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ENHANCEMENT OF HYBRID SERIAL FIBER AMPLIFIER BASED ON HIGHER ORDER RAMAN SCATTERING

M.Sc. Thesis by

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"ENHANCEMENT OF HYBRID SERIAL FIBER AMPLIFIER BASED ON HIGHER ORDER RAMAN SCATTERING"** completed by **SURA AL-GBURI** under the supervision of **DR. ÖĞR. ÜYESI THAMER AL-MASHHADANI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ENHANCEMENT OF HYBRID SERIAL FIBER AMPLIFIER BASED ON HIGHER ORDER RAMAN SCATTERING

ABSTRACT

A broadband serial hybrid fiber amplifier (SHFA) schemes based on second order Raman scattering is demonstrated using OptiSystems 14. Employing of second order Raman scattering can provide an amplification bandwidth and generate a spectrally flat gain enhancement in WDM transmission systems without the need for any gain flatting filters technique. The thesis carries out the design, optimization, and development of a wideband hybrid fiber amplifier covering wavelength of 1524 to 1622 nm. The proposed design combines two gain mediums; Erbium-doped fiber amplifier (EDFA) as linear gain that consist of 3 m EDF with 1480 nm pump power, and the nonlinear gain of Raman fiber amplifier (RFA) which provided by 7 km dispersion compensation fiber (DCF) and two Raman pump units of RP1 and RP2. The performance of the system is analyzed and discussed in term of overall gain level, amplification bandwidth, gain dynamic range, and the noise figure. Wide flat gain bandwidth of 98 nm (1524-1622) that has 19.6 dB gain average is presented at small input signal power of -30 dBm. In addition, relatively low gain variation about 2.71 dB and an acceptable 5.12 dB noise figure are achieved at the same input signal power.

Keywords: Serial hybrid fiber amplifier, flat gain bandwidth, fiber amplifiers, Raman amplifier, wideband hybrid fiber amplifier, optimum pump condition.

İKİNCİ DERECEDEN RAMAN SAÇILMALARINADAYALI SERİ HİBRİT FİBER YÜKSELTEÇ GELİŞTİRILMESI

ÖZ

İkinci dereceden Raman saçılmalarına dayalı bir geniş bant seri hibrid fiber amplifikatör (SHFA) düzenleri OptiSystem 14 kullanılarak gösterilmiştir. İkinci dereceden Raman saçılması , bir amplifikasyon bant genişliği ve herhangi bir kazanç düzleştirme filtreleme tekniğine gerek kalmadan WDM iletim sistemlerinde spektral düz kazanç sağlanmıştır. Bu tez çalışmada, 1524 nm ile 1622 nm dalga boyunu kapsayan geniş bantlı hybrid fiber amplifikatörün tasarımını, optimizasyon ve geliştirilmesi gerçekleştirilmiştir. Önerilen tasarım iki kazanç ortamını birleştirerek; 3 m EDF'den 1480 nm pompa gücüyle oluşan doğrusal kazanç, 7 km dispersiyon kompanzasyonlu fiber (DCF) ile RP1 ve RP2'nin iki Raman pompa birimi tarafından sağlanan Raman fiber yükselteçin (RFA) doğrusal olmayan kazancıdır. Sistemin performansı, genel kazanç seviyesi, yükseltme bant genişliği, kazanç dinamik aralığı ve gürültü faktörü açısından analiz edilmiş ve tartışılmiştir. 19.6 dB kazanç ortalamasına sahip 98 nm (1524-1622) düz kazançlı ve geniş bant genişliği, -30 dBm'lik küçük giriş sinyali gücü için elde edilmiştir. Buna ek olarak, nispeten düşük kazanç dalgalanmasi yaklaşık 2.71 dB ve kabul edilebilir bir 5.12 dB gürültü faktörü aynı giriş sinyalleri için elde edilmiştir.

Anahtar kelimeler: Seri hibrit fiber yükselteç, düz kazanç bant genişliği, fiber yükselteç, Raman yükselteçi, geniş bantlı hibrit fiber yükselteç, optimum pompa şartları.

CONTENTS

NOMENCLATURE

Roman Letter Symbols

g	Gain
g_o	Small Signal Gain Coefficient
p	Signal Power
p_s	Signal power
P_P	Pump Power
g_R	Raman Gain Coefficient
w_P	Angular Frequency of the Pump
w_S	Angular Frequency ofthe Signal
L	Fiber Length
P_{SBS}	Stimulated Brillouin scattering threshold
A_{eff}	Effective Area of the Fiber
g_B	Peak Value of the Brillouin Gain
L_{eff}	Effective Length of the Fiber
G_A	On-off Gain
P_0	Input Pump Power at Z=0
P_{sat}	Saturation Power
P_{ASE}	Amplified spontaneous emission power
B_{opt}	Optical Filter Bandwidth
n_{SP}	Spontaneous Scattering Factor
hv_0	Average Photon Energy
Gav	Average Gain
G_{var}	Gain Variation
G_{max}	Maximum Gain
G_{min}	Minimum Gain
NF_{EDFA}	Erbium Doped Fiber Amplifier Noise Figure
SNR	Signal–to–noise ratios
λ	wavelength
ξ	Takes Values Of ±1
α_S	Attenuation Coefficient of the Signal

Acronym

DCF	Dispersion Compensating Fiber
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EPU	Erbium Pump Unit
HFA	Hybrid Fiber Amplifier
NF	Noise Figure
OPP	Optimum Pump Power
OPW	Optimum Pump Wavelength
OSA	Optical Spectrum Analyzer
S-HFA	Serial Hybrid Fiber Amplifier
P-HFA	Parallel Hybrid Fiber Amplifier
SNR	Signal to Noise Ratio
RFA	Raman Fiber Amplifier
RPU	Raman Pump Unit
SBS	Stimulated Brillouin Scattering
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SRS	Stimulated Raman Scattering
TLS	Tunable Laser Source
WDM	Wavelength Division Multiplexing
CSP-HFA	Combined Serial Parallel Hybrid Fiber Amplifier
S-BAND	Short Band
C-BAND	Conventional Band
L-BAND	Long Band
GE	Germanium
FBG	Fiber Bragg Grating
ASE	Amplified Spontaneous Emission
DRA	Distributed Raman Amplifier
MHZ	Megahertz
GHZ	Gigahertz
THZ	Terahertz
FWM	Four Wave Mixing
DSF	Dispersion Shifted Fiber

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CHAPTER 1

INTRODUCTION

1.1 Background

In the 19th century, the idea of telecommunications emerged and spread widely throughout the world due to the urgent needs to it in all areas. At that time, metal wires made of copper were the means used for many years, as these wires provide high efficiency up to 10 MHz frequencies. In this context, the metal wire is difficult to meet these requirements. So, it is important to find another alternative method with higher properties than metal wire. Recently, low loss optical fiber considered as one of the important solutions to achieve such requirements.

The good specification of the optical fiber such as low loss, wide capacity range and high bit rate made it an inevitable source for high speed optical communication system. Using fiberglass to carry optical communication signal originated with Alexander Graham Bell. However, this idea had to wait some 80 years for better glasses and low-cost electronics for it to become useful in practical situations.The early 1960s, Development of fibers and devices of optical communications began and continue strongly today. But the real alteration came in the 1980s [1]. During this decade optical communication in public communication networks developed from the status of curiosity into being the dominant technology.

There are several inventions and developments that have participated in this advance like the development of low loss optical fiber at the 1970s and the invention of the optical fiber amplifier 1980s. Besides these features, there are various effects limit the transmission performance of the optical communication systems; dispersion, scattering, absorption, non- linear phenomena, etc., that affects the transmitted signal level. In order to avoid all these limitations, regeneration the optical signal is required for long fiber span. Mainly two regeneration types of optoelectronics repeaters and an optical amplifier structure were proposed. Using optoelectronics regeneration repeaters, the input signal should be converted to an electrical signal to be amplified electrically. Then it should be reconverted into an optical signal again.

Using such optoelectronics repeater a drawback was listed such as the complexity for high speed multiple channel system and once it installed for a certain system it is very difficult to upgrade it. Therefore, more attention has been done to improve an optical amplifier system in which the signal is optically amplified directly. Initially conventional Raman fiber amplifier (RFA), erbium doped fiber amplifier (EDFA) and semiconductor optical amplifier (SOA) were used in wavelength division multiplexed (WDM) networks. Each amplifier has its own drawbacks and benefits.

Hybrid fiber amplifiers (HFAs) are an enabling and promising technology for future dense wavelength division multiplexed (DWDM) multi-terabit systems. Hybrid Raman/erbium-doped fiber amplifiers are designed in order to maximize the span length and to enhance the bandwidth of EDFAs. The design of an optimal HFA is a complex problem with several degrees of freedom [2].

1.2 Problem Statement

Optical amplifier systems such as EDFA, RFA and SOA has been reported and developed by many researchers in literature. However, the gain flatness bandwidth was the issue. Mainly the introduced gain with an optical amplifier is depend on or restricted to the energy bands radiation frequencies. Therefore, HFA can achieve wide gain flatness related to the two-energy bands for two amplifier types. Gain flatness can be improved by using various gain flattening techniques (such as filters, DCF, FBG, and so on) but this leads to an expensive system. For a cost-effective solution, we have optimized the various parameters of a hybrid EDF-Raman amplifier using a higher order pumping to attain better gain flatness.

1.3 Research Objective

1. Design and evaluate an efficient serial hybrid fiber amplifier (S-HFA) in the wide band optical communication window (S+ C +L band) utilizing higher order pumping sources.

2. Extend the amplification bandwidth and generate a spectrally flat gain profile.
3. Minimize the number of pump power units used in the system.

1.4 Scope of Research Work

The main goal of this research work is to create an efficient HFA in the S+C+L band communication window that is capable of making a high gain level with a broad amplification bandwidth using higher order pumping source. As shown in Figure 1.1.The research work is divided into three essential categories to obtain that aim: investigation, optimization, and enhancement depend on a single technology and hybrid technology.

The proposed design consist of two amplification stage are combined serially. The first stage is EDFA followed by RFA as a second stage. SHFA is simulated, to investigate the impact of the input design parameters on the performance parameters for the proposed EDFA, RFA and HFA. The investigation focused on the effect of the pump sources in term of power and wavelength on the overall performance parameters of the system. Influence of the pump is appeared through using higher order Raman pumping technique, where two pump units for Raman fiber amplifier were used in the design.

The optimization step is the basic stage in designing this work and evaluating its performance. The optimization focused on finding the optimum values of the pump power and pump wavelength to achieve an optimal performance in terms of high gain level, wide bandwidth, flat gain and low noise figure.

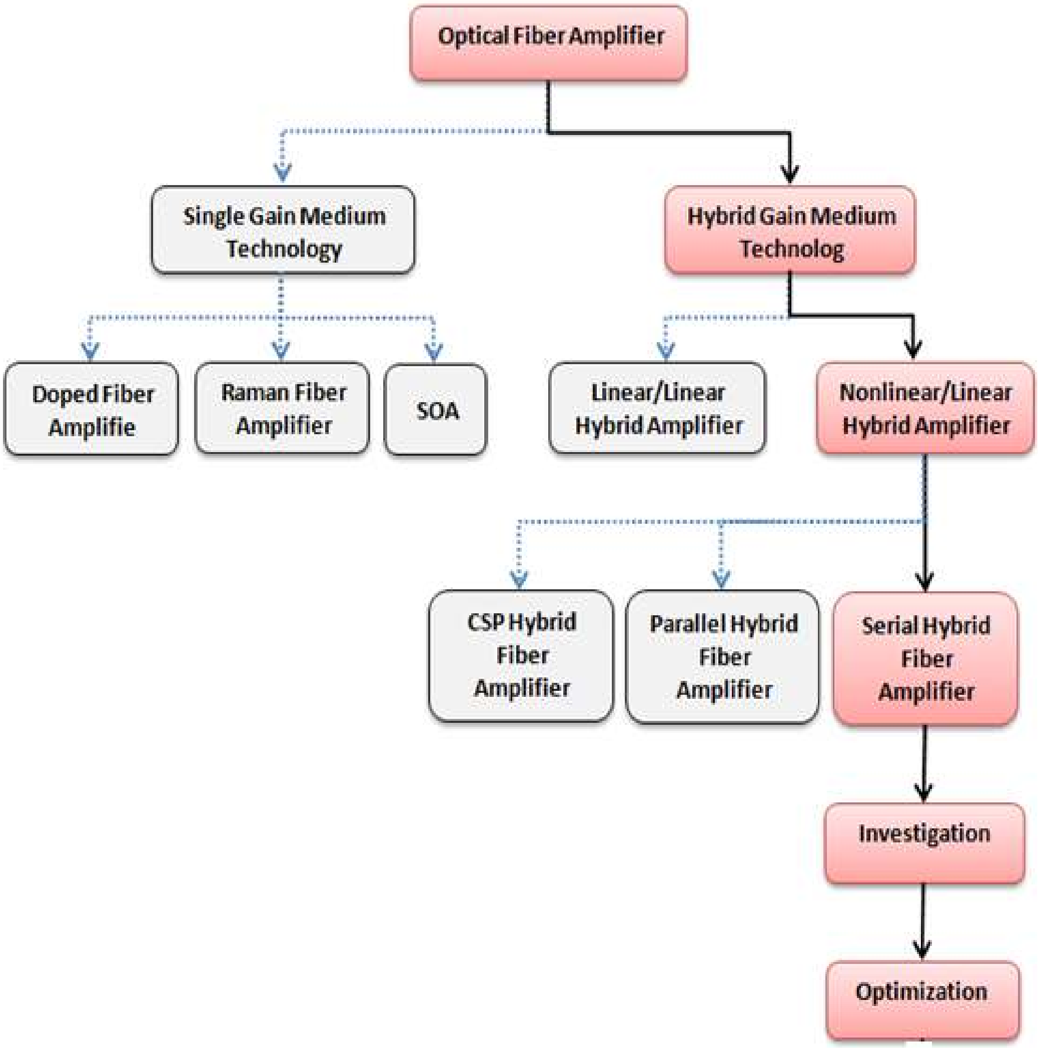

Figure 1.1 Scope of the research work

1.5 Thesis Outline

Chapter 1: provides a concise introduction and background of optical communication systems and optical amplifier development. This chapter also discusses the problem statement, research objectives, and scope of the research work.

Chapter 2: This chapter begins with a brief discussion on the optical amplifier. Theoretical reviews of EDFA and RFA based on previously published works are subsequently conducted and discussed, pump configurations are explained also. The classification of the HFA is also covered. The final section of this chapter represents a critical review for HFA.

Chapter 3: discusses the general methodology used in the simulation works conducted in this research. The input design parameters, research activities, and performance parameters are explained using proper flowcharts. In addition, the major performance parameters are defined and investigated.

Chapter 4: consists of the performance analysis of the SHFA. This chapter includes simulation setup, and pump power optimization and discuses all the results.

Chapter 5: summarizes the major conclusions based on the achieved results, and ends up with the recommendations for future works dealing with the same concept.

CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter intends to give the theoretical background and the literature review for the hybrid fiber amplifier. HFA is a combination of two gain medium, which is exhibited so as to improve the gain flatness and enlarge the gain bandwidth. As well as this chapter contains the theoretical examination of both EDFA and RFA performance. Finally, the literature review of HFA is also presented.

2.2 Optical Amplifier

The entry of the optical amplifier in the history of optical fiber communication systems was a significant milestone due to the ability of amplifying the optical signals optically and no need to signal transformation to the electrical field. The flexibility of the optical amplifier that provided high bit rates allows for the electrical repeater electrical bottleneck overcoming that able to provide a 40-80 GB/s as a maximum bit rat [3]. The principle operation of the optical amplifier is mainly related to stimulated emission which has a mechanism same as in laser operation. An external laser diode is needed as a pump power sourced that caused a population inversion which generate the stimulated process inside the fiber [1].

The amplification amount that takes place is known as “gain” and is usually given in units of dB. Optical amplifier can be placed at different points in the communication link of the system. There are three common classes are booster, in-line and pre-amplifiers. When the amplifier is placed on the start of the communication link after the transmitter source end (Tx) directly, it will be known as a booster amplifier as shown in figure 2.1(a). In this Category at first input signal power is amplified before launching into the fiber link, thus, enhance the transmitted power signal. In general, the main merit of the booster amplifier is to achieve high output power that can extend for long transmission distance up to 10- 100 km [3].

Second Category is in-line amplifier depicted in figure 2.1 (b). In-line amplifiers are taken place along the link of the transmission system to compensate for the losses afforded during propagation of the signal power and then re-send down the fiber link. The last category in figure 2.1 (c) is pre-amplifier set at the end of the transmission link before the receiver (Rx). It can increase the incoming signal level before the takes place the photo-detection by the detector at the receiver. Consequently, provide an improvement in the sensitivity of the detector effectively.

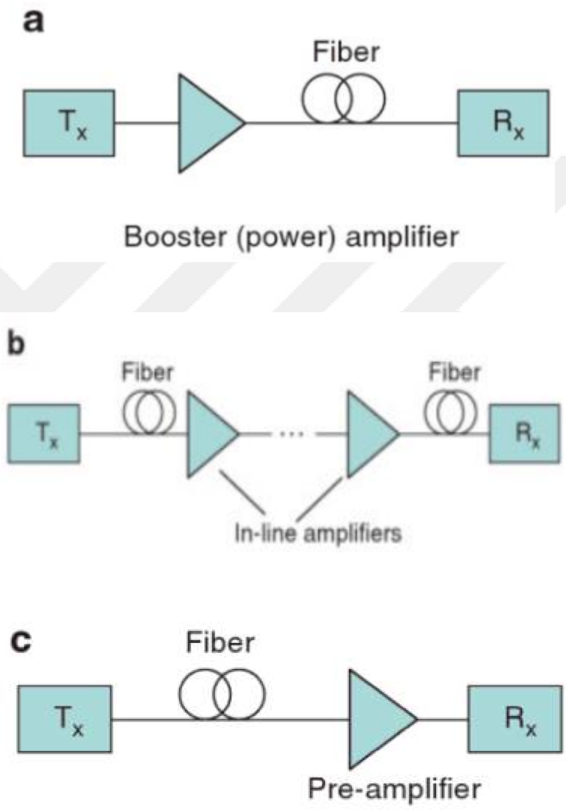

Figure 2.1 Classes of amplifier. (a) Booster amplifier. (b) in-lineamplifier. (c) pre-amplifier [1].

2.3 Types of Optical Amplifiers

Optical amplifiers are classified based on the structure, namely:

a. Semiconductor optical amplifiers (SOAs), which utilize stimulated emission from injected carriers.

b. Fiber amplifiers, in which the gain is provided by either rare-earth dopants or stimulated Raman scattering.

As well, the optical amplifiers can be classified based on gain medium characteristics:

- Linear gain medium (Rare–earth doped amplifiers and SOA).
- Non–linear gain medium (RFAs and Brillouin amplifiers).

Optical amplifier used in the practical applications can be selected by determining the required spectral bandwidths. Figure 2.2 illustrates the typical gain sketch for different optical amplifier kind in the range of 1.3 and 1.5 μm wavelength window. It is noticed that all amplifiers provide wide spectral bandwidths except for the Brillouin fiber amplifier has a very narrow spectral bandwidth, probably around 50 MHz, and for that reason cannot be utilized for wideband amplification [1].

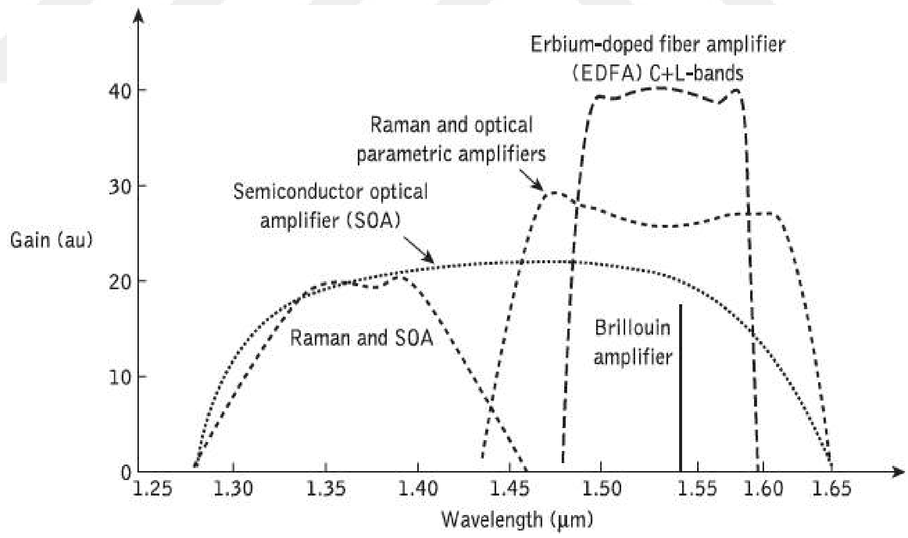

Figure 2.2 Gain–band width characteristics of various optical amplifiers [1].

The research work in this thesis is focused on the optical amplifier based fiber; however, the optical fiber amplifiers (OFA) are designed to match the requirements of the applications in the optical communication systems. Moreover, optical amplifiers work either individually as a single gain medium or as a hybrid design (combining several amplifiers with them) as a hybrid gain medium.

2.4 Topology for Single Gain Medium

The system of the optical amplifiers are indispensable optical components to compensate for distribution losses in the WDM optical network nodes, insertion and optical fiber attenuation [4].In the amplifier's gain medium, the incident light is amplified due to stimulated emission in dozens of meters of EDFA, and this is known as a linear gain amplifier [5]. The other kind is a nonlinear gain amplifier that amplifies the optical signal through many kilometres of RFA. Raman scattering of incoming light with phonons in a lattice of the gain medium generates a coherent photon to the incoming photons [6]

2.4.1 Rare-Earth Doped Amplifier (EDFA)

With a wide gain bandwidth, typical Erbium-doped fiber amplifiers (EDFAs) enable wavelength-division-multiplexed (WDM) based optical networking by amplifying all channels simultaneously without signal distortion and crosstalk [4]. An EDFA has a comparatively wide wavelength range of amplification, rendering it useful as a transmission amplifier in optical fiber communication systems.

Theoretically, EDFA is suitable to operate at the conventional (C) band and L-band ranging from 1500-1600 nm. EDFA by itself has a very high-gain and acceptable noise figure at the C-band unlike its performance at the L-band. Most realizations of L-band EDFA implement a long length of erbium-doped fiber (EDF) to pump up its gain, the L-band EDFA has a larger noise figure than C-band EDFA [7]. However, practically, there are two communication windows; the C and L bands. This allows the data signal to stimulate the excited atoms to release photons [8].

The EDFA consists of three basic components; erbium doped fiber, the pump laser source and optical coupler to combine the signal and pump wavelengths, as shown in Figure 2.3. The input signal is combined with the pump light by a WDM coupler and launched to the EDF. The pump light launched to the EDF creates population inversion and the input signal is amplified by stimulated emission. The optimum fiber length used depends upon the pumps power, input signal power, amount of erbium doping, and pumping wavelength [9].

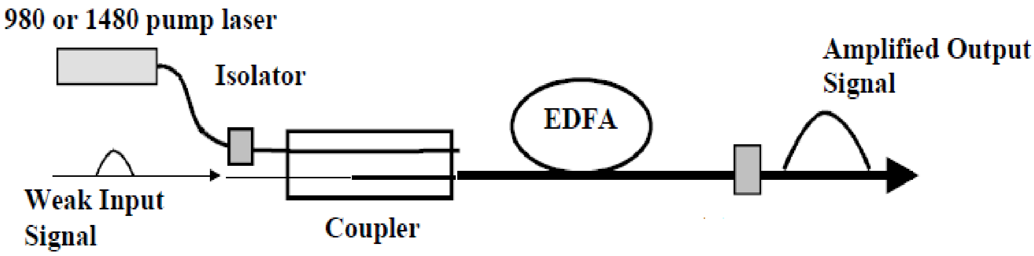

Figure 2.3 General Configuration of EDFA Amplifier [9].

Two types of pumps are usually employed to pump EDFAs with a wavelength of 980 nm or 1480 nm[10]. The 980 nm pump wavelength provides better gain and better noise figure, which showed gain efficiencies of around 10 dB/mW, whereas the 1480 nm pump has better optical conversion efficiency [11]. Typically, the gains are about 25 dB, while the noise figure lies between 4–5 dB with forward pumping, and equivalent figures for backward pumping are 6–7 dB, assuming 1480 nm pumping light was used [12].

However, there are many features for EDFA can be summarized by the following points [3]:

- High gain level.
- Large dynamic range.
- High output power greater than 100 mW.
- Low noise figure.
- amplification bandwidth is wide.
- Reletivly low insertion loss.

2.4.1.1 EDFA Basic Concept

The basic theory of the EDFA is that the input signal light was amplified using amplifiers via stimulated emission, which is like the mechanism utilized by lasers for the same purpose.

In EDFs, at first the gain can take place as the external pump power unit is used to excite the erbium ions (Er^{+3}). By exciting erbium ions to higher gain level (3-level or 4-level approach) as depicted in the figure 2.4 reported by [13]

For both cases, when sufficient pump power is launched to the dopants fiber it will be excited to a higher energy state by absorbing the pump photons, and population inversion is created between the ground state and excited state, followed by rapid relaxation to a lower excited level. The released energy amplified the signal through stimulated emission process. The lower level in the three level schemes is the ground state, while in the four-level scheme; the ground state is the excited state that comes with a fast relaxation time. The lifetime of the excited state E3 is relatively short, and as a result, the Er ion is immediately relaxed to the Excited state E2 by radiating heat (i.e. no photon emission). This difference refers to use higher pumping in the 3–level scheme in order to achieve population inversion [14].

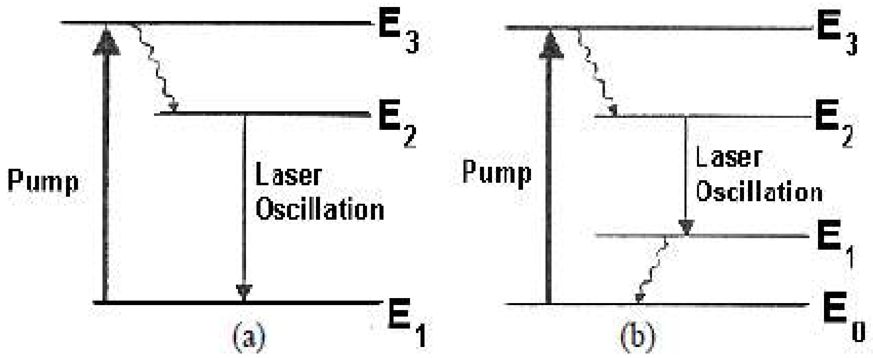

Figure 2.4 Schematic illustration of (a) Three level pumping scheme (b) Four level pumping scheme [13].

2.4.1.2 Gain Parameters Performance

As mentioned, population inversion can be provided via an external pump unit. This population inversion subsequently provided an additional gain ($g = \sigma(N_2\text{-}N_1)$, where σ is the transition cross–section) to the inserted input signal. The gain spectrum of the EDFA was considered as a board spectrum due to both of presence of dopants material and the amorphous silica. This broad gain spectrum allows EDFA for WDM application as illustrated in the Figure 2.5 reported by [13]

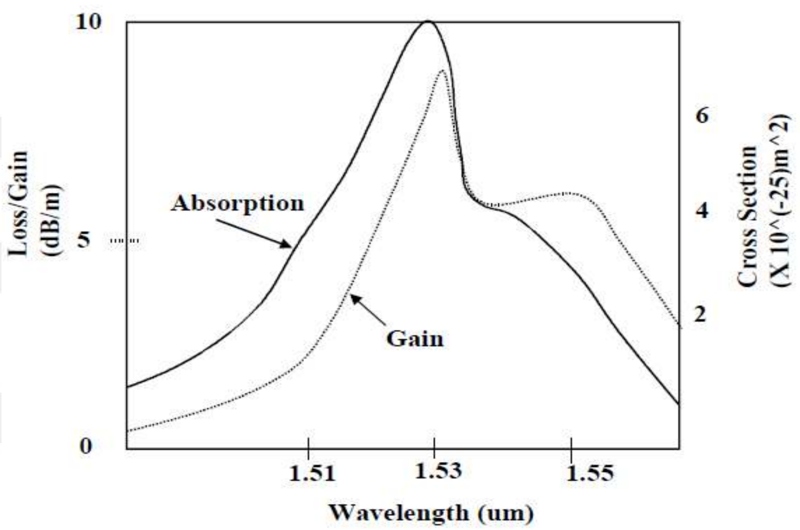

Figure 2.5 Absorption an dgain spectra of an EDFA whose core was co–doped with Germania [13].

The relationship between the signal power level and the gain coefficient is inversely proportional, which is common and ordinary in the optical amplifier systems as gain saturation. Generally, the gain coefficient was represented by [15]:

$$g = \frac{g_o}{1 + p/p_s} \qquad (2.1)$$

Where $g_o$is the small–signal gain coefficient at a given wavelength, $p$is the signal power, and $p_s$is the saturated signal power, defined as the power required for the gain to drop 3 dB.

2.4.1.3 EDFA Limitations

The main degradation in EDFA system has a non-uniform gain spectrum. That's why multiwavelength channels in DWDM regime experiences different amplification power. Cascades EDFAs chain were implemented to solve this problem. The emission band of the EDFA (1530-1570nm) is another issue that it can be used only in the C-band region [3].

2.4.1.4 Erbium Doped Fiber Amplifier Noise

This subsection aims to clarify the amplified spontaneous emission noise in EDFA, as well as the noise figure definition.

- ***Amplified Spontaneous Emission Noise***

The main factor which limits the gain available of the erbium-doped fiber amplifier is the amplified spontaneous emission (ASE) noise. The decay of the excited photons spontaneously resulted in releasing noise photons. However, as the signal and noise photons propagate inside the medium gain, both of them can be amplified. Hence ASE reduces the efficiency of the pump. As a result, higher pump is needed to achieve a specific gain. [16]Showed the noise power associated with a single mode bandwidth *dv*:

$$p = hvn_{sp}(G(v) - 1)dv \qquad \mathbf{(2.2)}$$

It is indicated that the noise is proportional to both of gain and n_{sp}

- ***EDFA Noise Figure***

The presented noise power in Equation (2.2) does not afford precision information regarding the system performance. The eventual limiting factor related to the system performance is the optical signal to noise ratio (OSNR). According to this, the definition of the NF was presented as [17]:

$$NF_{EDFA} = \frac{(SNR)_{in}}{(SNR)_{out}} \qquad \mathbf{(2.3)}$$

Where: NF_{EDFA} is the noise figure of the EDFA, $(SNR)_{in}$ and $(SNR)_{out}$ are signal–to–noise ratios of the input and output ends, respectively.

2.4.2 Raman Fiber Amplifier

Raman amplifier (RA) is one of the enabling technologies for high-capacity long-distance dense wavelength division-multiplexed (DWDM) transmission systems. RA provides wider amplification bandwidth, low-noise characteristics and simplicity [18].The transformation of a small fraction power from the incident light to the scattered light is called the spontaneous Raman scattering. This phenomenon was discovered by C. V. Raman in 1928 [19].

Generally, the incident light varies from those of the frequency of the scattered light by an amount defined by the vibrational levels of the medium. The spontaneous Raman scattering is considered as a weak operation. For example, if the light is propagated through a medium with a volume of 1 cm3, only one part of the millions of the incident light will be scattered into the Stokes frequency.

However, if an intense laser source is incident on a molecular medium, there might be an occurrence of high scattering component, and more than 10% of the incident power is transferred to the scattering components [20]. This type of nonlinear scattering was discovered in 1962, called the stimulated Raman scattering (SRS) phenomenon [21].

Raman amplifier has several advantages described in [11]. A First, the Raman optical amplifier can operate over all defined wavelength bands of an optical fiber by adjusting the pump's wavelengths. For instance, multiple pump lines can be used to increase the optical bandwidth, and the pump distribution determines the gain's flatness. This feature is theoretically analyzed by ref. [18]. Second, the gain is non-resonant, which is available over the entire transparent region of the fiber. Third, the Raman gain exists in every fiber, which provides a cost–effective means of upgrading the terminal ends. Another advantage is that it is a relatively broadband amplifier, with a bandwidth of > 5 THz, and the gain is reasonably flat over a wide wavelength range.

There are two types of Raman amplifiers discrete (lumped) and distributed Raman amplifier. Distributed type Raman amplifier (DRA) utilizes transmission optical fiber as an active medium [22] if the amplifier is contained in a box at the transmitter or receiver end of the system it is called a discrete Raman amplifier. Another distinctive feature between distributed and discrete Raman amplifiers is the length of the fibers. Typically, distributed Raman amplifiers are longer than 40 km, whereas discrete Raman amplifiers are around 5 km. This might result in slightly differing considerations.

2.4.2.1 Basic Concept

Stimulated Raman scattering is a loss mechanism when it steals energy away from the shorter wavelength and transfers it to longer wavelength. It means that Raman amplification can extract energy from a pump beam to amplify a weak optical signal at another wavelength [23]. The Raman Effect is an interaction between light and a material that causes some of the light to be shifted to a different wavelength, usually to a longer wavelength. The amount of shift depends on the material and the energy of an excitation like an automatic vibration.

The SRS is an important nonlinear phenomenon that can convert the optical fibers into wideband Raman amplifiers and tunable Raman fiber lasers. It can also strongly limit the WDM communication system's performance by relocating a fraction of power from one wavelength to another [24].

In the SRS nonlinear phenomenon, the incident light works as a pump source, and is called the Raman pump power (RPP), while the transmitted power is known as the residual RPP. The scattering components, which is shifted to lower frequencies (red–shift), are known as Stokes waves, while those shifted to higher frequencies (blue–shift) are called anti–Stokes waves [21, 24].

The origin of the Stokes generation lies in the energy exchange between the photons and the material's molecules. The quantum mechanical energy diagram for Raman scattering is shown in Figure 2.6. In the Stokes generation process, the incident photon of frequency excites a molecule from the ground state to the virtual state.

Then, this molecule returns to the vibrational state, and releases a Stokes photon of frequency. Since the energy between the virtual state and the vibrational level is smaller than the energy between the ground and the virtual states, it results in. On the contrary, in the anti–Stokes process, the excitement molecule will be within the vibrational level. Hence, the frequency of the anti–Stokes signal exceeds the incident photon [25].

Furthermore, the intensity of the Stokes waves is many orders of magnitude higher than the intensity of the anti–Stokes waves. This is due to the anti–Stokes process requiring the vibrational state to be initially populated with a phonon of right energy and momentum. In what follows, the anti–Stokes process was ignored, as it plays an insignificant role in Raman amplification.

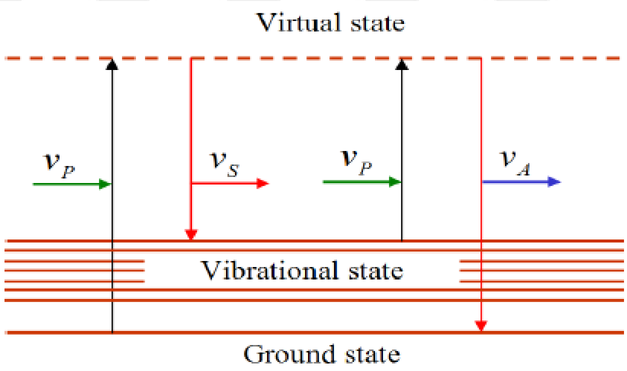

Figure 2.6 Quantum–mechanical energy diagram for Raman scattering [25].

2.4.2.2 Gainperformance

The Raman gain coefficient (g_R) is regarded as the most important parameters characterizing the Raman gain spectrum, and it is also related to the cross section of spontaneous Raman scattering. In addition, the growth of the Stokes power through the SRS is described by this gain. In a simple approach that is valid under CW and quasi–CW conditions, the initial growth of the Stokes power is described by [26]:

$$\frac{dp_s}{dz} = g_R P_P P_S \qquad (2.4)$$

Where:

P_P is the pump power and $P_S$is the Stokes power. The Raman gain coefficient was measured for silica fibers in the early experiments on SRS [27].

Generally, it depends on the composition of the optical fiber and on whether the pump and Stokes are co-polarized or orthogonally polarized. In silica fibres, the Raman gain spectrum extends over a large frequency range (up to 40 THz) with a broad peak located near 13 THz. This behavior is due to the amorphous nature of silica glass [28].

Figure 2.7 shows the Raman gain coefficient for a DCF, a nonzero dispersion fiber, and a super large area fiber of 15, 55, and 105 µm2, respectively. In all cases, the fiber was pumped at 1450 nm and provided a gain of near 1550 nm. The main point to note is that a DCF is approximately 10 times more efficient in the context of Raman amplification. An increase by a factor of 7 is expected from its reduced effective core area. The remaining increase is due to a higher doping level of germania in DCFs (GeO2 molecules exhibit a larger Raman gain peaking near 13.1 THz). Spectral changes for three fibers can be attributed to GeO2 doping levels [19]. It is evident from Figure 2.6 that when a pump beam is launched into the fiber together with a weak signal beam, it will be amplified, due to the Raman gain, and as long as the frequency difference lies within the bandwidth of the Raman gain spectrum.

The signal gain depends considerably on the frequency difference up to maximum when the signal beam is down shifted from the pump frequency by 13.2 THz (about 100 nm in the 15xx nm region) [29]. The Raman gain exists in all spectral regions; that is, optical fibers can be used to amplify any signal provided an appropriate pump source is used.

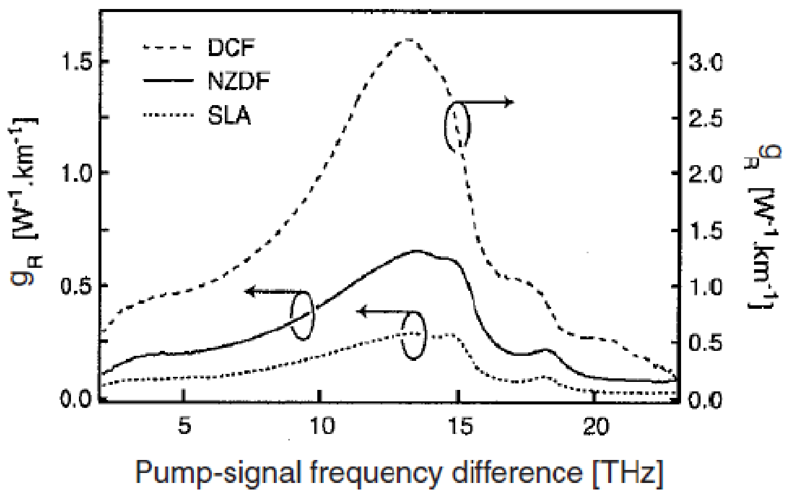

Figure 2.7 Raman gain spectra for three different fibers pumped at 1450 nm [19].

The evolution of the pumpP_P and signal powers P_S along the longitudinal axis of the fiber z in a Raman amplified system can be expressed by the following equations [19]:

$$\frac{dp_s}{dz} = g_R P_P P_S - \alpha_S P_S \qquad (\mathbf{2.5})$$

$$\xi \frac{dp_s}{dz} = \frac{w_P}{w_S} g_R P_P P_S - \alpha_S P_S \qquad (\mathbf{2.6})$$

Where (W^{-1} m^{-1}) is the Raman gain coefficient of the fiber, normalized with respect to the effective area of the fiber (A_{eff}), and are the attenuation coefficient of the signal and pump, respectively. And are the angular frequencies of the signal and pump, respectively. The parameter takes values of ±1, depending on the pumping configuration; the minus sign should be used in the backward–pumping case. In both Equations (2.5) and (2.6), the first term on the right–hand side represents the signal gain (pump depletion) due to SRS; the second term represents the intrinsic signal (pump) loss. If there is no pump light; it can be easily found that by:

$$P_s(L) = P_s(0)\, exp(-\alpha_s L) \qquad (\mathbf{2.7})$$

The RFA possesses attractive features compared with the traditional EDFA, such as broad bandwidth, small noise figure, and low nonlinear effect. However, the gain saturation due to the stimulated Brillouin scattering (SBS) phenomenon is a critical concept, and many researches were investigating this effect [28–31].

When the signal power is increased, the gain of the amplifier was kept similar at first, and then begins to obviously decrease. Gain saturation plays an important role in optical communication. When a signal with a new wavelength is added to the fiber of DWDM systems, the RFA gain will change rapidly if the signal power exceeds the saturation power, which needs to be avoided. Thus, it is crucial for designers to be aware of the exact value of the saturation power and study what gain saturation depends on [32].

In RFA, when the incident signal exceeds the SBS threshold, most of the power is transferred to the backscattered Stokes light. The threshold of SBS can be obtained by [25]:

$$P_{SBS-th} = \frac{21\, A_{eff}}{g_B L_{eff}} \qquad \mathbf{(2.8)}$$

Where: g_B is the peak value of Brillouin gain, $A_{eff}$is the effective area of the core of the fiber. So, we can obtain the on–off gain G_A of RFA for the small signal as:

$$G_A = exp\left(g_R \frac{P_0}{A_{eff}} L_{eff}\right) \qquad \mathbf{(2.9)}$$

In other words, when Ps, is small enough, the on–off gain of RFA remains unchanged with Ps, and is close to constant. However, when Ps is large enough to become comparable to the saturation power, g_R is not a constant anymore. Once Ps reaches the threshold obtained from Equation (2.9), SBS occurs, leading to the decrease in the gain. So, the gain is inversely proportional to signal power. Under this condition, g_R can be expressed as:

$$g_R = \frac{g_0}{1 + P_s/P_{sat}} \qquad \mathbf{(2.10)}$$

Where g_0 is the maximum gain coefficient and P_{sat} is the saturation power.Assuming that the attenuation coefficient of the fiber is included ing_0, the distributed signal power is [33]:

$$\frac{dP_s}{dz} = g_R P_s = \frac{g_0}{1 + \frac{P_s}{P_{sat}}} P_s \qquad (2.11)$$

Where g_0 concerned with the pump power. Obviously, an integral to Equation (2.13) can be made along the fiber. Simultaneously, using $P_s(L) = GP_s(0)$,the saturation gain is given by:

$$G = G_0 exp\left[(1 - G)\frac{P_s(0)}{P_{sat}}\right] \qquad (2.12)$$

Where: G_0 is the gain of the small signal.

2.4.2.3 Raman Fiber Amplifier Noise

The performance of the RFA is affected by the generated noise during the amplification process. Furthermore, three main noise sources in RFA are detailed in the following manner:

- ***Spontaneous Raman Scattering***

Spontaneous Raman scattering adds to the amplified signal and appears as a noise due to the random phases associated with all spontaneously generated photons [34]. This noise mechanism mirrors spontaneous emission influencing the performance of EDFA, with the notable exception in the Raman case, where it relies on the phonon's population in the vibrational state, which is in turn dependent on the temperature of the Raman amplifier. Going deeper, the evolution of the signal vis-a-vis noise added by spontaneous Raman scattering should also be taken into account in this case.

However, in reality, there will only be noise that exceeds the amplifier's bandwidth that can be further reduced by locating an optical filter at the amplifier's output. The total ASE power after the RFA is determined by [19]:

$$P_{ASE} = 2S_{ASE}B_{opt} \qquad (\mathbf{2.13})$$

Where:B_{opt} Is the optical filter bandwidth and is the ASE spectral density given by:

$$S_{ASE} = n_{SP}hv_0 g_R G(L) \int_0^L \frac{P_P(Z)}{G(Z)} dz \qquad (\mathbf{2.14})$$

Where: n_{SP} Is the spontaneous scattering factor and is the average photon energy.

- ***Rayleigh Backscattering***

The phenomenon that limits the performance of distributed Raman amplifiers mostly turned out to be Rayleigh backscattering [34, 35]. Rayleigh backscattering occurs in all fibers, and is the fundamental loss mechanism in their case. Although most of the scattered light escapes through the cladding, a part of backscattered light can couple into the core mode, supported by a single mode fiber. Normally, this backward propagating noise is negligible, because its power level is smaller by more than 40 dB compared with the forward–propagating signal power [36].

However, it is possible to amplify it over lengthy fibers using distributed Raman gain. Rayleigh backscattering influences the performance of Raman amplifiers in two manners. Firstly, it is possible that a part of backward–propagating ASE to appear in the forward direction, which will serve to improve the overall noise. However, this noise is relatively miniscule, and will not be of much concern to the Raman amplifiers. Secondly, the double Rayleigh backscattering of the signal creates a crosstalk component in the forward direction, which possesses a similar spectral range as the signal (in–band crosstalk). Rayleigh–induced noise, amplified by the distributed Raman gain, that becomes the major source of power penalty in Raman–amplified light wave systems [19].

Figure 2.8 shows the schematics of the phenomenon of double Rayleigh backscattering of the signal. Density fluctuations at the location z2 inside the transmission fiber reflect a small portion of the signal through Rayleigh backscattering. This backward–propagating field is reflected a second time by density fluctuations at the location z1, and thus ends up propagating in the same direction as the signal. Of course, z1 and z2 can vary over the entire length of the fiber, and the total noise is obtained by summing over all possible paths. For this reason, the Rayleigh noise is also referred to as originating from multiple–path interference [37].

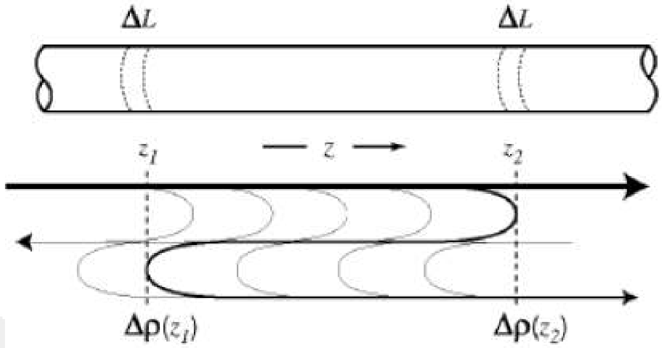

Figure 2.8 Schematic illustration of double Rayleigh back scattering in distributed Raman amplifiers. Thesignal is first reflected at z2 and then again at z1 through local density fluctuationsΔρ at these two locations [37].

- ***Pump–Noise Transfer***

It is understood that all lasers demonstrate some form of intensity fluctuations. This is regarded as worse for semiconductor lasers utilized for pumping a Raman amplifier due to the fact that the level of power fluctuations in such lasers can be relatively high from their miniscule size and large rates of spontaneous emission. As seen from Equation (2.19), the gain of a Raman amplifier relies on the exponential power of the pump. It can be surmised from this equation that any changes in the pump's power would be increased, resulting in an even larger change within the amplified signal power. If this is the case, then the source of the noise is regarded as pump–noise transfer. A detail associated with noise transfer relies on multiple factors, such as amplifier length, pumping scheme, and the dispersion characteristics of the fiber used for making the Raman amplifier.

Power fluctuations of semiconductor lasers are quantified through a frequency–dependent quantity called the relative intensity noise (RIN). This value represents the spectrum of intensity or power fluctuations [37].

2.4.2.4 PumpingConfiguration

- ***Single-Pump Raman Amplification***

A schematic of an optical telecommunication system employing Raman amplification is shown in Figure 2.9. The signal propagates from the transmitter (Tx) to the receiver (Rx). The pump traveling parallel to the signal is termed the co– or forward–pump, while the pump moving in the opposing direction is termed the counter– or backward–pump. The combine between of forward and backward is bidirectional pumping.

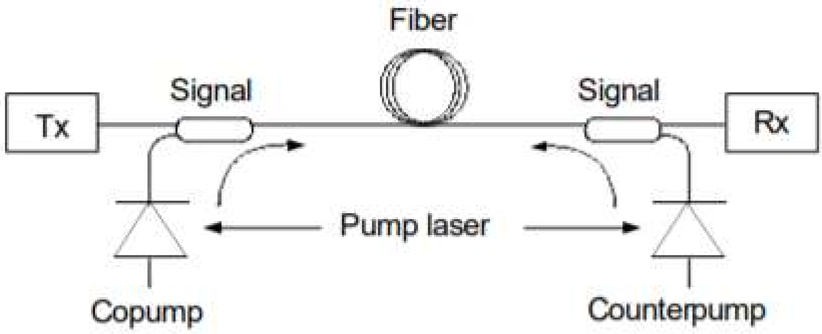

Figure 2.9 Schematic of an optical communication system employing Raman amplification [30].

In the case of the forward pumping, the population inversion is smaller at the input, and hence, the ASE noise is smaller at the input end than at the output end. Thus, forward pumping displays better noise performance than backward pumping. In the case of backward pumping, the saturation signal power is higher than forward pumping. Toward the end of the amplifier fiber, the signal intensity has become higher and closer to saturation. With backward pumping, the pump power is largest toward the end of the fiber, where the high intensity is needed to raise the saturation signal power. Not only is the saturation signal power increased, but the total gain of the amplifier is also increased. If not for the increased pump power, the gain would have been saturated and the overall power would have been reduced. Thus, backward pumping has the advantages of higher saturation power and higher gain [38].

An advantage of bidirectional pumping compared to backward or forward pumping is the ability to transmit signals in both the forward and the backward direction, that is, bidirectional pumping and bidirectional signal transmission. Finally, rather than launching very high power from one end, now the power requirement is split between two launch sites[19].

- ***Multiple-Pump Raman Amplification***

The RA operation is the energy transfer of the pump to the signal due to Raman interaction between the optical modes and the vibrational modes of the medium molecules [39]. FRAs have certain advantages such as wavelength flexibility, because gain depends on the frequency shift between pump and signal, Multi-wavelength pumping scheme is usually used to increase the gain flattening and bandwidth for high capacity WDM transmission systems [23].

Multiple-pump Raman amplifiers make use of the fact that the Raman gain exists at any wavelength as long as the pump wavelength is suitably chosen. Thus, even though the gain spectrum of a single pump is not very wide and is flat only over a few nanometers, it can be broadened and flattened considerably by using several pumps of different wavelengths. Each pump creates a gain profile that mimics the spectrum shown in Figure 2.10. Superposition of several such spectra can produce relatively constant gain over a wide spectral region when pump wavelengths and power levels are chosen judiciously [19].

Figure 2.10 shows a numerical example when six pump lasers operating at wavelengths in the range of 1420–1500 nm are employed [40]. The individual pump powers (vertical bars) are chosen to provide individual gain spectra (dashed curves) such that the total Raman gain of 18 dB is nearly flat over an 80-nm bandwidth (solid trace). Pump powers range from 40 to 200 and are larger for shorter wavelength pumps because all pumps interact through SRS, and some power is transferred to longer wavelength pumps within the amplifier.

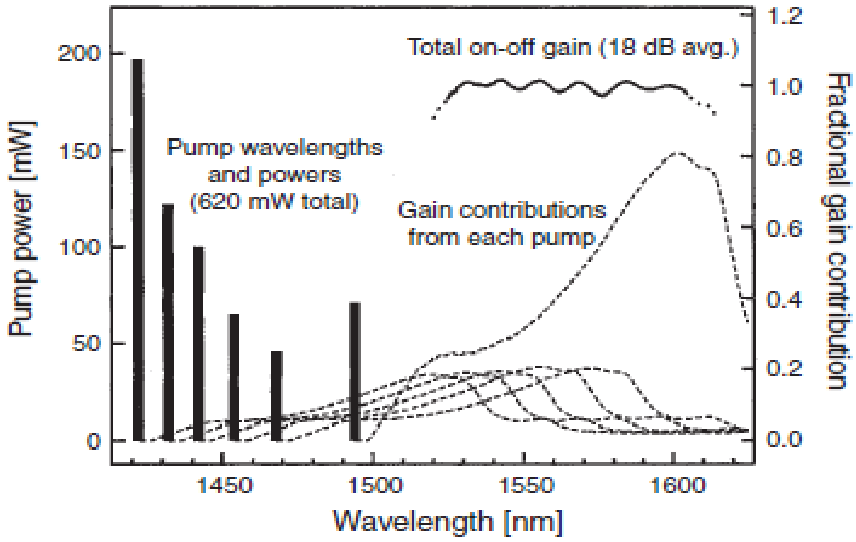

Figure 2.10 Numerically simulated composite Raman gain (solid trace) of a Raman amplifier pumped with six lasers with different wavelengths and input powers (vertical bars). Dashed curves show the Raman gain provided by individual pumps. [26].

However, they require numbers of high power pump lasers to achieve high-gain and high bandwidth which makes it very expensive at the initial deployment stage where the WDM bandwidth is not in full use [23].

- ***Higher Order Pumping***

Higher Order Pumping (HOP) considered as an Advanced Pumping Configurations due to its ability to overcome the major obstacles resultant from using the forward pumping as the pump–signal cross talk as well as double Rayleigh scattering (DRS) which are consequently, contributes in an additional noise that may override the benefits otherwise obtained from the uniform gain distribution.

Higher Order Pumping method depends upon using another pump wavelength shifted about 100 nm away from the first pump wavelength coupled into the transmission fiber together with the WDM channels. By principle, shorter wavelength pumps do not amplify the WDM channels directly but provide distributed Raman amplification (exciting the stimulated Raman scattering (SRS) process) for longer wavelength pumps, which in turn amplify the channel signals inside the transmission spin [41].

HOP allows a significant enhancement in terms of maximum unrepeated system reach an improvement in the optical equivalent noise figure. As well as HOP can produce flat power distribution and lower amplified spontaneous emission (ASE) noise with some nonlinearity [42]. Further, keeping the nonlinearity under control improves the effective noise figure and increases the bandwidth by adjusting the second to first order pump powers ratio [43-44].

The second-order pump may be launched from the same end as the first pump or from the other end of the amplifier, as shown in Figure 2.11a and b respectively In the last case, the first order pump is amplified close to the signal input end and as a result of the first pump now provides gain for the signal both at the input and at the output end of the fiber span. Thus, the signal power will improve gradually [19].

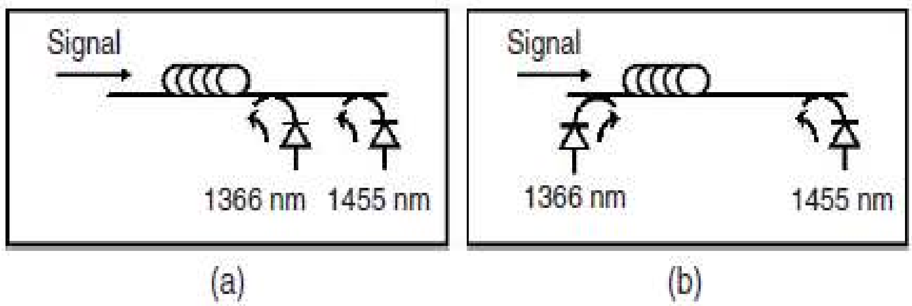

Figure 2.11 Configurations of second-order pumping. In (a) the first- and second order pumps are co-propagating but both are counter-propagating agains the signal, whereas in (b) the first- and second-order pumps are counter-propagating against each other [19].

The more the amplification is pushed into the fiber, the larger the noise figure improvement is. Therefore, higher-order Raman pumping has been applied and performance improvement has been obvious in various publications [37-42]. Increasing the order of the pumping scheme helps to push the amplification deeper into the transmission fiber and, thus, to increase the noise figure improvement.

Commercial systems are available up to third order, but results for schemes making use of sixth order pumping have already been published [45].

2.5 Hybrid Gain Medium Technology

At present, the HOAs are promising and widely used technology for today's high-speed broadband applications to enhance system performance without using costly techniques. Two popular types of optical amplifier, the EDFA and RFA, were studied by many researchers [46–49].

In general, the combination of more than one optical amplifier in any configuration is called an HOA [50]. Islaam described the net gain of the hybrid Raman-erbium doped fiber amplifier (EDFA) HOA, Hybrid, as the sum of the two individual gains (in dB) of Raman and EDFA, respectively. Therefore, in the case of Raman-EDFA HOA the net gain is:

$$G_{Hybrid}=G_{EDFA}+G_{Raman}$$

By cascading amplifiers, the performance of the system can be enhanced.

Like most technologies, HOAs also come with some drawbacks that should be taken into account. These include transient response, induced crosstalk, as well as other sources of noise that are particular to fiber Raman amplifiers (FRAs), such as double Rayleigh backscattering, pump-mediated relative intensity noise transfer, and problems with nonlinearities, due to high-path average power in the fibers [50].

EDFA is mainly used for C–band from 1530 -1570 nm. However, the C–band is fully utilized for DWDM system, rendering EDFA unsuitable for similar purpose. Erbium doped fiber length can be increased in the form of a quick solution in shifting the amplification's bandwidth to a longer communication window (L–band). However, this approach requires high pump power, lower gain, and higher NF compared to the C–band EDFA [51]. Moreover, HFA was proven to increase bandwidth and its corresponding gain flatness. HFA was obtained by merging multiple gain mediums, either (linear–linear) or (nonlinear–linear).

2.5.1 Linear–Linear Hybrid Fiber Amplifier

Constructing hybrid amplifiers that combine several amplifiers with different gain bandwidths is one of the effective ways to extend the gain bandwidth of the optical amplifiers. These amplifiers can be connected either in parallel or in series. In parallel configuration, WDM signals input to the amplifiers are first de-multiplexed into several wavelength-band groups with a WDM coupler, then they are amplified by amplifiers that have gains in the corresponding wavelength band, and then they are multiplexed again with a WDM coupler. The parallel configuration is very simple and applicable to all amplifiers. In addition to that, it has extensibility that is; one can initially start with only one amplifier and add up other amplifiers later on according to the capacity demand expansion. The examples of the configuration are the C + L band hybrid amplifiers combining C- and L-band erbium-doped fiber amplifiers (EDFAs) S + C + L band amplifiers combining thulium-doped fiber amplifiers (TDFA), C-band and L-band EDFAs [52].

2.5.2 Nonlinear–Linear Hybrid Fiber Amplifier

A hybrid Raman/EDFA combines two gain medium, namely, nonlinear RFA and linear EDFA gains. Hybrid Raman/erbium–doped fiber amplifiers are an enabling and promising technology for future DWDM multi–terabit systems, as shown by recent experimental results [53–58].

Hybrid fiber amplifiers are designed to maximize the span length, minimize the impairments caused by fiber nonlinearities, enhance erbium doped fiber amplifier (EDFA) bandwidth, provide a sufficient increase in overall signal gain and enhance the pump conversion efficiency [59, 60]. This thesis is focused on hybrid Raman–erbium doped fiber HFA.

2.6 Literature Review of Hybrid Fiber Amplifier.

The basic concept of HFA includes combining of two gain Medias of the overall gain flatness can improve. Generally, two configurations were proposed; serial hybrid fiber amplifier (SHFA) and parallel hybrid fiber amplifier (PHFA).

In 1999, Masuda and Kawai reported a wide and seamless bandwidth with high gain in C and L bands using a discrete SHFA. The bandwidth of 80 nm within 3 dB gain variation was obtained. The peak gain was larger than 26 dB and low optical noise figures under 6 dB for the bandwidth examined [61]. However, this design was complex and costly which They used three amplification stages and multiple pumping sources with different wavelength to pump EDF and Raman fiber, and employed gain equalizing filter for gain flattening.

In 2002, a single cavity capable of providing 1st and 2nd-order pumping has been presented figure 2.12. 16 dB ON–OFF gain with 31 nm gain flatness covered C-band region by using the dual-order pumping which are rewards three first-order pumps that can cover the same bandwidth. Dual-order pump gave a 1.5dB improvement in noise figure and 0.9dB improvement receiver sensitivity over than 1st-order pump in system performance on an 80 km SSMF span [62].

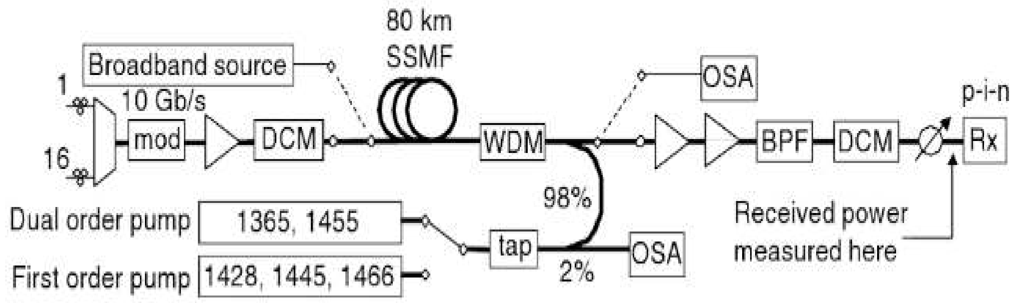

Figure 2.12 Experimental setup [26]

In the same year, Bolshtyansky et. al reported two stages of DCF as Raman gain medium that combined with EDFA as a SHFA. Flatness gain of 30 nm (1610-1640 nm) with peak gain level of 14 dB was presented. In this work, a single Raman Pump unit via 50/50 coupler at 1536 nm has been used to pump the Raman stages, while

1480 nm was used to pump the EDFA [63]. However, there was deficient in gain level and bandwidth.

In 2003, the authors utilized a few pumping schemes, such as bidirectional pumping and high-order pumping in order to enhance the performance of Raman pump diodes. These configurations can achieve flatter power distributions than backward pumping, and in this manner they can produce lower amplified spontaneous emission (ASE) output at identical nonlinearity. Clearly, the uniformity of signal power distributions as well as the ASE performance will be additionally enhanced when bidirectional dual-order Raman pumping (BiDP) is used [64-66].

Y. Hadjar et.al. In 2004 tried to reduce the noise figure tilt in wide bandwidth systems using Second-Order Raman Amplification, figure 2.13. They have strongly benefited from the energy transferred from the second to the first-order pump which pushes the distributed gain further back into the fiber, thus, achieving a significant reduction in the NF tilt over the 70-nm band [67]. Furthermore, the same group demonstrate experimentally that the second-order pumping of Raman amplifier increases the double Rayleigh back-scattering noise up to 2 dB compared to only first order pumping with 16 dB Raman gain in ref [68] and 0.8 noise figure improvement at 13dB nominal gain for ref [68], as well observed that even though increased double Rayleigh back-scattering DRBS penalty, significant enhancements in Q factor achievable by this technique because the improvement in lumped noise figure outweighs the increase in noise level.

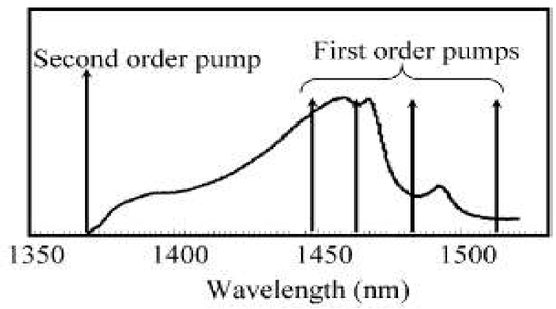

Figure 2.13 First- and second-order pump wavelengths relative to Raman gain Spectrum arising from the second-order pump in SSMF [67].

The best performance of OSNR was achieved by a theoretical investigation between the bidirectional first-order pumping (BiFP) and bidirectional dual-order Raman pumping (BiDP) schemes for both short and long-span transmission systems. BiDP appears an optimal OSNR performance for most conditions by choosing a suitable second-order pump wavelength and second-to-first-order pump power ratio [69].

H. S. Seo et.at. in 2005, proposed a HFAs covering the S+C bands using a special silica fiber with an erbium-doped cladding and a germanium doped core. The S-band signals were amplified by the stimulated Raman scattering (SRS) in the core, and C -band signals by stimulated radiative transition of Er-ions in the cladding at single pump wavelength [70]. In the same year they developed their work since they were able to increase the transmission capacity which expands the flat gain bandwidth about 105 dB covering range of S, C, and L bands by using the same amplification mechanism with two pump laser diode [71].

G. Bologninat.el in 2006, proposed high-power and low relative-intensity-noise (RIN) pump lasers for first- and second-order co-propagating Raman in which a low-noise and high power pump light is achieved 25 dB of ON–OFF gain at 1450 and 1360 nm by amplifying laser diodes through counter-pumped discrete Raman amplifiers [72]. These pump lasers have been used in WDM transmission experiments, combined with standard first-order counter-propagating pumping, demonstrating the successful transmission of 8 × 10-Gb/s WDM channels in the C-band over 70 and 72 dB of standard single-mode fiber (SMF) in the case of first- and second-order co-pumping schemes, respectively [73], [74].

H. S. Seo et.at in 2007, reported an experimental study of wide band SHFA covering S+C+L bands in a range of (1,500-1,600 nm) through a combined medium of EDF and DCF and using of two-tone pumping scheme. Up to 20 dB gain level with 5 dB gain variation were presented. An acceptable NFs of 9 to 5 dB was achieved within the entire gain band width [75]. However, it suffers from using high Raman pump power of 2.8 W.

S.K. Liaw et al. in 2008 proposed wide flat gain P–HFA about 70 nm (1530-1600 nm)flat gain bandwidth utilizing simple parallel configuration, by splitting the pump power going into gain media. The optimum ratio of pump power going to erbium and Raman was found to be 1:29. The gain variation is 3–dB within small signal region of –20 dBm. However, the system suffers from degradation about 4 dB and 6 dB in gain flatness at the large signal region of -10 dBm and 0 dBm, respectively [76].

SHFA was report byLiaw and Huang [77]. Wideflatness gain range of 65 nm (1530-1595nm) with low variation gain of 0.2 dB was recorded. Due to the double pass amplification produced by the reflector, the pump efficiency was enhanced. However, fiber grating mirrors was employed to achieve such low gain variation. The effect of stimulated Raman scattering (SRS) in long band EDFA was studied by Abu Bakar et. al. in 2009. SRS was utilized as a secondary pump for EDFA hence, the pump efficiency was improved. [78].

At the same year, G. Bologniniat. el. carried out a theoretical analysis on the double Rayleigh scattering noise (DRS) in distributed Raman amplifiers with higher order pumping schemes as shown in figure 2.14. They noticed an unexpected significant DRS noise reduction for HOP schemes over than third order by performing a simplified analytical model treatment, semi-analytical and full numerical methods, allowing reduced DRS-induced penalties together with ensuring a high optical signal-to-noise ratio improvement, thus improve the overall performance of the system[79]

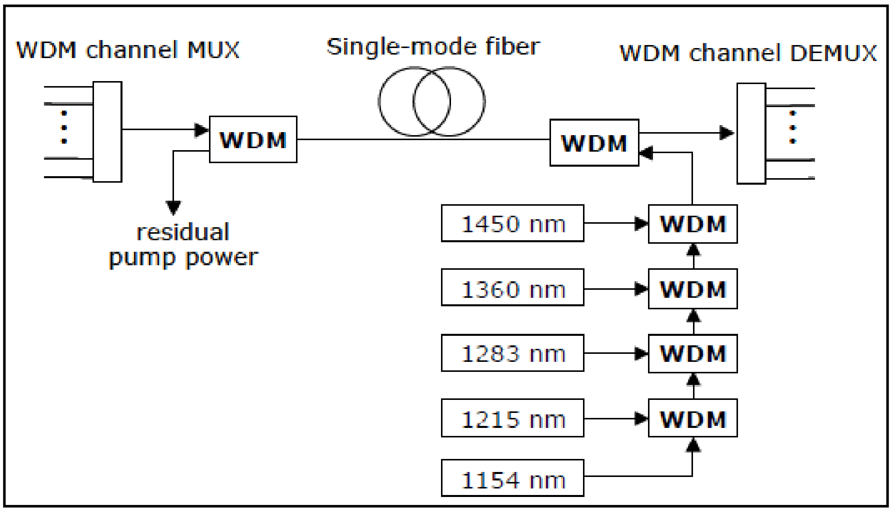

Figure 2.14 Scheme of simulated counter-propagating Raman amplification with increasing pumping orders [79].

By 2010, widely SHFA gain flattens utilizing particle swarm algorithm was introduced by Afkhami et. el. Two different Raman pump units of 6 and 10 were implemented. Wide flatness gain bandwidth of 98 nm (1529.2-1627.1 nm) with a gain variation of 1.392 and 1.043 dB for Raman pump units of 6 and 10, respectively [80].

In addition, in 2011, a secondary pumping scheme using SRS was employed in an R_EDFA design for input signal power of –30 dBm. Overall transmission performance was measured as well and demonstrated an encouraging outcome with gain as high as 24 dB while the noise figure was maintained at about 11 dB. The outcome of this study emphasized the feasibility of secondary pumping scheme using SRS in L-band gain enhancement. However, it is preferable also to utilize a single wavelength pump laser without the existence of internally generated Raman stokes in order to eliminate the requirement for extra filtration parts, thus reducing the total loss caused by the design [81].

In 2013, Abu Bakar et. al., demonstrated L–band R–EDFA/Raman SHFA with enhanced higher order pumping scheme utilizing stimulated Raman scattering. The technique benefits from the use of higher-order pumps that are realized by generating C-band SRS and ultra-long Raman fiber laser (ULRFL) to produce better gain performance. Additionally, the technique employs C–band SRS thus providing flexibility for C–band hybrid amplifier to operate in L–band without the need for L–band specific Raman amplification [82].

Wideband of S+C cost effective HFA was proposed by A. M. Rocha et al. proposed in 2014. Only one external pump unit was used in this design. Genetic algorithm has been employed for optimization purpose. Through the optimization, an optimized EDFA length was presented that achieved higher gain level [83].

M. H. Ali et. al., proposed a new technique was used to control the divided input signal power ratio into two branches of (EDFA and RFA) in parallel design. By optimizing the coupling ratio of the input signal power they were able to obtain a flatness gain range of 60 nm (1530-1590 nm) over C+L bands. The gain variation is about 1.06 dB for coupling ratios of 0.4 at the small signal of -30 dBm and 0.77 dB for coupling ratios of 0.8 at the large input signal of -5 dBm. However, the gain flatness is improved and the gain dynamic range is increased as well compared with the conventional P-HFA [84].

Then, the same group after one year presented the effect of cascading amplification stages of a wideband serial hybrid Raman-erbium-doped fiber amplifier. Two schemes are proposed in this study, type A, in which the RFA is placed before the EDFA, and type B, in which the RFA is placed after the EDFA. A 20-dBaverage gain over 40 nm flatness has been achieved at low input signal for both type. Hybrid gain level are affected more by the second amplification stage than the first in both design, while the first amplification stage is dominated in the hybrid NF [85].however, this work was utilized a single (1480 nm) pumping laser to pump the RFA, and the residual Raman pump to pump the EDFA, thus, gain flatness is improved and the gain dynamic range is increased as well compared with the conventional design.

In (2016) Dual-Order Raman Pumping has been investigated using four first-order pumps and one second-order pump scheme in C band (1,525–1,565nm) wavelength in the setup of figure 2.15. The main advantage of the scheme is that only 50 mW second-order pump shows appreciable improvement in the system performance to be useful for long haul optical transmission systems based on multiple pumping schemes. The work done recommends 50 mW SOP power and a sum of 300mW FOP powers as best suitable choice for less gain ripple 1.79 dB and noise figure tilt 0.8237 dB [86].

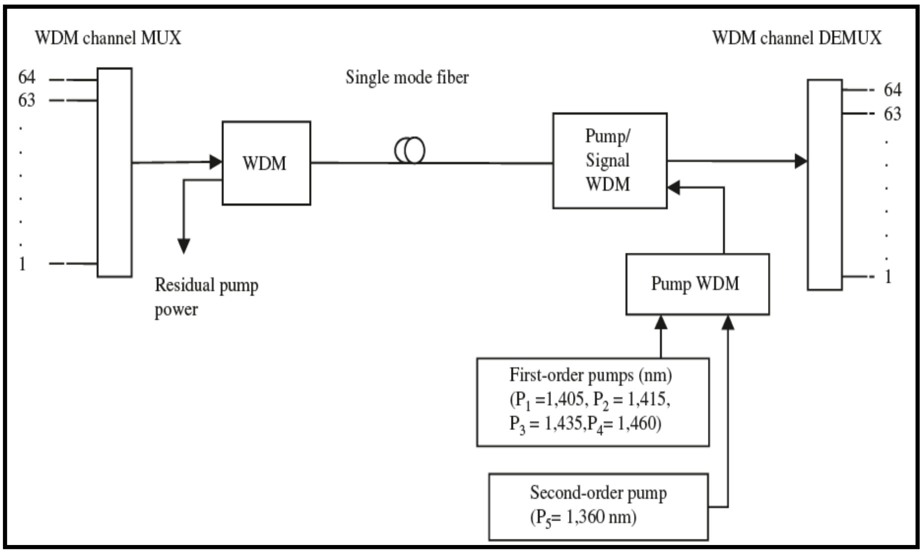

Figure 2.15 Schematic model of WDM optical transmission system employing second-order fiber Raman amplification [86].

An experiment was conducted in Germany using existing field optical fiber cable with a distance of 210 Km and third order distributed Raman amplification [87]. The pump used was of 4 W optical output level at a wavelength of 1276 nm (third order pump) which excited a wave at 1356 nm (second order) with an optical level of about 0 dBm, which in turn excited a first order wave of 1455 nm at an optical level of 10 dBm. This last first order wave acted as a pump for the signal of 1550 nm. Total amount of span attenuation was 67 dB. The signal launched was at a level of 15 dBm of 170 Gb/s. The BER obtained at the end of the 210 Km was 1.5×10^{3} with FEC, indicating error free transmission. The experiment was further extended to eight channels each of 170 Gb/s but to a distance of 165 Km with a total optical loss of 44

dB and 300 GHz channel separation, and the result was a BER of 2×10^{3} with FEC, indicating error free transmission.

The Influence of Raman Pump Direction on the Performance of Serial Hybrid Fiber Amplifier in C+L-Band demonstrated in [88]. The backward pump (counter-pumping) shows better performance as compared to the forward one (co-pumping) where it has wider gain dynamic range, higher gain saturation power and lower average noise figure. This differences can be attributed to the fact that in forward pump saturation happens faster due to stimulated Brillouin scattering(SBS) in the Raman gain media.

The Parallel hybrid fiber amplifiers configuration in ref. [84] which utilized gain control technique was enhanced in 2018 to be combine serial-parallel hybrid fiber amplifiers. As shown in figure 2.16 by adding a DCF in series with the EDFA branch, the problems of dispersion compensation in EDFA branch is eliminated and improves the overall system performance. By optimizing the pump parameter (power and wavelength) and coupling ration of the proposed design, the gain bandwidth increased by 5 nm to be 65 nm and the splitting ratio fixed at 0.7 for small and large power signal [89].

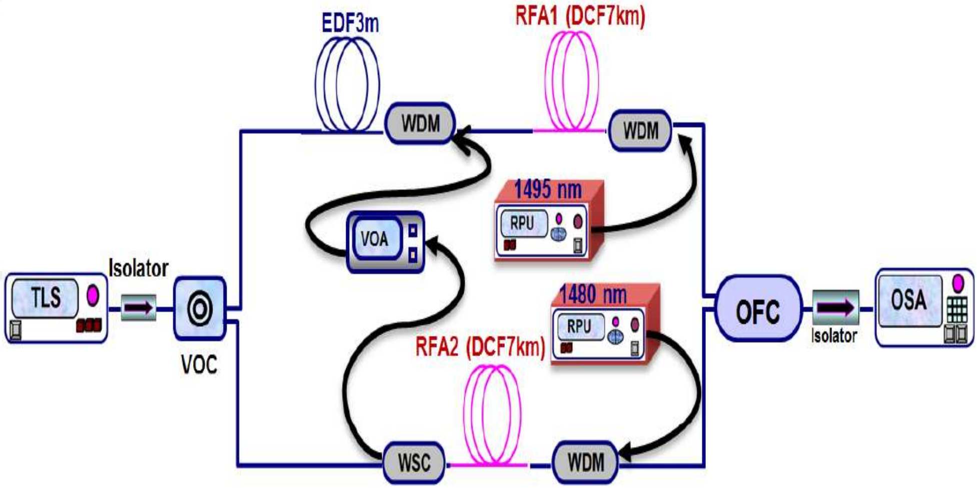

Figure 2.16 Schematic diagram of CSP–HFA utilizing gain controlled technique [89].

K. Singh MALHI al.et.in 2018 [90], employing higher order pumping schemes to analysis the Performance of distributed fiber Raman amplifiers in terms of their characteristic performance parameters such as effective NF, OSNR, and DRBS noise in WDM systems figure 2.17. The results indicate that the second order pumping configuration employed exhibits reduction of 2 dB in ENF at 36 dB and higher on–off gain. Moreover, 2 dB OSNR improvements at 1 dB input optical power over the investigated fiber length is obtained. The results showed that the higher order pumping configuration is useful because only 50 mW of conventional first order pump power is deployed. It is a considerable reduction of pump power achieved and suggests that first order lasers pumps of this power range can be easily integrated on chip for multi-pumping in Raman amplification applications.

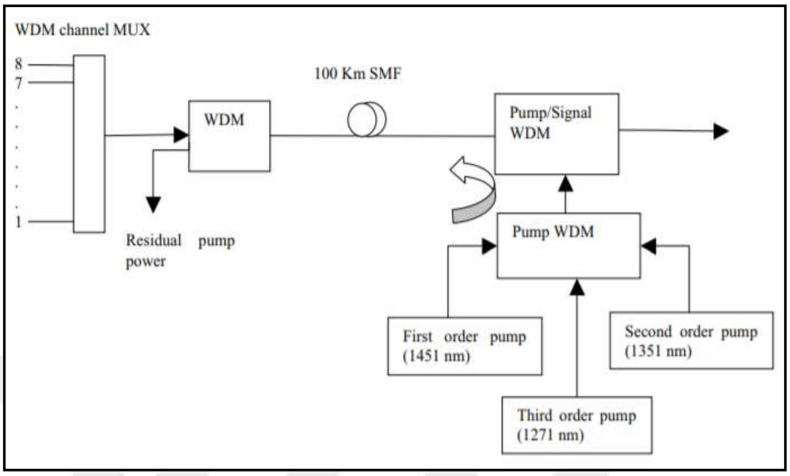

Figure 2.17 System setup of distributed fiber Raman amplification employing higher order configurations in 8-channel optical transmission system [90].

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter briefs the methodology adopted in this research work. The First section of this chapter clarifies the general procedures undertaken to achieve the aim of this research. Also contains definitions of the essential performance parameters for fiber amplifier, the components utilized in simulation design. In addition, the investigation and optimization of hybrid fiber amplifier are discussed. At the end of the chapter, enhancement in pumping sources is discussed in some of the input signals.

3.2 General Research Flowchart

The research processes of the proposed work are illustrated by the general research flowchart in Figure 3.1. In this work, serial hybrid fiber amplifier based on higher order pumping is discussed by dividing it into three essential sections: investigationand optimization as mention in chapter one. Generally, the investigation, which occurs for all amplifier structures, gives a prediction to set the optimum conditions. The optimization is divided into three categories, namely: the input signal power, pump power and the pump wavelength. First, input signal power is optimized at (-30 to 0 dBm). Second, pump power optimization is determined at the broad gain bandwidth within 3-dB and higher average gain level that can be acquired. Finally, the pump wavelength optimization of EDFA was set at 1480 nm. 1495 nm and 1412 nm were set for pumping RFA as a first and second order pumping, respectively.

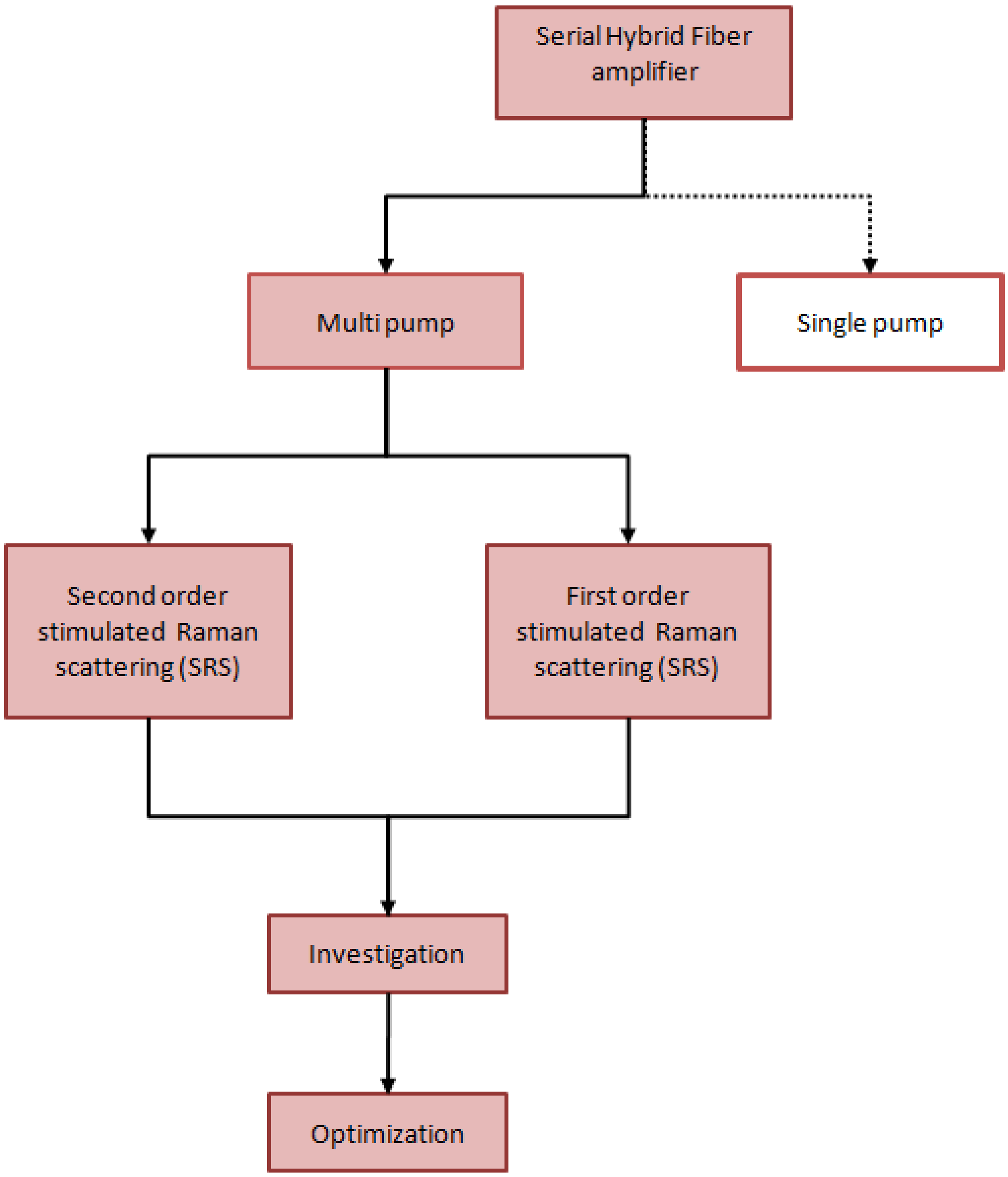

Figure 3.1 General research process flow chart

3.3 HFA Design Parameters

The design parameters for the suggested amplifiers include the input signal wavelength, input signal power and pump power, as clarified below.

3.3.1 Input Signal Wavelength

Input signal wavelength used in proposed design is swept from 1520 nm to 1625 nm in order to determine the gain bandwidth within linewidth of 150 kHz.

3.3.2 Input Signal Power

The input signal power for all proposed amplifiers is acquired from a tunable laser source (TLS) with the power range between –30 dBm to 0 dBm with a step of 5 dBm to monitor both of the gain spectra and gain dynamic range.

3.3.3 Pump Power Level

The pump power is acquired from erbium pump unit (EPU) of 10 mw and Raman pump unit (RPU) with a maximum power of 350 mW and 900 mW for first and second order pumping, respectively. In hybrid technology the pump wavelength is tuned at 1480 nm for EDFA and combine 1412 nm with 1495 nm for RFA.

3.4 HFA Performance Parameters

The performance parameters for any amplifier can be considered as a measure of the efficiency of that system and utilized to set the quality of the techniques involved. Considering that the HFA depended on a complex contribution between two gains medium, the performance parameters can be set by optimizing this contribution. In the following sections, the essential performance parameters of this kind of amplifier are defined**:**

3.4.1 Amplifier Gain

The amplifier gain or the signal gain can be considered as the one of the most important parameters of optical amplifier which is defined as [91]:

$$G = \frac{Pout}{Pin} \qquad \textbf{(3.1)}$$

Where: *G* is the amplifier gain, *Pin* and *Pout* are the input and output power signals, respectively.

The total gain of SHFA is given by [105]:

$$G_{SHFA} = G_{EDFA} * G_{RFA} \quad (3.2)$$

Where G_{SHFA} is the total gain of SHFA that results from cascading an EDAF and RFA on a single path**.** AG_{RFA} is the gain of the RFA; $G_{EDFA}$is the gain of EDFA. The SHFA gain is expressed in (dB) as:

$$G_{SHFA}(dB) = G_{EDFA}(dB) + G_{RFA}(dB) \quad (3.3)$$

Moreover, several parameters associated with amplifier gain are utilized to evaluate the gain performance, like; average gain, gain variation, gain bandwidth and gain saturation. These parameters can be interpreted as follows.

3.4.1.1 Average Gain

The amplifier gain can be expressed in term of average gain during certain bandwidth form ($\lambda 1$ to λn) in which the average gain equals the summation of gain values divided by the number of wavelengths entire the bandwidth as [39]:

$$Gav = \frac{G(\lambda 1) + G(\lambda 2) + \ \ldots . + G(\lambda n)}{n} \quad (3.4)$$

Where: *Gav* is the average gain of the optical amplifier, *G* (λ*1*) is the amplifier gain at certain wavelengths λ*1* and *n* is the number of wavelengths entire the bandwidth.

3.4.1.2 Gain Variation

In addition, another parameter regards to the gain of an optical amplifier is necessary to describe the gain flatness that is the gain variation which represented during certain gain bandwidth by:

$$G_{var} = G_{max} - G_{min} \quad (3.5)$$

Where: G_{var} is gain variation, G_{max} and G_{min} are maximum and minimum gain, respectively.

3.4.1.3 Gain Bandwidth

The gain bandwidth or amplification bandwidth is the width of the optical wavelength range in which high gain is available from an amplifier as shown in figure 3.3. In addition, the gain bandwidth can be defined as the full width at half-maximum (FWHM) of the logarithmic gain, measured in decibels [92].

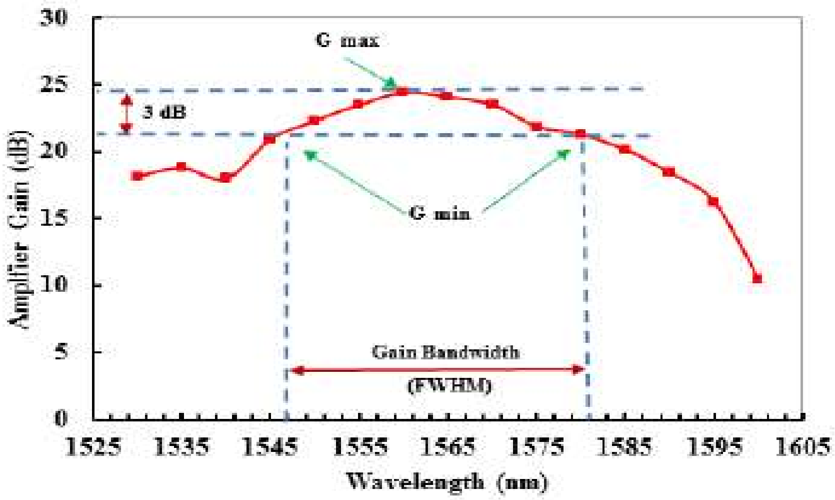

Figure 3.2 Gain parameters used to evaluate the amplifier gain [92].

3.4.1.4 Gain Saturation

The gain saturation occurs when the signal power increases, the amplifier saturates and cannot produce any more output power, and therefore the gain reduces as presented in figure 3.2. Saturation is also commonly known as gain compression. The gain saturation is occurring in RFA due to the SBS effect, when the input signal exceeds the SBS threshold, a portion of the input signal is reflected in opposite direction with shift about 0.08 nm in wavelength.

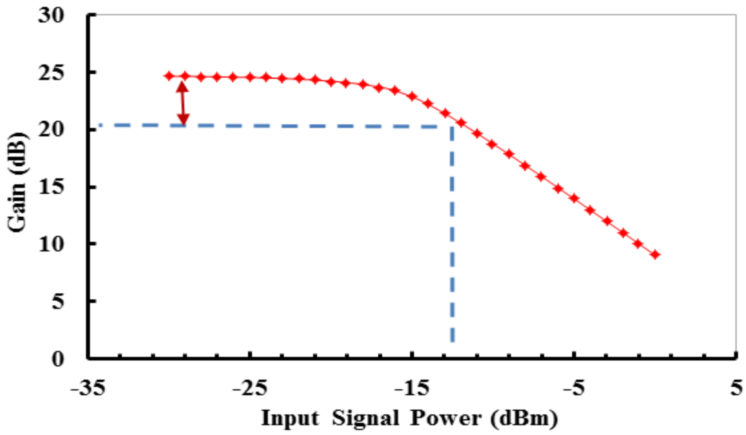

Figure 3.3 Amplifier gain saturation [92]

3.4.2 Noise Figure

The optical noise figure is a parameter utilized for quantifying the noise penalty added to a signal because of the insertion of an optical amplifier. That is before the light enters an amplifier the signal to noise ratio is SNR_{in}, after amplification it is SNR_{out}. Thus, the optical noise figure can be defined as the ratio between SNR_{in} to SNR_{out}. In other words, the noise figure represents the drop in signal to noise ratio for the optical amplifier.

The noise figure of two stages SHFA is given by [125]:

$$NF_{SHFA} = NF_1 + \frac{NF_2 - 1}{G_1} \qquad (3.6)$$

Where $NF_{SHFA}$is the noise figure of SHFA, $NF_1$is the noise figure of first stage amplifier, $NF_2$is the noise figure of the second stage amplifier and $G_1$is the gain of the first stage amplifier. Equation (4.3) shows that the NF of two stages cascaded amplifier is dominated by the noise figure of the first stage [95].

3.5 Simulation Software tools

The optical design for S-HFA is simulated via OptiSystem-7. Optisystem is an advanced vectorial fiber simulator tool that takes into account all important phenomena, including fiber loss, chromatic dispersion, birefringence, polarization mode dispersion (PMD), Kerr non–linearity and amplified spontaneous emission accumulation .

Optisystemis capable of calculating more than 15,000 km of nonlinear fiber with high accuracy, in a reasonable time. The fiber is simulated by solving the nonlinear Schrodinger equation using a modified version of the standard Split–Step Fourier (SSF) method, which solve the problems related to the cyclical numerical convolution effects intrinsic to the standard SSF method by implementing a true linear numerical convolution by means of component processing techniques (overlap–and–add algorithm) [93].

Optisystem is actually the fastest simulator because all the simulation components are based on a time domain computation [94]. With Optisystem, it is possible to model very closely at “real” ultra–long haul system and achieve realistic results. In addition, a continuous adjustment of the design parameters can be performed to achieve optimal results, which is difficult to perform in the hardware implementation environment because it can be costly, time-consuming and relatively inflexible.

The optical components that are utilized in simulation design, measurements, monitoring and data collection is recorded in Table 3.1.

Table 3.1 General specifications of the components used in simulation analysis.

Components	General Specifications
Tunable Laser Sources (TLS)	Wavelength: 1520 nm-1625 nm Line width: 150 kHz Power: (–30 dBm - 0 dBm)
EDF	Length: 3 m Core radius andEr doping radius:1.65 µm
EPU	Operating wavelength: 1480 nm Power: 10 mW
DCF	Length: 7 Km Effective area: 20 µm^2
RPU	Operating wavelength: 1412 nm, 1495 nm. Power: 900 mW, 350 mw
OSA	Resolution bandwidth: 0.01 nm
WDM/WSC	Wavelength: 1480 nm / C+L-band Wavelength: 1495 nm / L-band
VOC	Operating Wavelength: 1520 nm –1630 nm Maximum Insertion loss: 0.4 dB
WDM Transmitter	Modulation type: RZ Bit rate: 40 Gbps Freq. Spacing: 250 GHZ
Optical receiver	PIN photodiode
MUX	input ports: 22
SMF	Length:44 km

3.6 Investigation and Optimization of Pump Parameters

The OPP for the fiber amplifier is defined as the pump power in which the longest 3–dB flat gain bandwidth, reasonable Gavg, proper noise figure (NF) and lowers Gvar are achieved. In order to determine the optimum pump power for the fiber, the gain profile is investigated in the small signal region. The Pin is set at –30 dBm and the signal wavelength (λs) is tuned from 1520 nm to 1625 nm with a step of 5 nm. The EPP is fixed at wavelength of 1480 nm with 10 mw. The wavelength of RP2 is tuned at the values of 1480 nm, 1485 nm, 1490 nm and 1495 nm at each those wavelengths, the pump power changed by range of (200 to 350 mw) with a step of 50 mw. The optimum pump power and the optimum pump wavelength for RP2 was 350 mw, 1495 nm respectively.

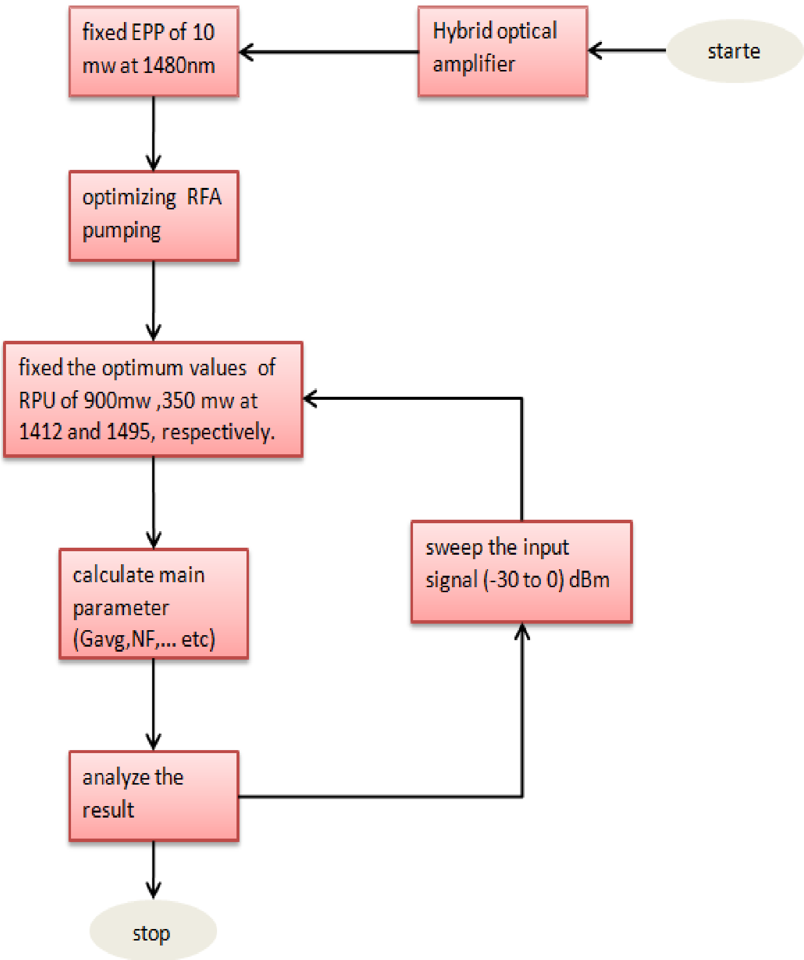

Figure 3.4 Flowchart of characteristics HFA

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The proposed design of serial hybrid fiber amplifier (SHFA) consists of cascading two amplification stages of EDFA (linear) and RFA (nonlinear). In SHFA architecture the input signal has two stages of amplification based on a single path, in other word, the output signal of the first stage used as an input signal for the second stage. Although this type of amplifier has high overall gain levels and acceptable NF, pump conversion efficiency remains deficient in the RFA stage. In this chapter, the RPP and EPP are optimized in which higher average gain with lower gain variation are obtained.

4.2Simulation Design

Figure 4.1 shows a simulation setup of wideband hybrid Erbium-doped/Raman fiber amplifier utilizing the multi-pump for Raman amplifier. The hybrid gain is a combining of gain mediums for C-band amplification by EDFA and for both of S+L band amplification by RFA. The proposed design is composed of 3 m EDF having an Er3+ ion concentration, core radius and Er doping radius of 1000 ppm, 1.65µm and 1.65µm, respectively. EDFA backward pumped by erbium pump unit (EPU) placed at1480 nm at 10 mw was injected through wavelength division multiplexing (WDM) to EDFA. The output signal of the first stage of EDFA employed as the input to the second stage of DCF in the serial scheme.RFA consisted of a DCF with 7 km length, total loss and an effective area of 0.44 dB and 20 µm2, respectively.RFA is pumped via two Raman pump units RP1 and RP2 that coupled by pump combiner and injected to the DCF via wavelength division multiplexing (WDM).RP1 with high power of 700 mW at 1412 nm was chosen for S-band region, while RP2 is 350 mW at different wavelengths of 1480, 1485 and 1490 nm was implemented to achieve good gain flatness at L bands. Furthermore, a dual port WDM analyzer is employed to measure the gain and noise figure. In addition, an optical spectrum analyzer (OSA) was used to monitor the output spectrum of the optical hybrid amplifier scheme. The input signal power that achieved by tuneable laser source (TLS) within linewidth of 150 kHz was fixed at –30 dBm in order to make sure that both of EDFA and RFA is working under the saturation point.

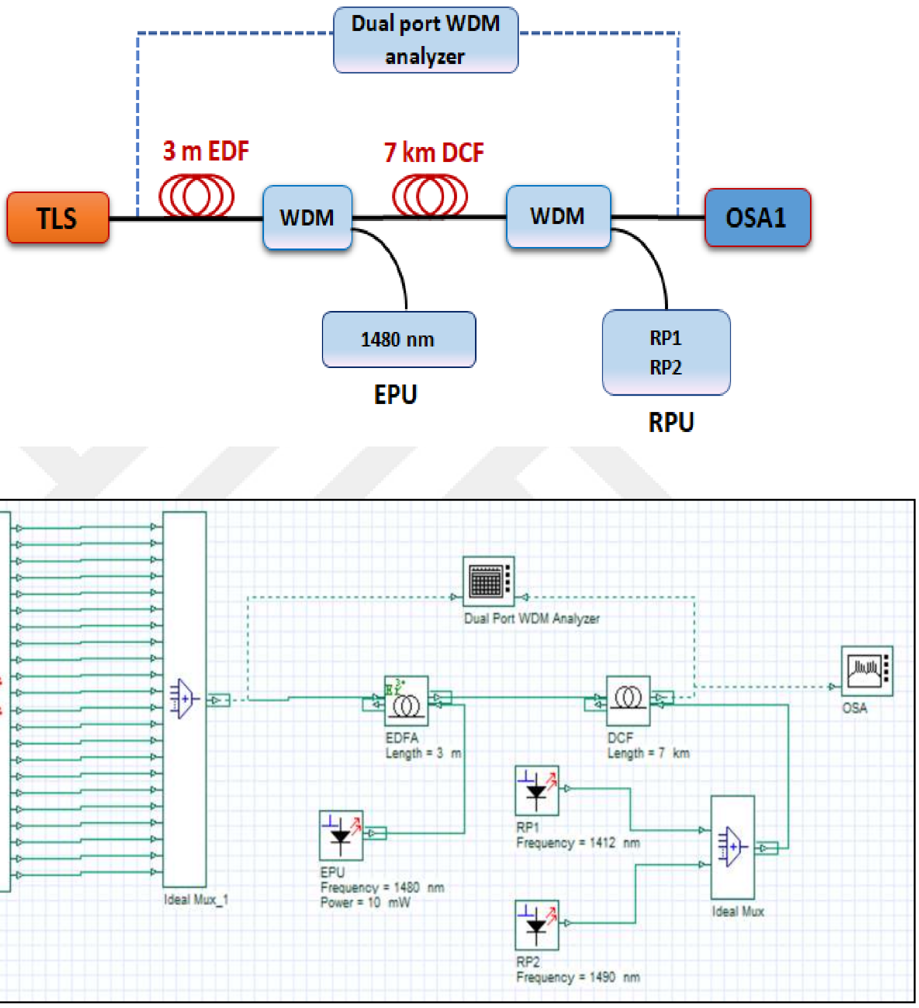

Figure 4.1 Simulation setup

4.3 SHFA with First Order Raman Scattering

At first RP1 unit of 1412 nm was investigated in term of Raman Stokes signal with the variation of RP1 powers. Figure 4.2 shows the Raman scattering as a function of RP1 powers. RP1 power was varied from 0 to 800 mW with a step of 100 mW.

Related to results obtained, the first stimulated Raman scattering (SRS) signal at 1520 nm starts to be oscillated at 400 mW then it is becomes effective at 600 mW. Increasing pump power further, first order SRS signal was saturated at 800 mW. The generated first order SRS signal achieved a good gain performance at S-band region and also boosts the erbium gain in C-band region.

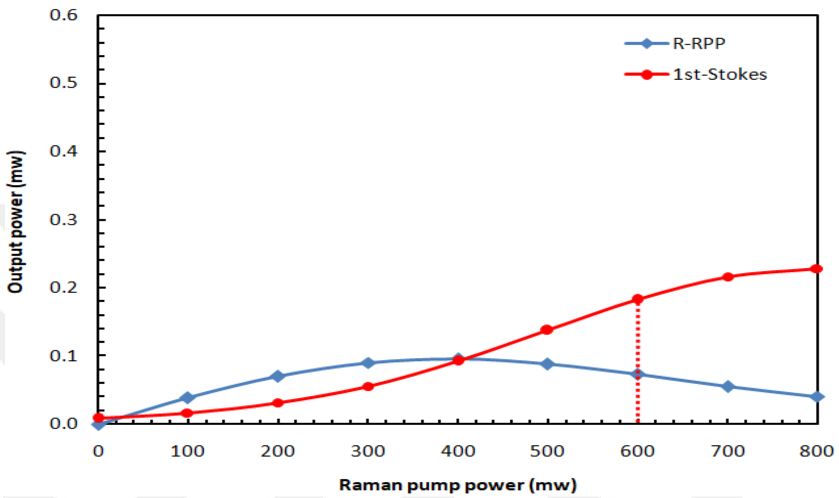

Figure 4.2 Raman peak gain as a function of RP1 power

The proposed design firstly optimized in term of Raman pump power at different Raman pump unit wavelength. RFA has been examined at different wavelength as well as the produced noise figure. The input signal power was fixed at –30 dBm, while the input optical signal wavelength range was tuned from 1520 nm to 1625 nm with a step of 5 nm. An optimization of RP2 which related to the L-band region was presented. It was swept from 200 mW to 350 mW with a step of 50 mW at different pump wavelengths of 1480 nm, 1485 nm, and 1490 nm. These three wavelengths range were chosen to find the optimum overall gain flatness. At first, RP2 with 1480 nm was optimized by varying its power within the range of 200 to 350 mW. As depicted in figure 4.3, relatively low flatness gain bandwidth of 20 nm at 200 mW and a maximum gain flatness of 25 nm in the range of 1545 to 1570 nm were achieved for maximum power of 350 mW. Trade-off to the low flatness gain, high gain level of 21.18 dB was recorded.

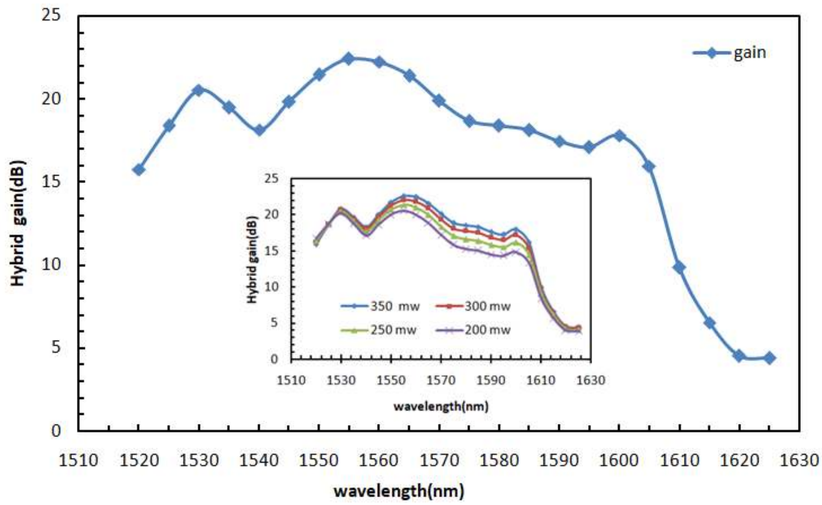

Figure 4.3 Overall gain specturm as a function of RP2 pump power for the pump wavelength of 1480 nm and at input signal power of -30 dBm.

On the other side wider gain flatness was illustrated using 1485 nm at the same pump power ranges. Up to 30 nm in the range of (1545-1575) gain flatness with lowest average gain level of 20 dB was illustrated as depicted in figure 4.4.

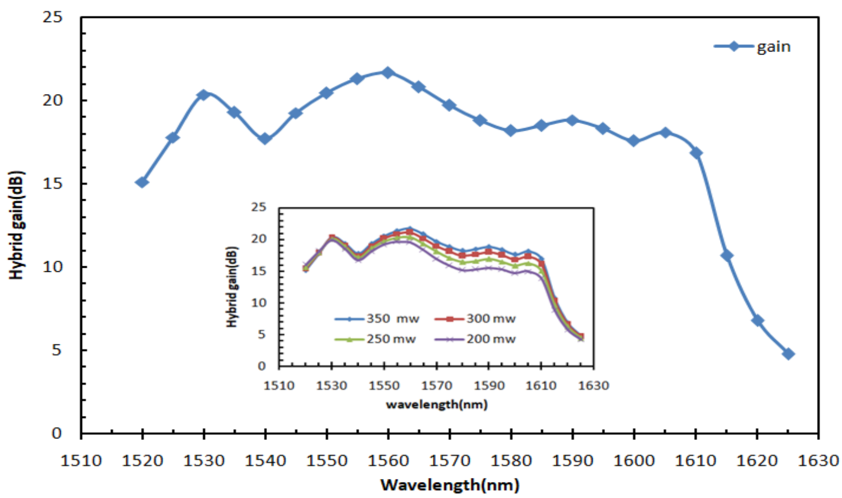

Figure 4.4 Overall gain spectrums as a function of RP2 pump power for the pump wavelength of 1485 nm and at input signal power of -30 dBm.

More improvement realized in gain flatness for all pump power range at 1490 nm. Up to 85 nm (1525-1610) as gain flatness was achived at the highest pump power of 350 mW. Again a trade-off is taken for the average gain level. In this time up to 18.5 dB as an average gain is achieved as shown in figure 4.5. In general related, inceasing the pump power at the certain Raman pump wavelength, wider gain flatness can be ahieved. In addition, shifting the wavelength of the pump power more in L-band region, resulted in expanding gain flatness range.

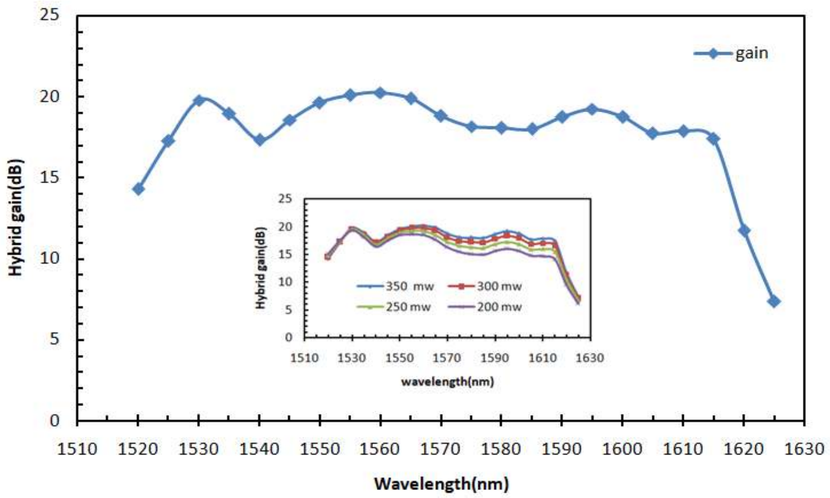

Figure 4.5 Overall gain specturm as a function of RP2 pump power for the pump wavelength of 1490 nm and at input signal power of -30 dBm..

In this context, these three different RP2 wavelengths were compared at the maximum pump power of 350 mW in terms of overall gain spectrum and noise figure as depicted in Figure 4.6 (a) and (b).The noise figure was almost same for the all pump wavelengths, that can be attributed to the RFA which was not saturated at such low input signal power of -30dBm.To clarify the obtained results, table 1 was used to illustrate the SHFA performance for these three pumps at the maximum pump power of 350 mW.

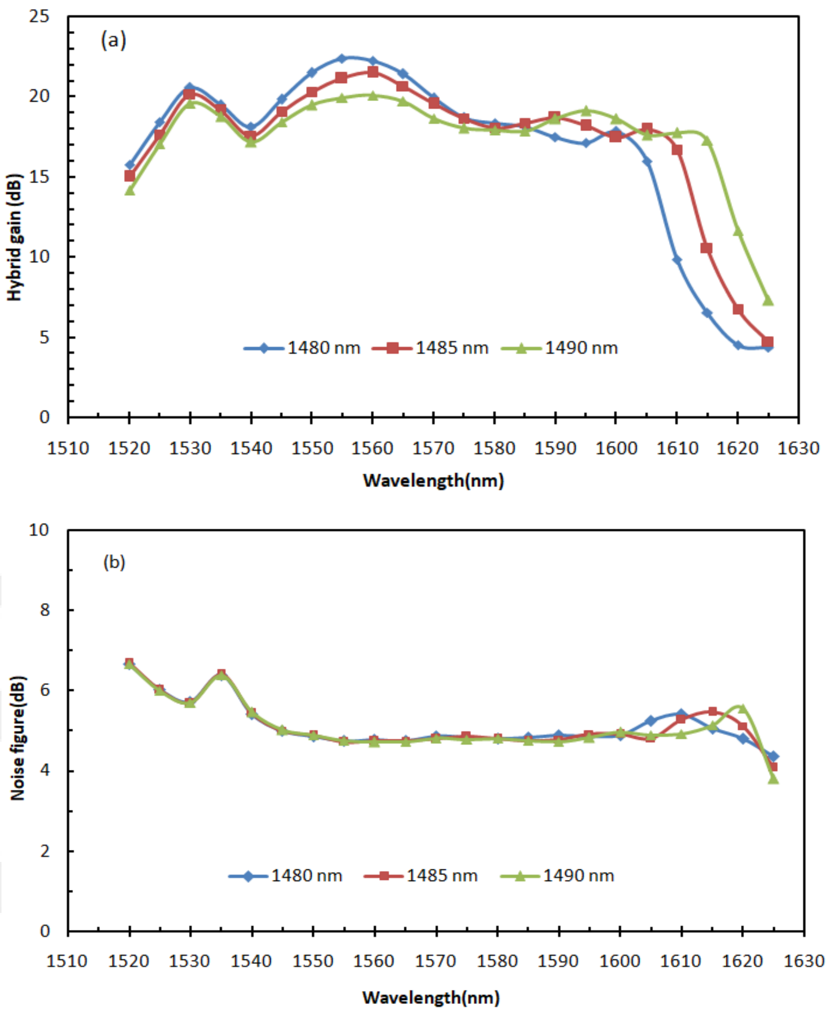

Figure 4.6 (a) overall gain spectrum (b) NF of SHFA at the maximum RP2 power of 350 mW and input signal power of -30 dBm at different RP2 wavelengths.

To clarify the results, table 1 was used to illustrate the SHFA performance for these three pumps at the maximum pump power of 350 mW.

Table 4.1 Results of the main parameters during the optimization process

RP2(nm)	Gavg. dB	Gvar. dB	NFavg. dB	GBW. (nm)
1480 350 mw	21.18	2.57	5.14	25 (1545-1570)
1485 350 mw	20.09	2.82	5.13	30 (1545-1575)
1490 350 mw	18.56	2.91	5.04	85 (1530-1615)

4.4 SHFA with Second Order Raman Scattering

More investigation study was conducted by optimized RP1 at 1412nm. Figure 4.7 shows the Raman gain as a function of RP1 powers. RP1 power was varied from 0 to 2000 mW with a step of 100 mW. According to the result, the first SRS signal was become effective at 600 mW which has a Raman peak gain at 1520 nm (almost 100 nm beyond RP1 wavelength). Increasing pump power further, second SRS stokes signal is achieved to be effective at 900 mW. This second SRS stokes has a Raman peak gain wavelength at 1600nm that can be used as a boost Raman gain in the ultra L-band region.

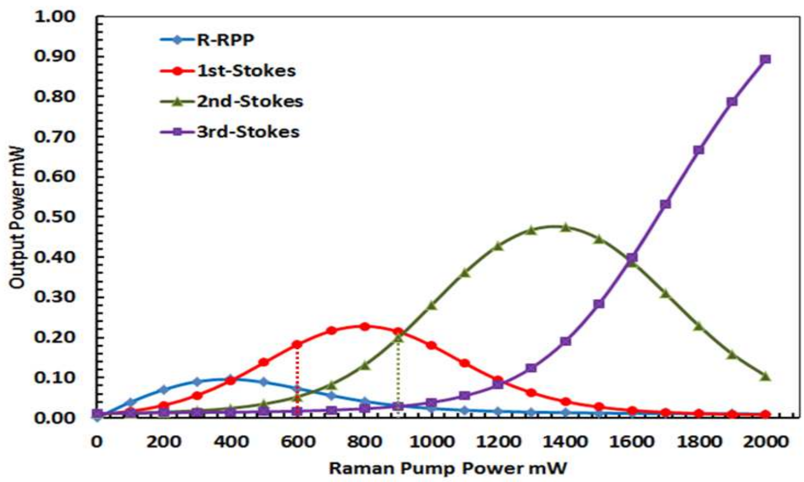

Figure 4.7 Raman peak gain as a function of RP1 power.

Regarding to the second SRS signal RP1 power optimization is conducted and the overall hybrid gain is illustrated in Figure 4.8. It can be seen from the result that at low pump power of 500 mW, the overall flatness gain was limited to 40 nm (1530-1570 nm) with an average gain of 17.6 dB. Same flatness gain was recorded at 600 mW with slightly improvement in the average gain that 18.14 dB was achieved. Significant flatness gain improvement was recorded when the pump power was increased to 700 mW. Up to 80 nm (1530-1610nm) flatness gain with an average gain of 18.6 dB were recorded. An average power of 19.16 dB and flatness gain of 90 nm (1530-1620nm) is illustrated at 800 mW of RP1. Finally, using the maximum RP1 power of 900 mW, highest flatness gain bandwidth of 98 nm (1524-1622 nm) that covers three optical communication band (S+C+L bands) and highest average gain of 19.62 dB were achieved. These results mentioned above were optimized at RP2 wavelength of 1495 nm with 350 mw.

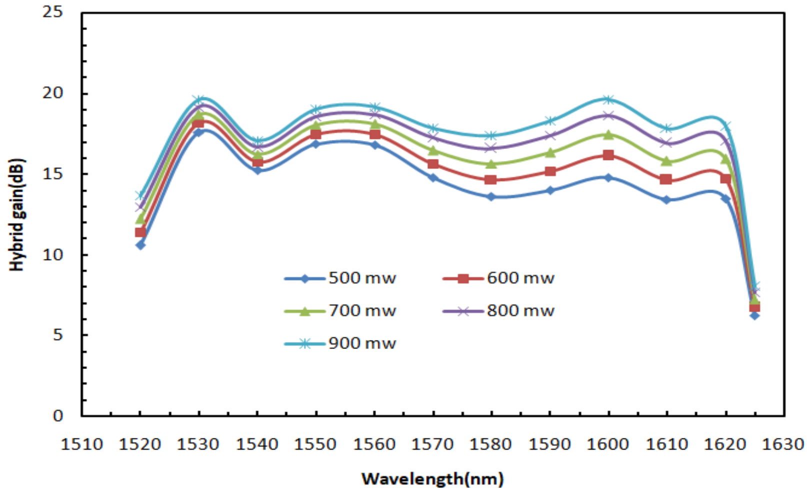

Figure 4.8 Overall gain spectrum at different RP1 pump powers.

In order to explain the obtained wide flatness gain bandwidth, Figure 4.9 presents the gain profile for each amplifier and the hybrid overall gain level at the maximum pump power for RP1 of 1412 nm with 900 mw, RP2 of 1495 nm with 350 mw and EPU of 1480 nm with 10 mw. It can be noticed that two Raman peak gain is presented; 1520 nm and 1600 nm. The first Raman peak was achieved by the first SRS caused by RP1. While the second SRS stokes signal caused by RP1 and first order SRS caused by RP2 was responsible for appearing the second Raman peak gain at 1600 nm. A normal amplification C-band for EDFA section was recorded at the maximum EPR power. As a result to the combination of these three amplification bands, wider flatness gain bandwidths in the S+C+L is achieved.

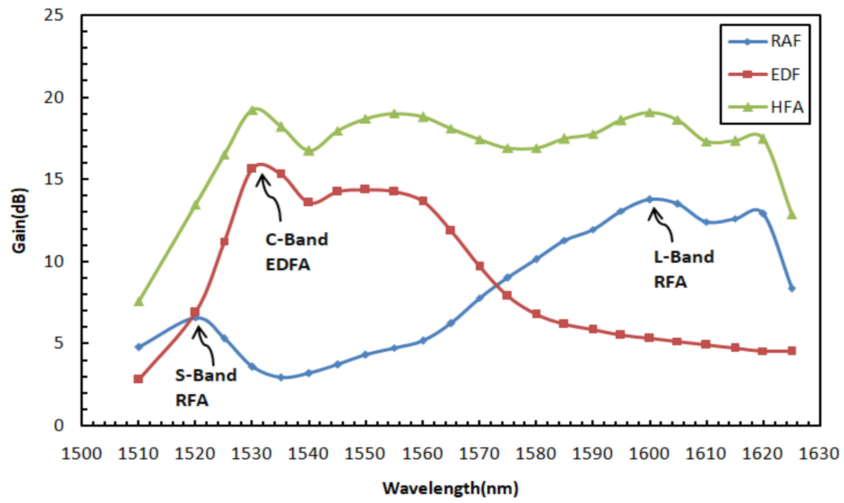

Figure 4.9 Gain characteristics of HFA, EDF and RFA versus signal wavelength at signal power of –30 dBm at the OPP.

The overall gain profile and the noise figure of the proposed SHFA at the maximum pump powervalues with small signal power of -30 dBm are depicted in Figure 4.10. Input signal wavelength is varied in the range of 1520 nm to 1625 nm. The hybrid gain profile exhibited its maximum value of 19.6 dB at 1530 nm over a Wide gain flatness of 98 nm (1524 to 1622nm) within 3-dB fluctuation. However, the noise figure was an acceptable value of 5.12 dB.

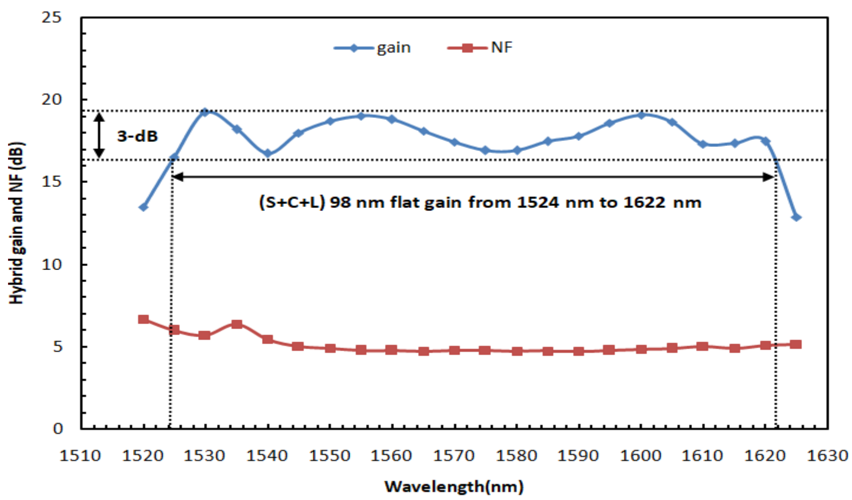

Figure 4.10 Gain and NF characteristics of HFA versus signal wavelength at signal power of –30 dBm.

Different input signal powers are implemented within the proposed design of -30 to 0 dBm in step of 5 dBm as illustrated in figure 4.11. At small Pin of –30 dBm, both of amplifiers were worked within the saturation area, which resulted in a high average gain of 19.6 dB over 98 nm gain flatness with gain variation of 2.71 dB. Same flatness gain of 98 nm at range of (1524-1622) nm was achieved using input signal powers of -25 and -20 dBm but the average gain level was decreased to 16.6 dB and 14.6 dB for these powers, respectively.Moreover, at -15 dBm, the gain average was reduced to 11.9 dB within gain bandwidth of 96 nm over a range of (1526-1622) nm. Using high signal power greater than -10 dBm, the overall gain was saturated due to the saturation in the EDFA. In addition, for input signal power more than -5 dBm, RFA will be also saturated that lead to give negative gain in the S-band region.

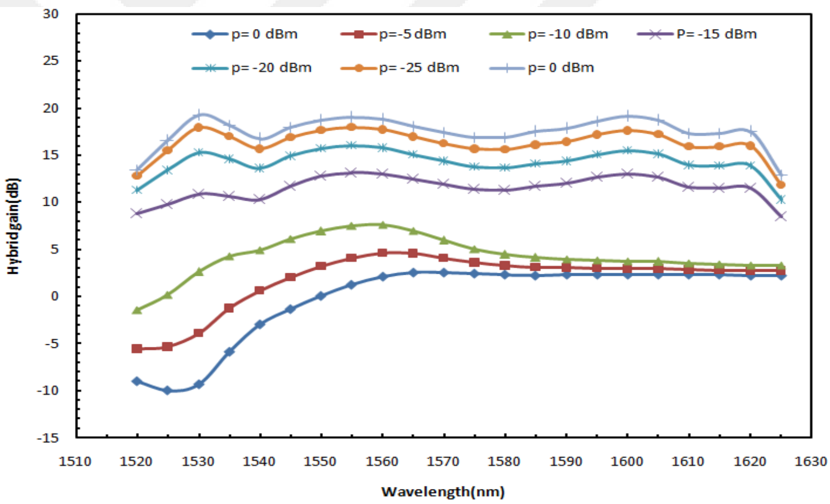

Figure 4.11 Gain profile of HFA versus signal wavele ngth at different signal power.

Moreover, the noise figure at different input signal powers for the proposed structure is illustrated in figure 4.12. Same acceptable noise figure behavior was recorded for input signal power ranges of (-30 to -15 dBm). That is because both of EDFA and RFA were not saturated yet. Two different noise figure behavior were recorded for input signal power greater than -10 dBm. At -10 dBm, slightly maximum noise figure of 10 dB was recorded at C-band region and an acceptable noise figure bout 3 dB at L band region. This is due to the EDFA saturation which responsible for C-band. Further increment in input signal power greater than -5 dBm, both of EDFA and RFA are saturated that led to worst noise figure at C-band region. The acceptable noise figure in the L-band region even for high input signal power (greater than -5 dBm) can be attributed to the gain provided by the second order Raman stokes achieved by RP1 and the first order Raman scattering achieved by RP2.

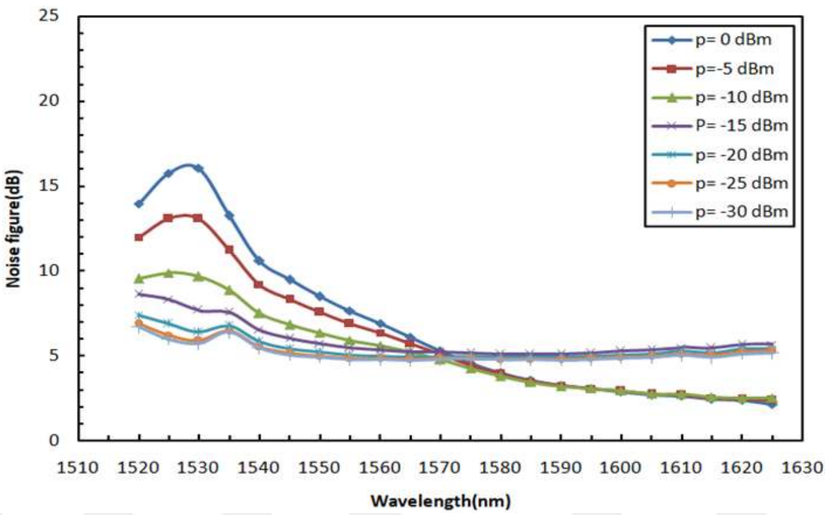

Figure 4.12 Noise figure of SHFA versus signal wavelength at different signal power.

CHAPTER 5

CONCLUSION

In this thesis, an enhancement of SHFA utilizing second order Raman scattering has been presented. Wide flatness amplification bandwidth of S+C+L is achieved. Two Raman pump units is used; RP1 with a wavelength of 1412nm and high pump power of 900 mW and RP2 at 1495 nm and 350 mW pump power. Using high pump power for RP1, first and second order Raman scattering can be generated. The first order Raman scattering can support S band region. While the second order Raman scattering can be used as a booster amplification band for L band region which assist the amplification band caused by the RP2 unit. On the other side, EDFA is implemented for achieving good flatness gain in C-band region. The proposed setup of SHFA provided broadly flatness bandwidth of 98nm (1524-1622 nm) with an average gain of 19.6 dB, gain variation of 2.71 dB and relatively low noise figure of 5.12 dB.

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