Analysis of optical signal propagation through free space optical medium

Sathyasree J[1], Sivaranjani A[2], Ashok P[3]

[1,2] UG Student, Department of Electronics and Communication Engineering,
Prince Shri Venkateshwara Padmavathy Engineering College, Tamilnadu, India

[3] Asst Prof., Department of Electronics and Communication Engineering,
Prince Shri Venkateshwara Padmavathy Engineering College, Tamilnadu, India

ABSTRACT

The study is based on the implementation of optical signal propagation through a wireless medium since optical communication acquires maximum efficiency in signal propagation. It also deals with various analyses such as channel analysis, transmitter and receiver analysis. The channel analysis includes various losses and the methods to overcome those losses. The transmitter analysis deals with the generation of photons from the Quantum Cascade laser, which is a high efficiency laser and the On-Off Keying modulation technique, which is used to modulate the information signal in order to deliver the signal over a longer distance. The receiver analysis deals with Quantum well infrared photodetector which is used to convert the optical signal of infrared region into current. The light in the form of infrared region is used for this analysis.

Keyword: - *Quantum cascade lasers, free space optics, Signal to noise ratio, Bit error rate.*

1. INTRODUCTION

The Free Space Optics (FSO) is used for the commercial deployments because of its optical signal propagation in different atmospheric conditions has become essential, and thus arises the need to analyze the effects of atmospheric channel on terrestrial FSO links. In this study, the preliminary results of our effort to simulate the atmospheric free space terrestrial optical channel with precise mathematical models of the most deterrent attenuators were presented. Attenuations due to fog, rain, snow and scintillation and the transmitter and receiver parameters were considered.

The concept of transmitting information signal through the air by means of a modulated light signal is quite complex and although significant advances have been made over the past decade a narrow beam of light is launched at a transmission side by means of a laser, transmitted through the atmosphere i.e., free space and subsequently received at the receiver side. The advances in the technology, now referred to as FSO, have come about in response to a need for greater bandwidth and improved communication systems. Fig-1 refers the complete transmission between the transmitter and the receive using the free space optics. The block diagram shows the various parameters involving in the transmission process.

Fig-1 Free space optics block diagram

2. CHANNEL MODELLING

Thus the following losses were considered

- Geometric loss
- Rain attenuation
- Fog attenuation
- Snow attenuation
- Scintillation loss

These losses were analysed individually in order to analyse the various factors that attenuate the signal while transmission occurs. Thus this analysis helps to identify various factors that causes the attenuation while transmitting the signal and it concludes that what are the parameters that causes attenuation and also deals with the steps that how it can be minimized based on the wavelength and the channel length which is 9μm (wavelength) and 1500m (channel length).

2.1 Geometric losses

It depends on the transmitter and receiver parameters such as diameter of the transmitter's active area ($d_{transmitter}$), diameter of the receiver ($d_{receiver}$), length of the channel (l) and field of view (θ). The geometric losses P_{geo} [dB] are calculated from the equation [1]. From the geometric loss it is concluded that P_{geo} increases with increase in channel length.

$$P_{geo} = 10.log\left(\frac{d_{receiver}}{(d_{transmitter}+(l*\theta))}\right)^2 \qquad [1]$$

2.2 Fog attenuation

The main challenge is fog. Fog is generally vapour composed of water droplets, which are only a few hundred microns in diameter but can change the light characteristics or completely delay the passage of light by the following factors such as absorption, scattering, and reflection. This can lead to a decrease in the efficiency of the transmitted beam, decreasing the effectiveness of a free space optical link.

The two most widely used models for this implementation and simulations are the Kruse model and the Kim model. The specific attenuation is calculated in equation [2], with the variables visibility V [km], wavelength λ [nm], visibility reference at wavelength λ_o [nm] and for transmission of air drops to V % percent of the clear sky. The wavelength dependency in this expression is expressed by q, which is in the Kruse model given by equation [3] and in the Kim model by equation [4]. At very high attenuations the Kim model is the better than the Kruse model. From the Kim and Kruse model it is concluded that the fog attenuation increases with increase in visibility. The fog attenuation fully depends on the visibility and the wavelength. Thus if the wavelength increases the channel length decreases.

$$a_{spec} = \frac{10.\log V\%}{V[km]}\left(\frac{\lambda}{\lambda_o}\right)^{-q} \text{ [dB/km]} \qquad [2]$$

$$q = \begin{cases} 1.6\,, & V > 50\text{km} \\ 1.3, & 6\text{km} < V < 50\text{km} \\ 0.585 * V^{1/3}\,, & V < 6\text{km} \end{cases} \qquad [3]$$

$$q = \begin{cases} 1.6\,, & V > 50\text{km} \\ 1.3, & 6\text{km} < V < 50\text{km} \\ 0.16.V + 0.34, & 1\text{km} < V < 6\text{km} \\ V - 0.5, & 0.5km < V < 1km \\ 0, & V < 0.5km \end{cases} \qquad [4]$$

2.3 Rain attenuation

Rain is also an important attenuator for the optical signals and the specific attenuation for rain has been modelled as in equation [5+]. The rain attenuation mainly dependent on the rain rate R [mm/hr]. The rain attenuation is calculated from equation [5]. Thus it can be concluded that the rain attenuation increases along with the rain rate, also the rain attenuation does not depend on the wavelength and the channel length.

$$a_{rain} = 1.076.R^{2/3}\text{[dB/km]} \qquad [5]$$

2.4 Snow attenuation

The attenuation due to snow fall has been modelled based on dry or wet snows and the specific attenuation is given by equation [6] where S is the snow rate in [mm/h]. Two types of snow were considered in this analysis namely dry snow and wet snow. The Parameters a and b are given for dry snow in equation [7] and for wet snow in equation [8] where λ represent the transmission wavelength in [nm]. Thus it can be concluded that dry snow causes major attenuation compared to the wet snow. From the equation [7] and [8] it is concluded that the snow attenuation for both the Kim and Kruse model decreases with increase in wavelength.

$$a_{\text{snow}} = a.S^b \text{ [dB/km]} \qquad [6]$$

$$a = 5.42.10^{-5}.\lambda + 5.4958776 \qquad \text{b=1.38} \qquad [7]$$

$$a = 1.023.10^{-4}.\lambda + 3.7855466 \qquad \text{b=0.72} \qquad [8]$$

2.5 Scintillation losses

The influence of thermal turbulence causes randomly distributed cells under inside the propagation medium; the wave fronts vary causing the focussing and defocusing of the beam. Such fluctuations of the signal are called scintillations. The amplitude and frequency of such thermal turbulences depends on the size of the cells compared to the beam diameter. The intensity and the speed of the scintillations frequency increase with the wave frequency.

For a plane wave, a low turbulence and a specific receiver, the scintillation variance can be expressed as in equation [9] where λ represent the transmitter wavelength in [nm], *l* the channel-length in [m] and $\mathrm{C_n}^2$ the refractive index structure parameter in [m-2/3]. $\mathrm{C_n}^2$ is for low turbulence 10^{-16}, for moderate turbulence 10^{-14} and for high turbulence 10^{-13}. For strong turbulences i.e., scintillations a saturation of the variance is given by the above relationship. The parameter $\mathrm{C_n}^2$ does not have the same value at millimetre waves and at optical waves.

$$a_{scin} = 2\sqrt{23.17\left(\frac{2\pi*10^9}{\lambda}\right)^{7/9} C_n{}^2 l^{11/6}} \qquad [9]$$

3. TRANSMITTER ANALYSIS

Quantum Cascade Lasers (QCLs) have been of great interest for a variety of reasons. They can be used for detection of toxic chemicals and gases by midinfrared spectroscopy. Their narrow line widths make them attractive in coherent applications, such as coherent optical communications. Their large direct intensity modulation (IM) bandwidth is attractive for IM optical communication systems. QCLs are also known as inter sub band semiconductor lasers as opposed to interband semiconductor lasers used in 0.8–1.6- m wavelength range in fiber optic communications.

Direct IM refers to IM of light by varying the drive current of the laser as opposed to indirect IM of light using modulators external to the laser. It has been reported that QCLs can have theoretical direct IM bandwidths in the terahertz range, while interband semiconductor lasers have IM bandwidths limited to a few tens of gigahertz. As the expression for the IM response is complicated, a second-order model has been used by several researchers to explain the direct IM bandwidth of QCLs. Next an expression for IM response using simplified rate equations for QCLs is obtained.

3.1 Rate equations of QCL

For the analysis of QCL output power is calculated form the equation [10] as given below in which P is the photon number, R is the reflectivity calculated from the refractive index n, c is the speed of light, n is the refractive index and λ is the wavelength. Thus it can be concluded that as time increases the transient power also increases and after some time the transient power will be maintained constant.

$$P_{opt} = P * (1 - R) * h\left(\frac{c}{\lambda}\right)\left(\frac{c}{n}\right)\left(\frac{1}{L}\right) \qquad [10]$$

The rate equations are solved using the ODE solver in the MATLAB. Under the steady state condition, the steady state response is obtained by solving these equations. The graph in the figure [2] is plotted with the various input bias currents against the output power. The input current is varied from a range of 0A to 2A where the input threshold current is found to be 1.1108A for the device. The figure [3] depicts the transient response of the device where the graph is plotted against the time and various other parameters. The response is that it increases gradually and finally settles to a constant value. The circuit simulator carries out the delay time. It is defined as the time required by the photon number to reach 10 % of its steady value from a zero initial condition. Thus it can be concluded that QCL acquires the maximum steady state photon number within a minimum time period.

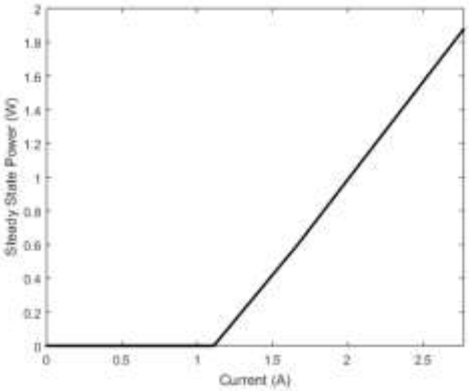

Fig-2 Current vs. Steady state power

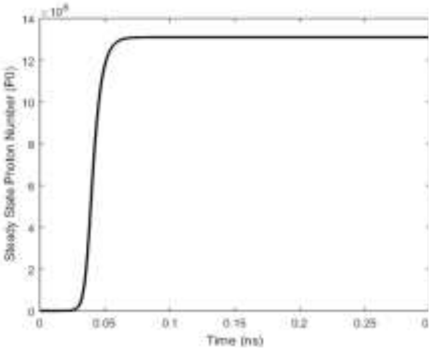

Fig-3 Time vs. Steady state photon number

4. RECEIVER ANALYSIS

At the receiver side the transmitted power in watts received as μW due to the channel losses which as to be amplified which is represented in figure [4]. Optical signals have a carrier frequency that is much higher than the modulation frequency (about 200 THz and more). This way the noise covers a bandwidth that is much wider than the signal itself. The resulting signal influence relies mainly on the filtering of the noise. To describe the signal quality without taking the receiver into account, the optical SNR (OSNR) is used. The OSNR is the ratio between the signal power and the noise power in a given bandwidth. The SNR value is calculated from the equation [11].

$$\mathrm{SNR}=\frac{\mathrm{J}_{\mathrm{photon}}A}{\sqrt{(4g\mathrm{J}_{\mathrm{dark}}\Delta f)+(4g\mathrm{J}_{\mathrm{photon}}\Delta f)}} \qquad [11]$$

In the above equation, A represents area of the active region and Δf is the electrical bandwidth of the receiver, $\mathrm{J}_{\mathrm{dark}}$ and $\mathrm{J}_{\mathrm{photon}}$ are the dark current and photo current densities respectively and g is the photo conductive gain. It is obvious that as the received power increases, SNR also improves. The BER is computed from the SNR values as in equation [12]. The SNR and BER are inversely proportional. Hence if SNR increases, the BER decreases. The figure [5] shows the relationship between the SNR and BER.

$$\mathrm{BER}=\frac{1}{2}erfc\left(\frac{1}{2}*SNR\right) \qquad [12]$$

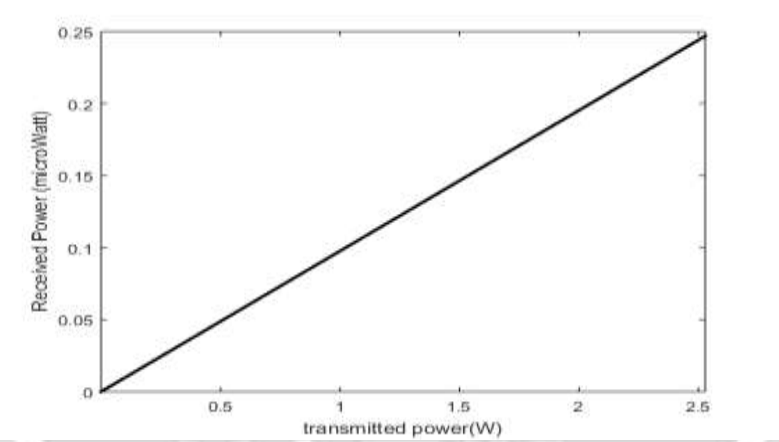

Fig-4 Transmitted Power (W) vs Received Power (μW)

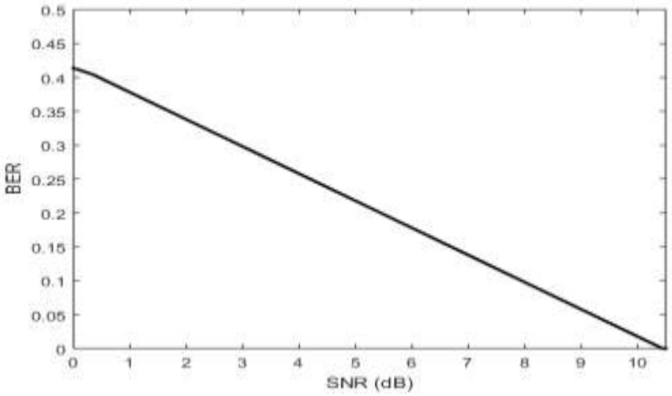

Fig-5 SNR (dB) vs BER

5. CONCLUSIONS

The optical signal propagation through free space has three section such as transmitter, channel and receiver. The major portion in propagation of optical signal is the atmosphere that is the channel through which the transmission occurs. Mathematical expression is used for the analysing and stimulating the losses for different wavelength range and channel length range. The wavelength used in this analysis is 9μm because the attenuation due to scattering have a less impact for longer wavelength and the reference length used is 1500m. In the transmitter, the threshold current (I_{th}**)** 1.111 (A) at which the power production starts and short pulse generation are generated at the value of 1.5*I_{th} (threshold current). The received power is in the range of mW (milli Watt) which has to be amplified for further processing.

6. REFERENCES

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