Raman/EDFA Hybrid System to Enhance the Optical Signal in the Optical Network

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***Abstract*—In this paper, a hybrid optical signal amplification system that includes Raman scattering and Erbium-doped fiber amplifier (EDFA) was simulated to take advantage of the amplification properties of the optical signal transmitted through the optical fiber network that connects the first and third campuses of the University of Mosul. The two types of optical signal amplifiers were studied individually and together, and the effect was observed in each case on the optical signal parameters such as the Q-factor, noise figure, signal-to-noise ratio, and gain. Optisystem ver.7.0 software was used to simulate the proposed system. The results showed that the Raman scattering and EDFA hybrid systems functioned effectively. The output signal power level is higher than the input signal power level that increased from (16 microwatts) to (83 mill watts). For each frequency, the gain is positive and the noise figure is relatively high. Although, this indicates that some noise introduced into the system. The output signal to noise ratio (OSNR) is high (55 dB). Moreover, the system is still able to maintain a high signal-to-noise ratio. The obtained results showed that the Raman scattering and EDFA hybrid system is a worthwhile technique for amplifying optical signals for the optical network connecting the first and third campuses of the University of Mosul.**

***Keywords*—Raman, EDFA, hybrid amplifiers, Optisystem7, Dense Wavelength Division Multiplex (DWDM), booster**

I. INTRODUCTION

In response to the increasing demand of consumers for higher speeds and larger data transfer capacities at the lowest cost and the lowest energy consumption, the need to develop traditional technologies and improve services has emerged [1]. Several methods are used to include wireless techniques such as millimeter wave and non-orthogonal multiple access techniques [2, 3]. Or by using hybrid connection methods to strengthen the signal at the edge of the cells by wireless transmission to several towers and connecting these towers using optical fiber [4, 5]. In addition to all of the above, fiber optic networks are considered one of the best communication technologies that achieve the aspirations of the users [6]. Stimulated emission is the mean principle of optical signal amplifiers that are transmitted during the fiber optic cable [7]. Optical signal amplifiers can deal directly with the signal on its status without the need to convert it into an electrical signal, and this gives the flexibility to deal with higher bit rates when the signal is in its optical form, thus bypassing the obstacle of electrical repeater limiters that cannot deal with high bit rates [8].

Hybrid optical signal amplification technology is considered one of the promising technologies for the future and improving the work of dense wavelength division multiplexing (DWDM) [9]. This hybrid design is used to increase the distance between repeaters furthermore, enhance the bandwidth achieved in EDFA. The Raman amplifier extensively reduces the nonlinear effects of the fiber [9]. In [10], a hybrid fiber optic amplifier (HFA) was studied to propose an optical amplifier in the S + C band, which used a single wavelength pump based on EDFA to achieve gain over the C band and a Raman amplifier over the S-band. The objectives were achieved through an available commercial optical fiber, and the numerical improvements of this system were calculated based on genetic algorithms. The hybrid system can extend the network to a distance of 100 km. In [11], a comparison of optical network performance was presented using different optical amplification systems such as EDFA, Raman, and Semiconductor Optical Amplifiers (SOA) separately. The performance was compared based on transmission distance and scattering with and without nonlinearity. The experiments showed that with a dispersion equal to 2 ps/nm/km and fewer channels. The best results can be obtained in the SOA system. In other words, when the dispersion increases to 10 ps/nm/km, the EDFA system is superior in terms of BER and output power but with a non-uniform spectrum gain. Finally, it was observed that the Raman amplifier gave the best amplification results in the L band with a flat gain due to its ability to reduce the effect of fiber nonlinearity. In [12], a comparison of the gain and noise was adopted of the hybrid amplification system, in addition to the optical signal-to-noise ratio calculated as a function of the signal wavelength. The lowest signal-to-noise ratio was obtained for a Raman amplifier at a wavelength of 1530–1600 nm, −30 dB for the input signal power, and 100mW for the Raman pumping power. Finally, the results showed that the gain flatness of the hybrid EDFA/Raman amplification system is higher than that of EDFA only or Raman only.

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In [13], an EDFA/RFA hybrid fiber amplifier of bridge scheme type with a range of 100 km over C and L bands. Pumping efficiency improved by recycling the remaining pumping power. Both experimental measurements and simulation results were achieved in this study. In [14], the behavior of Raman alone in comparison with different hybrid amplifiers was analyzed and its effect on the optical signal transmitted to long distances in terms of gain, noise form, bit error rate, and quality factor. The results showed that hybrid systems used are better. It gives high gain, less noise, high-quality factor, and a bit of error rate. In [15], improving the gain of the hybrid amplifier by evaluating the performance was proposed of the hybrid system assuming that there are several input channels simultaneously and it was represented using multiple Raman pump lasers and resulted in a significant improvement in the overall gain, ripple and the amount of noise compared to the proposed improvements. In [16], study a novel hybrid optical amplifier was proposed for a dense wavelength division multiplexing system that includes a mixture of Er-Yb doped materials with a multi-pump Raman amplifier for backpropagation. High and flat gain h+−+ has been achieved at wavelengths ranging from 1545 to 1565 nm with low noise effect, low bit error rate, and high-quality factor. By increasing the input power, the ripple gain increases. The application of this proposed amplifier is useful in long-range DWDM applications. In [17], a dense wavelength division multiplexing system was studied with 60 signal channels in the wavelength range of 1529.2–1627.1 nanometers, where wavelengths of laser pumping waves were added to improve the parameters to obtain better results compared to previous work. In [18] comparing several hybrid systems was accomplished to reach the best design that achieves the required results in terms of quality factor, bit error rate, and other optical signal parameters. In [19], a novel design of a broadband hybrid Raman/EDFA amplifier was achieved consisting of several amplification stages with an average gain of 15.4 dB, and a flatness of ±1.7 dB.

This article is organized as follows: after the introduction comes the theoretical background section, followed by the methodology section. Result and discussion represent the fourth section. The last section is conclusions and future work.

II. Theoritical Background

Optical signal losses limit the maximum distance the signal can reach without distortion in long-range optical communication systems. Therefore, optical amplifiers are developed to enhance signal reach to the recipient over long distances [20]. One of the most important types used in this field is the Raman scattering system, as it was used to improve the optical signal transmitted through optical fibers in the optical network that connects the first and third complexes of the University of Mosul, whose characteristics were studied in this research. The principle of Raman light scattering interacts with the type of matter in different ways. Some materials allow light to pass through them. While other materials do not allow the passage of light and reflection or (scattering) occurs as shown in Fig. 1.

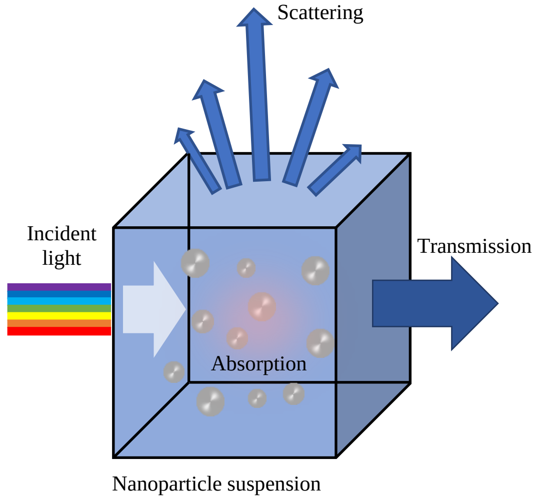

Figure 1. Schematic of light scattering, absorption, and transmission in nanoparticle suspension [21].

A. Scattering

Raman spectroscopy is an analytical technique where scattered light is used to measure the vibrational energy modes of a sample [22, 23]. Different types of scattering are shown in Fig. 2.

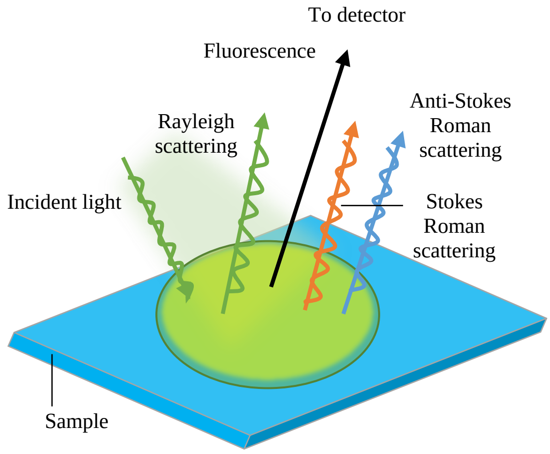

Figure 2. Types of scattering [24].

- Rayleigh Scattering

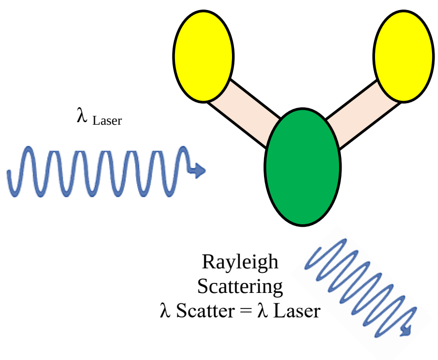

Figure 3. Rayleigh scattering [24].

A water molecule is used to clarify this case, where laser beams are shone at a specific wavelength. So, the rays scatter through the water, and the outgoing wave is the same length as the incident wave, and this is called Rayleigh Scattering, and it is the vast majority of scattered signals shown in Fig. 3 and Eq. (1).

$$\lambda_{\text{Scatter}} = \lambda_{\text{Laser}} \quad (1)$$

- Stokes Raman Scattering

It is the lowest part of the resulting signals, and it is of two types. The first type is the resulting wave with a wavelength greater than the incident laser wave that means a lower frequency. Therefore, less energy (electron. volt) than the original incident wave, as shown in Fig. 4 and Eq. (2).

$$\lambda_{\text{Scatter}} > \lambda_{\text{Laser}} \quad (2)$$

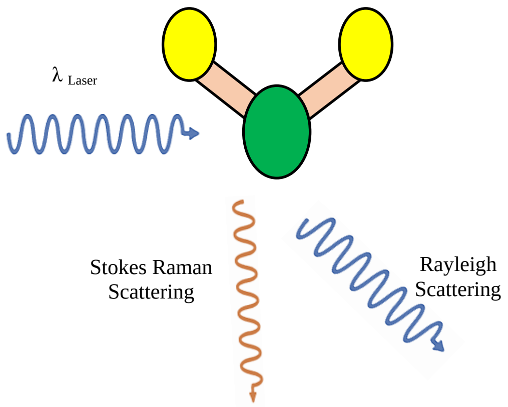

Figure 4. Stokes Raman scattering [23].

- Anti-Stokes Raman Scattering

The second type is the resulting wave with a wavelength less than the incident laser wave, which means a higher frequency. Therefore, higher energy (electron. volt) than the original incident wave, as shown in Fig. 5 and Eq. (3).

$$\lambda_{\text{Scatter}} < \lambda_{\text{Laser}} \quad (3)$$

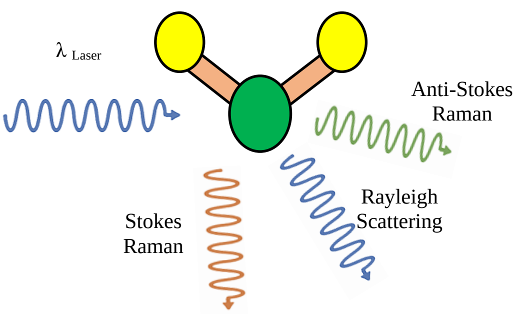

Figure 5. Anti-Stokes Raman scattering [23].

B. *Energy States of the Previous Three Types*

Light waves are classified into ultraviolet or infrared waves according to the energy level, as the longer, the rays are with wavelengths greater than red (>700nm), they are of lower frequency and therefore less energy (e.v) and are placed in the infrared region. The shorter the wavelengths of light than the violet (<400nm), the higher the frequency, and therefore the higher the energy (e.v), and placed in the ultraviolet region. So, the classification of waves based on their energy depends mainly on their wavelengths as shown in Fig. 6.

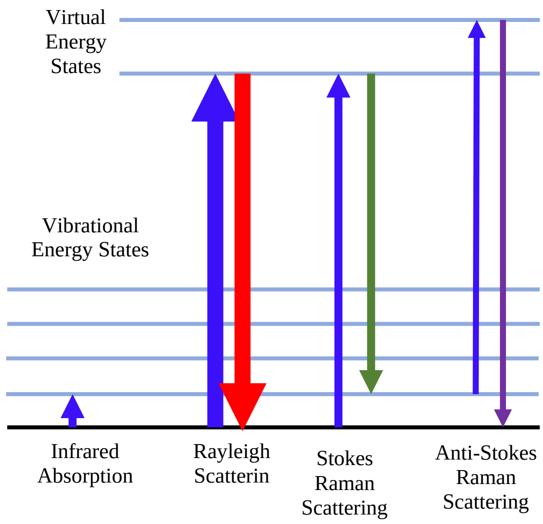

Figure 6. Energy levels [25].

In the case of infrared waves, we expose the electron to a low energy of less than 1.6 electron volts, which does not cause high excitation. When exposed to ultraviolet radiation, energy is higher than 3.5 electron volts. Thus, the electron gets excited and moves to a higher energy level in the conduction band [26]. In the case of Raman, there is an imaginary level of energy that does not exist in reality. Only the electron is excited, ensuring it is not raised to the conduction level. At the same time, it has a field of value that makes the electron vibrate only, and this is called the state of vibration energy [27].

We only excite the electron and take the reaction to it according to the three mentioned cases where we notice the energy of the returning electron after the jump. The first type (Rayleigh) is not utilized because the returning electron energy is the same as the electron energy before the transition. Therefore, the state of the electron must be tracked when it returns with a higher or lower energy of the electron transferred. This is meant by Raman scattering [28]. The difference in energy between the incident photons and the Raman scattered photon is equal to the vibration energy of the scattering molecule. A small part of the light, only one out of approximately ten million photons, is the one that achieves Raman scattering, that is, the scattering of light with a frequency higher (Anti-Stoke) or lower (Stoke). Usually, less than the frequency of the incident photon [29]. Therefore, we note that the discovery of the Indian scientist Raman, although it was achieved in the 1930s and won the Nobel Prize, the Raman device was not produced until after the 1960s when scientific research reached a light source that gives a huge number of photons, which is the laser [24].

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The word "laser" is an acronym for (light amplification by stimulated emission of radiation [8]. Erbium-Doped Fiber Amplifier

C. Erbium-Doped Fiber Amplifier

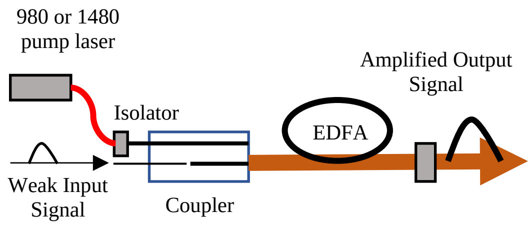

Figure 7. Erbium doped fiber amplifier [30].

EDFA includes three main components of a length of erbium-doped fiber, the laser pump, and the wavelength collector coupler to collect the signals and the pump wavelengths as shown in Fig. 7. The maximum length of the optical fiber depends on the pumping power, the input signal, the amount of erbium-doped, and the pumping wavelength. EDFA is widely used for optical communications due to its high compatibility with optical fibers [31]. EDFA amplifies wavelengths between 1500 and 1600 nanometers. It deals with wavelengths in the L and C bands. This allows the signal to stimulate the excited atoms to release photons [31].

D. Types of Amplifiers

Optical signal amplifiers are classified according to their location in the transmission line into three types: Booster, In-line, and Pre-line as shown in Fig. 8.

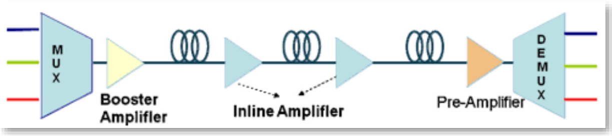

Figure 8. Types of amplifiers [7].

- Booster amplifiers

It includes all amplifiers placed at the beginning of the communication line immediately after the transmitter (TX). In this type, the input signal goes through the amplification stage before being injected into the optical fiber. This enhances the strength of the transmitted signal and makes it extend over longer distances that may reach 100 km [32].

- In-line amplifiers

These amplifiers are placed in locations on the transmission line to compensate for the signal propagation losses and then re-transmit them along the transmission line [33].

- Pre-line amplifiers

It is placed at the end of the transmission line before the receiver, as it improves the received signal before entering the photo-detector. It efficiently improves the sensitivity of the detector [34].

E. Raman Scattering and EDFA Hybrid System

Optical amplifiers are an essential element in long-distance data transmission systems. Various optical signal amplification systems combined in a hybrid system contribute to increasing the data transmission distance with efficiency, capacity, and high quality. Due to the high implementation costs, simulations are the best alternative for evaluating the performance of hybrid optical amplification systems [35].

Hybrid amplifiers are the future of DWDM systems because they provide high gain bandwidth and less noise [36]. A hybrid amplification system offers simultaneous loss and dispersion compensation, but achieving a flat spectrum gain that can be very expensive because it requires pumping at many wavelengths [19, 37].

In this paper, the action of Raman scattering and EDFA was simulated using optisystem7 software, in addition to the hybrid system simulation that combines the two types together to enhance the optical signal transmitted through the optical network that connects the first and third campuses of the University of Mosul to obtain the best signal strength in terms of quality, bit error rate, and other factors.

III. Methodology

Opti-system7 simulation software is a comprehensive program that provides a platform for designing, simulating, and testing optical networks in all their joints [38]. The environment of this program is strong and hierarchical, distinguished from other software environments by covering all components of optical networks [39]. OPTIWAVE SYSTEM INC. is the only company that offers an integrated set of tools to work on optical fiber simulation [40], which includes tools for analyzing results, waveforms, wavelength, energy, noise, spectrum and dispersion of signals, drawing polarity, and any point in this system can be analyzed to find out all its details and provides the feature of change and reactivation to conduct various experiments on the results and notice the difference immediately [41]. Optisystem7 works independently and does not depend on other programs. It depends on the realistic modeling of fiber optic communication systems. The systems can be easily expanded by adding the required components, linking them to the system, and simulating their impact. It has a graphical interface and its own library that can be used to create an integrated optical network and analyze its work [42].

The circuit is simulated in Optisystem7 software using the following steps:

A. The First Step

Adding two arrays of continuous laser (CW) with the operation frequency of (139.1THz) and combine them using an ideal multiplexer, as shown in Fig. 9.

B. The Second Step

Erbium-Doped Fiber Amplifier (EDFA) is a type of optical amplifier that is widely used in optical communication systems to boost the power of optical signals. The basic operation steps of an EDFA are as the following:

- Pumping: The EDFA contains a length of optical fiber doped with erbium ions, and these ions are excited by a high-powered laser, which pumps energy into the erbium ions and raises them to a higher energy level.
- Optical signal injection: The optical signal to be amplified is injected into the erbium-doped fiber. The optical signal can be injected at one end of the fiber optic or through a coupler that allows the optical signal to be coupled into the fiber optic from the side. As the excited erbium ions return to their ground state. They release energy in the form of photons that have the same wavelength as the input signal. These photons travel in the same direction as the input signal and amplify it by adding additional power to the optical signal.
- Output: The amplified signal is then transmitted to the receiver or to the next stage of the optical communication system.

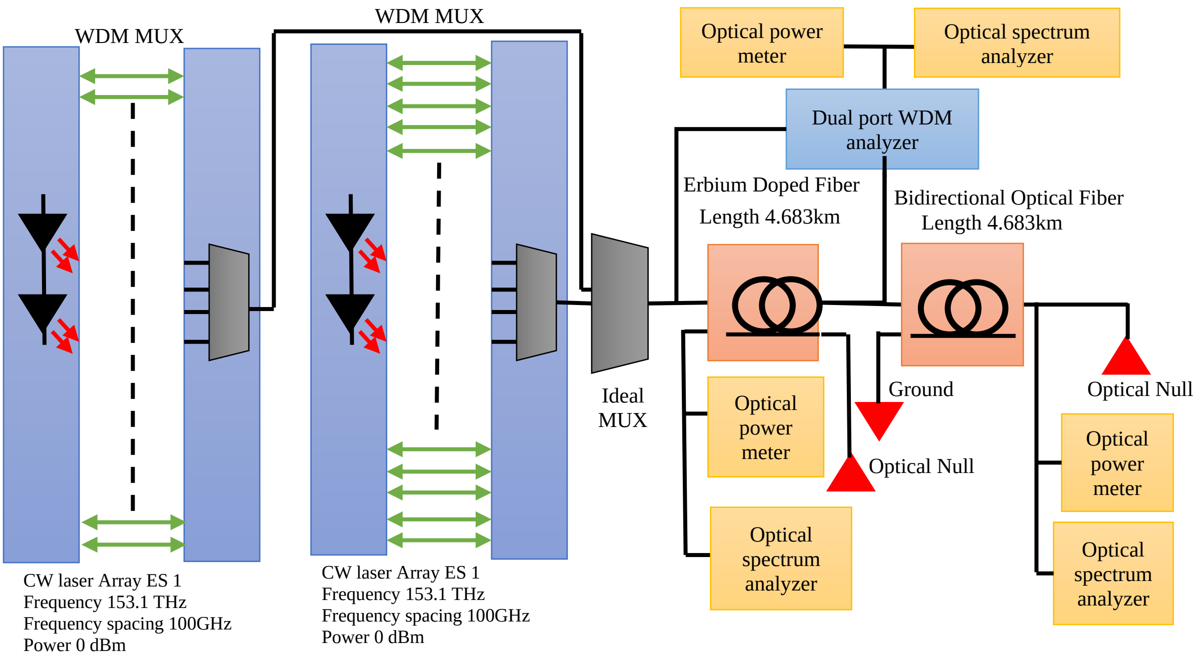

Figure 9. Hybrid system simulation.

C. *The Third Step*

In Raman scattering, the optical signal propagates through the fiber, interacts with the fiber material, and generates scattered photons through the Raman effect. The scattered photons have a longer wavelength than the input signal and travel in the opposite direction to the input signal. The scattered photons generated by the Raman effect travel back toward the input signal and interact with it.

This interaction leads to an additional power transfer from the scattered photons to the input signal, resulting in signal amplification. The circuit of the Raman Amplifier is shown in Fig. 9. After that, connect the input of the Raman scattering component to the output of the fiber span and the output of the Raman scattering component to the EDFA input.

IV. Result and Discussion

The (EDFA) component that is Erbium-Doped Fiber with a length of (5Km) and, optical Null, and the circuit is shown in Fig. 9. In this paper, two optical amplifiers are used. The Raman Amplifier and Erbium-Doped Fiber Amplifier. The results of each stage are shown in Figs. 10, and 11. The results included several factors that showed the proposed design, and these factors are as follows:

- Frequency: The frequency of the optical signal in terahertz.
- Wavelength: The wavelength of the optical signal in nanometers (nm).
- Gain: The gain of the optical amplifier in decibels (dB).
- Noise Figure: The noise figure of the optical amplifier in decibels (dB).
- Input Signal: The power level of the input signal in decibels relative to 1 milliwatt (dBm).
- Input Signal: The power level of the input signal in watts (W).
- Input Noise: The power level of the input noise in decibels relative to 1 milliwatt (dBm).
- Input Noise (W): The power level of the input noise in watts (W).
- Input OSNR: The input optical signal-to-noise ratio (OSNR) in decibels (dB).
- Output Signal: The power level of the output signal in decibels relative to 1 milliwatt (dBm).
- Output Signal: The power level of the output signal in watts (W).
- Output Noise: The power level of the output noise in decibels relative to 1 milliwatt (dBm).
- Output Noise: The power level of the output noise in watts (W).

- Output OSNR: The output optical signal-to-noise ratio (OSNR) in decibels (dB).

A. *Erbium-Doped Fiber Amplifier*

Table I shows the results for this amplifier. Fig. 10 shows Erbium-Doped Fiber Amplifier SNR.

B. *Raman Amplifier Result*

Table II shows the results for this amplifier. Fig. 11 shows Raman amplifier SNR.

TABLE I. RESULTS SAMPLE OF ERBIUM-DOPED FIBER AMPLIFIER

Frequency (THz)	Wavelength (nm)	Gain (dB)	Noise Figure (dB)	Input Signal (dBm)	Input Signal (W)	Input Noise (dBm)	Input Noise (W)	Input OSNR (dB)	Output Signal (dBm)	Output Signal (W)	Output Noise (dBm)	Output Noise (W)	Output OSNR (dB)
193.1	1552.52	4.41723	8.4035	5.42415	0.003487	–100	0	105.42	9.841	0.009641	–45.3728	2.90×10^{-8}	55.2141
193.2	1551.72	4.12775	8.52676	5.38616	0.003456	–100	0	105.38	9.513	0.008941	–45.5461	2.79×10^{-8}	55.06
193.3	1550.92	3.82513	8.82725	5.63073	0.003657	–100	0	105.63	9.455	0.008822	–45.5461	2.79×10^{-8}	55.0019
193.4	1550.12	3.50265	8.96293	5.65065	0.003673	–100	0	105.65	9.153	0.008229	–45.7416	2.67×10^{-8}	54.8949
193.5	1549.32	3.17748	9.11097	5.91339	0.003902	–100	0	105.91	9.090	0.008111	–45.9274	2.55×10^{-8}	55.0182
193.6	1548.51	2.83679	9.24813	5.66201	0.003683	–100	0	105.66	8.498	0.007078	–46.1417	2.43×10^{-8}	54.6406
193.7	1547.72	2.49256	9.40213	2.6386	0.001836	–100	0	102.63	5.131	0.003259	–46.3426	2.32×10^{-8}	51.4737

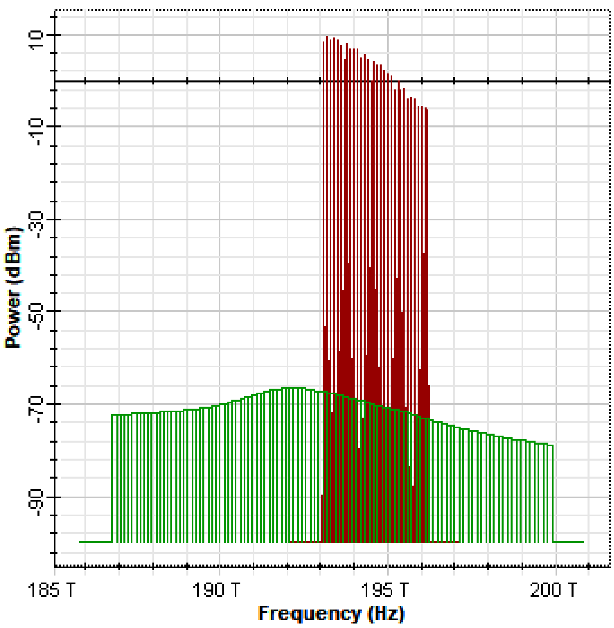

Figure 10. . Erbium-Doped Fiber Amplifier SNR.

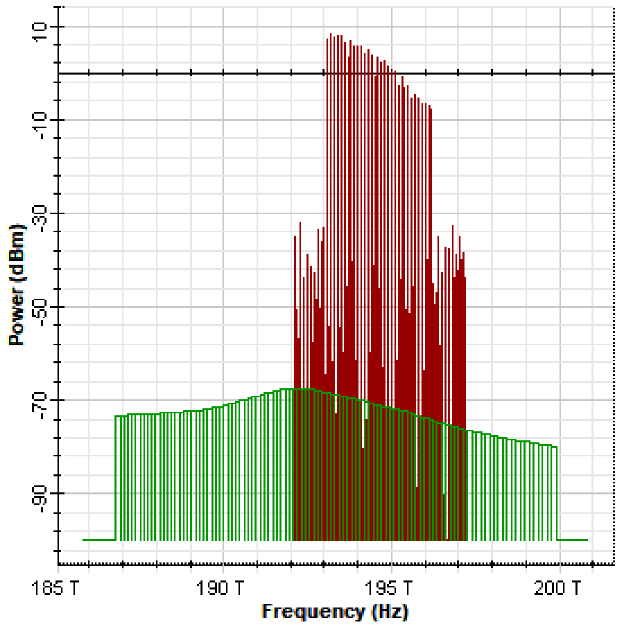

Figure 11. Raman Amplifier SNR.

TABLE II. RESULTS SAMPLE OF ERBIUM-DOPED FIBER AMPLIFIER

Frequency (THz)	Wavelength (nm)	Gain (dB)	Noise Figure (dB)	Input Signal (dBm)	Input Signal (W)	Input Noise (dBm)	Input Noise (E-08W)	Input OSNR (dB)	Output Signal (dBm)	Output Signal (W)	Output Noise (dBm)	Output Noise (W)	Output OSNR (dB)
193.1	1552.52	-1.0454	1.652	9.8413	0.009641	-45.37	2.90	55.2141	8.79591	0.00757	-46.3728	2.31×10^{-8}	55.16
193.2	1551.72	-1.0101	1.148	9.5139	0.008941	-45.54	2.79	55.06	8.50374	0.00708	-46.5461	2.22×10^{-8}	55.08
193.3	1550.92	-0.981	0.720	9.4558	0.008822	-45.54	2.79	55.0019	8.47416	0.00703	-46.5461	2.22×10^{-8}	55.02
193.4	1550.12	-0.9621	0.428	9.1533	0.008229	-45.74	2.67	54.8949	8.19113	0.00659	-46.7416	2.12×10^{-8}	54.93
193.5	1549.32	-0.9948	0.928	9.0908	0.008111	-45.92	2.55	55.0182	8.09603	0.00645	-46.9274	2.03×10^{-8}	55.02
193.6	1548.51	-1.0003	1.004	8.4988	0.007078	-46.14	2.43	54.6406	7.49847	0.00562	-47.1417	1.93×10^{-8}	54.64
193.7	1547.72	-0.9879	0.846	5.1311	0.003259	-46.34	2.32	51.4737	4.14324	0.00259	-47.3426	1.84×10^{-8}	51.48

C. *Input Power*

Fig. 12 shows the input values for each Input Power, Raman Amplifier Power, and EDFA Power.

Figure 12. Input power, raman amplifier power, EDFA power.

D. *The Result Discussion*

It is important to note that the EDFA requires a continuous supply of pumping energy to maintain its amplification capability. The pumping laser is typically operats at a higher power level than the input signal to ensure that the erbium ions are continuously excited and capable of amplifying the signal. Additionally, the EDFA is designed to maintain the polarization and wavelength characteristics of the input signal, ensuring that the amplified output signal is faithful to the original input signal.

It is important to note that the Raman amplifier can be implemented using either forward or backward pumping. In forward pumping, the pump laser is located at the input end of the fiber, while in backward pumping, the pump laser is located at the output end of the fiber. Forward pumping is typically used in long-haul transmission systems, while backward pumping is used in metro and access networks.

Additionally, the Raman amplifier combination with other types of optical amplifiers, such as the EDFA, to achieve higher levels of signal amplification. The implementation steps for these hybrid amplifiers would involve; the addition of the necessary components and configurations to incorporate the different types of amplifiers.

In general, both Raman amplifiers and EDFAs can achieve high SNR values. However, the SNR of Raman amplifiers is often lower than that of EDFAs, especially at longer distances. This is because Raman amplifiers rely on stimulated Raman scattering to amplify the signal, which is highly dependent on the pump power, and the dispersion properties of the fiber. These factors can introduce additional noise into the received signal, leading to a lower SNR. On the other hand, EDFAs use erbium ions to amplify the signal, which has a more consistent gain profile and lower noise than Raman amplifiers. Therefore, EDFAs are typically favored in long-haul communication systems where high SNR is critical. When collecting signals from Raman amplifiers and EDFAs, the SNR can be affected by various factors. One of the most significant factors is the attenuation of the fiber optic cable. As the signal travels through the fiber, it experiences attenuation due to various sources, including scattering, absorption, and bending losses. This can reduce signal power and increase the noise level, leading to a lower SNR.

Other factors that affect the SNR include dispersion, polarization mode dispersion, and nonlinear effects such as four-wave mixing. Therefore, it is essential to carefully design and optimize the fiber optic system to minimize these effects and maximize the SNR of the amplifier.

V. Conclusions and Future Work

In this work, the Raman scattering and EDFA hybrid system was proposed and simulated using OptiSystem7 software to connect between two sites of the University of Mosul via an optical network. The obtained results show that the Raman scattering and EDFA hybrid system is operating effectively with the output signal power level are higher than the input signal. The gain for each frequency is positive, which indicates that the optical signal is amplified. The noise figure for each frequency is relatively high, which means noise is being introduced into the system. Moreover, it is showed that the output OSNR is high, which indicates that the system is yet able to maintain a high signal-to-noise ratio. Thus, the obtained results suggest that the Raman scattering and EDFA hybrid system is a viable option for amplifying optical signals in a telecommunications network to connect between two campuses of the University of Mosul.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The first researcher presented the introduction, methodology, simulation and preliminary results. Abstract, conclusions, correspondence with the journal, and supervision of the arrangement of the manuscript, the work of the second researcher. General supervision and linguistic audit of the manuscript, the work of the third researcher; all authors had approved the final version.

References

[1] R. Róka, "Simulation of the optical erbium doped fiber amplification for performance analysis," *J. Electr. Eng.*, vol. 72, no. 3, pp. 168–175, 2021.

[2] S. A. Ahmed, S. A. Ayoob, A. O. Al Janaby, "On the performance of multi-user massive MIMO over mmWave channels," in *Proc. 7th International Conference on Contemporary Information Technology and Mathematics*, 2021, pp. 100–105.

[3] R. A. Hussein and S. A. Ayoob, "Performance analysis of NOMA using different types receivers," in *Proc. 2021 4th International Conference on Information and Communications Technology (ICOIACT)*, Yogyakarta, Indonesia, 2021, pp. 131–136, doi: 10.1109/ICOIACT53268.2021.9563918.

[4] R. A. Abed and S. A. Ayoob, "A proposed method to coordinate mmWave beams based on coordinated multi-point in 5G networks," *Journal of Communications*, vol. 17, no. 11, pp. 925–932, 2022.

[5] A. N. Hammodat and S. A. Ayoob, "Studying the effect of increasing capacity using COMP technology in LTE-A networks,"

Journal of Engineering Science and Technology, vol. 16, no. 1, pp. 556–570, 2021.

[6] R. Róka and P. Šalík, "An effective integration of the PM 16-QAM modulation in enhanced metropolitan networks with the EDFA amplification," *J. Electr. Eng.*, vol. 71, no. 5, pp. 317–325, 2020, doi: 10.2478/jee-2020-0043

[7] Sura AL-GBURI, "Enhancement of Hybrid Serial Fiber Amplifier Based On Higher Order Raman Scattering," Postgraduate Thesis, Ankara Yildirim Beyazit University, 2019.

[8] M. H. Ali, A. H. Ali, S. M. Abdulsatar, M. A. Saleh, A. K. Abass, and T. F. Al-Mashhadani, "Pump power optimization for hybrid fiber amplifier utilizing second order stimulated Raman scattering," *Opt. Quantum Electron*., vol. 52, no. 6, 2020, doi: 10.1007/s11082-020-02400-x.

[9] A. Carena, V. Curri, and P. Poggiolini, "On the optimization of hybrid Raman/erbium-doped fiber amplifiers," *IEEE Photonics Technol. Lett*., vol. 13, no. 11, pp. 1170–1172, 2001, doi: 10.1109/68.959353.

[10] A. M. Rocha and R. N. Nogueira, "Flexible single pump hybrid fiber amplifier for the S+C bands," *Opt. Commun.*, vol. 320, pp. 105–108, 2014, doi: 10.1016/j.optcom.2014.01.047.

[11] S. Singh, A. Singh, and R. S. Kaler, "Performance evaluation of EDFA, RAMAN and SOA optical amplifier for WDM systems," *Optik (Stuttg).*, vol. 124, no. 2, pp. 95–101, 2013, doi: 10.1016/j.ijleo.2011.11.043.

[12] O. Mahran, A. E. El-Samahy, M. H. Aly, and M. A. El Hai, "Comparative study of performance of EDFA/Raman hybrid optical amplifier with Raman only amplifier and EDFA only amplifier," *Optoelectron. Adv. Mater. Rapid Commun*., vol. 9, no. 5–6, pp. 575–581, 2015.

[13] H. Y. Hsu, Y. L. Yu, S. K. Liaw, R. Y. Liu, and C. S. Shin, "Theoretical and experimental study of multifunction C+L band hybrid fiber amplifiers," *Opt. Laser Technol*., vol. 56, pp. 307–312, 2014, doi: 10.1016/j.optlastec.2013.09.003.

[14] A. Hassan, A. Aboshosha, and M. El_Mashade, "Analysis of Gain and NF using Raman and hybrid RFA-EDFA," *Analysis*, vol. 4, no. 10, pp. 8482–8487, 2017.

[15] M. M. J. Martini, C. E. S. Castellani, M. J. Pontes, M. R. N. Ribeiro, and H. J. Kalinowski, "Performance comparison for Raman+EDFA and EDFA+Raman hybrid amplifiers using recycled multiple pump lasers for WDM systems," in *Proc. SBMO/IEEE MTT-S Int. Microw. Optoelectron.*, 2015, pp. 1–5, doi: 10.1109/IMOC.2015.7369103.

[16] H. M. Obaid and H. Shahid, "Numerical achievement of high and flat gain using Er-Yb co-doped fiber/Raman hybrid optical amplifier," *Optik (Stuttg).*, vol. 186, pp. 72–83, 2019, doi: 10.1016/j.ijleo.2019.04.089.

[17] H. Afkhami, A. Mowla, N. Granpayeh, and A. R. Hormozi, "Wideband gain flattened hybrid erbium-doped fiber amplifier/fiber raman amplifier," *J. Opt. Soc. Korea*, vol. 14, no. 4, pp. 342–350, 2010, doi: 10.3807/JOSK.2010.14.4.342.

[18] N. Thakral and L. Kumar, "Performance evaluation of different hybrid optical amplifiers for DWDM system," in *Proc. 2016 IEEE Annu. India Conf. INDICON*, 2017, pp. 16–19, doi: 10.1109/INDICON.2016.7838905.

[19] L. Krzczanowicz, I. Phillips, M. A. Iqbal, M. Tan, P. Harper, and W. Forysiak, "Hybrid discrete Raman/EDFA design for broadband optical amplification in metro WDM systems," in *Proc. Int. Conf. Transparent Opt. Networks*, 2017, pp. 3–6, doi: 10.1109/ICTON.2017.8025083.

[20] L. Sirleto and M. A. Ferrara, "Fiber amplifiers and fiber lasers based on stimulated Raman scattering: A review," *Micromachines*, vol. 11, no. 3, 2020, doi: 10.3390/mi11030247.

[21] X. Wang and Y. Cao, "Characterizations of absorption, scattering, and transmission of typical nanoparticles and their suspensions," *J. Ind. Eng. Chem.*, vol. 82, pp. 324–332, 2020, doi: 10.1016/j.jiec.2019.10.030.

[22] A. W. Parker, *Spatially Offset Raman Spectroscopy*, 3rd ed. Elsevier Ltd., 2016. doi: 10.1016/B978-0-12-409547-2.12151-1.

[23] S. Mosca *et al.*, "Spatially offset raman spectroscopy–how deep?" *Anal. Chem.*, vol. 93, no. 17, pp. 6755–6762, 2021, doi: 10.1021/acs.analchem.1c00490.

[24] W. S. Pelouch, "Raman amplification: An enabling technology for long-haul coherent transmission systems," *J. Light. Technol.*, vol. 34, no. 1, pp. 6–19, 2016, doi: 10.1109/JLT.2015.2458771.

[25] L. Sirleto, A. Vergara, and M. A. Ferrara, "Advances in stimulated Raman scattering in nanostructures," *Adv. Opt. Photonics*, vol. 9, no. 1, p. 169, 2017, doi: 10.1364/aop.9.000169.

[26] M. Karpov *et al*., "Raman self-frequency shift of dissipative Kerr Solitons in an optical microresonator," *Phys. Rev. Lett*., vol. 116, no. 10, pp. 1–5, 2016, doi: 10.1103/PhysRevLett.116.103902.

[27] G. Zatryb, P. R. J. Wilson, J. Wojcik, J. Misiewicz, P. Mascher, and A. Podhorodecki, "Raman scattering from confined acoustic phonons of silicon nanocrystals in silicon oxide matrix," *Phys. Rev. B - Condens. Matter Mater. Phys.*, vol. 91, no. 23, pp. 1–11, 2015, doi: 10.1103/PhysRevB.91.235444.

[28] S. Loranger, V. Karpov, G. W. Schinn, and R. Kashyap, "Single-frequency low-threshold linearly polarized DFB Raman fiber lasers," *Opt. Lett.*, vol. 42, no. 19, p. 3864, 2017, doi: 10.1364/ol.42.003864.

[29] A. G. Griffith *et al.*, "Coherent mid-infrared frequency combs in silicon-micro resonators in the presence of Raman effects," *Opt. Express*, vol. 24, no. 12, p. 13044, 2016, doi: 10.1364/oe.24.013044.

[30] S. K. Tiwari, P. A. K. Jaiswal, M. Kumar, and S. S. Singh, "Performance analysis of optical amplifiers for incorporation in optical network," *Int. J. Adv. Technol. Eng. Sci*., vol. 2, no. 10, pp. 238–247, 2014.

[31] C. Kumar, G. Kumar, and R. Goyal, "Optimization of hybrid RAMAN-EDFA-RAMAN optical amplifier for super dense wavelength division multiplexing system," *Indian J. Pure Appl. Phys.*, vol. 59, no. 12, pp. 845–849, 2021, doi: 10.56042/ijpap.v59i12.36950.

[32] K. K. Qureshi, "A continuously tunable booster optical amplifier-based fiber ring laser covering L and extended L bands," *Fiber Integr. Opt*., vol. 39, no. 4, pp. 203–211, 2020, doi: 10.1080/01468030.2020.1829753.

[33] M. M. A. Eid, A. Ibrahim, and A. N. Z. Rashed, "In line and post erbium-doped fiber amplifiers with ideal dispersion compensation fiber Bragg grating for upgrading optical access networks," *J. Opt. Commun*., 2021, doi: 10.1515/joc-2020-0306.

[34] M. Ibrahimi *et al*., "QoT-aware optical amplifier placement in filterless metro networks," *IEEE Commun. Lett*., vol. 25, no. 3, pp. 931–935, 2021, doi: 10.1109/LCOMM.2020.3034736.

[35] M. Bonkalo and R. Roka, "Simulation of the hybrid optical amplification connections for performance analysis," *Lecture Notes in Networks and Systems*, vol. 501, pp. 68-78, July 2022. DOI: https://doi.org/10.1007/978-3-031-09070-7_7.

[36] J. D. Bonilla, "Survey of hybrid Edfa/Raman in C and L bands," *Rev. Ing. Matemáticas y Ciencias la Inf.*, vol. 4, no. 7, pp. 13–24, 2017, doi: 10.21017/rimci.2017.v4.n7.a18.

[37] D. Kaur and G. Singh, "Investigation and analysis of hybrid optical amplifiers under four wave mixing," *International Journal of Creative Research Thoughts*, vol. 6, no. 2, pp. 327–332, 2018.

[38] A. A. Hussien and A. H. Ali, "Comprehensive investigation of coherent optical OFDM-RoF employing 16QAM external modulation for long-haul optical communication system," *Int. J. Electr. Comput. Eng*., vol. 10, no. 3, pp. 2607–2616, 2020, doi: 10.11591/ijece.v10i3.pp2607-2616.

[39] D. A. Kadhim, A. J. Allah Shakir, A. N. Mohammad, and N. F. Mohammad, "System Design and simulation using (OptiSystem 7.0) for performance characterization of the free space optical communication system," *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 3297, pp. 4823–4831, 2007, doi: 10.15680/IJIRSET.2015.0406132.

[40] J. Taylor and S. Tanev, "Photonic simulation software tools for education," *Opt. InfoBase Conf. Pap*., pp. 1–5, 2007, doi: 10.1364/etop.2007.etd1.

[41] S. K. Tiwari, P. A. K. Jaiswal, M. Kumar, and S. S. Singh, "Performance analysis of optical amplifiers for incorporation in optical network," *Int. J. Adv. Technol. Eng. Sci*., vol. 2, no. 10, pp. 238–247, 2014.

[42] J. Zhu, X. Xiao, and Y. Luo, "An experiment teaching method based on the Optisystem simulation platform," in *Proc SPIE*, 2017, p. 198, doi: 10.1117/12.2269886.