensure that the PPP link is set up

3. Enable IP forwarding on the Host :

   ```
   sudo sysctl -w net.ipv4.ip_forward=1
   sudo iptables -t nat -A POSTROUTING -o eth0 -j MASQUERADE
   ```

4. Set the appropriate Gateway on the Client : We have to set up an Internet gateway on the Client so that it can connect to the outside world. In our case the Host is the gateway through which the client can connect to the Internet, therefore the Host's IP address will serve as the Client gateway. The following command on the client does this:-

   ```
   route add default gw 10.21.0.148 ppp0
   ```