Performance Development of Cascaded Guided Light Link: Optimized Er^{3+} Ion Density with MIMO Impacts in S_EDFA for Future Communications

Dr. S. Semmalar[1],
[1]*Asssociate Professor, Manakula Vinayagar Institute of Technology, Puducherry, India.*

Dr. S. Malarkkan[2]
[2] *Principal, Manakula Vinayagar Institute of Technology, Puducherry. India.*

Abstract

The Erbium Doped Fiber Amplifier (EDFA) stands as the most widely utilized fiber amplifier in optical communication networks. To improve the efficacy of these systems, various cascading methods such as Double Series EDFA, Triple Series EDFA, and Quad Series EDFA are implemented alongside different pumping techniques. This study assesses the performance of Double, Triple, and Quad Series EDFAs with various pumping methods with multiple inputs and multiple outputs. The evaluation is performed using Optisystem, taking into account different input power levels, fiber lengths, and pumping powers. The findings reveal that the Triple Series EDFA achieves better output performance than both the Double Series and Quad Series EDFAs.

Keywords: EDFA, Optical Fiber Communications, Cascaded, Series EDFA, QF, Tη, transmission power Efficiency, Noise figure and Gain.

1. Introduction

Fiber amplifiers, particularly the Erbium-Doped Fiber Amplifier (EDFA), represent an important class of optical amplifiers. Unlike regenerators or repeaters, which necessitate optical-electrical-optical (O-E-O) conversion, optical amplifiers amplify the input signal directly without this intermediary step. The EDFA efficiently boosts the incoming signal while maintaining its optical quality. EDFA simulations focus on the signal-to-noise ratio (SNR) equation to minimize gain and decrease noise power [1]. Wavelength-division multiplexing (WDM) systems commonly utilize EDFAs to improve gain [2]. Recently, single-stage EDFAs have been deployed in various setups, including pre-fiber amplifiers, inline fiber amplifiers, and booster fiber amplifiers. Nevertheless, a single EDFA usually has a high noise figure and yields a relatively lower amplified output.

The application of a power-monitoring strategy to ensure continuous control of power channels through its display has notably improved the performance of photonic crystal fibers (PCFs) when utilizing the 1480 nm EDFA, while also lowering the noise figure [3]. The significant pump-to-signal modulation index emphasizes the influence of profound EDFA saturation gain [4]. Different pulse shapes have been used to assess EDFA performance based on essential metrics like power output, Bit Error Rate (BER), and Quality Factor (QF) [6]. Input-output and equalization links have been utilized with EDFAs, successfully decreasing bandwidth demands and data rates [7]. Furthermore, gain degradation is reduced by using adjustable pump power in EDFAs [8].

By utilizing integrated electronics, power consumption is enhanced through the use of longer spans in RAMAN amplifiers and shorter spans in EDFAs. Double-cascaded series EDFAs are employed for various purposes, such as wireless adapters and fiber-based Wi-Fi broadband connections. Fiber optical amplifiers provide moderate gain and a lower noise figure in comparison to a single EDFA. Cascaded fiber amplifiers are divided into two categories: cascaded parallel optical amplifiers and cascaded series optical amplifiers. In the case of the latter, several EDFAs are connected in series to create the cascaded series optical amplifiers.

1.2. Cascaded Pumping

In order to ensure amplification, external photons that can be absorbed by the signal photons are supplied during the pumping phase. Multiple pumping techniques are used instead of single pumping to improve noise performance and increase gain.

Double-pumping sources are widely used to enhance the performance of fiber amplifiers. In this configuration, the optical amplifier is powered by two pump sources, pump source 1 and pump source 2 operating in both forward and reverse orientations. Signal attenuation occurs in the forward direction when the information source and pump source 1 propagate together over a specific distance [8]. This attenuation results in low gain, as the information source absorbs energy from pump source 1.

Conversely, maximum gain and significant noise are produced by the reverse pump source 2, which is supplied in the opposite direction relative to the signal propagation. Additionally, erbium-doped fiber amplifiers (EDFAs), which typically exhibit low gain performance, can achieve improved performance through a four-stage connection with optimized pump power [5].

Cascaded fiber amplifiers have been developed to solve the issues of low amplified optical output power, inadequate gain, and high noise in optical communication systems. These amplifiers increase system performance by increasing power, boosting gain, and lowering noise.

The paper [9] dealt with digital optical communication in saturated EDFA in space communication. The paper [10] discussed about EDFA with different layers of core coupled with bent characteristics. The paper [11] discussed with amplification of l band extended silica EDFA. The paper [12] dealt with doping of different materials glass with erbium, ytterbium, alumino phospo glass structure EDFA. The paper [13] described about coding pulse long distance communication using QPSK. The paper [14] dealt with SMF optical amplification in distributed over analog fiber link. The paper [15] EDFA amplified using four types of core fibers in integrated prototype. The paper [16] described that the EDFA with orbital multiplexed angular momentum amplification mode. The paper [17] discussed about EDFA using C band in 8 channels forward DWDM scheme of pumping with SPM and CPM provided constant speed. The paper [18] described about TDF ASE noise analysis with 1479 to 1555nm wavelength ranges using the simulation method. From the analysis of all the above papers shown that the reduced gain and high performance of noise.

This paper is organized into four sections. Section 2 presents and discusses the proposed work. Section 3 demonstrates the model Simulation details. Finally, the paper concludes in section 4.

2. S_EDFA optical Amplifiers

Series-cascaded optical amplifiers, one of the several cascaded approaches, are made especially to boost the strength of weak input signals compared to other models. Series EDFA can be denoted as S_EDFA. Three primary types of optical amplifiers can be distinguished based on the cascade approach: double series EDFA denoted as 2S_EDFA, triple series EDFA denoted as 3S_EDFA, and quad series EDFA denoted as 4 S_EDFA with four inputs and four outputs called as MIMO technique used in between an optical amplifier link. As illustrated in Fig. A-1, a three-stage series optical amplifier is used in this investigation and its performance is examined. A digital sequence generator produces the four digital input signals used by the system. A Gaussian Optical Pulse Generator, which generates optical pulse signals, is attached to the sequence generator's output. A power combiner, which acts as the transmitter, is then used to combine these several optical pulses.

The transmitted signal is amplified by the series EDFA link, which receives the power combiner's output. After being amplified, the signal is sent to the receiver via the fiber. A power splitter at the receiver splits the signal into several outputs, each of which is routed to its intended location. To determine the best optical communication link for broadband services, privacy, and high signal strength, this work focuses on the cascade configuration of EDFAs. By examining important metrics like gain, noise figure, output power, and quality factor about changes in input power, fiber length, and pump power, it assesses performance. Through an analysis of characteristics like gain, noise figure, output power, and quality factor across several configurations, it is shown that the series-cascaded EDFA produces improved amplifier performance. In particular, cascaded EDFAs with double-, triple-, and quad-series were used in the simulations. Variations in input power (0 dBm, 5 dBm, and 10 dBm), fiber length (20 m, 100 km, and 200 km), and pump power (200 mW to 400 mW) were used to assess performance. Line charts were used to plot the simulation results for comparison. The Triple Series EDFA with quadruple pumping (3S_EDFA-QP), shown in Fig. 1, performs admirably in the suggested paradigm. The three EDFA stages in this arrangement are connected in series, and each stage uses a single reverse pumping at a wavelength of 980 nm. A total of four pumping stages are achieved by varying the pumping power between 200 and 400 mW. Furthermore, another concept that has been suggested uses quad-pumping at a wavelength of 980 nm to connect two stages of EDFA in series with an EYCDFA. As illustrated in Fig. A-2, this arrangement is known as the triple-stage ED-EYCDFA-ED QP.

Two EDFA stages with two stages of 980 nm pumping each link together in sequence to form the 2S_EDFA system. The output, commonly referred to as the channel output, is connected to the receiver in the 3S_EDFA-QP system. A user-configurable digital sequence generator creates the four digital channels that make up the transmitter input. Two Gaussian optical pulses are produced by connecting two of the outputs to a Gaussian pulse generator, and two sequence optical pulses are produced by sending the remaining two outputs to a sequence pulse generator. The transmitter output is created by combining these four light pulses using an optical power combiner. Positioned between the transmitter output and receiver input, the 3S_EDFA-QP functions as a fiber amplifier. A power splitter is used at the receiver to divide the input signal into four parts, which are subsequently processed by optical receivers or avalanche photodiodes (APDs) to restore the signals to their original state.

Optical Transmitter uses the frequency from 193.1THz to 193.4THz, Power input of 1mw (0dBm), Modulation type NRZ model, Bit rate is 1e+010Bps. The channel consists of EFDA and EYCDFA connected with reverse amplification pumping. EDFA uses the erbium ion density 1E+025m^-3 and 3E+025m^-3 values for performance enhancement. EYCDFA uses erbium ion density 5.4E+025m^-3 and ytterbium ion density 6.2E+025m^-3, signal loss 0.1dB/m, and pump loss 0.15dB/m.

Operating in the 980 nm wavelength band, the pump laser is distinguished by its high gain and low loss characteristics. During operation, the pump power fluctuates between 100 mW and 400 mw. The cutoff frequency for the optical receiver is set to 0.75 times the bit rate (in Hz). The photodetector's specifications include a dark current of 10 nA, a responsivity of 1 A/W, and an ionization ratio of 0.9 dB. The low-pass filter is a fourth-order filter with a depth of 100 dB and an insertion loss of 0 dB. Thermal noise fixed as 1E-022 W/Hz. The 2ED or 2S_EDFA and 4S_EDFA-5P configurations are used to compare the performance of the Triple Series EDFA and the Triple Series EDFA and EYCDFA combo. Several combinations of amplifiers have been used to recreate the Triple Series setup. Fig. A-3 shows the Triple Series EDFA with a Raman amplifier that uses four stages of 980 nm pumping. Fig. A-4 displays the Triple Series combination that was simulated using EDFA and SOA. Furthermore, Fig. A-5 shows a simulation of the Triple Series Raman amplifier with eight users managing at various wavelengths.

3. Simulation and Analysis

The simulation models of different combinations of optical amplifiers are shown in Fig. A-1, Fig. A-2, Fig. A-3, fig. A-4, and Fig.A-5 explained in the proposed work. The suggested models, 3S_EDFA-QP and ED-EYCDFA-ED QP perform better than the 2S_EDFA and 4S_EDFA-5P configurations, according to the performance comparison. Using an erbium ion density of 1E+025m^-3, input signal power of 1mw or 0dB, pump power of 400mw, pump wavelength of 980nm, and signal input wavelength of 1550nm. Table 1 compares the performance of several series-cascaded optical amplifiers with an input signal power of 1 mW (0 dB), a pump power of 400 mW, a pump wavelength of 980 nm, and a signal input wavelength of 1550 nm. Gain, noise figure, transmission efficiency, quality factor, and bit error rate (BER) are among the metrics that are evaluated in the comparison.

An optimistic analysis of the same parameters for several cascaded series EDFA setups is shown in Table 2, which has an improved erbium ion density 3E+025m^-3, The outcomes of each sector's simulation are used to produce the results. The simulation relies on a dual-port WDM analyzer, optical spectrum analyzer, optical power meter, and electrical power meter as key components for output measurement and analysis. The ratio of input power from the transmitter output to output power from the channel is known as transmission efficiency (Tη). Because it has a direct effect on the communication system's performance, this statistic is crucial.

Another important metric for assessing the performance of optical amplifiers is the Quality Factor (QF). A higher QF number denotes excellent quality and low power dissipation, indicating the quality of the received signal. In order to provide the best possible optical communication services: To cut down on noise and enhance signal clarity, the Noise Figure (NF) should be kept to a minimum. To guarantee powerful signal amplification, the Gain (G) ought to be increased. Effective and dependable communication is achieved by having a low Bit Error Rate (BER), which denotes few transmission errors.

Table 1. Performance comparison of cascaded S_EDFA concerning Erbium ion density

	Gain (dB)	NF(dB)	Tη	QF	BER
2S_EDFA	32.44	3.67	59.28	3.3	4.7e-04
3SEDFA-QP	36.29	3.17	59.7	4.2	8.04e-005
(ED-EYCDFA-ED)QP	35.78	3.2	57.5	4.1	1.27e-005
4S_EDFA-5P	37.9	1.41	59.5	4.28	9.26e006

Table 2 Performance comparison of cascaded Series EDFA concerning Enhanced Erbium Density (Er^{3+})

	Gain (dB)	NF(dB)	TƞȚ	QF	BER
2S_EDFA	47.22	10.96	56.7	2.38	0.000843
3S_EDFA-QP	**53.37**	**3.82**	**48.65**	**5.2**	**7.76e-008**
(ED-EYCDFA-ED)QP	**53.99**	**5.2**	**46.72**	**3.4**	**1.27e-005**
4S_EDFA-5P	40.52	3	50	3.4	0.00029

Tables 1 and 2 present the performance analysis for Series EDFA with erbium ion density and Series EDFA with improved erbium ion density, respectively. The comparison of output metrics from each type of optical amplifier, including bit error rate, quality factor, transmission efficiency, gain in dB, and noise figure in dB.

Comparison deals with Table 1 and Table 2 provide the highest gain identified in 3EDFA-QP and (ED-EYCDFA-ED) QP and lesser noise figure obtained in 3EDFA-QP. Fig. 6 and Fig.7 show the chart analysis of parameters comparison of various optical amplifiers.

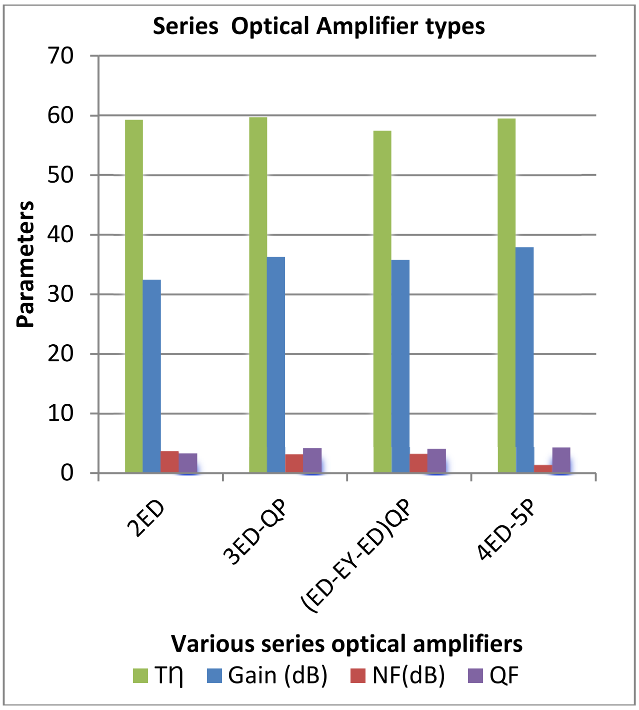

Fig. 6 **. Parameters comparison of cascaded Series EDFA concerning Erbium ion density**

A dual-port WDM analyzer is connected to the transmitter and channel output in order to measure a number of parameters, such as gain, noise figure, OSNR, input noise, output noise, and others. Transmission power efficiency can be determined by the difference between power meter output and power meter input. An optical spectrum analyzer plots the input and output noise after sampling and analyzing the input multiplexed signal. The optical power meter reliably shows the optical power value wherever it is connected. It is connected between the transmitter input and the channel output to measure optical output. Between the optical receiver and the destination, an electrical power meter is utilized to measure the electrical output power. The measurement results from several triple-series optical amplifiers with four pumping stages are shown in Table 3 after the simulation. According to the analysis, the triple-stage EDFA with four pumping stages may sustain eight continuous channels while running at 0 dB (1 mW) of input power and 400 mW of power from an external pumping source.

According to Table 4, the simulation's parameter values were measured, the results were collated, examined, and it was determined that the 3EDFA-QP and two EDFA stages combined in series with EYCDFA used four pumping stages with a maximum wavelength of 400 mw and four channels.

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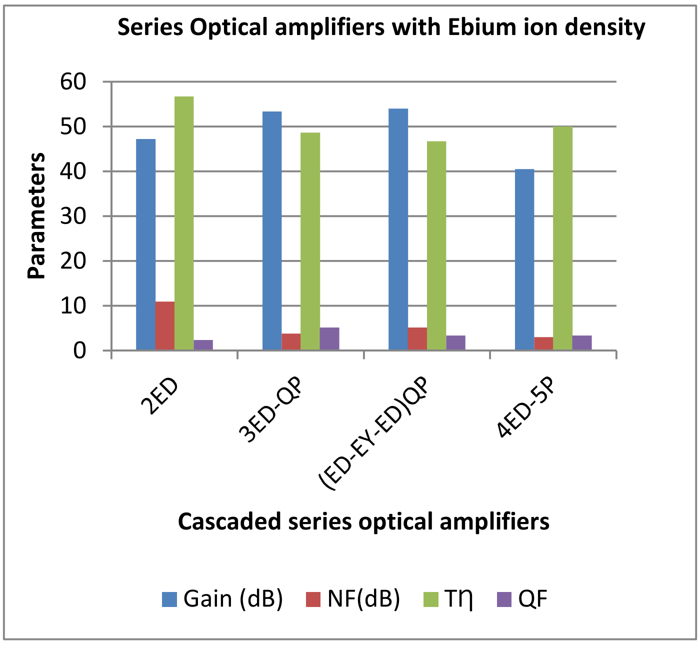

Fig. 7 **. Parameters comparison of cascaded Series EDFA concerning Enhanced Erbium ion density**

Table 3. Amplifiers using 8 channels of source

Triple series (TS) Amplifiers	**8 channels – Optical amplifier with same pump power- 400mw**			
	G (dB)	NF (dB)	OSNR (dB)	Remarks (G)
TS-EDFA-QP	**23.3**	**3.82**	55	**High**
TS-Raman-QP	-5.99	6.16	67	Very low
TS-SOA-QP	3.06	13.7	42	low

Fig 6 and Fig. 7 Show the Parameters comparison of different combinations of optical simulated amplifier results with normal value of erbium ion density and enhanced value of erbium ion density are measured from the output, tabulated, and plotted with a bar chart. Compared to Fig 6, Fig. 7 produced a good comparison with maximum values of gain and reduced noise figures in three stages of optical amplifiers. Table 3 compares the resultant values of different combinations of optical amplifiers with three stages of optical amplifiers using 8 channel sources and Table 4 shows only channel sources of three stages of optical amplifier performance compared in quad pumping stages.

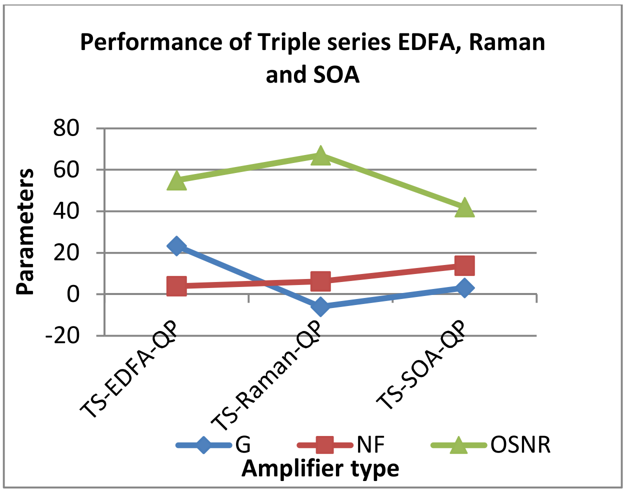

Fig. 8 Amplifiers using 8 channels of performance improvement

Table 4. Performance improvement of optical amplifiers with 4 channels

Triple-series Amplifiers with quad pumping	**4 channels – Optical amplifiers with same pump power = 400mw**			
	G(dB)	NF (dB)	OSNR (dB)	QF(dB)
(ED-RAMAN-ED)QP	30.3	3.15	53	4.85
(ED-SOA-ED)QP	26.3	-0.68	56	6.87
(ED-EYCDFA-ED)QP	**32.63**	**3.11**	**53.6**	**4.85**
3S_EDFA QP	**32.8**	**3.08**	**53.6**	**4.85**

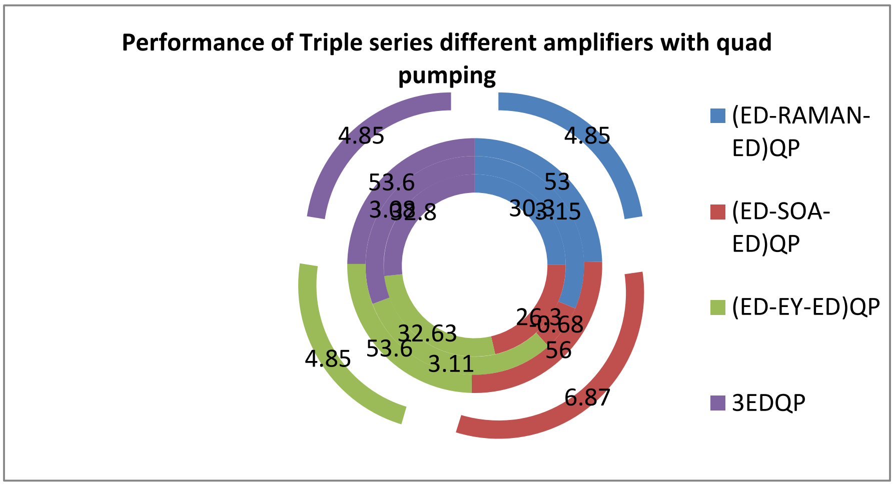

Fig. 9. Comparison of cascaded triple series amplifiers

Fig. 8 and Fig. 9 show the plot of performance of different amplifiers comparison with eight and four channels respectively. To optimize gain and reduce noise in the communication link, three series amplifiers use three pumping source stages, and three optical amplifier types use four pumping source types. In any optical amplifier design, the number of amplifiers determines the necessary pump power. In optical communication systems, obtaining the best gain depends critically on pump power.

4. CONCLUSION

In the final analysis, careful design and setup of optical amplifiers and pumping sources are necessary for optical communication systems to maximize gain and minimize noise. A key factor in improving system performance is the quantity of amplifiers and the associated pump power. Communication systems can achieve high gain, low noise, and efficient transmission by integrating modern optical amplifier types like EDFA and EYCDFA and using series amplifiers with numerous pumping stages with MIMO technique. These developments guarantee enhanced signal quality, dependable data transfer, and compatibility with broadband communication networks with large capacities. The parameters Gain, Noise figure, Transmission efficiency, BER and Quality factor for the different types of cascading optical amplifiers like 2S_EDFA, 3S_EDFA-QP, (ED-EYCDFA-ED) QP and 4S_EDFA-5P simulated, the output values measured, tabulated, analyzed and plotted. The models 3S_EDFA-QP and (ED-EYCDFA-ED) QP produced better results with an enhanced Erbium ion (Er^{3+}) density. A gain of 53.99dB and a noise figure of 5.2dB were obtained and compared to double and Quad EDFA cascaded methods.

Nomenclatures

G	Gain
NF	Noise Figure
OSNR	Optical Signal to Noise Ratio
Tƞ	Transmission Efficiency
QF	Quality Factor

Abbreviations

EDFA	Erbium Doped Fiber Amplifier
EYCDA	Erbium Ytterbium Co Doped Fiber Amplifier
2S_EDFA	Two stages of EDFA
ED-EYCDFA-ED	EDFA connected in series with EYCDFA and EDFA
3 S_EDFA-QP	3 stages of EDFA connected in series with 4 stages of reverse pumping
QP	Quad Pumping

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Appendix A

Simulation models

A. 1. Simulation models of three stages of S-EDFA

The simulation model Shown in Fig. A-1 denotes the three stages of optical amplifiers link.

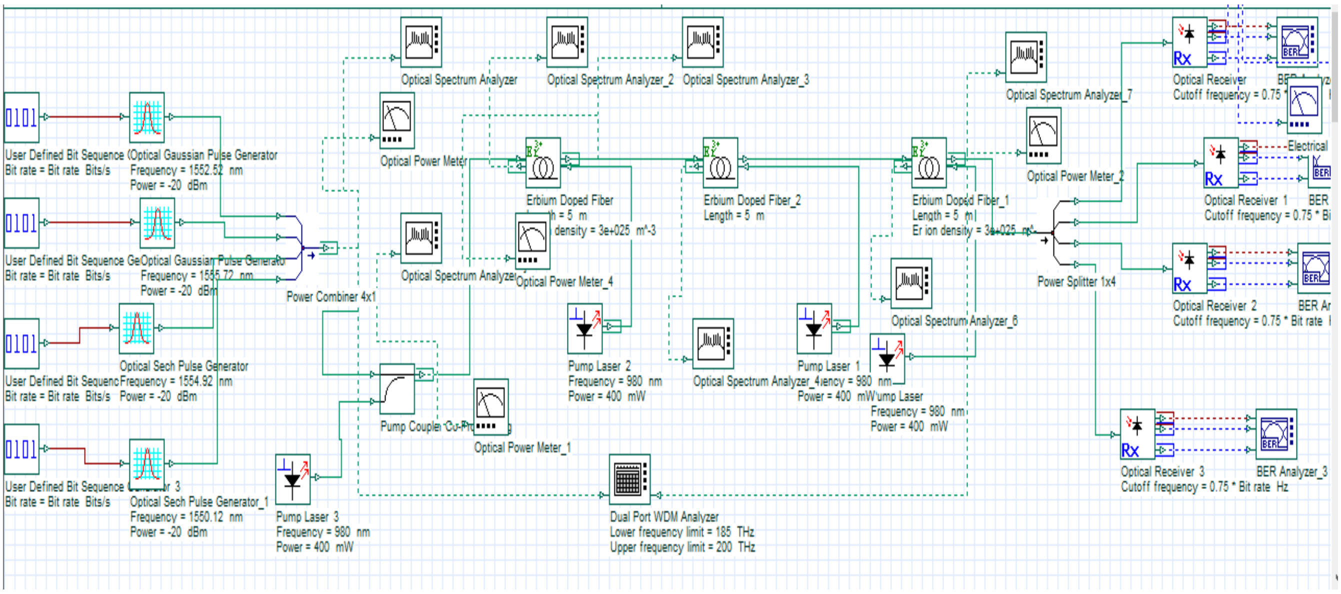

Fig. A-1. Three stages of series EDFA denoted as 3S-EDFA with quadruple pumping of Digital input data.

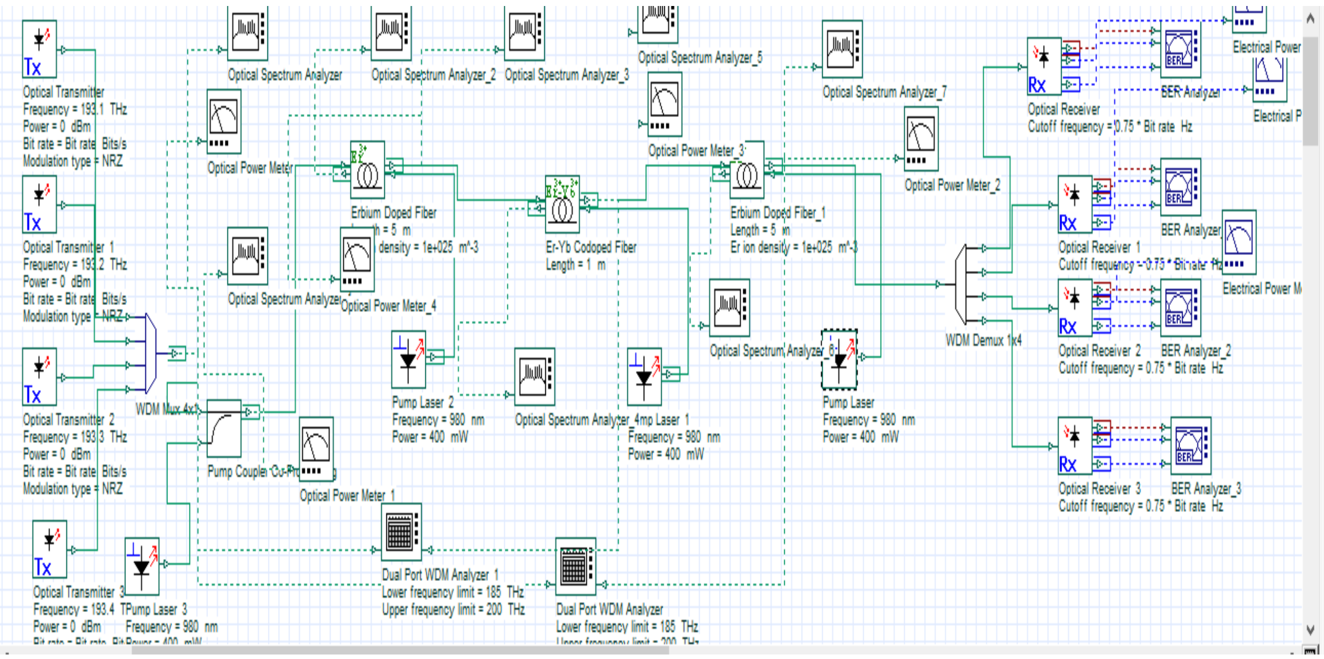

Fig. A-2. Simulation- ED-EYCDFA-ED Amplifier

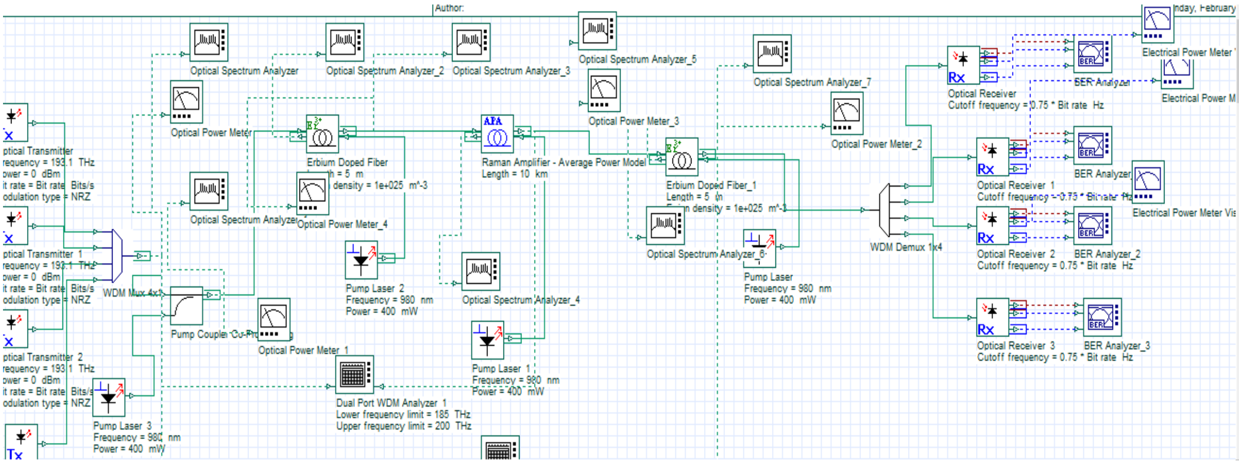

Fig. A-3. Simulation of triple series Optical Amplifiers- EDFA and RAMAN with four stages of pumping

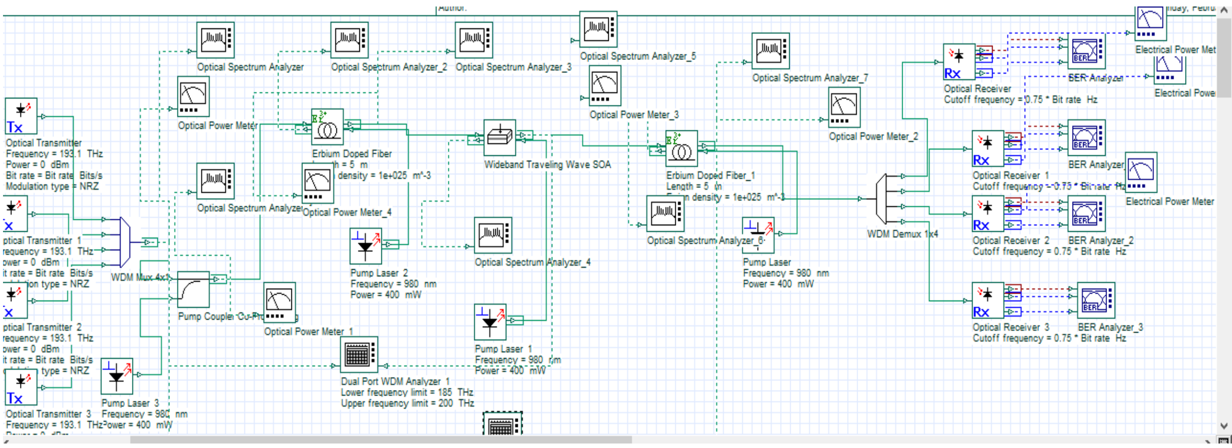

Fig. A-4 . Simulation- Triple series optical amplifiers (EDFA and SOA) using four stages of pumping

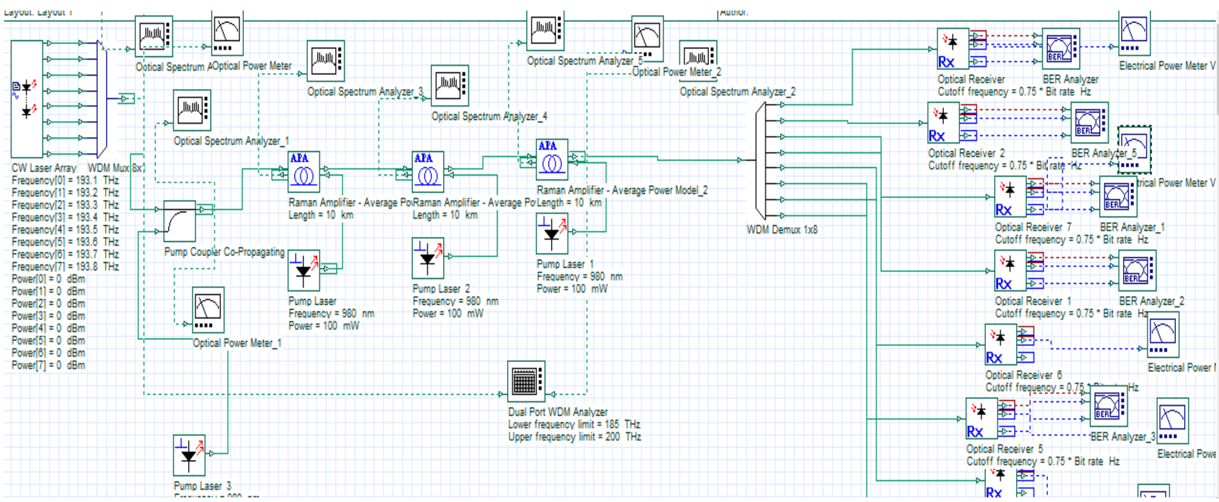

Fig. A-5. Simulation- Series RAMAN Amplifier