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Ucuk Darusalam
Informatics Engineering, Faculty of Information and Communications Technology, Universitas Nasional, Jakarta 12520, Indonesia, ucuk.darusalam@gmail.com

Arockia Bazil Raj
Department of Electronics Engineering, Defence Institute of Advanced Technology, Pune 411025, India

Fitri Yuli Zulkifli
Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

Purnomo Sidi Priambodo
Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

Eko Tjipto Rahardjo
Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

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Performance of Free-space Optical Communication Systems using Optical Amplifiers under Amplify-forward and Amplify-received Configurations

Ucuk Darusalam[1*], Arockia Bazil Raj[2], Fitri Yuli Zulkifli[3], Purnomo Sidi Priambodo[3], and Eko Tjipto Rahardjo[3]

1. Informatics Engineering, Faculty of Information and Communications Technology, Universitas Nasional, Jakarta 12520, Indonesia
2. Department of Electronics Engineering, Defence Institute of Advanced Technology, Pune 411025, India
3. Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

[*]*e-mail: ucuk.darusalam@gmail.com*

Abstract

With the growth of digital technology in the stage of industrial revolution 4.0, the demand for broadcasting large amounts of information to last mile users has increased. Free-space optical (FSO) communication is one of the telecommunication platforms that has shown immense potential in meeting the demand for information broadcasting. In this work, the performance of FSO communication based on wavelength division multiplexing with a data rate of 80 Gbps is investigated through simulations. The configuration of optical amplifiers in the FSO system is set up on the basis of the amplify-forward and amplify-received configurations to expand the network. The investigation is aimed at identifying the best optical signal amplification between an erbium-doped fiber amplifier (EDFA) and a semiconductor optical amplifier (SOA) under an atmospheric channel. Simulation results show that the EDFA performs better than the SOA in terms of the optical signal amplification for eight channels of the C band. The maximum optical propagation path length under the atmospheric channel for the amplify-forward and -received schemes using the EDFA is 1.7 km, with the bit error rate achieved at 10^{-6}.

Abstrak

Kinerja Sistem Komunikasi Optik Ruang Bebas dengan Menggunakan Penguat Optik pada Konfigurasi Penguatan Maju dan Penguatan yang Diterima. Dengan pertumbuhan teknologi di dalam tahapan revolusi industri 4.0, permintaan untuk menyiarkan sejumlah besar informasi ke para pengguna last mile terus meningkat. Komunikasi optik ruang bebas (Free-space optical (FSO)) merupakan salah satu dari platform telekomunikasi yang telah menunjukkan potensi yang sangat besar dalam memenuhi permintaan akan penyiaran informasi tersebut. Di dalam kajian ini, kinerja komunikasi FSO yang berbasis pada multipleksi pembagian panjang gelombang dengan suatu laju data sebesar 80 Gbps diteliti melalui simulasi. Konfigurasi penguat optik di dalam sistem FSO ditetapkan berdasarkan pada konfigurasi-konfigurasi penguatan-maju dan penguatan-yang diterima untuk mengekspansikan jaringan. Penelitian ditujukan untuk mengidentifikasi penguatan sinyal optik terbaik antara suatu penguat serat yang didoping erbium (erbium-doped fiber amplifier (EDFA)) dan suatu penguat optik semikonduktor (semiconductor optical amplifier (SOA)) pada suatu saluran atmosferik. Hasil-hasil simulasi menunjukkan bahwa EDFA memiliki kinerja yang lebih baik dibandingkan dengab SOA dalam hal penguatan sinyal optik untuk delapan saluran pita C. Panjang lintasan penyebaran optik maksimum pada saluran atmosferik untuk skema-skema penguatan-maju dan penguatan-yang diterima dengan menggunakan EDFA adalah 1,7 km, dengan tingkat kesalahan bit mencapai 10^{-6}.

Keywords: amplify-forward, amplify-received, erbium-doped fiber amplifier, free-space optical communications, semiconductor optical amplifier, wavelength division multiplexing

1. Introduction

Despite its free license, low-cost implementation platform, and high data rate capacity, free-space optical (FSO) communication has faced immense challenges in supporting industrial revolution 4.0 [1]. To the best of our knowledge, FSO communication systems have been developed as communication platforms that can be integrated with and support high-altitude, mobile, satellite, and terrestrial platforms [2]. With the rapid growth and increased complexity of communication systems, FSO communication systems can also be implemented in wavelength division multiplexing (WDM), dense wavelength division multiplexing (DWDM), and code-division multiple access [3]–[5]. The numerous modulation formats for transmitters have been widely investigated to determine the best electrical signals or information to be transmitted out into atmospheric channels [6]–[8]. Thus, FSO communication systems are suitable communication platforms that should be developed intensively to support the vast development of information and communications technology.

The era of digital technology has entered the stage of industrial revolution 4.0, in which big data, cloud computing, Internet of Things (IoT), and artificial intelligence have become broadly implemented in many areas [9]. These disruptive technologies still require communication platforms that can support and enable the broadcasting of voluminous data and information without being hindered by limited bandwidths. To the best of our knowledge, the 5G system is the best communication system that can meet existing demands [10]. With regard to the potential application of FSO systems and the demand for them in industrial revolution 4.0, one idea is to integrate the 5G system into an optical communication system so as to transmit massive amounts of information to an unlimited number of users worldwide or to interfaced devices (IoT). The FSO system is one such optical communication platform that can meet current requirements. FSO communication is advantageous to use given its high data rate capacity and free licensing.

To address the demand for broadcasting information and the need to share huge amounts of data, FSO communication can be implemented in a WDM system that can transmit information from computer networks to complex networks in the scale of gigabytes per second (Gbps). Extensive research has reported the successful implementation of WDM in FSO communication. In [11], FSO transmission over a distance of 1 km was successfully achieved with a data rate of 160 Gbps under the scheme of WDM. In [12], FSO transmission over a link distance of 1 km was also achieved at a data rate of 10 Gbps under the WDM scheme. In [13], the successful transmission of data at a rate of 10 Gbps over a link a distance of 5.8 km was reported. In [14], DWDM-based FSO transmission over a link distance of 3 km was demonstrated at a rate of 32 × 40 Gbps.

These results indicate that FSO systems based on the WDM or DWDM scheme require optical signal amplification to transmit data in short or long distances. Erbium-doped fiber amplifiers (EDFAs) and semi-conductor optical amplifiers (SOAs) are most commonly used for optical signal amplification in FSO systems [15], [16]. With the open atmosphere serving as a propagation medium for signals given its optical properties is random media for the absorption and others optical phenomena [17], optical amplifiers are needed to boost signal strength in long-distance data transmission. For WDM-based FSO systems, the use of optical amplifiers facilitates long-distance data transmission and offers a wide spectrum for optical signal amplification. For example, EDFAs and SOAs can amplify optical signals in the spectrum range of several nanometers within the C or L band [18]. Thus, optical amplifiers can amplify the channels of carrier frequency to deliver large amounts of information and connect networks.

The open atmosphere is a medium for optical propagation for the channels of carrier frequency and is known for its high absorbance of optical signals. Hence, the attenuation factor must be considered in the design of a WDM-based FSO system that uses an optical amplifier to link networks. The free space of the atmosphere is characterized as dynamic and random in terms of optical properties. Extensive research has reported that the capability of optical amplifiers in FSO communication is limited by the aforementioned conditions. The limitations are not caused by the strength of the amplified optical signal as the output from an optical amplifier that can propagate into the free space of the atmosphere. Rather, they are attributed to the random fluctuation of optical signals that consequently degrades system performance.

In the current work, we investigate the performance of optical signal amplification through the implementation of optical amplifiers that are configured for the schemes of amplify-forward (AF) and amplify-received (AR) in FSO communication. The major limitation of the FSO system in reaching last mile users is the optical propagation path length that tends to shorten under the influence of atmospheric channel effects. Thus, in this research, we investigate the implementation of an EDFA or SOA under the AF and AR schemes in an FSO system. For the FSO system to support high rate data transmission, we design the WDM configuration in the FSO system in eight channels of carrier frequency (C Band). Each channel modulates electrical signals into return-to-zero (RZ) or non-return-to-zero (NRZ) signals. We compare the performances of the EDFA and SOA under the AF and AR schemes. The goal of the investigation is to determine the best optical amplifier to be implemented in the WDM-based FSO communication system in the channel frequency of the C band. The system should be able to transmit voluminous information at a rate of 80 Gbps under the influence of atmospheric turbulence. The simulation of the WDM-based FSO system under the AF and AR schemes is performed using Optisystem 7.0.

2. Experiment

In previous experiments [19], the FSO performances of EDFAs and SOAs under the AF and AR schemes were not specified. As FSO systems are limited by atmospheric channels, the main issue of scintillation is solved with an optical amplifier. However, the implementation of an optical amplifier requires AF and AR configurations so as to minimize the scintillation effects because the strength of optical signals from optical amplifiers is maximized in atmospheric channels. Thus, after a signal propagates under atmospheric turbulence, the minimum attenuation and the broken spectra need to be recovered with an optical amplifier [20], [21]. The AR configuration of optical amplifiers ensures minimum fade-out probability, as stated in Ref. [22], where scintillation frequently caused the signal intensity to fall below the threshold of detection. Thus, optical amplifiers under the AR configuration can maintain signals in the upper level of detection.

Figure 1 shows the main steps for configuring the FSO system with WDM under the AF and AR schemes in Optisystem. The WDM transmitter (Tx) consisting of eight laser transmitters is chosen as the light source. The parameters set on Tx are the power output, type of electrical signal modulation, data rate transmission, and channel frequency. Henceforth, the outputs of Tx are coupled into WDM Mux to produce a single output of light transmission. The output of Mux is then coupled with the optical amplifiers as the AF configuration under atmospheric turbulence. The optical amplifiers are the EDFA and SOA. A signal is amplified by the optical amplifier with high intensity coupled with an optical collimator to transmit the optical signal to the atmospheric channel. The optical signal propagation is received by an optical receiver (OR). The collected light of the optical propagation from the OR is coupled into the optical amplifiers under the AR configuration. In the Optisystem, the output parameters are set to ensure the high gain of signal amplification. Then, the atmospheric channel is set with a Rytov factor of 25 dBm/km. This high setting of the atmospheric channel is chosen to represent the maximum turbulence effects that induce optical propagation from the optical amplifier. The output of the optical amplifier in the AR configuration is split by the Demux component into eight channels as the Tx source. Each channel is then received by a photodetector (PD). Thereafter, the receiver is set such that the main component is a PD serving as the Rx. The output of the Rx is measured by a bit error rate (BER) tester. The measurement instruments used in the simulation include an optical spectrum analyzer and a WDM analyzer. Both instruments are coupled into the output of the optical amplifier in the AR configuration before the Rx.

Figure 2 shows four schemes of the simulation setup for the WDM-based FSO system using eight channels of the C band in the AF scheme in the Tx and the AR scheme in the Rx; each scheme implements an optical amplifier. The list of channels is shown in Table 1; each channel has a spacing frequency of 100 GHz. The channel is modulated with a data or signal in a scale of 10 Gbps. The laser source uses a WDM transmitter with a signal power of 0 dB. The signal from the WDM transmitter is coupled into the WDM Mux and then moves to the optical amplifier so as to be amplified as the AF scheme. The amplified optical signal goes through the atmospheric channel or the so-called FSO channel. The output from the FSO channel is received by the optical amplifier as the AR scheme. The amplifier of the optical signal from the AR scheme is coupled into the WDM Demux to split the channel on the basis of the carrier frequency. Each channel frequency is received by a PD. The optical amplifiers implemented in the simulations are the EDFA and SOA. The WDM in the FSO system in the simulation is categorized into four schemes, as shown in Figures 2(a–d), to determine the best scheme of optical signal amplification for the eight channels.

In the simulation, the WDM transmitter consists of a laser transmitter with a frequency spacing of 100 GHz for each channel, line width of 10 MHz, and modulation type of RZ or NRZ. The FSO channel is set up with the following properties: distance range of 0–2 km, log-normal probability density function, attenuation of 25 dB/Km, transmitter aperture diameter of 5 cm, receiver aperture diameter of 20 cm, transmitter and receiver loss of 0 dB, and geometrical loss of 0. In WDM, the Mux and Demux are assumed to have no loss insertion and a noise dynamics of 3 dB. For the PD, it is set up with a responsivity of 1 A/W, dark current of 10 nA, and noise

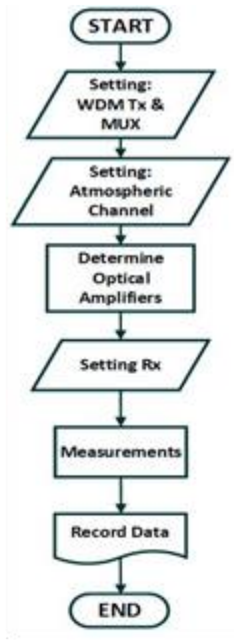
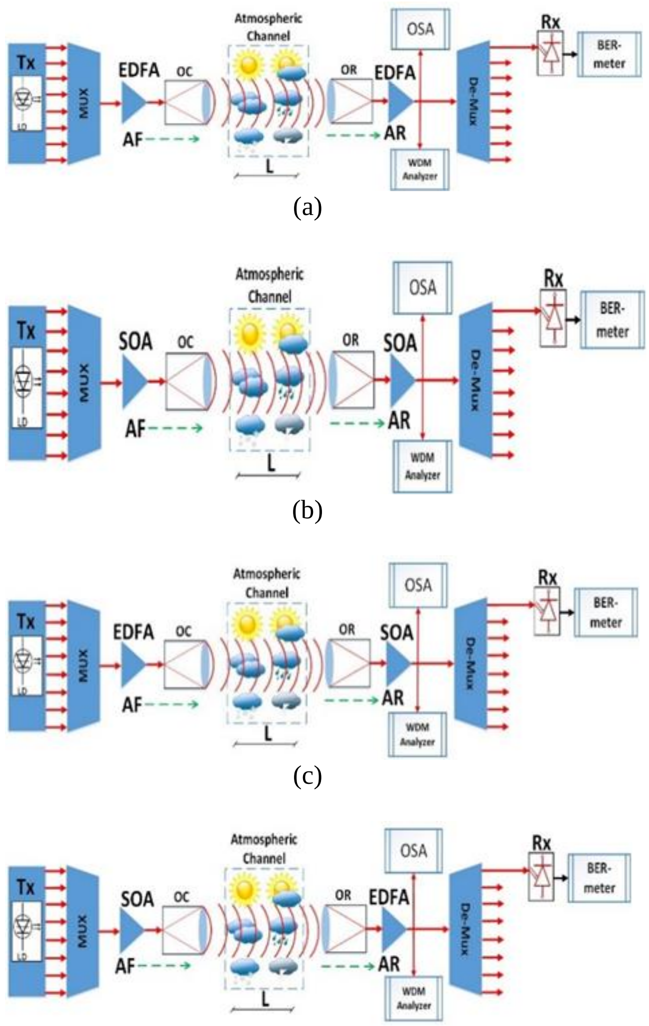


Figure 1. General Flowchart of Simulation in Optisystem 7.0 for FSO Configuration under Amplify-forward and -received Schemes



(a) (b) (c) (d)

Figure 2. Simulation Setup of WDM in FSO System using Eight Channels in the AF and AR Schemes. (a) EDFA-AF and EDFA-AR (b) SOA-AF and SOA-AR (c) EDFA-AF and SOA-AR (d) SOA-AF and EDFA-AR

Table 1. Channels of WDM in FSO System used for the Simulations Based on ITU Standards

Channel-n	Frequency (THz)	Wavelength (nm)
1	193.1	1568.77
2	193.2	1567.95
3	193.3	1567.13
4	193.4	1566.31
5	193.5	1565.50
6	193.6	1564.68
7	193.7	1563.86
8	193.8	1563.05

such as thermal noise, amplified spontaneous emission (ASE), noise of signal to ASE, and shot noise. The noise distribution in the PD is assumed to be Gaussian as well. For the EDFA, the setup properties are as follows: operation mode of gain control, gain of 20 dB, saturation power of 10 dBm, and noise figure (NF) of 4 dB. For the SOA, the setup properties are an injection current of 0.15 A, volume dimensions of 5×10^{-4} m × 3×10^{-6} m × 8×10^{-8} m, optical confinement factor of 0.3, differential gain of 2.78×10^{-20} m^2, carrier density of 1.4×10^{24} m^3, line width enhancement factor of 5, and initial carrier density of 3×10^{24} m^3.

The simulations for the four schemes of AF and AR (Figure 2) are performed by determining the maximum propagation path length of the optical link in the FSO channel, in which the value of the BER is high at 10^{-6} or low at BER << 1, in which case the channel can still receive the optical signal. As the optical signal amplification from the optical amplifiers in the AF and AR schemes is quite high or strong, the performance must be high for a short optical propagation path length in the FSO channel. In this case, we can measure the performance of the FSO channel in the maximum propagation path length. Thus, the investigation can be performed by comparing the performances of the schemes under the maximum distance.

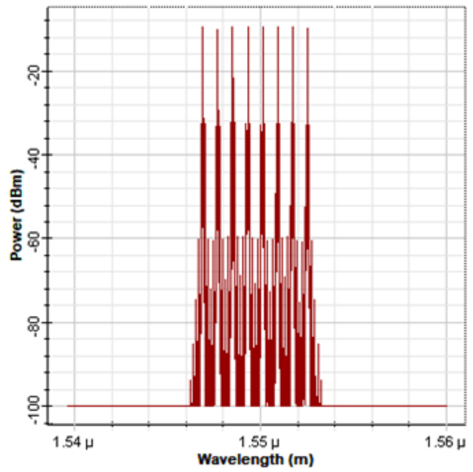
3. Results and Discussion

The results of the simulation are shown in Tables 2–5 and Figures 3–6. The EDFA-AF and EDFA-AR schemes are the best among all schemes. The L_{max} in the former reaches 1.72 km, whereas that in the other schemes does not exceed 0.1 km. The signal quality of the EDFA-AF and EDFA-AR schemes is also superior to that of the other schemes. The eye diagram shows few corrupted electrical signals, and the transition is clear enough (Figures 3b, 4b, 5b, and 6b). The gain signal spectra from the EDFA and SOA are presented in Figures 3a, 4a, 5a, and 6a. The gain from the EDFA for all channels is flat and smooth because of the signal or channel in the region where the gain slightly varies. Meanwhile, the gain of the signal spectrum from the SOA is uneven and rough because of the signal amplification in which ASE–ASE noise dominates the signal output.

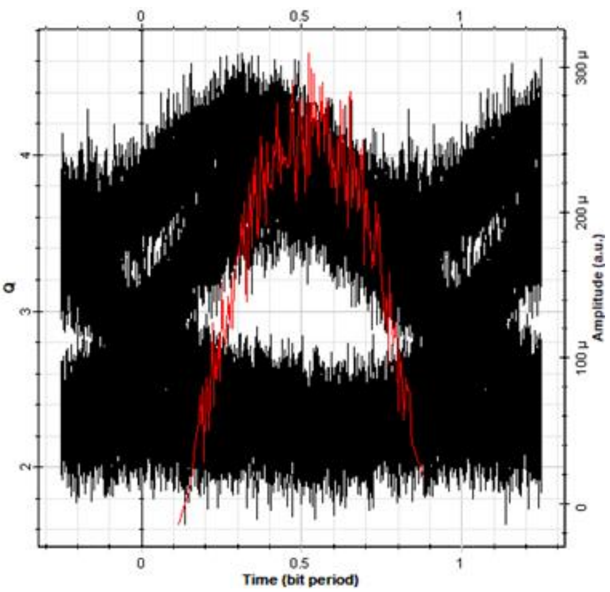
EDFA-AF and EDFA-AR. In Figure 2a, the gain of the signal spectrum from the EDFA-AF and EDFA-AR is smooth, and it does not show a raw gain for all channels. The gain from the EDFA-AF is high and can achieve the maximum propagation path length (L_{max}) in the FSO channel of 1.72 km. Thus, the quality of the electrical signal in the PD is good, with the Q value being 4.5, as shown in the eye diagram of Figure 2b.

Table 2. Performances of EDFA-AF and EDFA-AR FSO at Maximum Propagation Length; the Sample is Channel 8

Performances	Value
L_{max}	1.72 Km
OSNR	25.2 dB
BER	2.9×10^{-6}
Q	4.5



(a)



(b)

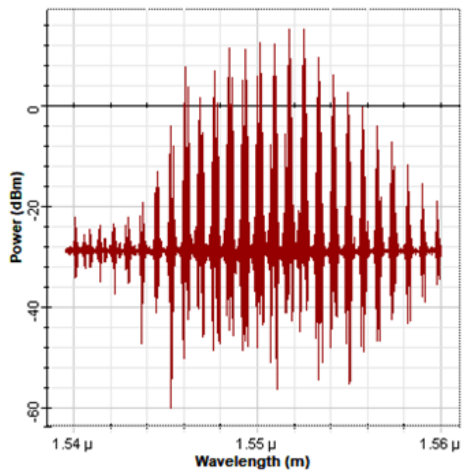
Figure 3. Gain Spectrum and Sample of Channel 8 in BER Eye Diagram for EDFA-AF and EDFA-AR (a) OSNR (b). BER Eye Diagram

SOA-AF and SOA-AR. In Figure 4.a, the gain of the signal spectrum from the SOA-AF and SOA-AR is noisy and raw for all channels. The high noise modulation in the signal spectrum from the sources causes the optical signal to interact with noise modulation in optical propagation. This condition explains why the distance of the optical propagation path length is only 0.1 km. Thus, the BER is only 1.1×10^{-6}, and the eye diagram appears corrupted, as shown in Figure 4b.

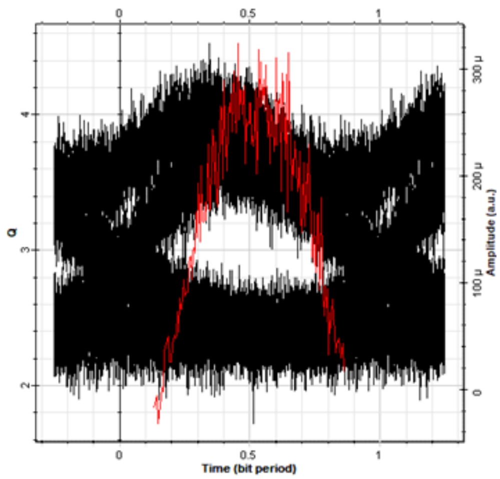
EDFA-AF and SOA-AR. In Figure 5a, the gain of the signal spectrum from the EDFA-AF and SOA-AR also shows maximum noise modulation. Thus, L_{max} does not

Table 3. Performances of SOA-AF and SOA-AR FSO at Maximum Propagation Length; the Sample is Channel 8

Performances	Value
L_{max}	0.15 Km
OSNR	14.8 dB
BER	1.1×10^{-6}
Q	4.73



(a)



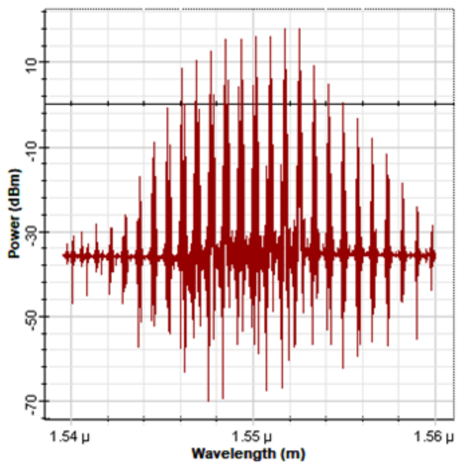
(b)

Figure 4. Gain Spectrum and Sample of Channel 8 in BER Eye Diagram for SOA-AF and SOA-AR (a) OSNR (b). BER Eye Diagram

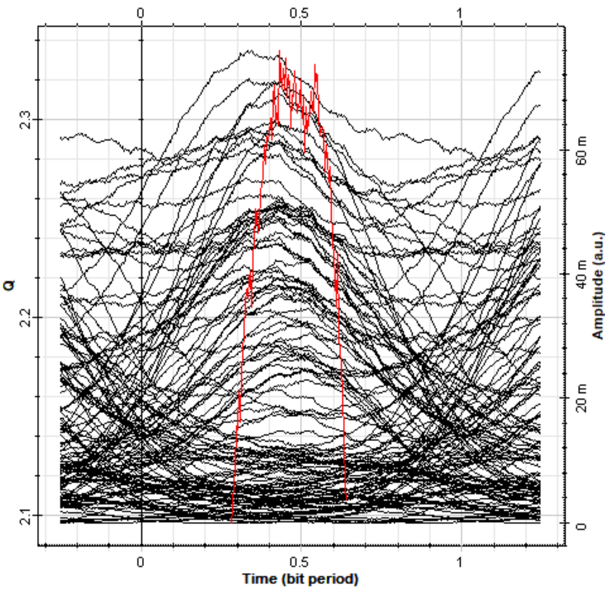
increase and falls in the 0.1 km range as well. The eye diagram also shows a corrupted electrical signal, and the transition appears fuzzy, as shown in Figure 5b.

Table 4. Performances of EDFA-AF and SOA-AR FSO at Maximum Propagation Length; the Sample is Channel 8

Performances	Value
L_{max}	0.1 Km
OSNR	27.7 dB
BER	9×10^{-3}
Q	4.73



(a)



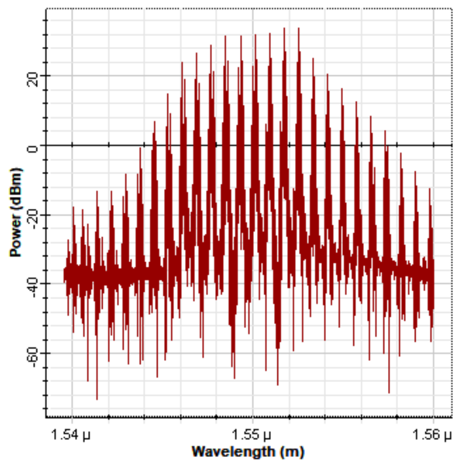
(b)

Figure 5. Gain Spectrum and Sample of Channel 8 in BER Eye Diagram for EDFA-AF and SOA-AR (a) OSNR (b) BER Eye Diagram

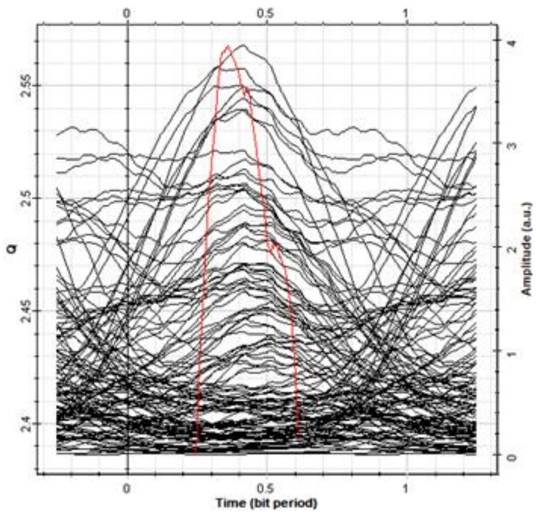
SOA-AF and EDFA-AR. In Figure 6a, the gain of the signal spectrum from the SOA-AF and EDFA-AR shows the same worst case as that of EDFA-AF and SOA-AR. We deduce that the optical signal amplification from the SOA exhibits the maximum ASE-to-ASE reception. Thus, the optical signal modulates noise and interacts with the background noise and turbulence effects.

Table 5. Performances of SOA-AF and EDFA-AR FSO at Maximum Propagation Length; the Sample is Channel 8

Performances	Value
L_{max}	0.1 Km
OSNR	63.7 dB
BER	4×10^{-3}
Q	2.5



(a)



(b)

Figure 6. Gain Spectrum and Sample of Channel 8 in BER Eye Diagram for SOA-AF and EDFA-AR (a) OSNR (b) BER Eye Diagram

Comparing Figures 3 and 4 show that the EDFA in the AF and AR schemes performs better than the SOA in the same AF and AR schemes. The EDFA performs optical signal amplification on the basis of a fiber medium that is generated by the light emission of a laser pump. By contrast, the SOA performs optimal signal amplification on the basis of the active region initiated by the current injection. Thus, ASE in the EDFA is lower and narrower than that in the SOA. Furthermore, the noise figure (NF) is < 5 dB for the EDFA and 8 dB for the SOA. Thus, the EDFA produces high-intensity optical signal to be transmitted to the atmospheric channel as a disturbance medium.

The accumulation of noise modulation based on the ASE and NF is received by a second optical amplifier in the AR configuration. The EDFA, which is based on the fiber detection method, suppresses the scintillation effects. The numerical aperture (NA) of the fiber, as the optical signal reception, limits the fluctuation of intensity caused by beam wandering [2]. This condition is different in the SOA, in which the value of NA is high. Thus, the SOA receives a wide spectrum of noise modulation gathered on the basis of the ASE and NF. Moreover, the amplification of an optical signal in the SOA is weak due to the amplified background noise, ASE, and NF. This condition results in a competition for high signal gains under amplified background noise, ASE, and NF. The analysis confirms the results in Figures 5 and 6, which shows that the SOA with the AR configuration has a lower OSNR than the EDFA with the AR configuration.

The results of the simulations presented in Tables 2–5 and Figures. 3–6 indicate that the EDFA under the AF and AR schemes is the best optical amplifier to amplify the channels in the spectra of 1568.77, 1567.95, 1567.13, 1566.31, 1565.50, 1564.68, 1563.86, and 1563.05 nm (C band). The EDFA produces amplified optical signals with a high gain and a flat and smooth profile, whereas the SOA produces a low gain and maximum noise. The performance of the EDFA is considered superior because the channel frequency of a signal lies in the region with a flat gain spectrum near the L band and the gain slightly varies as the function of the channel is not high. On the contrary, the SOA causes gain fluctuation due to the channel frequency of the signal falling in the region of a decreasing gain spectrum near the L band. Thus, the EDFA in the AF and AR configurations is better than the SOA as it covers a longer optical propagation path length under the FSO channel.

4. Conclusion

Simulations are performed in this work to compare the performances of EDFAs and SOAs implemented under the AF and AR configurations in WDM in an FSO system with eight channels and data rate transmission of 80 Gbps. The performances are measured by the parameters of OSNR, BER, and Q factor, as shown in Tables 2–5. The simulation results show that the EDFA performs better than the SOA. Moreover, the implementation of the EDFA in the AF and AR schemes covers the maximum optical propagation path length under strong turbulence in the atmosphere. The implementation of the EDFA in the AF and AR configurations can achieve maximum transmission at a distance of 1.72 km; the OSNR, BER, and Q factor are 25.2 dB, 2.9×10^{-6}, and 4.5, respectively. The most important finding is that the SOA cannot be effectively implemented in the FSO system under the AF and AR configurations because the ASE, NF, and a wide spectrum of noise modulation can be amplified given the value of NA being higher than that for the EDFA. Nevertheless, the SOA is simple to install and inexpensive to implement. The drawbacks of the SOA can be minimized with the implementation of an optical filter that can limit the wide noise bandwidth from the atmospheric channel before an optical signal is received by the SOA.

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