Journal of Communications, vol. 18, no. 8, August 2023

Performance Evaluation of Optical Amplifiers in a Hybrid RoF-WDM Communication System

Tagnon P. Okoumassoun [1], Anita Antwiwaa [2], and Nana K. Gerrar [2, *]

[1] Electrical and Computer Engineering Department, University of Ottawa, Ottawa, Canada;
Email: tokou034@uottawa.ca (T.P.O.)
[2] Department of Electrical/Electronics Engineering, Cape Coast Technical University, Cape Coast, Ghana;
Email: draantwiwaa@anu.edu.gh (A.A)
*Correspondance: nanagerrar@yahoo.com (N.K.G.)

Abstract —**Recent developments in various applications have led to the rapid growth in demand for bandwidth by users. It has enhanced the need for solutions that provide abundant bandwidth at a reduced cost. Radio-over-fibre (RoF) enables simpler and more efficient transmission of communication signals compared to traditional radio frequency (RF) methods. Wavelength-division multiplexing (WDM) enhances optical communication by enabling the transmission of optical signals at multiple wavelengths thereby increasing the bandwidth capacity of the transmission process. Hybrid RoF/WDM systems have also found applications in recent communication methods. Despite their advantages, RoF-WDM systems suffer from significant power loss and dispersion over long distances, optical amplifiers are therefore usually used to improve signal reception. In this paper, the performance of an Erbium-doped fiber amplifier (EDFA), a semiconductor optical amplifier (SOA), and a Raman amplifier is investigated over a long-distance RoF-WDM communication system. The EDFA exhibited improved received power at all destination lengths, with the best being 19.2128 dB at the 10 km destination length. The SOA had the best Q-factor and BER performance at the 10 km and 25 km destination lengths. Specifically, SOA produced BER of 1.21666×10^{-7} and 5.62603×10^{-8} and a Q-factor of 5.15645 and 5.2966 at 10 km and 25 km respectively. At the 60 km destination length, the Raman amplifier exhibited the best Q-factor (4.6517) and BER (1.27797×10^{-6}). In conclusion, for transmission using RoF-WDM systems over long distances, EDFA and Raman amplifiers are most suitable.**

***Keywords*—radio-over-fibre, wavelength-division multiplexing, Erbium-doped fibre amplifier, semiconductor amplifier, raman amplifier**

I. INTRODUCTION

Today, optical technology has become an important method for communication systems globally. Optical fibres are now employed to achieve high signaling speeds in various communication applications such as mobile communications and the internet of things [1, 2]. Factors that have increased bandwidth demands in recent times include image transfer, video streaming, cloud services, machine-to-machine (M2M) communication and the internet of things [3]. The ever-increasing traffic over the internet and demand for bandwidth is leading to improvements in transmission techniques for optical fibre networks. Capacity is an issue in communications systems today owing to different growth rates of existing technologies and traffic demands. Optical communications favour the transmission of large amounts of data over long distances with fast response times [4].

Communication using the millimeter wave (mmWave) spectrum has also emerged in recent times as a solution to the requirement of high speed and bandwidth for today's communication networks. Some of the notable advantages of using the mmWave include high data rate, wide bandwidth, low latency, limited reflection, limited penetration, small antennas, and multi-antenna array beamforming [5]. Despite these advantages, exposure to significant propagation loss, scattering, line of sight dependence, and atmospheric attenuation can adversely affect the available bandwidth [6]. These effects can be mitigated by employing a distributed antenna system (DAS) for coverage of a large area [7]. DAS is well-suited for improving the coverage and capacity of wireless transmission systems [8]. High precision and stable radio frequency (RF) distribution provide new opportunities in deep-space networks, distributed synthetic aperture radio systems, and very long baseline interferometry (VLBI) [9].

Implementation of 5G systems involves the utilization of smaller cell sizes than in existing mobile network standards like 3G and LTE. A large number of cells increases power consumption owing to the use of several remote antenna units (RAUs). However, cloud-radio access network (CRAN) systems are able to reduce the number of required cells and their geographical locations [10]. Additionally, the behaviour of radio signals makes the implementation of 5G difficult in indoor surroundings including homes and commercial buildings. Radio-over-

---

Manuscript received March 28, 2023; revised May 19, 2023; accepted June 6, 2023.

doi:10.12720/jcm.18.8.522-536

fibre (RoF) systems enable a more efficient implementation of 5G in indoor conditions. An advantage of optical solutions for last-mile connection is the availability of non-expensive optical modules that have simple connections and do not require optical isolators. However, these solutions can lead to increased noise and signal distortion requiring protection from external optical feedback [11].

RoF, commonly implemented in fibre-wireless (Fi-Wi) systems, has the advantage of abundant bandwidth associated with optical fibre coupled with the ease of use and flexibility of wireless networks. Fi-Wi systems enhance a faster roll-out of micro/pico cellular architecture in a wireless network at a reduced cost. The benefit of Fi-Wi is the provision of larger network capacity and spectrum allocation. RoF-based Fi-Wi system makes centralized processing and adaptive radio resource management possible. RoF also finds application in mmWave wireless systems where they are well suited for transmitting signals in the midst of high attenuation. Some challenges in implementing Fi-Wi on a large scale include low power-handling capability, lower dynamic range for some optical transmitters, and the requirement for smaller radio cells than in traditional purely RF systems. Also, channel estimation and equalization are difficult owing to nonlinear distortion in the RoF link and multipath dispersion of the wireless channel [3, 12].

Since the late 1990s, there has been a revolution in optical systems through the use of wavelength-division multiplexing (WDM) systems supported by optical amplifiers [4]. WDM systems facilitate sending data using various light wavelengths (or colors). On a single fibre, two or more colours of light can travel, and numerous signals at different wavelengths or frequencies on the optical spectrum can be conveyed via an optical waveguide. This technique enables the exponential growth of capacity and permits bidirectional transmission over a single channel [13].

There is limited research on the application of RoF-WDM technology in emerging communication methods. This paper focuses on the performance of RoF-WDM systems over long distances. Optical amplifiers are integrated into the RoF-WDM communication system configuration. Specifically, the performance of the Erbrium-doped fibre amplifier (EDFA), semiconductor optical amplifier (SOA), and Raman amplifiers in RoF-WDM are investigated over long distances using numerical simulations considering the following parameters: BER, Q-factor, and signal power.

The rest of the paper is organized as follows. Section II contains the related literature. In section III, WDM, RoF, and RoF-WDM communications systems are discussed. The system model appears in Section IV. Section V contains the comparative analysis of the performance of optical amplifiers on RoF-WDM links. Conclusions are in Section VI.

II. RELATED LITERATURE

Kao *et al*. [11] showed a technique for RoF transmission of an orthogonal frequency division multiplexing (OFDM) signal using graded-index plastic fiber (GI PoF) for up to 100 m. Their experimental results show less noise and intermodulation distortion compared to traditional multimode fibre (MMF). The authors of [14] considered a wide-area wavelength-division-multiplexing passive optical network (WDM-PON) that has a wavelength-shifted protection capacity. In [15], the authors presented a multiservice digital radio over fibre [DRoF] system for a neural-host fronthaul link. Data compression, multiband, multiplexing, and synchronization algorithms were implemented in both forward and reverse links. Their design showed a better RF dynamic range and reduced bit rate. The system makes it possible for different networks to use the same fibre network infrastructure. The authors of [8] presented an intermediate frequency-over-fibre (IFoF) based remote access network (RAN) for a mmWave network operating at 28 GHz which extends to a larger coverage area compared to similar mmWave-based 5G networks. The authors of [16] set out to reduce data rates on analog-to-digital-compression RoF (ADX-RoF) at signal fidelity sufficient for high-order radio modulation. Their scheme relies on low-latency MIMO compression. Long haul optical transmission is exposed to low SNR of the received signal and degradation frequency stability. In [9], the authors considered the prospects of long-haul information transmission using optical fibre through ultra-stable RF without the use of a relay system. Their experimental results showed a stable RF transmission test in about 1007 km optical fibre.

In order to have even better-quality networks, the implementation of hybrid RoF and WDM systems have been integrated to ensure efficiency and low cost [17]. WDM is useful for RoF signals owing to the fact that the insertion loss of the WDM de-multiplexer is in general consistent notwithstanding the number of antenna sites. Additionally, different RoF signals can be transmitted at different wavelengths [7]. However, there are still some challenges bedeviling RoF-WDM systems that are currently receiving attention from researchers. These challenges include chromatic dispersion, signal losses, and nonlinear effects, all of which have a substantial impact on the performance of optical networks [18]. To mitigate the effects of power loss, which is an important component of optical transmission, an optical amplifier can be used. Optical amplifiers have facilitated the implementation of optical WDM systems [19].

Nakamura *et al.* [20] investigate the performance of an RoF-WDM scheme with different fibre propagation losses. It was shown that over a long distance (about 60 km), the RoF-WDM system has a low bit error rate (BER) but a significant decrease in Q-factor, and power loss. The implementation of an optical amplifier with a 20 dB gain figure and a 4 dB noise figure significantly increased the performance of the system. Tong *et al.* [7] developed a WDM-RoF multiplexer for a frequency-modulated continuous-wave (FW-CW) using a delivery system. They evaluated their design using a 4-channel WDM 48 GHz band FW-CW RoF signal. The design is also suitable for different frequency-band signal deliveries. Yeh *et al.* [21] proposed a WDM FSO network for up to 51 km. Their technique reduced the effect of Rayleigh backscattering (RB). The significant growth in optical communications systems enabled by WDM slowed down as more efficient ways to utilize the available bandwidth were developed [4]. Pandey *et al.* [22] proposed an inexpensive transmission method using a directly modulated laser (DML)-based WDM-RoF transmission system in 5G networks. The error vector magnitude (EVM) obtained with this method for 4/16/64-QAM meets the 3GPP standard for 5G. Kumar *et al.* [23] evaluated the performance of a 16-channel 160 Gbps data rate WDM-RoF system at different input power levels. The authors applied dispersion compensation fibre (DCF) and fibre Bragg grating (FBG) at a channel spacing of 50 and 100 GHz. Their results indicated an optical power level of −5 dBm at 100 GHz channel spacing. There has also been a strong interest by researchers in the continual improvement of optical amplifiers. In [24] and [25] for example, some recent developments in EDFA and SOA design technology are discussed. Chichkov *et al.* [24] showed that amplification in the 2.78 μm wavelength band is possible using mid-infrared diode lasers for the Erbium-doped fluoride fibre amplifier. The authors consider continuous wave (CW) and ns-pulsed input signals to evaluate their amplification technique. Zhao *et al.* [25] implemented a particle swarm optimization algorithm in the inverse design of a semiconductor optical amplifier. They used the scaled conjugate gradient propagation neural networks to accomplish parameter extraction of multiple solutions at high speeds and obtain excellent results. Their choice of swarm algorithm is based on the fact that deep neural networks expose input-output relationships that can be exploited to enhance photon prediction and inverse design.

III. WDM, RoF and RoF-WDM Hybrid Communication Systems

In this section, WDM, RoF, and RoF-WDM system configurations are discussed. Additionally, various optical amplifiers that enhance the transmission process of optical communication systems are also discussed.

In WDM, several optical carrier signals are multiplexed on a single optical fibre channel through the altering of the wavelength of laser beams [26]. WDM addresses the challenge of inadequate bandwidth by increasing the capacity of existing optical communication networks at reduced complexity and cost. Additionally, WDM supports bi-directional communication solutions for routing, switching, and channel selection. It is also a flexible approach to network design. WDM also finds application in radio broadcasting where it aids in the transmission of different frequencies with little or no interference. Fig. 1 illustrates a typical optical WDM system. The system is composed of a multiplexer, fibre cable, laser, filter, photodetector, and demultiplexer. A multiplexer, which is simply an optical combiner, is used in WDM to combine optical signals from several sources and then integrate or combine them using different wavelengths for the transmission process. A single optical cable transports the combined signal. A demultiplexer, also a splitter, separates the incoming beam into its components at the receiving end, and each component is sent to the appropriate receiver according to its respective wavelength. The lasers operate at a set wavelength. WDM filters and photodetectors aid in the reception of the signal [27].

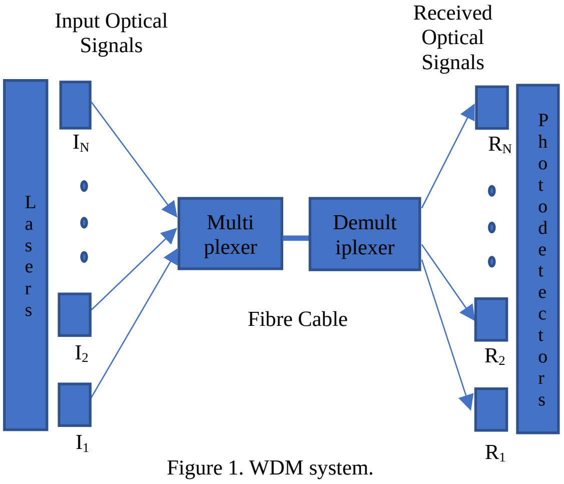

Figure 1. WDM system.

There are some additional components of the WDM system. Add/drop multiplexers separate a wavelength from one fibre cable and direct the signal to another fibre. They are usually placed between the inception of the transmission process and the final destination of the signal. Routers in the WDM network serve as a means to direct signals to specified destinations without interfering with the respective wavelengths of the signals. WDM couplers are used to combine or separate different wavelengths in the WDM network. Types of WDM couplers include a diffraction grating, prism, and dichroic filter [26].

In RoF, light is modulated using a radio frequency, and the resulting signal is transmitted via an optical medium usually a fibre optic cable. RoF is known for simple antenna configuration, higher bandwidth, low cost, reduced energy consumption, and greater wireless network coverage compared to using an entirely RF communications system. RoF systems are however exposed to noise and distortion peculiar to analogue transmission systems. Also, RoF suffers from signal dispersion in the fibre optic cable. The choice of optical and electro-optic modulation methods poses a challenge to the implementation of RoF systems. RoF can be applied in mobile communications, the transmission of television signals, satellite communication, and for wireless coverage in areas where the backhaul connection is difficult. RoF aids the transmission of radio signals over longer distances because of less attenuation in the optical fibre which eliminates the need for signal amplification necessary in more traditional systems. RoF enables the sharing of communication infrastructure and the integration of fixed and mobile networks. An RoF system can further be put into two categories: radio frequency over fibre (RFoF) and intermediate frequency over fibre (IFoF). With RFoF, the radio frequency signal is modulated by a light wave signal before subsequent transmission by optical means. In IFoF, an intermediate radio frequency is used for modulating the light signal before the transmission in the optical medium. In remote antenna applications, an RoF link is utilized to distribute signals for microcell, nanocell, or picocell base stations [12]. Fig. 2 shows a typical RoF system. The system makes use of a laser source, optical transmission medium and photodetectors/photoreceivers.

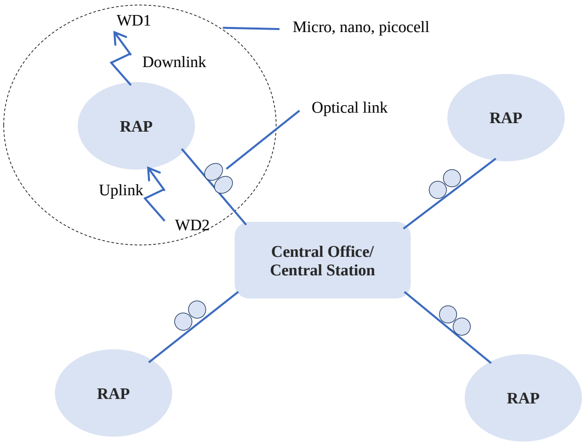

Figure 2. RoF system.

At the central office (CO)/central station (CS) the RF signal is modulated to obtain the baseband signal. The RF signal is converted to an optical signal by using a modulated laser source or by external electrooptic modulators. At the BS the optical signal is converted to an electrical signal. The received RF signal is amplified and sent to user handsets/devices wirelessly via antennas. The electro-optical (E/O) and optoelectronic (O/E) conversion of signals is achieved through the CO and a remote access point (RAP) respectively. On the other hand, photodetectors and photoreceivers aid in obtaining an electrical signal from the received optical signal. The uplink configuration is similar but in reverse. The RF signal is transmitted via the wireless channel, it reaches the central base station (CBS) over optical fibre links. In RoF systems, modulation can be achieved through baseband-RF or RF-optical means. In the more traditional baseband-RF modulation, the RF carrier is modulated by the based data sequence of the CBS. Per the RF-optical modulation, the optical carrier is modulated with an RF signal at the laser or using a suitable external modulator. The downlink and uplink configuration in the network is described next. In the downlink configuration, the data undergoes baseband-RF modulation at the BS. Following this, through the intensity modulator, the carrier at the optical transmitter is modulated by the radio signal. The RF-modulated light wave is then transmitted by optical fibre to a remote RAP. A RAP will typically contain at least one O/E convertor, an E/O converter, and a radio antenna. Upon receipt of the signal at the RAP, the RF signal is extracted from the optical carrier using a suitable photodetector and bandpass circuitry. The received RF signal is amplified and sent to the various user devices wirelessly as shown in Fig. 2 [3, 28].

WDM improves the capacity of optical transmission and provides the opportunity to implement further processing and control like dynamic resource allocation. This advantage is especially important in current and future mobile communications standards such as 5G [29]. In a WDM-RoF, the originating signal is directed to a transmitter unit. The transmitter unit is composed of an RF modulator, a continuous wave (CW) laser, and an MZM. From the transmitter, a multiplexer combines the different wavelengths, and the resulting signal is transmitted through an optical fibre. At the receiver, a demultiplexer separates all the wavelengths and passes the output to the BS. After processing through a photodiode and a filter, the signal is transmitted through a photodiode and a filter, the signal is then transmitted to other stations via antennas [23].

Optical amplifiers are responsible for mitigating the effects of reduced signal quality and power loss in an optical communication network. They perform the function previously done by optoelectronic repeaters. Optical amplifiers, unlike optoelectronic repeaters, can be used at multiple wavelengths. They are also applicable in WDM-configured systems. Additional advantages include enhanced power amplification ability and adaptability to different configurations. However, optical amplifiers do not provide assistance for signal reshaping and timing issues and as such require additional optical components for that purpose. Optical amplifiers also introduce amplified spontaneous emission (ASE) which is undesirable in the network. The process of optical amplification commences after transparency. Transparency describes an occurrence where electron densities at the upper and ground states are equal. Also, at transparency, the net absorption equals net emission. EDFA, SOA, and Raman amplifiers are some of the most commonly used in optical communication systems. An EDFA is made by doping an optical fibre core with Erbium ions (ER^{3+}). EDFAs have wide spectral bandwidth, and high gain, and can be used around the 1550 nm wavelength. Additionally, EDFAs have low noise gain and can be used with many channels in dense WDM systems. However, the use of EDFAs in WDM systems is faced with a non-uniform gain profile and variable amplification across channels. EDFAs achieve amplification by completing a three-level energy process. First, the pump energy excites the ions to a higher energy state, they subsequently decay to a metastable state. This results in either amplification or ASE. The gain of an EDFA depends on the amplification length and pump power. SOAs can be categorized using the reflectivity of the cavity and facet. This gives us the Fabry-Perot amplifier (FPA) and the traveling wave amplifier (TWA). FPAs have facet reflectivity from 0.1-3.2%. They are susceptible to polarization and fluctuations in the bias current. Owing to very low facet reflectivity, gain ripples are eliminated in TWAs. TWAs additionally have a broad spectrum and better noise performance when compared to FPAs. In general, EDFAs are favoured over SOAs due to higher gain, better noise performance, low insertion loss, and stronger immunity to polarization. Raman amplification enables the attainment of gain in the transmission fibre itself through distributed amplification. Raman amplifiers have very linear gain and are thus less liable to saturation and crosstalk between channels at high input powers compared to EDFAs. However, Raman amplifiers experience low power efficiency and safety concerns at high optical powers. They are also associated with additional noises, specifically double Rayleigh backscattering (DRB), and pump-mediated relative intensity noise (RIN) transfer [30, 31].

IV. SYSTEM MODEL

In this section, we present the proposed RoF-WDM model. In the Fig. 3 shows the setup of the hybrid RoF-WDM system with no amplifier. The system comprises three major components: a transmitter, a receiver, and the transmission medium. A pseudo-random bit sequence (PRBS) generator produces a pseudo-random sequence of bits that represent the binary pulses of a consistent pattern. The output feeds the non-return to zero (NRZ) pulse generator. The NRZ generator is used here because it has high dispersion tolerance as compared to the return to zero (RZ) generator [32]. The output of the NRZ generator is fed to the Mach-Zehnder (MZ) modulator subsystem. The amplitude of the optical wave is controlled via the MZ modulator. Two waveguide interferometer arms are created from the input waveguide. The voltage supplied across one of the arms causes a phase change in the wave traveling through that arm. The phase difference between the two waves is translated to an amplitude modulation when the two arms are recombined [33]. The most common optical source in optical communication systems is the laser diode, though, high-power LEDs could also be used [34]. In the Fig. 4, the layout of the transmitter is shown. In the Fig. 5 displays the WDM receiver layout. Optical amplifiers are used to compensate for the attenuation of the optical signal during transmission over long distances in the RoF-WDM communication system. The resulting signal passes through the WDM demultiplexer. The WDM demultiplexer distributes four output signals to four different optical receivers. At each of the receiver terminals, the optical signal is detected by a photodetector PIN. A photodetector PIN is a photodetector with an intrinsic (I) region between the p-region and n-region. In this study, the PIN photodetector is preferred to the avalanche photodetector (APD). This choice is made because a PIN diode emits less noise than a comparative APD diode and requires a higher voltage level for operation. The APD diode is more sensitive than the PIN diode [35]. The optical signals are filtered using a low-pass Bassel filter. Bessel filters have a good sensitivity and linear phase response. Additionally, they have been fine-tuned to have the shortest possible time delay. However, flatness in the pass-band and rate of roll-off is compromised in the process. The cut-off frequency is defined at a point of 3 dB [36]. The transfer function of a low-pass Bessel filter is given by [37].

$$H(s) = \frac{\theta_n(o)}{\theta_n\left(\frac{s}{w_o}\right)} \tag{1}$$

where w_o is the cut-off frequency, $\theta_n(s)$ is a reverse Bessel polynomial. The BER of the electrical signal is calculated and displayed using the BER visualizer. BER is computed as the number of bits received correctly compared to the number of bits transmitted, and it aids in the analysis of the performance of the optical link. Another important parameter used in the analysis of the performance of the optical communication network is the Q-factor. The relationship between BER and Q-factor is given in [38] as

$$BER = \frac{1}{2}\left(\frac{Q}{\sqrt{2}}\right) \tag{2}$$

A function defined for any x(t) by [39] is given as

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_{x}^{\infty} e^{-t^2}\,dt \tag{3}$$

where *erfc* is the complementary error function.

Eq. (2) and Eq. (3) show that the greater the value of the Q-factor, the smaller the BER.

V. COMPARATIVE ANALYSIS OF OPTICAL AMPLIFIERS ON ROF-WDM LINKS

In this section, we evaluate the performance of various optical amplifiers in the RoF-WDM system over long distances. The optical amplifiers considered for this evaluation are EDFA, SOA, and Raman amplifiers. The proposed system is implemented using Optisystem 7.0. Table I lists the parameters used in the simulations.

TABLE I. ROF-WDM SYSTEM PARAMETERS

Parameter	Value
Wavelength (λ)	1550 nm
Bit rate	2.5 Gpbs
WDM bandwidth	10 GHz
Cut-off frequency	7.5×10^9 Hz
Optical fibre length	10 km, 25 km, 60 km
Attenuation	0.2 dB/km
Dispersion	16.75 ps/nm/km

A. *RoF-WDM System over 10 km Optical Fibre Length*

The performance of the RoF-WDM system is simulated over 10 km without an amplifier and with each of the stated amplifiers. In the Fig. 6 shows the RoF-WDM system with an amplifier.

Figs. 7a–7c shows the performance of the RoF-WDM system at 10 km fibre length without an amplifier. Fig. 7a displays the eye diagram, Fig. 7b displays the BER analyzer, and Fig. 7c displays the received power.

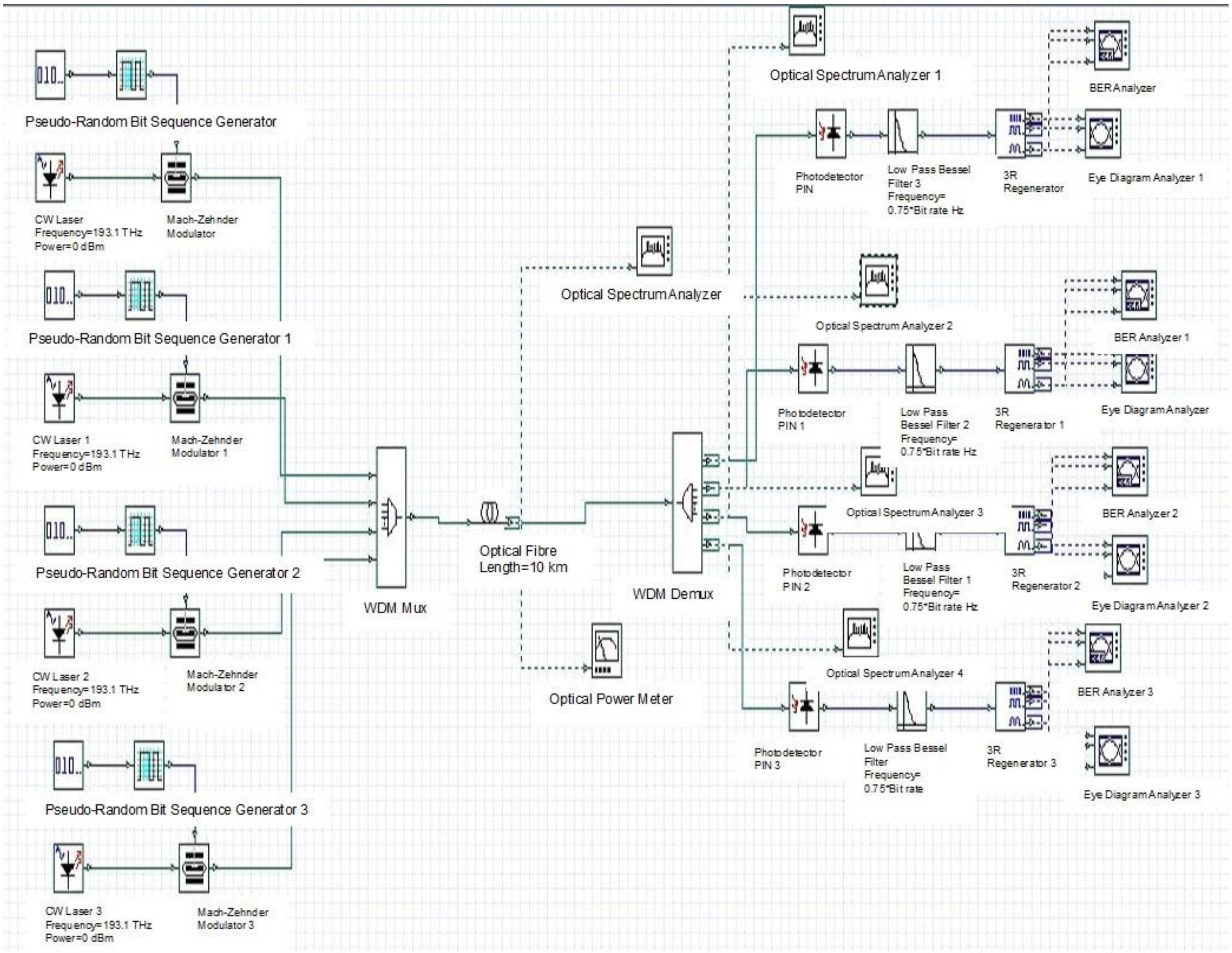

Figure 3. RoF-WDM system without an amplifier.

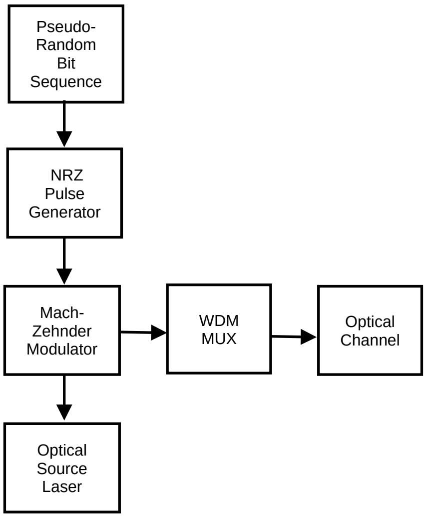

Figure 4. WDM transmitter layout.

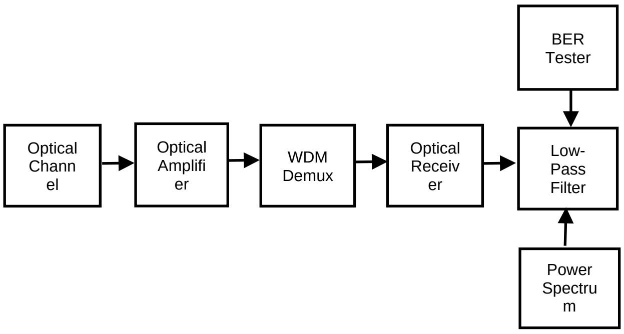

Figure 5. WDM receiver layout.

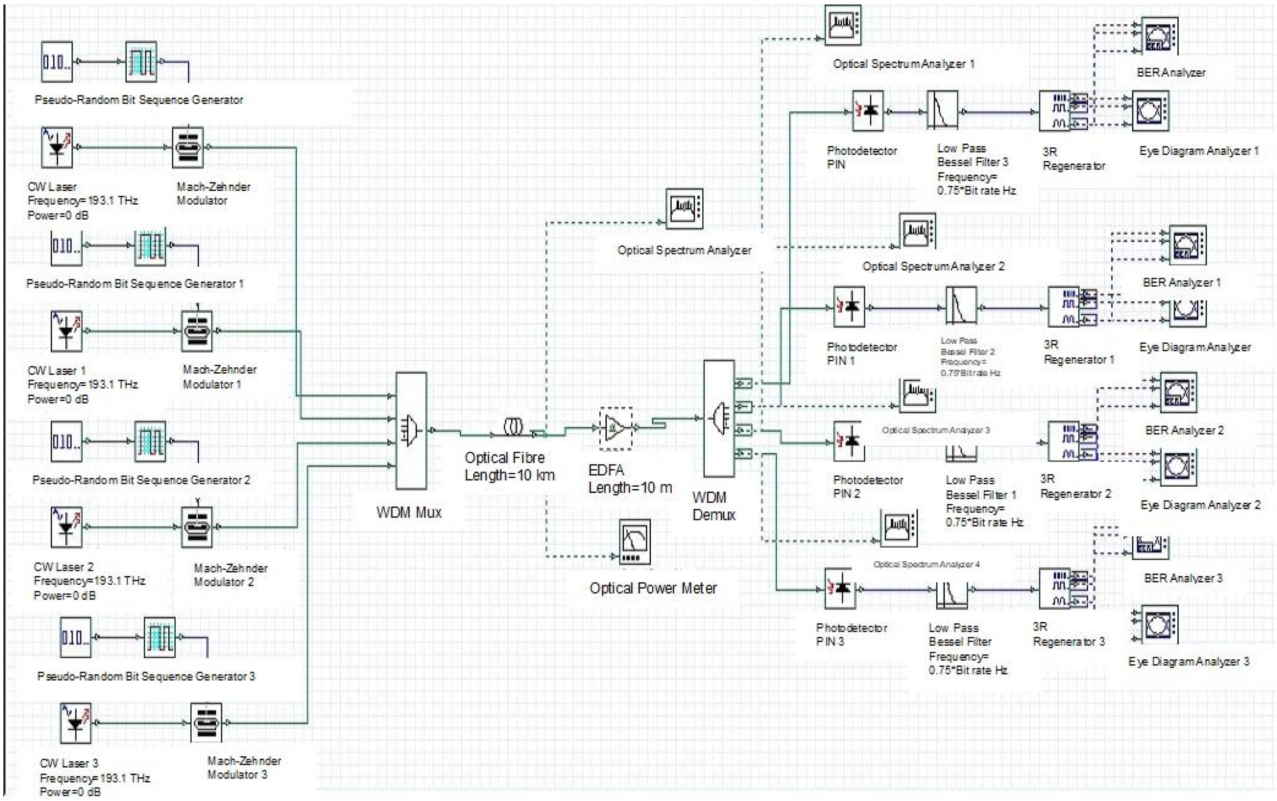

Figure 6. RoF-WDM system with an amplifier.

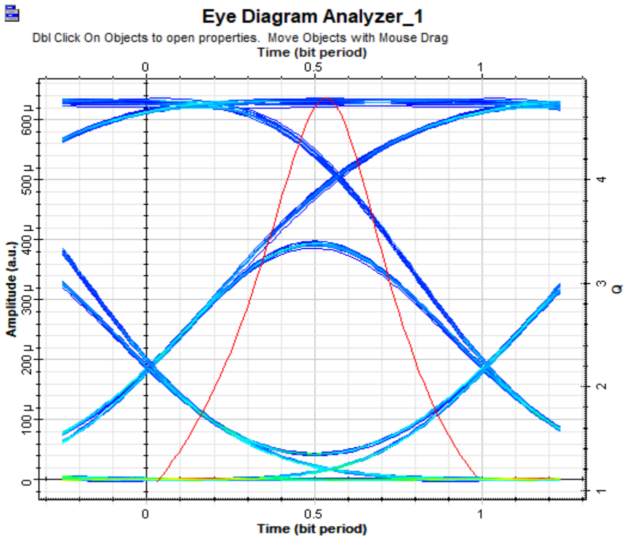

Figure 7a. Eye diagram and Q-factor at 10 km without an amplifier

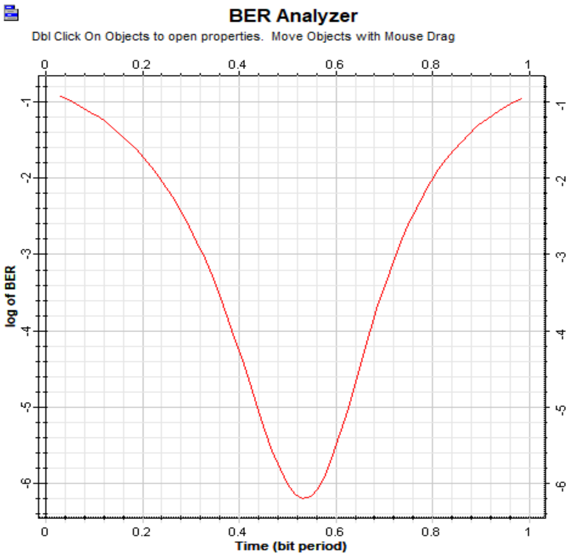

Figure 7b. BER pattern at 10 km without an amplifier.

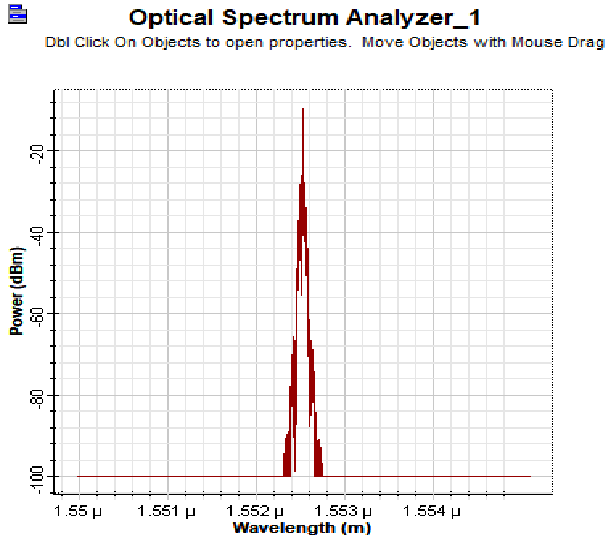

Figure 7c. Receiver power at 10 km without an amplifier.

Figs. 8a–8c displays the performance of the RoF-WDM system at 10 km with EDFA. Fig. 8a displays the eye diagram, Fig. 8b displays the BER analyzer, and Fig. 8c displays the received power.

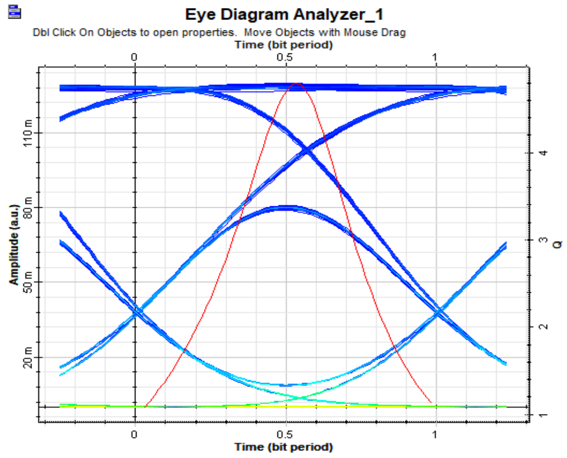

Figure 8a. Eye diagram and Q-factor at 10 km with EDFA

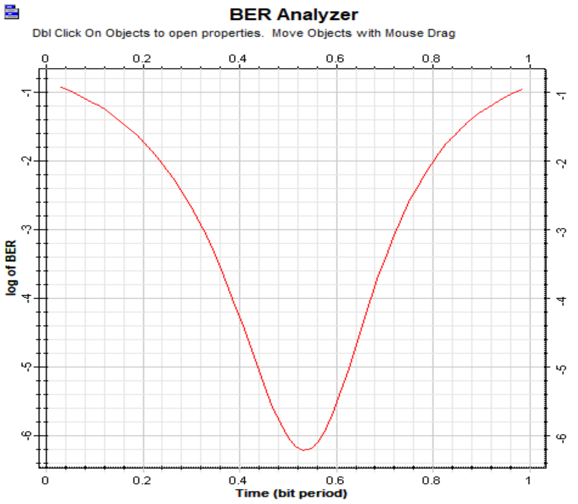

Figure 8b. BER pattern at 10 km with EDFA.

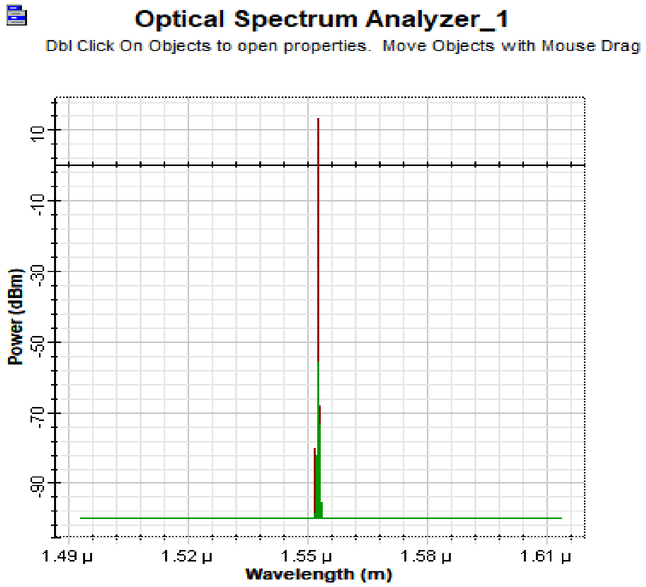

Figure 8c. Receiver power at 10 km with EDFA.

Figs. 9a–9c show the performance of the RoF-WDM system at 10 km with SOA. Fig. 9a displays the eye diagram, Fig. 9b displays the BER analyzer, and Fig. 9c displays the received power.

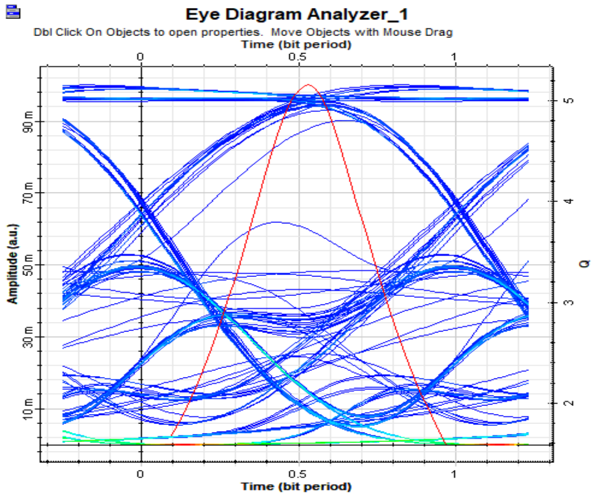

Figure 9a. Eye diagram and Q-factor at 10 km with SOA.

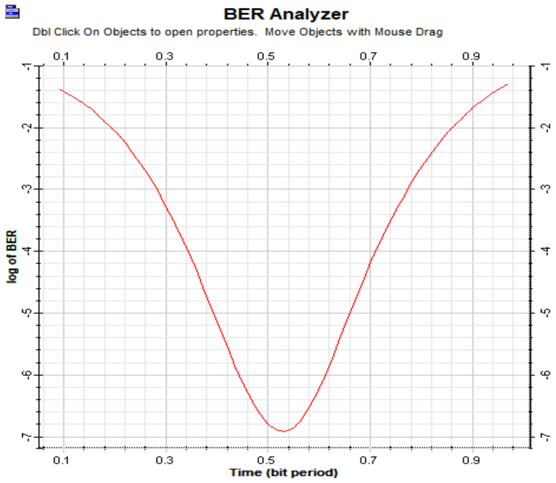

Figure 9b. BER pattern at 10 km with SOA.

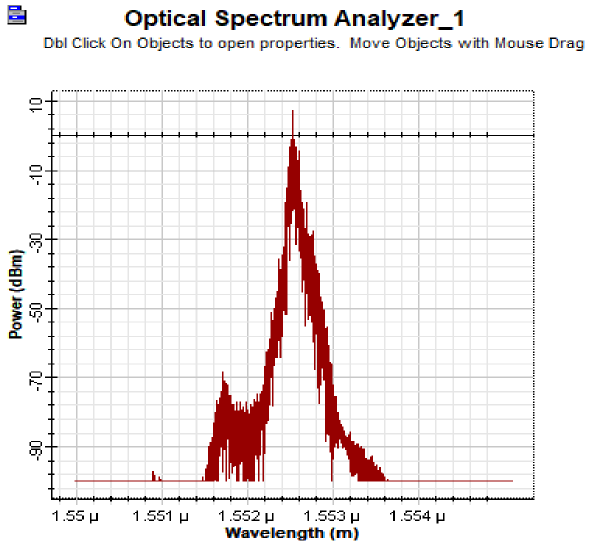

Figure 9c. Receiver power at 10 km with SOA.

Figs. 10a–10c shows the performance of the RoF-WDM system at 10 km with the Raman amplifier. Fig. 10a displays the eye diagram, Fig. 10b displays the BER analyzer, and Fig. 10c displays the received power.

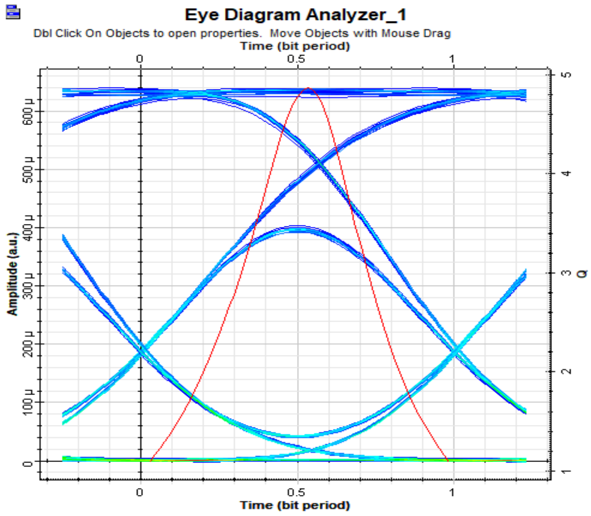

Figure 10a. Eye diagram and Q-factor at 10 km with Raman Amplifier.

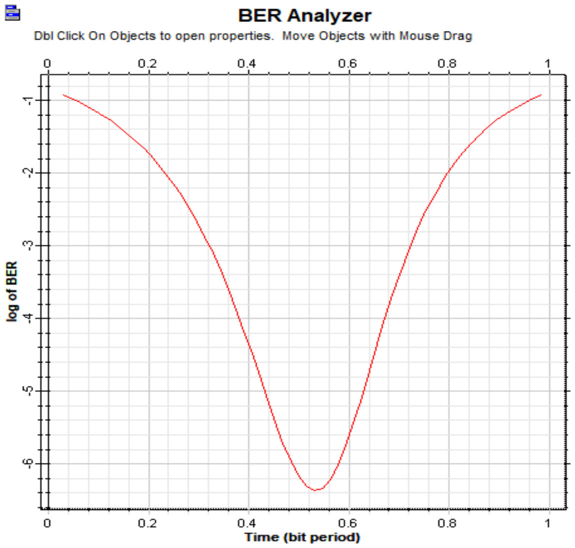

Figure 10b. BER pattern at 10 km with Raman Amplifier.

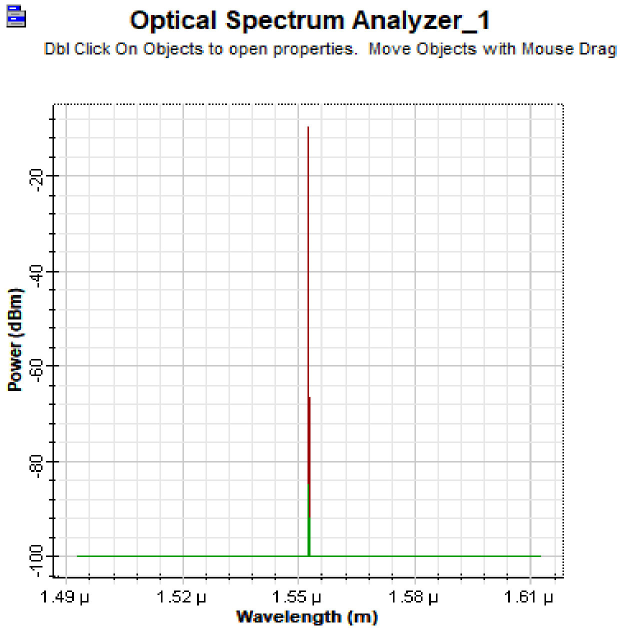

Figure 10c. Receiver power at 10 km with Raman Amplifier.

A summary of the results of the simulations performed with a 10 km fibre length is provided in Table II.

TABLE II. SIMULATION RESULTS FOR 10 KM FIBRE LENGTH

	No Amplifier	**EDFA**	**SOA**	**Raman Amplifier**
Maximum Q factor	4.78616	4.79034	5.15645	4.86219
Minimum BER	6.23911×10^{-7}	6.11311×10^{-7}	1.21666×10^{-7}	4.31724×10^{-7}
Power in dB	–5.0287	19.2128	12.8366	–4.99595

It can be observed from Table II that the RoF-WDM system without an amplifier has received a power of –5.0287 dB, a minimum BER of 6.23911×10^{-7}, and a maximum Q-factor of 4.78616. The EDFA has the best-received power of 19.2128 dB and a minimum BER of 6.11311×10^{-7}. The maximum Q-factor with SOA is 5.15645, and the SOA exhibits the lowest BER at 1.21666 $\times10^{-7}$. The received power achieved with SOA was 12.8366 dB. The configuration with the Raman amplifier has received a power of –4.99595 dB, a minimum BER of 4.31724×10^{-7}, and a maximum Q-factor of 4.86219.

B. RoF-WDM System over 25 km Optical Fibre Length

Figs. 11–13 show the performance of the RoF-WDM system at 25 km fibre length with EDFA, SOA, and Raman amplifiers respectively. Figs. 11a–11c shows the performance of the RoF-WDM system at 25 km with EDFA. Fig. 11a displays the eye diagram, Fig. 11b displays the BER analyzer, and Fig. 11c displays the received power.

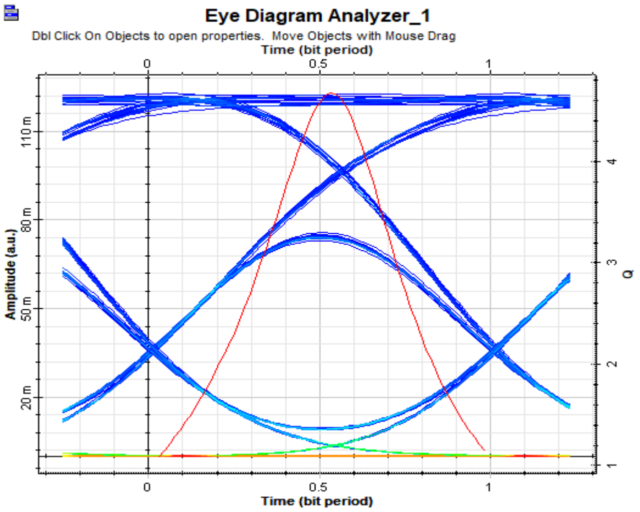

Figure 11a. Eye diagram and Q-factor at 25 km with EDFA.

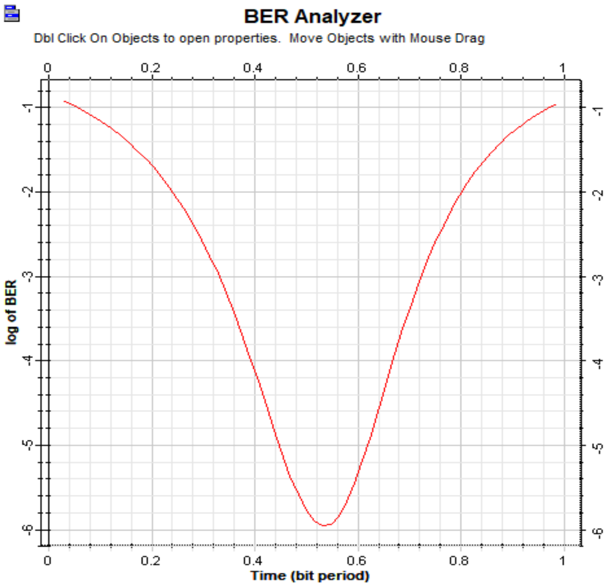

Figure 11b. BER pattern at 25 km with EDFA.

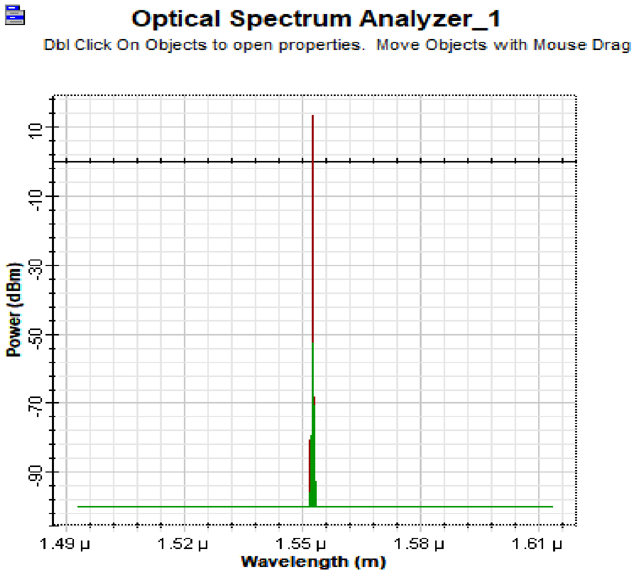

Figure 11c. Receiver power at 25 km with EDFA.

Figs. 12a–12c show the performance of the RoF-WDM system at 25 Km with SOA. Fig. 12a displays the eye diagram, Fig. 12b displays the BER analyzer, and Fig. 12c displays the received power.

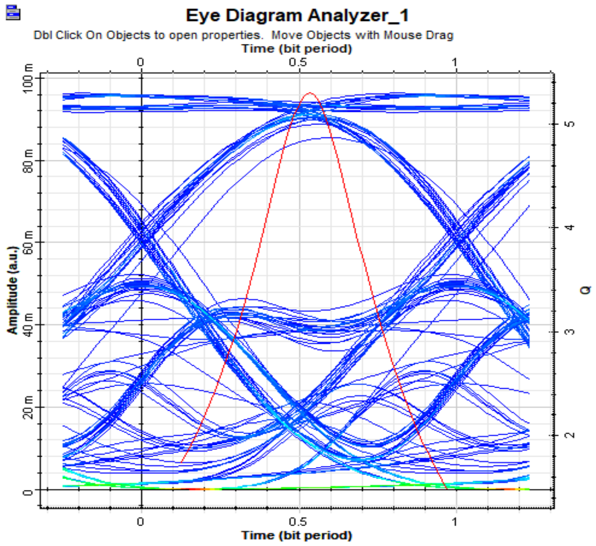

Figure 12a. Eye diagram and Q-factor at 25 km with SOA.

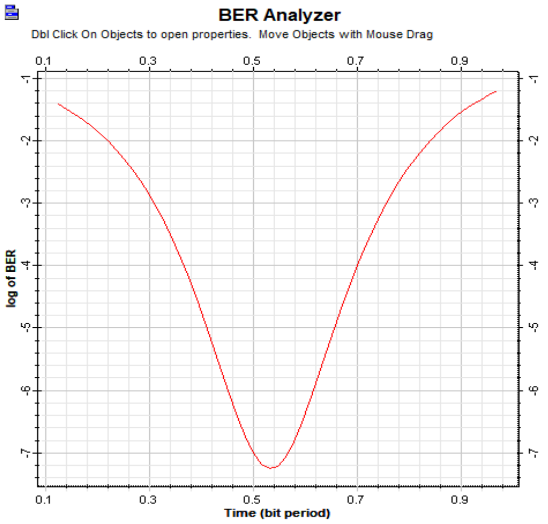

Figure 12b. BER pattern at 25 km with SOA.

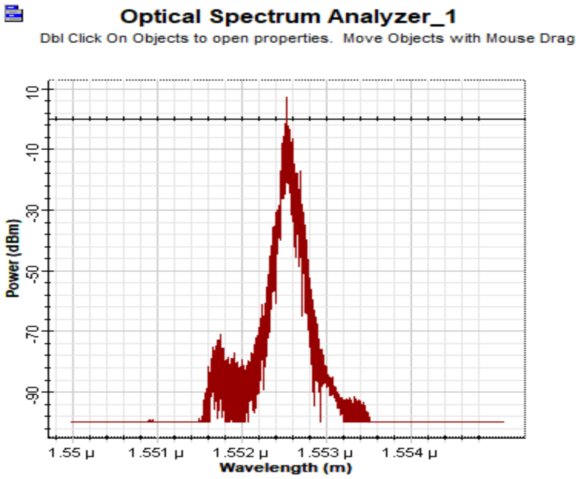

Figure 12c. Receiver power at 25 km with SOA.

Figs. 13a–13c show the performance of the RoF-WDM system at 25 km with the Raman amplifier. Fig. 13a displays the eye diagram, Fig. 13b displays the BER analyzer, and Fig. 13c displays the received power.

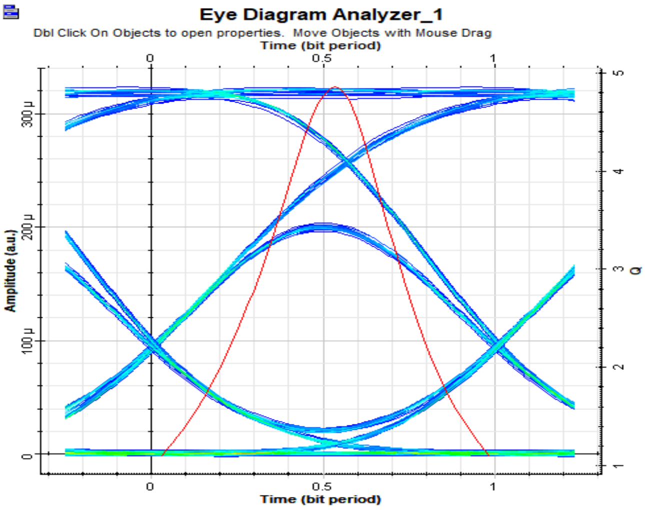

Figure 13a. Eye diagram and Q-factor at 25 km with Raman Amplifier.

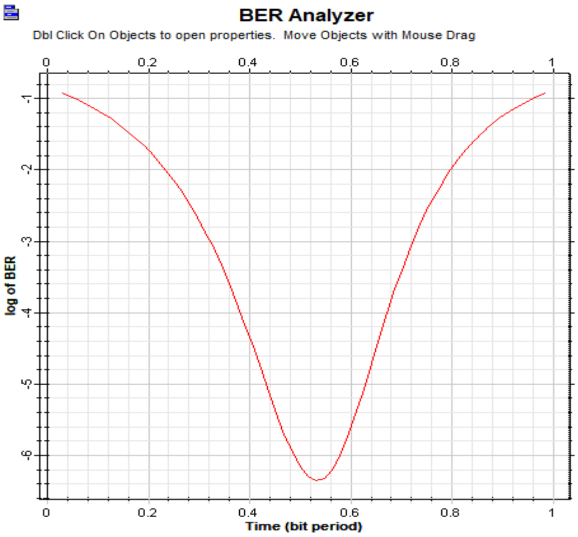

Figure 13b. BER pattern at 25 km with Raman Amplifier.

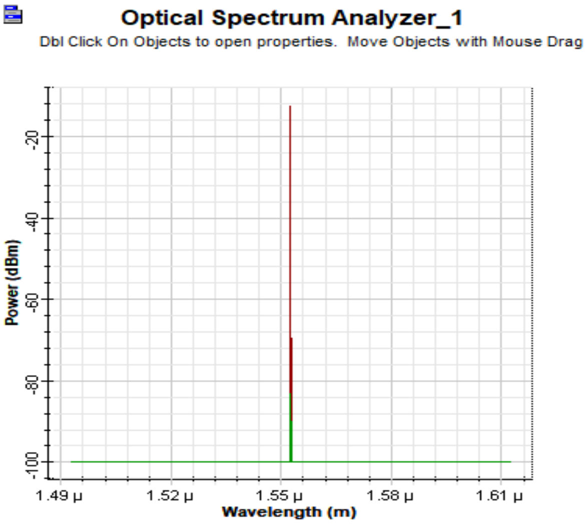

Figure 13c. Receiver power at 25 km with Raman Amplifier.

A summary of the results of the simulations performed with a 25 km fibre length is presented in Table III. From Table II, it can be seen that the RoF-WDM system without an amplifier has received power of -8.1769 dB, a minimum BER of 1.0847×10^{-6}, and a maximum Q-factor of 4.6802. The EDFA has the highest received power of 18.9428 dB, a minimum BER of 1.1197×10^{-6}, and a Q-factor of 4.67268. With SOA, the maximum Q-factor achieved is 5.29662, BER 5.62603×10^{-8}, and received power of 12.7606. The Raman amplifier results in a received power of –8.11746 dB, a minimum BER of 4.44249×10^{-7}, and a maximum Q-factor of 4.85659.

TABLE III. SIMULATION RESULTS FOR 25 KM FIBRE LENGTH

	No Amplifier	**EDFA**	**SOA**	**Raman Amplifier**
Maximum Q factor	4.68023	4.67268	5.29662	4.85659
Minimum BER	1.08466×10^{-6}	1.11973×10^{-6}	5.62603×10^{-8}	4.44349×10^{-7}
Power in dB	–8.17687	18.9428	12.7606	–8.11746

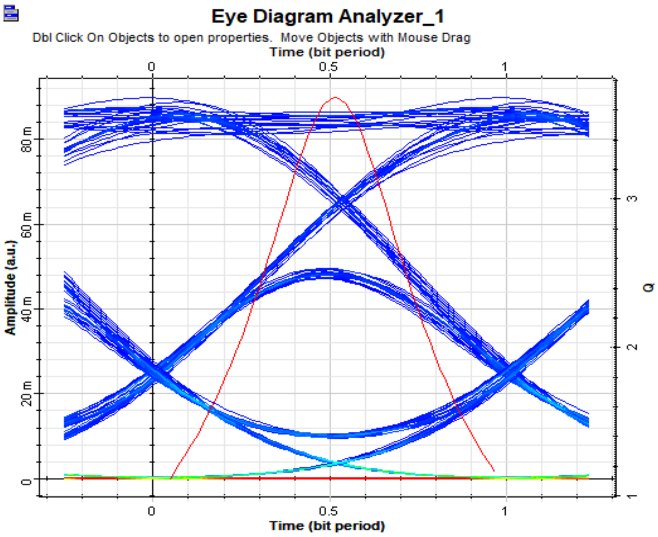

Figure 14a. Eye diagram and Q-factor at 60 km with EDFA.

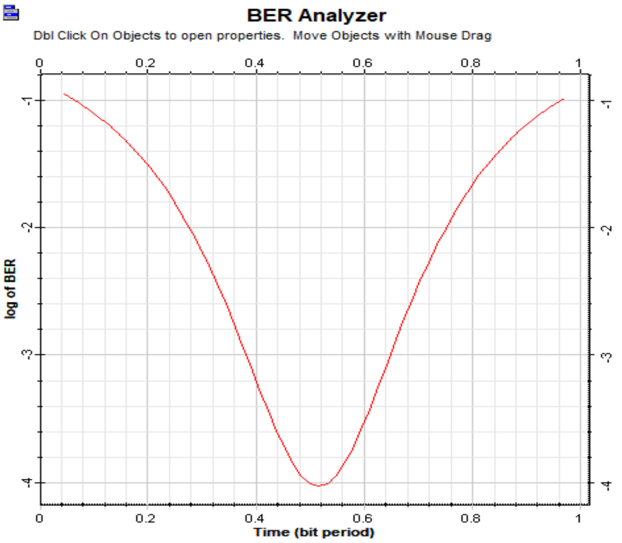

Figure 14b. BER pattern at 60 km with EDFA.

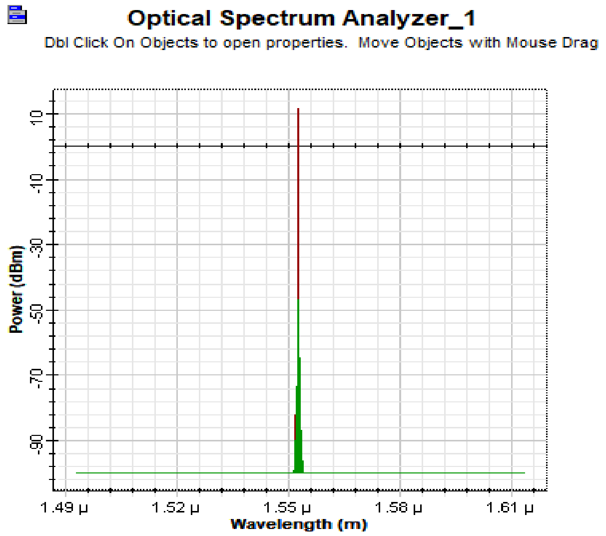

Figure 14c. Receiver power at 60 km with EDFA

C. RoF-WDM System over 60 km Optical Fibre Length

Figs. 14–16 show the performance of the RoF-WDM system at 60 km fibre length with EDFA, SOA, and the Raman amplifier, respectively. Figs. 14a–14c shows the performance of the RoF-WDM system at 60 km with EDFA. Fig. 14a displays the eye diagram, Fig. 14b displays the BER analyzer, and Fig. 14c displays the received power.

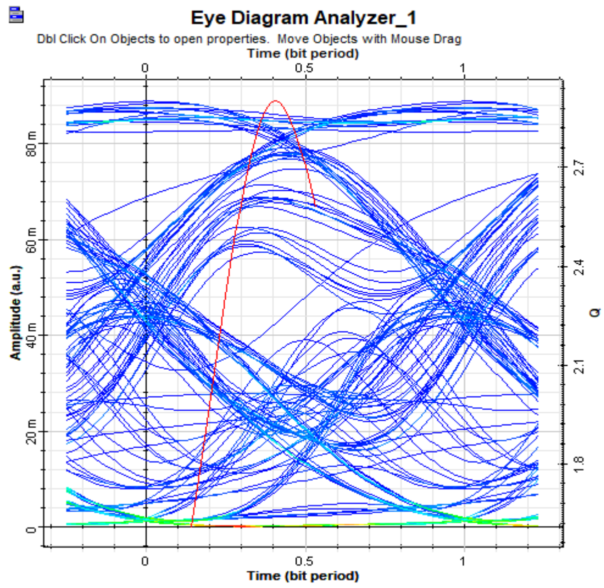

Figure 15a. Eye diagram and Q-factor at 60 km with SOA.

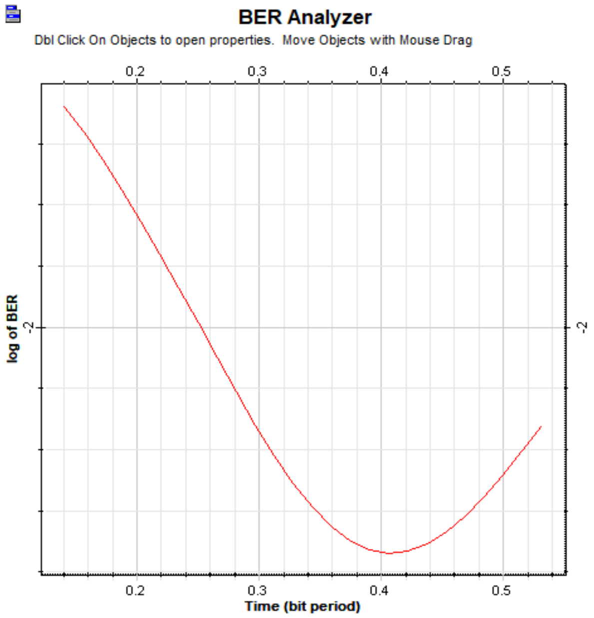

Figure 15b. BER pattern at 60 km with SOA.

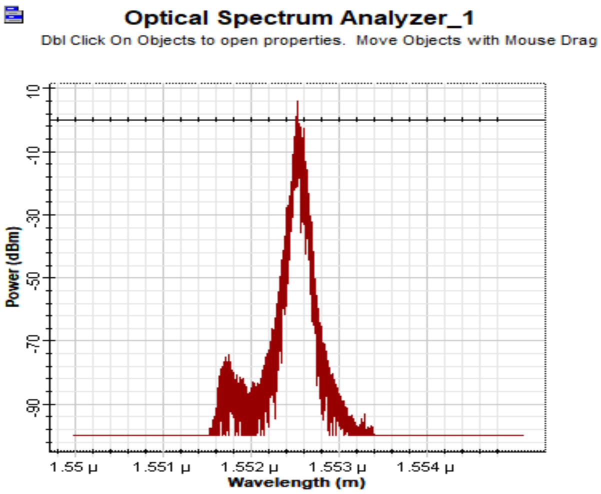

Figure 15c. Receiver power at 60 km with SOA

Figs. 15a–15c show the performance of the RoF-WDM system at 60 km with SOA. Fig. 15a displays the eye diagram, Fig. 15b displays the BER analyzer, and Fig. 15c displays the received power.

Figs. 16a–16c show the performance of the RoF-WDM system at 60 km with the Raman amplifier. Fig. 16a displays the eye diagram, Fig. 16b displays the BER analyzer, and Fig. 16c displays the received power.

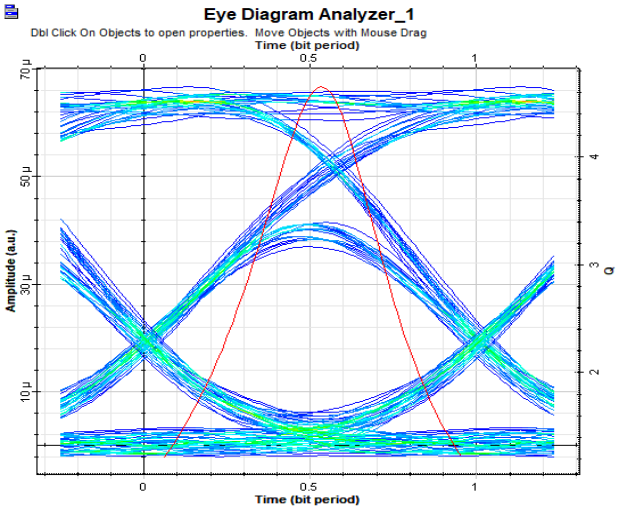

Figure 16a. Eye diagram and Q-factor at 60 km with Raman Amplifier.

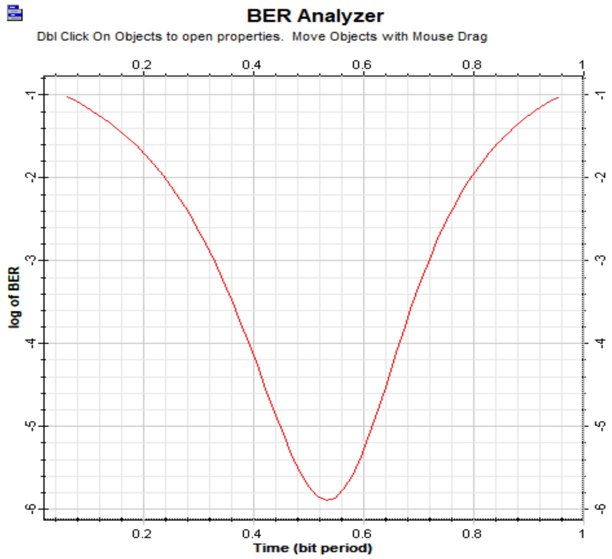

Figure 16b. BER pattern at 60 km with Raman Amplifier.

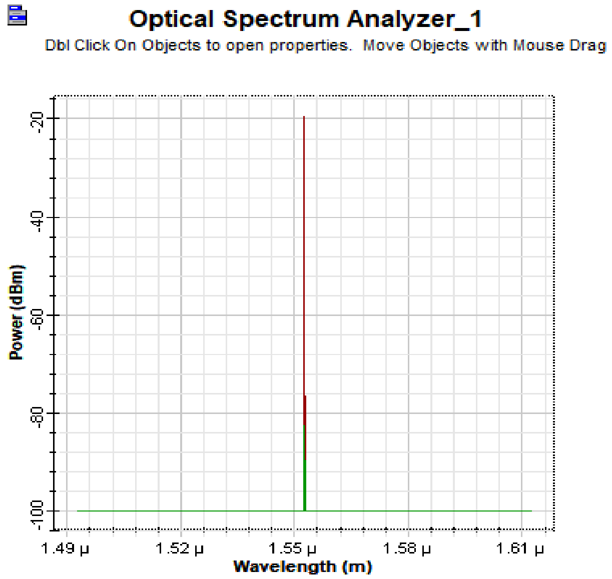

Figure 16c. Receiver power at 60 km with Raman Amplifier.

A summary of the results of the simulations performed with 60 km fibre length appears in Table IV.

TABLE IV. SIMULATION RESULTS FOR 60 KM FIBRE LENGTH

	No Amplifier	**EDFA**	**SOA**	**Raman Amplifier**
Maximum Q factor	35.5357	3.68251	2.90085	4.65117
Minimum BER	15.625×10^{-4}	9.4003×10^{-5}	1.81884×10^{-3}	1.27797×10^{-6}
Power in dB	−1.55242	1.73017	1.14959	−1.54546

It can be observed from Table IV that the RoF-WDM system without an amplifier has received a power of −15.5242 dB, a minimum BER of 15.625×10^{-4}, and a maximum Q-factor of 35.5357. The EDFA has the highest received power with 17.3017 dB. The Raman amplifier has the best BER of 12.7797×10^{-6}. Also, with the Raman amplifier, the best Q-factor of 4.65117 was obtained.

A number of deductions can be made from the performance evaluation results of the RoF-WDM communication system at different destination lengths and employing different amplifiers in the configuration. At the different simulated lengths (10.25, and 60 km) without an amplifier in the setup, it can be seen that there is an increase in power loss, an increase in the minimum BER, and a decline in the Q-factor with increasing destination length. This is to be expected as signal strength tends to weaken as the destination lengths are increased in most optical communication systems owing to noise, nonlinear and polarization effects, chromatic dispersion, and other causes.

Differing results are obtained with different amplifiers (EDFA, SOA, and Raman amplifier) inserted in the RoF-WDM setup. The addition of optical amplifiers in the configuration led to an improvement in all the observed parameters (Q-factor, BER, received power). The EDFA exhibited the best-received power at all the destination lengths considered in the study. The SOA had the best Q-factor and BER performance at the 10 km and 25 km destination lengths. With the Raman amplifier, the received power was almost at par with the no-amplifier configuration. However, at the longest destination length considered (60 km), the Raman amplifier produced the best Q-factor and BER. The results of this study agree with the findings in [19] which indicates that the EDFA improves the received power in an optical communication system. When the results obtained in [20] are compared to the results obtained in this study. The following observations can be made. In [20], the results indicated that BER and Q-factor worsening at increasing destination lengths. The use of EDFAs in the configuration improves the performance of the communication system in respect of these parameters. The results agree with the results of this study. Also, in current study, the authors consider the performance of additional amplifiers, besides EDFAs, in the RoF-WDM communication system.

The different optical amplifiers considered in this study possess unique characteristics that influenced the results obtained. EDFAs have independent polarization and have no crosstalk during the amplification of WDM signals. At longer distances, EDFAs can lead to increased chromatic dispersion. Raman amplifiers are able to complement EDFAs owing to the fact that exhibit good performance (gain) at multiple wavelengths. EDFAs had been limited to operation in the C-band and L-band (1528–1605 nm). Raman amplifiers on the other hand rely on fibre nonlinearities. Multiple pumps can be used at different powers to simultaneously tailor the overall Raman gain shape. Raman amplifiers react instantaneously to pump power, leading to volatile gain showing as crosstalk, especially between the WDM signals. Additionally, EDFAs and SOAs are developed based on the phenomenon of stimulated emission of radiation atoms enhanced by an electromagnetic field. SOAs are thus prone to serious crosstalk, especially in WDM systems. Owing to their higher input coupling loss, SOAs experience a higher noise figure compared to EDFAs. Another factor that explains the performance of SOAs and EDFAs is the lifetime of electrons transitioning between energy states. While the lifetime of an SOA is within the neighborhood of nanoseconds, the spontaneous emission lifetime in an EDFA is about 10 ms. As such, in WDM systems, EDFAs are better suited compared to SOAs [18].

From the discussion above, EDFAs should be selected if the received power is the greatest concern in the RoF-WDM system. However, at longer distances (above 60 km) and with emphasis on Q-factor and BER, then the Raman amplifier is the preferred amplifier in the RoF-WDM system.

VI. CONCLUSION

In this paper, we investigated the performance of an RoF-WDM communication system over long distances (10, 25, and 60 km). The simulation results showed that over long distances, there was a significant power loss, poor BER, and Q-factor. To mitigate the observed poor performance, various optical amplifiers (EDFA, SOA, and Raman amplifier) were introduced in the RoF-WDM setup at different destination lengths. From the simulation results, EDFA produced the best received power for all the selected destination lengths, with up to 17.3017 dB at 60 km length. SOA achieved the best Q-factor and BER performance at 10 km and 25 km destination lengths. The Raman amplifier achieved the best Q-factor and BER at the longest destination length (60 km). It can therefore be said that for RoF-WDM systems over long distances, EDFA and Raman amplifiers are most suitable. A hybrid EDFA-RAMAN amplifier configuration could be investigated in the search for further improvements in the transmission performance of an RoF-WDM system over long distances.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Tagnon P. Okoumassoun conducted the experiments and obtained the results; Anita Antwiwaa analyzed the data and provided the corresponding interpretations; Nana K. Gerrar wrote the paper; all authors worked on the concept, and literature survey and approved the final version.

REFERENCES

[1] T. Umezawa, P. Dat, K. Jitsuno *et al.*, “Radio over FSO communication using high optical alignment robustness 2D-PDA and its optical path switching performance,” *Journal of Lightwave Technology*, vol. 39, no. 6, pp. 5270–5277, 2021.

[2] T. Okoumassoun, A. Antwiwaa, and N. Gerrar, “Free space optics link performance estimation under diverse conditions,” *Journal of Communications*, vol. 17, no. 9, pp. 714–722, 2022.

[3] X. Fernando, *Radio Over Fiber for Wireless Communications*, UK: Wiley, 2014.

[4] R. Essiambre and R. Tkach, “Capacity trends and limits of optical communication networks,” *Proceedings of the IEEE*, vol. 100, no. 5, pp. 1035–1055, 2012.

[5] C. Lim *et. al.*, “Fiber-wireless networks and subsystem technologies,” *Journal of Lightwave Technology*, vol. 28, no. 4, pp. 390–405, 2010.

[6] X. Tong, Z. Jiang, C. Yi, X. Xu *et al.*, “Low-profile, broadband, dual-linearly polarized, and wide-angle millimeter-wave antenna arrays Ka-band 5G applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 10, pp. 2038–2042, 2021.

[7] T. Kuri, A. Kanno, and T. Kawanishi, “Performance evaluation of wavelength division multiplexing radio-over-fibre de-multiplexer in frequency-modulated continuous-wave signal delivery systems,” in *Proc. 2014 International Tropical Meeting on Microwave Photonics (MWP) and the 2014 9th Asia Microwave Photonics Conf.*, Hokkaido, 2014, pp. 218–221.

[8] M. Sung, J. Kim, E, Kim, and S. Cho, “RoF-based radio access network for 5G mobile communications systems in 28 GHz millimeter-wave,” *Journal of Lightwave Technology*, 2019.

[9] C. Liu, S. Zhou, Z. Zhao *et al.*, “Ultrastable long-haul fibre-optic radio frequency transfer based on PLL frequency mixing,” in *Proc. 2020 Joint Conf. of the IEEE Int. Freq. Control Symp. and Int. Symp. on Applications of Ferro Electronics (IFCS-ISAF)*, Keyston, 2020.

[10] D. Montero, J. Lopez-Cardona, F. Al-Zubaidi, and P. Lallana, “The role of power-over-fibre in C-RAN fronthauling towards 5G,” in *Proc. 2020 22nd Int. Conf. on Transparent Optical Networks (ICTON)*, Bari, 2020.

[11] K. Muramoto, A. Inoue, and Y. Kokie, “Noise and distortion reduction in OFDM radio-over-fiber link by graded-index plastic optical fiber,” *IEEE Photonics letters*, 2020.

[12] H. Kao, S. Ishimura, K. Tanaka, *et al.*, “End-to-end demonstration of fiber-wireless fronthaul networks using a hybrid multi-IF-over-fiber and radio-over-fibre systems,” *IEEE Photonics Journal*, vol. 13, no. 4, 2021.

[13] P. Haigh, A. Burton, P. Chvojka *et al.*, “Visible light communications: Filter-less wavelength division multiplexing,” in *Proc. 2020 12th Int. Symp. on Communication Systems, Networks and Digital Signal Processing*, Porto, 2020.

[14] H. Nakamura, H. Suzuki, J. Kani, and K. Iwatsuki, “Reliable wide-area wavelength division multiplexing passive optical network accommodating gigabit ethernet and 10-Gb ethernet services,” *Journal of Lightwave Technology*, vol. 24, no. 5, pp. 20145–20151, 2006.

[15] W. Li, A. Chen, T. Li, *et al.*, “Novel digital radio over fibre (DRoF) system with data compression for neutral-host fronthaul applications,” *IEEE Access*, vol. 8, pp. 40680–40691, 2020.

[16] P. Zhu, Y. Yoshida, and K. Kitayama, “Ultra-low-latency, high-fidelity analog-to-digital-compression radio-over fibre (ADX-RoF) for MIMO fronthaul in 5G and beyond,” *Journal of Lightwave Technology*, pp. 1–9, 2020.

[17] S. Singh et. al., “Optimization and simulation of WDM-RoF link,” *International Journal of Scientific and Research Publications*, vol. 2, no. 1, pp. 2250–3153, 2012.

[18] R. Ramaswami, K. Sivarajan, and G. Sasaki, *Optical Networks*, Burlington, USA: Elsevier Science, 2010.

[19] C. Cheng, "Signal processing for optical communication," *IEEE Signal Processing Magazine*, vol. 23, no. 1, pp. 88–96, 2006.

[20] A. Ali and A. Farhood, "Design and performance analysis of WDM schemes for radio over fiber systems with different fiber propagation losses," *Fibers*, vol. 7, no. 3, 2019.

[21] C. Yeh, J. Chen, W. You, and C. Chow, "Hybrid WDM FSO fiber access network with Rayliegh backscattering noise mitigation," *IEEE Access*, vol. 8, pp. 96449–96454, 2020.

[22] G. Pandey, A. Choudhary, and A. Dixit, "Wavelength division multiplexed radio over links for 5G fronthaul networks," *IEEE Journal of Selected Areas in Communications*, 2021.

[23] S. Kumar, S. Sharma, and S. Dahiya, "WDM-based 160Gbps radio over fiber system with applications of dispersion compensation fiber and fiber Bragg grafting," *Frontiers in Physics*, vol. 9, pp. 1–3, 2021.

[24] Chichkov *et al*., "Amplification of GaSb-based diode lasers in an erbium-doped fluoride fiber amplifier," *IEEE Photonics Journal*, vol. 15, no. 1, 2023.

[25] T. Zhao et. al, "Highly Efficient inverse design of semiconductor optical amplifiers based on neural network improved particle swarm optimization algorithm*," IEEE Photonics Journal*, vol. 15, no. 2, 2023.

[26] W. Tomasi, *Advanced Electronics Communication Systems*, 6th ed. London, UK: Pearson, 2016.

[27] Wiley Encyclopedia of Telecommunications, John Wiley and Sons, 2003.

[28] A. Dixit, "Architectures and algorithms for radio-over-fibre networks," *Journal of Optical Communications and Networking*, vol. 10, no. 5, pp. 535–544.

[29] K. Kuroda, "Wavelength-division multiplexed interrogation of FBGs using a distributed-feedback laser array," *IEEE Photonics Technology Letters*, vol. 34, no. 10, pp. 509–512, 2022.

[30] M. Maduka, "Hybrid fibre and free-space optical solutions in optical access networks," Ph.D. thesis, Univ. of Nottingham, 2016.

[31] R. Kjaer, "Raman amplification in optical communication system," Ph.D. thesis, Tech. Univ of Denmark, 2008.

[32] M. Hayee, A. Willner, "NRZ versus RZ IN 10-40 Gbs dispersion-management WDM transmission systems," IEEE Photonics Letters, vol. 11, no. 8, pp. 991-994, 1999.

[33] Comsol. Mach-Zehnder modulator. Available: https://comsol.com/model/mach-zehnder-modulator-15061

[34] J. Mikolajczyk *et. al*., "Analysis of free-space optics development," *Metrology and Measurement Systems*, vol. 24, no. 4, pp. 653–674, 2017.

[35] Electronics 360. PIN vs APD: Different sensitivity, different applications. [Online]. Available: https://electronics360.globalspace.com/article/10397/pin-vs-apd-different-sensitivity-different-applications#:~:text=The%20main%20advantage%20of%20the,requires%20a%20higher%20operating%20voltage

[36] P. Sharma and H. Sarangal, "Simulation and analysis of filters using different photodiode and wavelength in free space optics," *Asian Journal of Computer Science and Technology*, vol. 5, no. 1, 2016.

[37] G. Bianchi and R. Sorrentino, *Electronic Filter Simulation and Design*, Boston, USA: McGraw Hill Professional, 2007.

[38] V. Ukagwu, J. Andikara, O. Awodu, and E. Edet, "The significance of Q-factor and signal to noise ratio (SNR) in submarine transmission," vol. 2, no. 33, 2018.

[39] E. Weissten. Erfc, mathworld.wolfram.com. [Online]. Available: https://mathword.wolfran.com/Erfc.html