Flexible High Power Free Space Optical System for Aircraft to Ground Communications

Antonis Hatziefremidis*, Konstantinos E. Zarganis, Kyriakos E. Zoiros
**Technological Educational Institute of Sterea Ellada, Psahna, Evia, 34400*
Tel: (302) 2280 99669, Fax: (302) 2280 99669, e-mail: ahatzi@teihal.gr

ABSTRACT

Nowadays Free Space Optical (FSO) systems are a promising approach for a variety of applications such as interconnection of network nodes and as rapidly deployable communication systems in disaster recovery situations. In particular deploying FSO technology for mobile links between Unmanned Aerial Vehicles (UAVs) and fixed Ground Stations (GS) introduces several interesting challenges. In this paper, we investigate the ability of a mobile FSO system to operate in different atmospheric conditions. Specifically, we report a detailed optical amplification model able to support a constant Quality of Service for different distances from 1 km up to 35 km at 10 Gbps with 1550 nm wavelength. A high power optical amplifier and a low noise optical amplifier with adaptive power controlled are proposed that are able to support different environment attenuation factors. An extensive analysis among different distances for the FSO configurations links considering the Bit Error Rate (BER), the Q factor, the received signal and noise is provided.

Keywords: mobile FSO, UAV, atmospheric turbulence, optical amplifier.

1. INTRODUCTION

In recent years, there has been a renewed interest in understanding and exploiting FSO communications, mainly because of the large potential bandwidth available compared to radio frequency and its flexibility compared to optical fibers. Currently, FSO technology is being developed for application involving ground to ground terminals, air to ground terminals and satellite uplink and downlink [1]. Future interest tends to be in the direction of UAVs scenarios rather than other flying vehicles (i.e. High Altitude Platforms - HAPs) due to its flexibility and the capability to achieve a better surveillance.

The mobile atmospheric optical transmission channel poses some challenges to the data links which are not found in a typical fiber link. The atmosphere itself causes on one side signal attenuation and on the other side distorts the wavefronts of the optical beam due to phase changes caused by fluctuations of refractive index of the atmosphere. It is sensible that reliability and availability of a FSO link is directly related to the prevalent atmospheric weather conditions and turbulence. A critical factor for the quality of a FSO link is the mitigation of the adverse impact of different weather conditions that a light beam experiences through the optical path.

In the literature, many techniques have been reported for the improvement of BER in a fixed and mobile version of a FSO link. Diversity of wavelength, utilization of multiples transmitters and receivers and implementation of optical amplifiers has been adopted by many researchers [2, 3]. Studies in FSO systems have concentrated on electrical amplification, where the received optical signal is converted into an electrical signal via a photodetector. Currently the optical amplifiers are used which directly amplify the transmitter optical signal and decreases the attenuation without conversion to electric forms. In any case, the sensitivity and the performance of the system are limited by the noise characteristics due to the fact that the optical receiver adds thermal and shot noises. Moreover there is a significant optical power loss caused by scattering and absorption mechanisms in light propagation through the atmosphere. The Semiconductor Optical Amplifiers (SOAs) and the Doped Fiber Amplifiers (DFAs) are the most common types of optical amplifiers which are used in optical communication systems. High Power Optical Amplifiers (HPOAs) that serve as a power booster at the transmitter are considered for free-space communication links in a wide range of environments. Specifically for airborne and space vehicles, unique environments as well as conditions experienced during deployment add significant requirements to the performance of free-space HPOAs. Unlike fiber optic communication links, issues of nonlinearity are eliminated in the link itself, thus allowing the launch of much higher power levels into the transmission path.

The present study is mainly concerned with the design of the Erbium Doped Fiber Amplifiers (EDFAs) in order to increase the output power, limiting at the same time the Amplified Spontaneous Emission (ASE) noise. Various parameters of EDFA such as Erbium ion density, doped fiber length, pumping power and doping radius can affect on ASE noise which in turn affects on the value of BER. The proposed system is based on the optimization of the parameters of the booster amplifier and of the low noise amplifier at the transmitter and receiver respectively in order to increase the overall system performance. A variable optical attenuator is implemented at the receiver to control the intensity of the signal to prevent saturation or catastrophic damage that might otherwise occur due to high power optical levels under specific circumstances. By maintaining a relatively constant power level we keep the bit error rate performance above an acceptance value independent of the distance between the UAV and the ground station and as well as the weather conditions. We derive the appropriate BER expressions for an Intensity Modulation/Direct Detection (IM/DD) FSO system taking into account different weather conditions, weak turbulence and all the possible main sources of noise related to the implementation of optical amplifiers and to the diodes at the receiver system. We further investigated the performance for different ranges in terms of BER, Q factor, eye closure, signal power and noise.

2. SYSTEM MODEL

The FSO system that we propose consists of a fixed ground terminal transceiver and the UAV terminal transceiver. We assume that the UAV is cruising with constant speed and at fixed altitude of 1km, while the laser beam travels across a slanted optical path. The transmitter involves a DFB laser diode, a Mach-Zehnder modulator, a booster amplifier and a telescope assembly. The receiver part consists of a telescope that focuses the optical power to an optical low noise amplifier and a PIN photodiode. This system is implemented and simulated using Optiwave software Optisystem 7 & Matlab.

The structure of the proposed booster optical amplifier is shown in Figure 1. It consists of two stages of amplification which provides at the end up to 1.986 W total average signal power with less than 6 uW noise and 2.9 mW remaining pump power. The first stage is a low noise pre-amplifier based on high power forward pumping at 980 nm to provide lower Noise Figure (NF). The second stage consists of four booster amplifiers co- & counter- propagating that are coupled together through 3 dB couplers and a phase shifter. The length of the Erbium fibers, the bandwidth of the optical filters and the pump power have been optimized for the best performance.

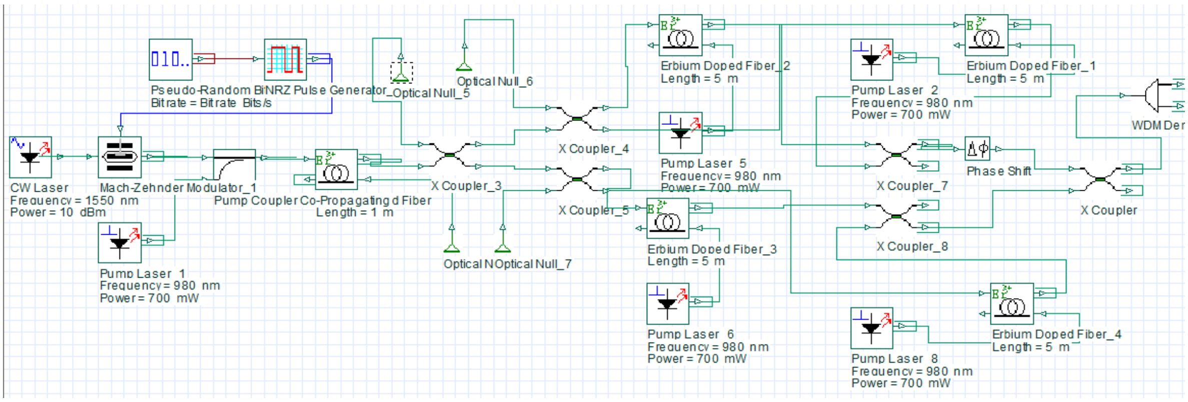

Fig. 1. Booster amplifier

The structure of the proposed low noise optical amplifier is shown in Figure 2. It consists of two stages co-propagating EDFAs separated by a 0.3 nm optical filter and a variable optical attenuator to control the output power.

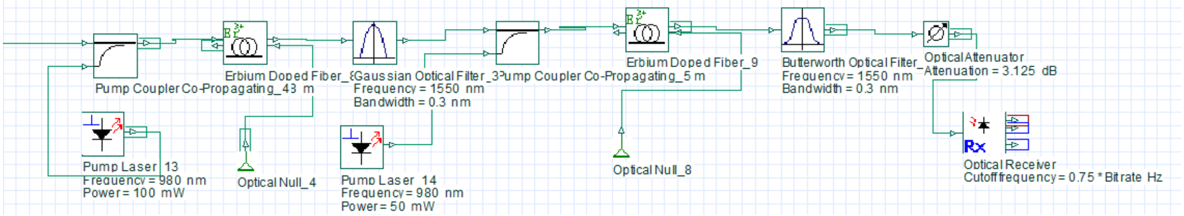

Fig. 2. Low noise amplifier

3. THEORY ANALYSIS

The BER of IM/DD with On-Off Keying (OOK) is given by $BER = p(1)p(0|1) + p(0)p(1|0)$ where $p(1)$ and $p(0)$ are the probabilities of sending 1 and 0 bits, respectively and denote the conditional bit error probabilities where bit 1 and 0 are transmitted, respectively. Considering $p(1) = p(0)$ =1/2 the BER equation can be expressed by $BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{2} erfc\left(\frac{1}{\sqrt{2}}\frac{i_1 - i_0}{\sigma_1 - \sigma_0}\right)$, where i_j and σ_j $(j = 0,1)$ are the photocurrents and the variances for bit 0 and 1, respectively. Assuming a photodiode PIN with responsivity R, the photocurrent become $i_j = RP_{r,j} + I_d$, where $P_{r,j}$ is the optical power for *j*-bit and I_d is the dark current of the photodetector. The calculation of $P_{r,j}$ assuming a booster amplifier with total gain G_1 and $P_{ASE(1)}$, and a low noise amplifier with total gain G_2 and $P_{ASE(2)}$, can be expressed $P_{r,j} = G_2 \cdot P_j + P_{ASE(2)} = G_2 \cdot L_{FSO} \cdot \left(G_1 \cdot P_{t,j} + P_{ASE(1)}\right) + P_{ASE(2)}$, where L_{FSO} is the FSO link calculation which combines attenuation and geometrical aspects based on the equation $L_{FSO} = G_{T_X} \cdot L_P \cdot L_{FS} \cdot G_{R_X} \cdot 10^{-(a_{atm}+a_{scin})10^{-1}L}$, with G_{T_X} and G_{R_X} are the gains from T_x and R_x system, respectively. L_P are the pointing losses, L_{FS} are the free space losses, a_{atm} is the attenuation factor due atmosphere $a_{atm} = \frac{3{,}91}{V}\left(\frac{\lambda}{550}\right)^{-q}$, where V is the visibility in km, λ is the wavelength of carrier in nm and q is a parameter evaluated between 0-1.6, according to weather conditions [4], and a_{scin} is the fading factor due scintillation, for the case of weak turbulence.

Due to the detector system, there are the inherent noise currents like thermal noise $\sigma_{th}^2 = \frac{4kTB_w}{R_L}$, shot noise $\left(\sigma_{sn}^2\right)_j = 2q_e R\left[G_2 P_j + n_{sp}\frac{hc}{\lambda}(G_2-1)\Delta f_{opt}\right]B_w$ and noise from the dark current $\sigma_{dc}^2 = 2q_e I_d B_w$, where q_e is the electron charge, h is the Planck constant, c is the velocity of light in vacuum, B_w is the bandwidth of the detector filter, k is the Bolzmann constant, T is the effective noise temperature, R_L is the effective input resistance of detector and n_{sp} is the spontaneous emission coefficient and Δf_{opt} is the response spectrum bandwidth of the detection system. Moreover, the utilization of amplifiers introduces two different types of ASE noises that can occur, those called amplified signal-spontaneous emission σ_{s-sp} and amplified spontaneous-spontaneous emission σ_{sp-sp}.The noise currents for the system that we propose, are given by $\left(\sigma_{s-sp}^2\right)_j = 4R^2 G_2 P_j n_{sp}\frac{hc}{\lambda}(G_2-1)B_w$ & $\sigma_{sp-sp}^2 = 2R^2\left[n_{sp}\frac{hc}{\lambda}(G_1G_2-1)\right]^2\left(2\Delta f_{opt} - B_w\right)B_w$. Finally the total rms noise, without taking into account the noise that comes from background power (sun radiation) is given by the formula $\sigma_j = \sqrt{\sigma_{th}^2 + \sigma_{dc}^2 + \sigma_{sp-sp}^2 + \left(\sigma_{sn}^2\right)_j + \left(\sigma_{s-sp}^2\right)_j}$.

4. RESULTS AND DISCUSION

Based on the analytical study presented in sections 2 & 3, simulation of ground-to-UAV FSO communication link, were performed in the Optisystem & Matlab environment, considering the effects of several parameters. Atmospheric losses are calculated through Beer's law in relation to the wavelength (1550 nm) and the visibility (2 km - haze and 10 km - clear sky). We consider the transmitter laser power to be 10mW in CW mode with 0.1 MHz linewidth modulated at 10 Gbit/s, the beam waist radius 5 cm and the receiver aperture diameter 20 cm, which are defined in order to eliminate atmospheric path losses through turbulence effects.

Figures 3 & 4 illustrate the results of the average BER & Q factor according to the range between the UAV and the GS for clear sky and haze conditions, respectively. The numerical results show that with the proposed amplification scheme, we achieve a reliable link for distances up to 43.2 km for clear sky conditions where BER and Q factor are better than 1.5e-13 and 7.2, respectively. At haze conditions, the corresponding parameters are a distance up to 8.7 km where BER and Q factor are better than 6.3e-15 and 7.6, respectively.

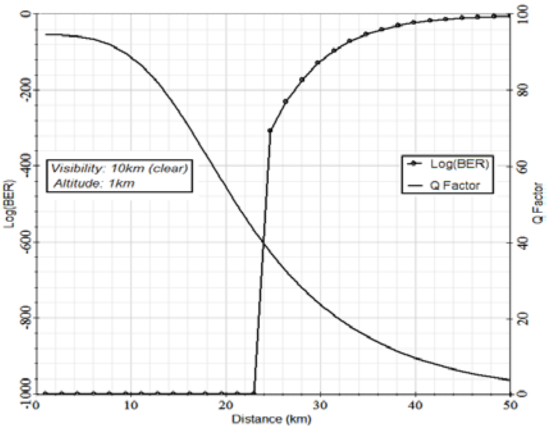

Fig. 3. BER & Q factor vs Range for clear sky conditions.

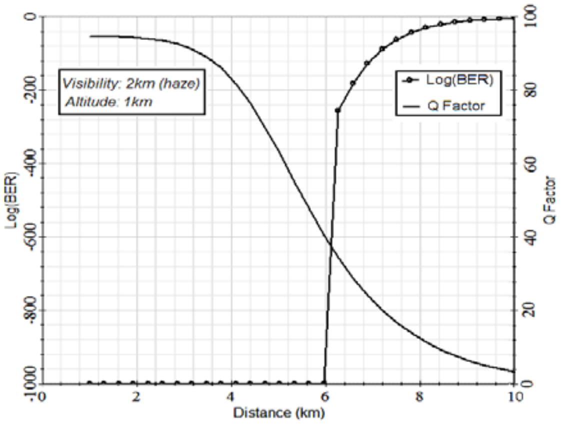

Fig. 4. BER & Q factor vs Range for haze conditions.

Figure 5 illustrates the variation of the signal & the noise level for clear sky conditions before the PIN photodiode. It is clear that signal decreases rapidly with distance while the noise increases and remains almost constant above 36.4 km distance due to the low noise amplifier at the receiver. Figure 6 illustrates the effectiveness of power control with a Variable Optical Attenuator (VOA) in front of the receiver photodiode. It is obvious that we achieve a communication link with almost constant Q factor (~15) keeping the amplifiers parameters (pump and signal) for optimal conditions.

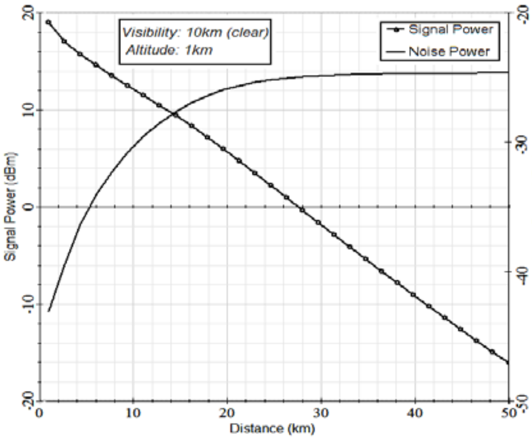

Fig. 5. Signal & Noise vs Range.

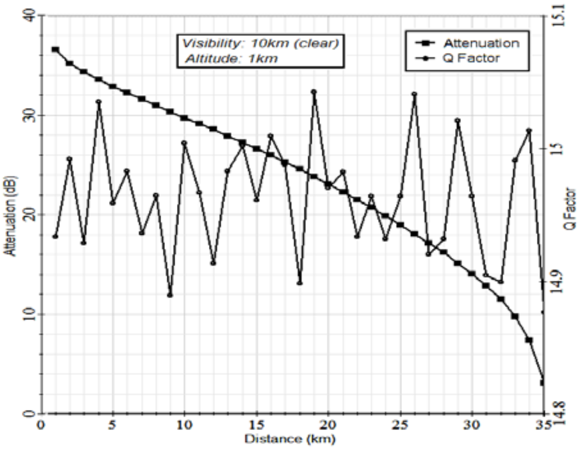

Fig. 6. Attenuation & Q factor vs Range with VOA.

Figures 7 & 8 illustrate the quality of the electrical signal after the PIN conversion from 1 km up to 35 km range between the UAV and the GS under clear sky conditions using the VOA.

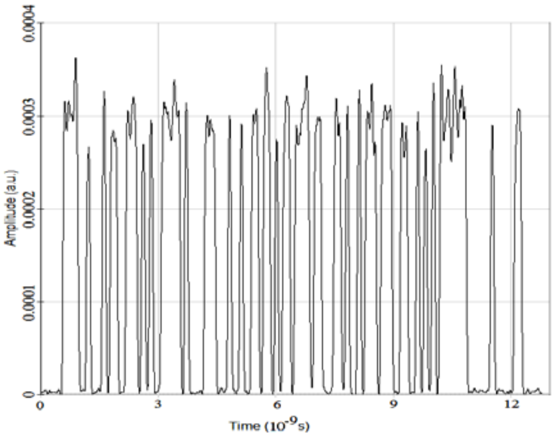

Fig. 7. Signal & noise vs time.

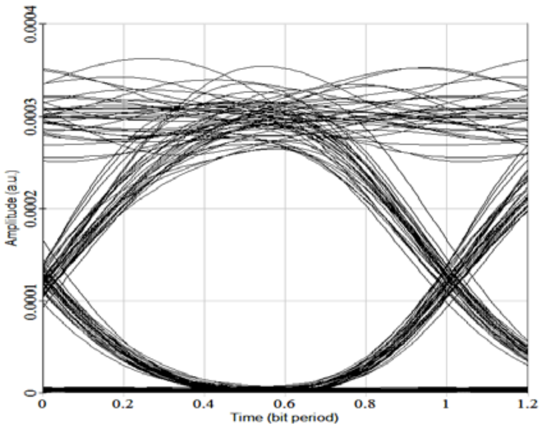

Fig. 8. Eye diagram.

5. CONCLUSIONS

In this work, a mobile FSO system was studied by optimizing EDFAs configuration and parameters in order to improve the quality of the signal reducing at the same time the noise. The system was evaluated in clear sky and haze atmospheric conditions calculating the BER & Q factor taking also into consideration amplifiers noise and as well as the shot and the thermal noise of the PIN diode. A variable optical attenuator has been implemented at the receiver to control the intensity of the signal. The obtained results showed that the system can provide a reliable communication link for variable ranges from 1 km up to 35 km at clear sky conditions.

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