ANKARA YILDIRIM BEYAZIT UNIVERSITY

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DESIGN AND ANALYSIS OF WIDE FLATNESS GAIN BANDWIDTH BASED ON SERIAL HYBRID FIBER AMPLIFIER

M.Sc. Thesis by

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DESIGN AND ANALYSIS OF WIDE FLATNESS GAIN BANDWIDTH BASED ON SERIAL HYBRID FIBER AMPLIFIER

ABSTRACT

A flat and wide gain bandwidth based on serial hybrid fiber amplifier is experimentally demonstrated in this study. The proposed amplifier consists of a serial combination of erbium doped fiber amplifier and Raman fiber amplifier. Low pump power of 30 mW of 1480 nm pump power is used as a pump unit for erbium amplifier. While 1495 nm pump unit with maximum pump power of 475 mW is used as a pump power for Raman amplifier. At the optimum pump power values and at small input signal power of -25 dBm, a gain flatness bandwidth of 81 nm (1525-1606) with an average gain level of 25 dB is achieved. On the other side, wider gain flatness bandwidth of 100 nm (1520-1620nm) with an average gain level of 14 dB is achieved at large input signal power value of -5 dBm. The overall gain spectrum and the gain dynamic range are tested under different input signal power range. In addition, an experimental demonstration of an efficient flatness gain bandwidth is presented. A double pass serial combination of erbium and Raman fiber amplifiers is employed. A pump power unit of 1480 nm with low pump power value of 30 mW is used for erbium amplifier. While a pump unit of 1495 nm with a pump power value of 300 mW is used for Raman amplifier. Under the optimization conditions, at low input signal power of -30 dBm, a flat bandwidth gain of 77 nm from 1530 to 1607 nm with an average gain level of 27 dB is achieved. At large input signal power of -5 dBm, wider flatness gain bandwidth of 93 nm from 1524 to 1617 nm with an average gain level of 11 dB is obtained. Finally, both of gain dynamic range and the overall gain spectrum are recorded at the variation of the input signal power.

Keywords: Erbium doped fiber amplifier, Raman fiber amplifier, Serial hybrid fiber amplifier, Flatness gain bandwidth, wide amplification band.

SERİ HİBRİT FİBER AMPLİFİKATÖR BAZINDA DÜZ KAZANÇ BANT GENİŞLİĞİ TASARIMI VE ANALİZİ

ÖZ

Seri hibrit fiber amplifikatöre dayalı düz ve geniş kazançlı bir bant genişliği bu çalışmada deneysel olarak gösterilmiştir. Önerilen amplifikatör, erbiyum katkılı fiber amplifikatör ve Raman fiber amplifikatörün seri kombinasyonundan oluşur. 30 mW düşük pompa güçlü 1480 nm pompa lazeri erbiyum yükseltici için pompa ünitesi olarak kullanılır. Raman amplifikatör için pompa gücü olarak maksimum pompa gücü 475 mW olan 1495 nm pompa ünitesi kullanılır. Optimum pompa gücü değerlerinde ve -25 dBm'lik küçük giriş sinyal gücünde, ortalama 25 dB'lik bir kazanç seviyesi ile 81 nm'lik (1525-1606) bir kazanç düzlük bant genişliği elde edilir. Öte yandan, -5 dBm'lik büyük giriş sinyal gücü değerinde ortalama 14 dB kazanç seviyesi ile 100 nm (1520-1620nm) değerinde daha geniş kazanç düzlük bant genişliği elde edilir. Genel kazanç spektrumu ve kazanç dinamik aralığı, farklı giriş sinyali güç aralığı altında test edilir. Ek olarak, verimli bir düzlük kazancı bant genişliğinin deneysel bir gösterimi sunulmaktadır. Erbiyum ve Raman fiber yükselteçlerinin çift geçişli bir kombinasyonu kullanılır. Erbiyum amplifikatör için 30 mW düşük pompa güç değerine sahip 1480 nm pompa lazer ünitesi kullanılmaktadır. Raman amplifikatörü için 300 mW pompa güç değerine sahip 1495 nm'lik bir pompa ünitesi kullanılırken. Optimizasyon koşulları altında, -30 dBm'lik düşük giriş sinyal gücünde, ortalama 27 dB'lik bir kazanç seviyesi ile 1530'dan 1607 nm'ye 77 nm'lik bir düz bant genişliği kazancı elde edilir. -5 dBm'lik büyük giriş sinyal gücünde, 11 dB'lik bir ortalama kazanç seviyesi ile 1524'ten 1617 nm'ye kadar 93 nm'lik daha geniş düzlük kazanç bant genişliği elde edilir. Son olarak, hem kazanç dinamik aralığı hem de genel kazanç spektrumu, giriş sinyali gücünün varyasyonunda kaydedilir.

Anahtar kelimeler: Erbiyum katkılı fiber kuvvetlendirici, Raman fiber kuvvetlendirici, Seri hibrit fiber kuvvetlendirici, Düzlük kazanç bant genişliği, geniş amplifikasyon bandı.

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

FWM	Four Wave Mixing
DSF	Dispersion Shifted Fiber

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CHAPTER 1

INTRODUCTION

1.1 Background

In the last century, telecommunications appeared and became broadly spread around the world because of the crucial needs in many applications. For many years, copper wires were the means used. Such wires were provided efficiency only up to 10 MHz frequencies. Therefore, for higher frequencies an alternative topology is required for more efficiency. To achieve such requirements, an optical fiber with low loss was considered as one of the potential solutions. Optical fiber has been implemented in optical communication system as an optical span due to the good fiber specifications like wide bandwidth, low loss, and high bit rate. Using optical fiber as an optical signal's carrier in optical communication was firstly discovered by Alexander Graham Bell. However, it was not applied practically in real time system until better fiber characteristics has been made after 80 years.

The development of the optical devices and the optical fiber began early of 1960s while the real modification came in 1980s. Through this decade, optical communication became a dominant topology in a public communication. The development of the low loss optical fiber in 1970s and the optical amplifier in 1980s were the development key of the optical communication system to be used in real time system. Even for such good features, there are many factors that effects the optical transmission signal in optical communication such scattering, dispersion, nonlinear phenomena, and, absorption, to avoid these limitations at the receiver side, regenerate the inserted input signal is essential especially if the signal passing through long optical span. Generally, two regenerations are proposed: optoelectronics repeater and optical amplifier. By implemented an optoelectronics repeater, at first the optical signal should be converted from optical to electrical and then from electrical to optical signal again in the input and output side of the repeater respectively. The mean drawback of the optoelectronics repeater that it will limit the bandwidth of the optical communication system to the bandwidth of the optoelectronics device in addition to the complexity of the high-speed multiple channels. These limitations were not in the optical amplifier especially that the signal is regenerated optically inside the amplifier. Therefore, the researcher has been concerned more attention to improve the optical amplifier system. Firstly, an erbium doped fiber amplifier (EDFA) which is mainly cover the conventional band (C-band) in optical communication system from 1530 to 1570 nm was implemented in the optical communication system. Then the Raman fiber amplifier (RFA) was proposed to be work in long band (L-band) region. Each one of these two amplifiers has its own benefits and drawbacks. Recently, hybrid fiber amplifiers (HFAs) have been suggested as an enabling topology for dense wavelength division multiplexed (DWDM). HFAs were design that combine two or more amplifiers type in one configuration. A combination of erbium/Raman fiber amplifies were proposed by many researchers to expand both of optical span and the bandwidth of the optical communication system.

1.2 Problem Statement

Hybrid fiber amplifiers (HFAs) has been proposed to improve the performance of the optical fiber amplifier such as: extend the optical span, expand the flatness gain bandwidth, increase pump efficiency, eliminate the fiber nonlinearity, and substitute the losses caused by the optical span [1], [2]. In general, HFAs EDFA and RFA. A serial combination between EDFA and RFA was presented by many researchers and the new proposed design was known as serial HFA (SHFA) [3]–[9]. In general, the input signal in SHFA can experiences two different gain bandwidths since two different amplifier’s types are used. The input signal is amplified in the first amplifier and the amplified signal is inserted into the second amplifier stage as an input signal. However, many issues must be considered in such kind of optical amplifiers:

- Narrow flatness gain bandwidth could be obtained since the two combined amplifiers have different maximum gain level.
- Overlapping the amplification bandwidth of these two amplifiers can be resulted in faster saturation. Therefore, low gain dynamic range could be recorded.

- High Raman pump power is needed for high Raman gain to achieve wide gain flatness. This will increase the induced gain within the amplifier.

1.3 Research Objective

1. Extend the amplification bandwidth of the proposed amplifier by optimizing the two amplifiers gain level.

2. Provide a wide fatness gain bandwidth by carefully optimizing the central wavelength of the amplification band of the two amplifiers.
3. Enhance the pump efficiency by reducing the required pump power and the pump units inside the amplifier.

1.4 Scope of Research Work

In this thesis, the main aim is to achieve experimentally an efficient HFA design that can expand the optical communication bands, achieve high gain level, low noise figure, and produce wide gain dynamic range. To obtain this goal, the experimental works is divided into investigation, optimization, and improvement band on hybrid fiber topology as illustrated in figure 1.1.

A serial combination between EDFA and RFA through single and double pass configuration is experimentally implemented in this study. In both signal and double pass setups, the investigation experiment study towards the SHFA performance is first presented. Through the investigation study, the effect of the pump powers and the pump unit's wavelength on the overall amplifier performance is recorded. The investigation shows that the pump power unit wavelength can play an important role to improve the performance of the SHFA. In addition, the optimization study in terms of pump power of the pump power unit is presented for good performance such as; high gain level, wide gain flatness bandwidth, low noise figure, and wide gain dynamic range.

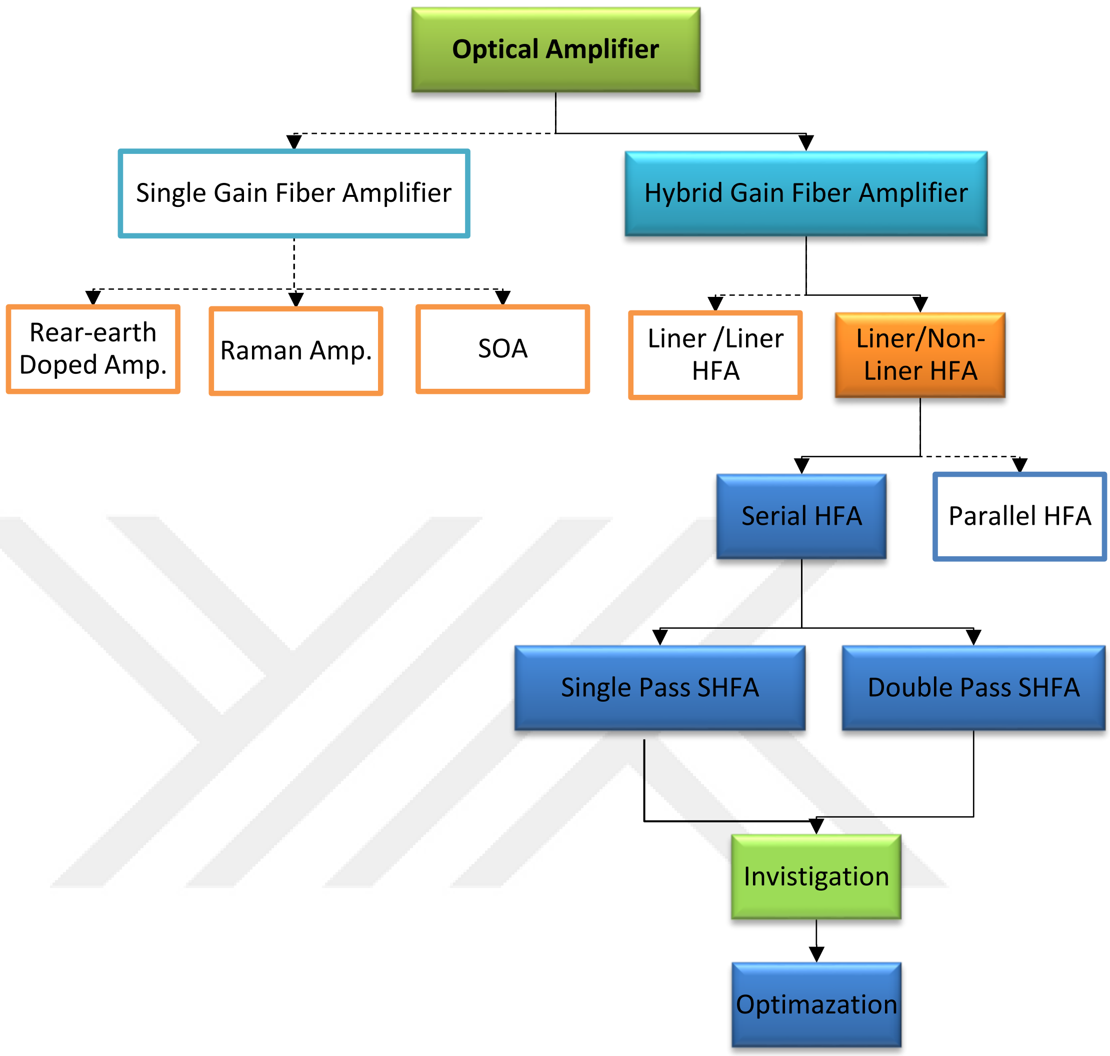

Figure 1.1 Scope of the research work

1.5 Thesis Outline

The introduction and the background of the optical communication system and the development of the optical fiber amplifier is provided in chapter 1. In addition, problem statement, research objective and the scope of the work is also discussed in this chapter.

While in chapter 2, the literature and theoretical background of the optical amplifier in terms of EDFA and RFA is presented. Many input parameters within the literature such as multiple pump power units and the pump direction in addition to the HFA classification is illustrated. Finally, a critical review of the HFA is presented in this chapter.

The general research methodology used in the conducted experimental study is presented in chapter 3. A flowcharts scheme is used to show the parameters of the input design, the research activities, and the performance parameters.

In chapter 4, the analysis of the SHFA is presented. The experimental setup of signal and double pass SHFA setups in addition to the pump power optimization are also included in this chapter. Finally, all the conducted experiment results are discussed in detail.

Based on the conducted results, chapter 5 concludes summarized the performance of the proposed amplifier setups. In addition, the recommendation for the future works is also illustrated in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter briefs the fundamental concepts of the individual erbium and Raman amplifiers. All the performance parameters such as flatness gain bandwidth, average gain level, gain dynamic range, and noise figure of the amplifier are described. It is also discussing the combination of these two different amplifiers as an HFA configuration. Finally, the critical review of the HFA is presented.

2.2 Optical Fiber Amplifier

Optical amplifier was considered as a significant milestone once it was implemented in optical communication system. That is because its ability to amplify the optical signals optically. In another word, no optoelectronic repeater is needed, and the signal will not have converted to electrical field. In addition, high bit rates of about 40-80 GB/s is applicable in case of optical amplifier [10]. Optical amplifier principal operation is mainly depending on the stimulated emission phenomenon which caused through the excitation process by the input signal power photons. To achieve such excitation process, an external laser pump (laser diode) should be used to excite the amplifier ions and to achieve a good population inversion [11]. The amount of the amplification that added to the inserted input signal power within the amplifier is called as a gain and the unit of that gain is in dB. In optical communication system, there are three types of optical amplifier according to the position within the system: booster, in-line, and pre-amplifiers as shown in figure 2.1. Booster amplifier is inserted directly after the transmitter source (Tx) to boost the input signal power inserted into the optical span (fiber transmission line) and to achieve wide transmission which may reach until 100 km [10] . In-line amplifier is inserted along the transmission link for losses compensation resulted from long propagation distance and to resend the fiber link down. While pre-amplifier type is placed just before the receiver (Rx) to increase the transmitted signal power and to improve the sensitivity of the detector.

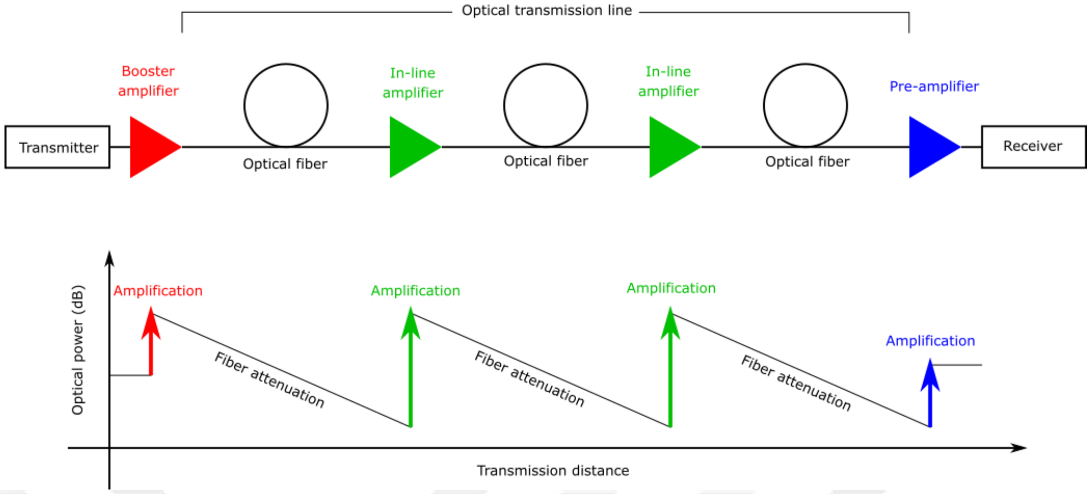

Figure 2.1 Optical amplifier categories Booster, in-line , and pre-amplifier reported by [11] .

2.3 Optical Amplifier's Types

According to the amplifier's structure, the optical amplifiers mainly are classified into two categories: fiber amplifiers and semiconductor optical amplifiers (SOAs). In fiber amplifiers (rare, the provided gain is achieved by the stimulated emission photons after the population inversion is takes place as a result to the external pump power. While the provided gain in SOAs is achieved by the injected carriers. In addition, the optical amplifier can be classified according to the characteristics of gain medium: linear gain (OSA and rare earth doped amplifier) and nonlinear gain (Brillouin and Raman amplifiers). Within the real practical applications, the optical amplifiers are selected according to its spectral bandwidth. In the range of optical band between 1.3 and 1.5µm, the amplification band for different optical amplifiers is presented as shown in figure 2.2. Obviously, wide spectral amplification bands were achieved for the most amplifier's types except of Brillouin amplifier that shows narrow amplification bandwidth up to 50 MHz that makes it not reliable in wide amplification applications [11] .

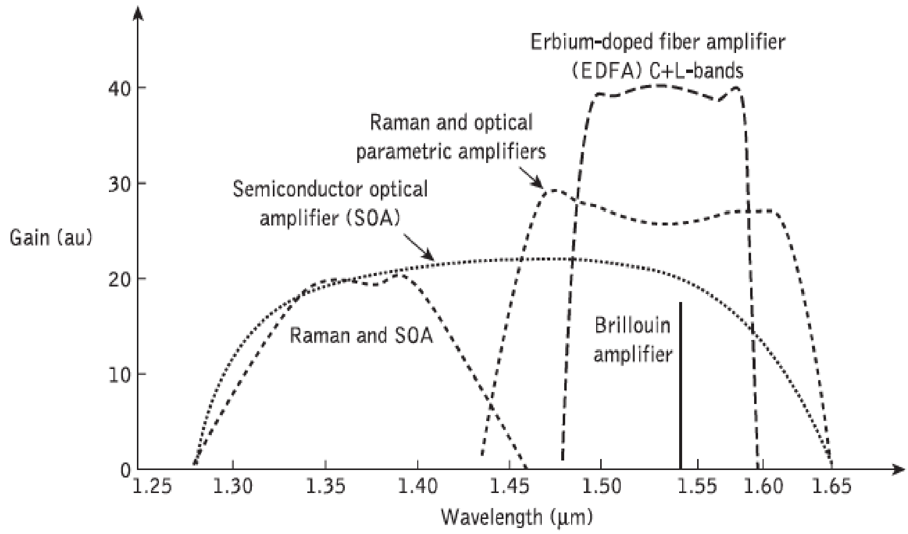

Figure 2.2 Spectral amplification characteristics for different optical amplifiers reported by [11]

In this thesis, the experimental research is concerned on the optical fiber amplifier (OFA) which are designed to achieve the wide and flat gain bandwidth in the conventional and long optical communication bands. Moreover, a combination of the two different individual amplifier's types (erbium and Raman fiber amplifiers) as a hybrid fiber amplifier (HFA) is proposed in this work.

2.4 Single Fiber Amplifier's Topologies

In WDM optical communication systems, the optical amplifiers are an essential component to compensate the optical fiber attenuation, insertion losses, and the distribution losses [12] . Generally, a single gain fiber amplifier can be classified into erbium and Raman fiber amplifiers. EDFA is considered as linear gain since the incident light is amplified within a dozen of meters due to the stimulated emission [13] . While RFA is considered as a nonlinear fiber amplifier gain. The nonlinearity in RFA is coming from the way of the amplification that mainly depends on the stimulated Raman scattering (SRS) inside the Raman gain medium that generates an additional coherent photon to the inserted light photon [14] .

2.4.1 Rare-Earth Doped Fiber Amplifier: Erbium Doped Fiber Amplifier (EDFA)

According to figure 2.2, the wide amplification bandwidth of EDFA (1500 to 1600 nm) provides an amplification without crosstalk and signal distortion in WDM communication system [12]. Therefore, it has been considered in optical communication system as a transmission amplifier. Generally, EDFAs are more suitable for C-band region (1530-1570nm). In addition, it has high gain level (up to 40 dB) and low noise figure. Unlike to C-band region, EDFA has worst performance in L-band region in terms of high noise figure[15]. In the optical system both of C- and L-bands permits the inserted optical photons to stimulate the excited atoms in the higher level to release the amplification photons [16]. Figure 2.3 illustrates the schematic configuration of the EDFA. An external laser pump power (980 or 1480 nm), erbium doped fiber (EDF), and WDM coupler to combine the inserted and the pump powers into the EDF. The function of the laser pump is to excite the erbium ions and to achieve a population inversion. Then as the inserted signal photons is lunched through EDF, a stimulated emission that amplify the input signal is occurred. Many parameters are contributed for an optimum erbium length such as pump wavelength, input signal power, erbium ions concentrations, and the value of the pump power [17]
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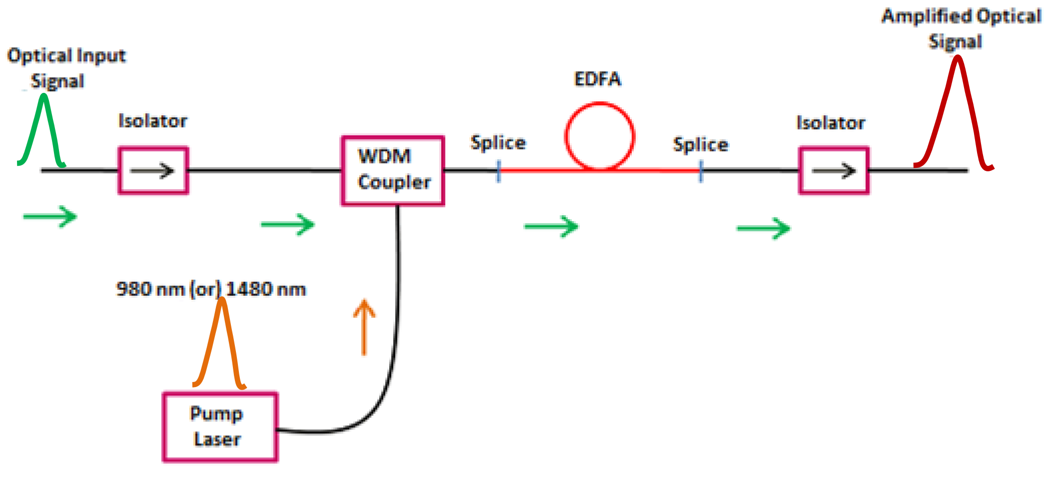

Figure 2.3 Shematic Setup of EDFA Amplifier reported by [17] .

As it mentiond two pump power values of 980 and 1480 nm are typically used in EDFAs [18] . Better gain level and noise figure could be achieved with 980 nm while better pump effeiceny could be obtained with 1480 nm [19] . Generally, high gain level of about 25 dB with a noise figure values between 4-5 dB and 6-7 dB are achieved with forward and backword pumping of 1480 nm [20].

2.4.1.1 Basic Concept For EDFA

The amplification in the EDFAs is caused by the stimulated emission that caused by the inserted input signal's photons which stimulate the excited erbium ions in the higher energy level. In the absence of an external pump power, the EDF is work like an absorber section. Once the pump power is inserted into EDF, the erbium ions can be excited into the higher gain level (level 3 or level 4) as shown in the figure 2.4 [21] . After short time, these excited ions tend to fall down spontaneously to the lower level and stay there until the input signal photons lunch to the EDF. When the input signal photons are inserted into EDF, each photon can stimulate one ion to be dropped into the ground level. While dropping a new photon that are in stimulated with the inserted input signal photon is generated and the amplification process is takes place.

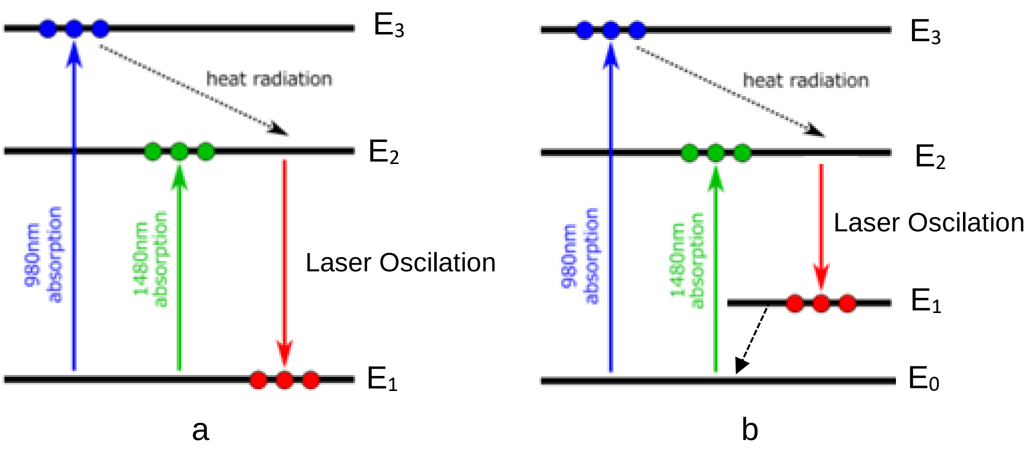

Figure 2.4 EDFA gain level system of (a) Three level (b) Four level reported by [21].

2.4.1.2 Performance of Gain Parameters

An additional gain could be provided by the population inversion ($g = \sigma(N_2\text{-}N_1)$, where σ is the transition cross–section) into the inserted input signal. The gain spectrum of the EDFA is mainly dependent on the absorption and the emission of the erbium ions and the concentration of these ions within the optical fiber. According to the wide emission spectrum of the erbium ions reported by [21], figure 2.5, EDFA considered to be used in optical communication system.

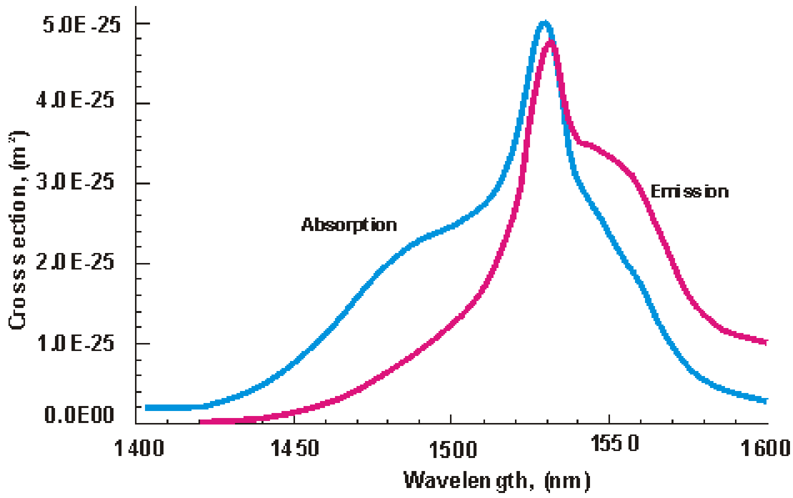

Figure 2.5 Emission and absorption spectra of an EDFA whose core was co–doped with Germania [21].

It is important to find the relation between the input signal power and the achieved gain in EDFA. Therefore, the equation of the gain was derived by [22] as below:

$$g = \frac{g_o}{1 + p/p_s} \tag{2.1}$$

Where $g_o$is the small–signal gain coefficient at a certain wavelength, p is the signal power, and p_s is the saturated signal power, at which the gain level was dropped more than 3 dB.

It is clear by referring to equation 2.1 that the provided gain in EDFA is inversely proportional to the inserted input power and at certain input signal wavelength, a saturation in the gain level is occurred. Physically this can be attributed to the large input signal photons (higher than the excited erbium ions in the higher level). So that there will be a number of input signal photons that will not stimulate any erbium ions. Subsequently, these additional photons will not produce an additional stimulated photon.

2.4.1.3 Limitations of EDFA

The main drawback of the EDFA is that there is no flat emission peak (figure 2.5) that can give a flat gain bandwidth. Therefore, for a multiple input signal wavelength there will be different gain level at the receiver side. Therefore, a multi-stage EDFAs are combined to solve this problem. However, the noise figure of such cascade systems will be an issue. In addition, the emission peak of the EDFA (1530-1570) which limited to the C-band region is another problem that makes it suitable only for this region [10].

2.4.1.4 Erbium Doped Fiber Amplifier Noise

a) Amplified Spontaneous Emission noise

The main limitation in the EDFA gain is the noise provided by the amplified spontaneous emission (ASE). The noise photons is released by the spontaneous emission of the excited photons at the higher gain level after a sufficient pump power. However, when both of signal and noise photons propagate inside the gain medium, an amplification could be occurred for both of them. Subsequently, the amplified noise of the ASE can reduce the pump efficiency and the optical signal to noise ratio (OSNR) of the amplified signal. The single mode bandwidth noise was presented by [23] as:

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

The noise is linearly proportional to the gain of the amplifier.

b) EDFA Noise Figure

For the system performance of the amplifier, equation 2.2 does not giving an accuracy information. The important limitation factor of the noise is related to OSNR of both of the input and the amplified signals as presented in [13]:

$$NF_{EDFA} = \frac{(OSNR)_{in}}{(OSNR)_{out}} \tag{2.3}$$

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

2.4.2 Raman Fiber Amplifier

Raman fiber amplifier (RFA) is considered as an enabling topology for large bandwidth distance of DWDM communication systems. That is because good performance of the RFA in terms of simplicity, low noise characteristics, and wide bandwidth [24]. The phenomenon of Raman scattering is the transformation of a fraction of the input light into scattered light and it was firstly discovered in 1928 by C.V. Raman [25]. When the laser source is injected through a molecular medium, more than 10 % of the injected light was converted into the scattered light [26]. This nonlinear scattering phenomenon was firstly discovered in 1962 and it was known as the stimulated Raman scattering (SRS) [21].

The main advantage of the RFA that it can operate over a wide optical communication band, and this can be achieved by adjusting the wavelength of the pump power. In order to increase the optical bandwidth of the RFA, multiple pump power units can be utilized [24]. In addition, the RFA gain is non resonant, which mean that the gain for the entire fiber region is available. Besides, the amplification bandwidth of the RFA is broadband for the entire wavelength range. Generally, RFA is classified into two types: discrete and distributed Raman amplifier. In discrete Raman amplifier type the amplifier is contained in box and there is an input and the output ends. While the whole transmission line is used as a Raman gain medium in distributed Raman amplifier [27]. The length of the utilized gain medium fiber is another distinctive between these two amplifier types. Typically, discrete Raman amplifiers uses fiber length around 5 to 7 km while more than 40 km fiber is used for distributed Raman amplifier.

2.4.2.1 Basic Concept of RFA

In transmission system of the optical communication, the SRS is considered as a loss mechanism since it converts some of the incident light energy into the longer wavelength. That means the RFA can uses the pump power energy to amplify the optical signal at different wavelength [28]. The effect of the Raman scattering is the interaction between the pump light and the fiber material which subsequently caused longer shift in the wavelength from the incident pump wavelength around 100 nm shift. When a sufficient pump power is inserted to the Raman gain medium, a Raman scattering is occurred and there will be two scattering component is achieved: lower frequency shift (red shift) which known as Raman Stokes signal and higher frequency shift (blue shift) which is known as Raman anti-Stokes signals [21] [27] [28] [29]. While the transmitted pump power at the end of the fiber is called the residual Raman pump power.

Figure 2.6 illustrates the energy diagram of the mechanical quantum energy of the Raman scattering. In the process of the Raman Stokes generation, the incident pump photons excite the ground molecules to the virtual state. The Raman Stokes photons are releases when the exited molecules return to vibrational state [21]. The Raman Stokes signals are achieved since the energy difference between virtual and vibrational states is smaller than the energy difference between the ground and the virtual states. Contrary to that, within the Raman anti-Stokes process, the excited molecules are within the vibrational level. Therefore, it shows higher frequency as compared to the incident pump photons.

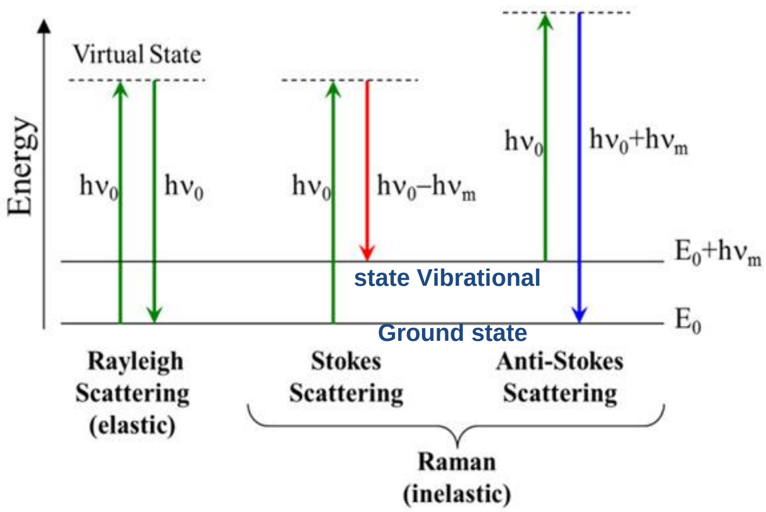

Figure 2.6 Quantum–mechanical energy diagram for Raman scattering [21].

In addition, Raman Stokes signals show higher magnitude (many orders) as compared to anti-Stokes Raman signals. This is because in anti-Stokes signals process, the initial excited molecules are started from the vibrational states that's mean high energy is required before the excitation process will take place. Therefore, the anti-Stokes signals are ignored in Raman amplifier.

2.4.2.2 Performance of Raman gain

One of the most important parameters that play an important role in the Raman gain spectrum characterization is the Raman gain coefficient g_R which is more affected by the spontaneous Raman scattering cross section. In addition, it is having vital effect on the growing of the Raman Stokes signal. In this context, the initial growth of the Raman Stokes power based on CW and quasi-CW condition is presented by [30]:

$$\frac{dp_s}{dz} = g_R P_P P_S \tag{2.4}$$

where: P_P is the inserted pump power, P_S is the Raman Stokes power, and $g_R$is the Raman gain coefficient.

For silica fibers, the g_R was measured experimentally based on SRS by [31]. The results conducted that g_R was mainly dependent on polarization between pump and Stokes signals as well as on the optical fiber composition. Based on the silica glass amorphous nature, wide Raman spectrum bandwidth of about 40 THz with a central and broad peak ling near 13 THz is observed [32].

The Raman gain coefficient for different Raman gain media (non-zero dispersion fiber, DCF, and super large area fiber) is shown in figure 2.7. These different was pumped by 1450 nm and the provided gain was near to 1550 nm. The results show that the Raman gain was more efficient in DCF is approximately 10 times with an increment factor of 7 compared to others. [25].

Generally, the gain spectrum of the Raman is mainly depending on the down shift frequency from the pump wavelength (13 THz) in 15xx region [33]. Due to this behavior, Raman gain spectrum could be existing in all of the spectral regions. That's why Raman gain is appropriate to amplify any signal wavelength by adjusting the pump wavelength.

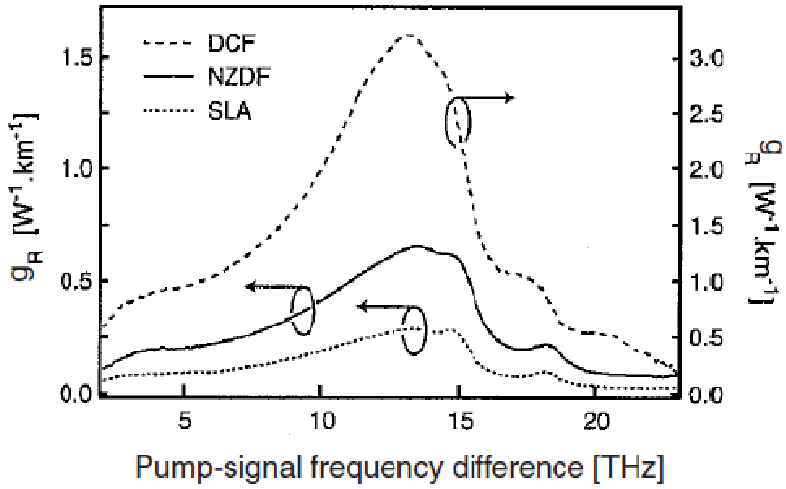

Figure 2.7 Raman gain spectra for three different fibers reproted by [25].

Based on CW, the propagation of the pump signal P_P and the signal P_S along the fiber length z in Raman amplifier was expressed by the [25]:

$$\frac{dp_s}{dz} = g_R P_P P_S - \alpha_S P_S \tag{2.5}$$

$$\frac{dp_p}{dz} = \frac{w_P}{w_S} g_R P_P P_S - \alpha_p P_S \tag{2.6}$$

where α_p, α_S are the attenuation coefficient of the pump, and signal respectively. The values w_P, w_S are the angular frequencies of the pump and signal, respectively. The parameter takes values of ± 1, depending on the pumping configuration; the minus sign should be used in the backward – pumping case.

The first term for both 2.5 and 2.6 equation represent the signal gain which is the pump depletion due to SRS. While the second term shows the intrinsic signal loss (pump). If no pump light is used:

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

Compared to the traditional EDFA, RFA has many attractive features such as low nonlinear effect, wider amplification bandwidth, and lower noise figure.

However, the gain saturation in RFA due to the stimulated Brillouin scattering (SBS) is a critical issue that needs to be solved. Therefore, many researchers were trying to solve such side effect [32] [33][34][35].

As the inserted input signal power is increased, the gain at first seems to be similar and then it is suddenly decrease due to the large input signal saturation mechanism. Therefore, it is so important for the researchers to avoid the gain saturation and not to exceed the saturation input signal level by managing the investigating the saturation parameters [35]. When the RFA is used, as the input signal power is inserted into the system and its power exceed the SBS threshold, most of the inserted power is converted into the Brillouin Stokes light. Thus, it is crucial to express the threshold equation for SBS [25]:

$$P_{SBS-th} = \frac{21\, A_{eff}}{g_B L_{eff}} \tag{2.8}$$

where: g_B is the Brillouin gain coefficient, $A_{eff}$is the fiber effective area .

Also, it is very important to find the on-off gain of RFA system at small input signal regime at which no saturation effect was takes place:

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

Referring to equation 2.9, at small input signal power regime, the Raman on-off gain is not affected by the value of the inserted input signal power and the gain remains almost constant. However, as the inserted input signal power reaches the SBS threshold value, the Raman gain is not constant anymore and the gain starts to decrease after this critical power value. Therefore, g_R is inversely proportional to the inserted input signal power after the threshold value:

$$g_R = \frac{g_0}{1 + P_s/P_{sat}} \tag{2.10}$$

Where g_0 is the maximum gain level (before the saturation) and P_{sat} is the critical saturation power. By including the fiber attenuation in g_0, the inserted signal power distribution along fiber z is [36]:

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

Clearly, by integration Equation (2.11) along the fiber length z (from z=L to z=0) and using $P_s(L) = GP_s(0)$, the saturation gain can express as:

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

where: G_0 is the maximum gain at small signal regime (before the saturation).

2.4.2.3 Noise for RFA

a) Spontaneous Raman Scattering

When the input signal is inserted to RFA, the spontaneous Raman scattering is added as noise to the input signal due to the random phases of the spontaneous photons [37]. This noise seems to be same as in EDFA except of one exception in Raman case that the phonon's population relies in the vibrational state and dependent on the Raman amplifier's temperature. However, the optical filter can be only used to eliminate the noise that lies outside the amplifier's bandwidth. Therefore, total power of the ASE in RFA system was expressed by [25]:

$$P_{ASE} = 2S_{ASE}B_o \quad (2.13)$$

where: B_o Is the filter bandwidth and S_{ASE} is the ASE spectral density:

$$S_{ASE} = n_{SP} h v_0 g_R G(L) \int_0^L \frac{P_P(Z)}{G(Z)} dz \quad (2.14)$$

Where: n_{SP} is the spontaneous scattering factor.

b) Rayleigh Backscattering

Rayleigh backscattering is considered as a side effect phenomenon in distributed Raman amplifiers that it limits the performance of the amplifier system[37][38]. In all fibers this phenomenon could be occurs and cause a fundamental loss in the transmitted signal. The high percentage of the scattered light breaks through the fiber cladding but the other part of the scattered light may combine through the fiber core in single mode fiber. Generally, the noise of the Rayleigh Backscattering light is insignificant since it has very small power value as compared to the forward signal power [39].

However, there is a possibility that this low power could be amplified through the long length of the distributed Raman fiber amplifier. The performance of the distributed Raman amplifier is influenced by the Rayleigh backscattering light in two different ways. At first, the overall noise could be improved by the in forward direction due to the propagation of the ASE backward propagation. However, this induced noise is very small and can be neglected in the Raman amplifier system. Secondly, a crosstalk component in the forward direction could be creates by the double Rayleigh backscattering signal and hold the spectral range of the signal. In general, in distributed Raman amplifier, the amplified Rayleigh noise became a major limitation in amplified Raman transmitted light signal [25]. The basic configuration of the double Rayleigh backscattering of the light signal is shown in figure 2.8.

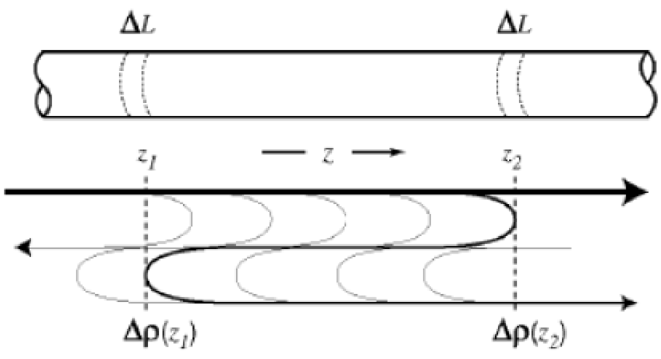

Figure 2.8 Configuration of double Rayleigh backscattering reported by [40].

Small portion of the signal is reflected at z_2 via the density fluctuation. The backward propagating noise signal is reflected to be in the forward direction due to the density fluctuations at z_1. The location of the z_1 and z_2 may vary along the fiber length and the total induced noise can be obtained by summing the noise for the different potential paths. Therefore, due to these different possible paths, the Rayleigh noise is coming from multi-path interference [40].

2.4.2.4 Pump Configuration Types

a) Single Raman Pump Unit

Figure 2.9 shows the general schematic of the distributed Raman amplifier system in which the optical span is used as a Raman gain. The input signal is propagating from the transmitter into the receiver though the optical fiber spam. Therefore, in case of co-pump, both of input and pump signals are propagating in the same direction. While in case of counter-pump, the input signal propagating in opposite direction to the pump signal. A bidirectional pump configuration could be achieved if more than one pump units are used as a co- and counter- pumps.

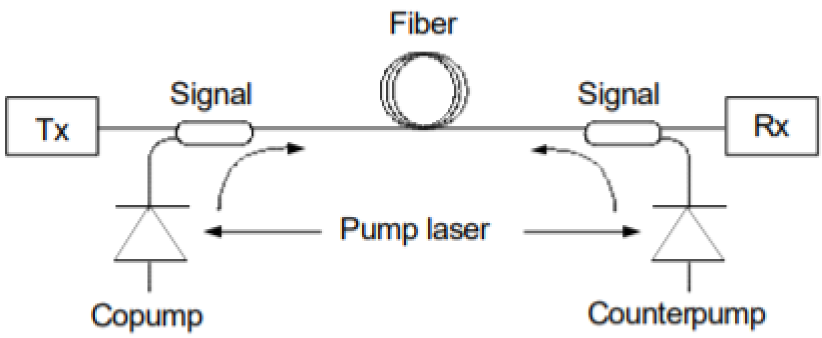

Figure 2.9 Co-counter- and bidirectional pump configration in distributed Raman amplifier reported by [34].

In the input side, the population inversion is small for forward pumping scheme that led to low ASE noise at the input side as compared to the output side. Therefore, lower noise could be achieved in forward pumping as compared to the backward pumping configuration. On the other side, higher saturation power value is achieved in the backward pumping. Subsequently, higher amplifier gain could be also achieved.

Therefore, higher gain and later gain saturation are achieved in the backward pumping compared to the forward pumping [41]. To achieve the advantages of both configurations, a bidirectional pumping scheme could be utilized so that low noise, later saturation power, and high gain level are obtained [25].

b) Multi-Raman Pump Units

With signal Raman pump unit, RFA is used for a certain amplification spectrum band depending on the Raman pump wavelength since the Raman amplification spectrum has frequency shift related to the wavelength of the pump signal. Therefore, different Raman amplification spectrum bands can be achieved by using simultaneous Raman pump units. Usually, multi-pump units are used to expand the optical bandwidth and to improve the gain flatness of the amplifier [28]. These pump units should be carefully chosen to avoid the overlap in the Raman amplification bands since the individual Raman pump unit provide a certain amplification band wavelength. Figure 2.10 shows the combination of multiple Raman pump power units, and the results conducted a flat gain bandwidth over a wide wavelength range [42].

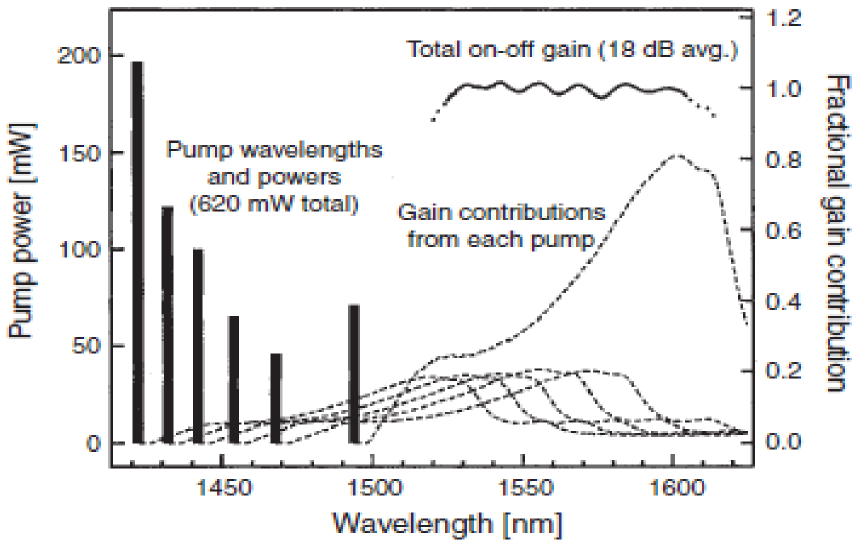

Figure 2.10 Distributed Raman amplifier with multiple-Raman pump units reported by [42].

However, to achieve such wide and high gain spectrum, high pump power is required that makes it too expensive and not applicable in real systems [28].

2.5 Hybrid Gain Media Topology

Now a days, HFAs are implementing for broadband applications instead of using costly distributed Raman amplifier with multiple pump units. Mainly two amplifier types are implemented in HFAs: RFA and EDFA [43][44][45][46][47]. Generally, the net gain provided by the HFA in serial combination is equal to the summation of the two individual gains in dB:

$$G_{HFA}(dB) = G_{EDFA}(dB) + G_{RFA}\,(dB) \tag{2.15}$$

Besides the good performance of the HFA, some of drawbacks are also observed such as induced crosstalk, transient response, intensity noise transfer, nonlinearity phenomena, and double Reyleigh backscattering [47]. Typically, EDFA is implemented in C-band region (1530-1570 nm) but this band within the DWDM system is fully utilized making such kind of amplifier unsuitable for related task. Using long EDF length was the fast solution to use such amplifier to be used in L-band region. However, high pump power is required, and low gain level was observed in addition to the high noise figure value [48]. Therefore, to increase and expand the optical bandwidth in the optical communication system, HFA topology was incorporated either by merging two linear amplifiers or nonlinear and linear amplifiers. In terms of linear-linear HFA, a combination of thulium doped fiber amplifier (TDFA), which used for C-band region, and long EDF for L-band region was proposed by[49]. While a HFA that combines nonlinear gain medium (RFA) and linear gain medium (EDFA) was proposed by many researchers as a promising technology for DWDM communication systems [50][51][52][53][54][55]. HFAs are proposed to improve the performance of the optical amplifier like expand the optical span length, reduce the nonlinearities, improve the optical bandwidth, enhance the optical gain level, and improve the pump efficiency [56][57].

2.6 Literature Review of Hybrid Fiber Amplifier.

In this section, a proposed HFAs configurations are discussed in terms of the optical amplifier performance. A wide flat amplification bandwidth was proposed by [6] based on SHFA. An optical bandwidth flat gain of 80 nm, high gain level of 26 dB and low noise figure value, less than 6 dB, were achieved. However, three amplifier stages with multiple pump units and high pump power were used that adds more cost and complexity to the design. The 1st and the 2nd order pumping were obtaining by a proposed single cavity[58]. Up to 31 nm in the C-band region with on-off gain level of 16 dB was recorded. The function of the dual pumping was to reduce the noise figure level by 1.5 dB and to improve the sensitivity of the receiver by 0.9 dB. The proposed design was tested under 80 km of SSMF span. A two Raman stages was combined serially with an EDFA by [59]. Single Raman pump unit of 1536 nm was utilized with a percentage ratio of 50%. However, narrow flatness gain bandwidth of 30 nm in the L-band region from 1610 to 1640 nm and low gain level of 14 dB were recorded.

High order pumping and bidirectional pumping schemes are implemented by many researchers [60][61][62] to improve the amplifier performance. The achieved results conducted that the utilizing such pumping schemes, both of flatness gain bandwidth and the noise level provided by the ASE were improved as compared to the backward pumping scheme. A second order Raman gain was proposed by [63] to reduce the noise figure level over a wide amplification bandwidth of 70 nm as shown in figure 2.11. The idea is to get benefit from the energy transfer that transferred from the second order to the first order pump and achieving high gain inside the fiber.

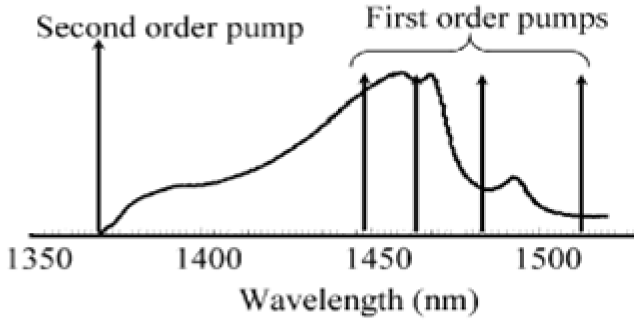

Figure 2.11 First- Second order Raman pumping reported by [63].

The idea is to get benefit from the energy transfer that transferred from the second order to the first order pump and achieving high gain inside the fiber. On the other side, same authors showed experimentally that using the second order pumping, the double Rayleigh backscattering noise was increased 2 dB as compared to first order pumping [64]. But on the other side, they observed that a significant enhancement in Q factor is achieved due to the lowest gain level noise.

For short and long transmission span length a better OSNR performance was achieved via an investigation between the bidirectional dual Raman pumping and bidirectional single Raman pumping schemes [65]. The conducted results showed that using a a suitable bidirectional dual Raman pumping, under different conditions, an optimal OSNR performance was achieved. A special fiber type with a germanium doped core and an erbium doped cladding was implemented by H. S. Seo et.at. in 2005 in HFA. Both of S-and C-bands were covered in their design. S-band region was amplified by the induced Raman gain within the core. While C-band optical signals were amplified by the stimulated radiative transition of the erbium ions within the cladding [66]. Same authors have developed their work by including L-band region in addition to the S- and C-regions by adding another laser pump to their design [67]. A discrete Raman amplifier was proposed by G. Bologninat.el in 2006 by using multi-pump units. An ON-OFF gain level of 25 dB was achieved [68]. These second order Raman pumping have combined with 1st order Raman pump and experimentally demonstrated the transmission of 8 channel with bit rate of 10 Gb/s within C-band region [69][70].

An experimental design of SHFA with a wide gain bandwidth of 100 nm from 1500 to 1600 nm and a gain variation of 5 dB was proposed by [71]. A combination of an EDFA and RFA was incorporated in this setup. In addition, a gain level of 20 dB and an acceptable noise figure range between 9 and 5 dB were recorded. However, high Raman pump power of 2.4 W were utilized. HFA setup with wide flatness gain bandwidth of 70 nm from 1530 to 1600 nm was proposed by S.K. Liaw et al. in 2008. Single pump power unit was used for the two amplifiers by splitting the pump power value into 1:29 for erbium and Raman amplifier respectively [72]. The achieved flatness gain bandwidth was under small input signal power of -20 dBm. However, a degradation in the flatness gain bandwidth of 4 and 6 dB were recorded for large input signal power of -10 and 0 dBm respectively. Liaw and Huang [8] proposed a SHFA with wide flatness gain bandwidth of 65 nm from 1530 to 1595 nm with low gain variation of 0.2 dB. The pump efficiency was improved through double pass amplification via the optical reflector. However, an array of fiber Brag grating were implemented that's add more cost and complexity to the design. Abu Bakar et. al. in 2009 proposed a HFA in which the EDFA was pumped by the 2nd order Raman scattering. Using such technique, the pump efficiency was enhanced [73]. For a year of 2010, a wide SHFA scheme was proposed by Afkhami et. el. With a particle swarm algorithm. A flatness gain bandwidth of 98 nm from 1529.2 to 1627.1 nm with a gain difference of 1.392 and 1.043 dB utilizing multiple Raman pump units of 6 and 10 respectively [74]. However, many Raman pump power were used with high Raman pump power that make such scheme out of real applications.

By 2011, an erbium-Raman hybrid fiber amplifier was proposed utilizing second order Raman pump at small input signal power of -30 dBm. A gain level of 24 dB with a noise figure value of 11 dB were recorded for the transmitted signals. However, using the internally Raman Stokes instead of using single wavelength pump power unit was the main drawback of this study [54]. A serial combination between erbium and Raman amplifier was proposed by Abu Bakar et. al., in 2013 based on SRS signal. To get better performance for C- and ultra-L-band regions, a higher order pumps are used and the SRS signals for these two different bands are realized [57]. By 2014, A. M. Rocha et al. proposed a wideband HFA scheme with single pump power unit that covers S+C bands. To find the optimal EDF length, a genetic algorithm was used, and an optimal gain level was determined [75]. A new design for HFA was proposed by M. H. Ali et. al., in which the input signal ratio was controlled. Under small input signal power regime, a flatness gain bandwidth of 60 nm from 1530 to 1590 nm. In addition, low gain variation of 1.06 and 0.77 dB were achieved for input signal power ratios of 0.4 and 0.8 corresponding to the small and large input signal powers respectively [76].Same authors have presented the effect of the cascading on the performance of the SHFA by swiping the location of the erbium and Raman amplifiers within the serial amplifier. The investigation results conducted that the overall gain saturation is more affected by the second amplifier stages while the noise figure of the amplifier is highly affected by the first amplifier stage [5].

An investigation study to show the effect of the Raman pump power direction to the serial amplifier performance was presented by [3]. The investigation showed that the backward pumping scheme was better in performance compared to forward pumping in terms of higher gain level, wider gain dynamic range, later saturation power, and lower noise figure values. They claimed that the drawback of forward pumping is due to the faster generation of the stimulated Brillouin scattering (SBS) in forward pumping.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the experimental methodology for the research study is clarified. The general procedures which used to obtain the aim of the study and the definition of the input parameters of the amplifier is presented. This chapter also briefs the specification of the utilized components along the experiment. In addition, the investigation and the optimization of the HFA are also discussed.

3.2 General Research Flowchart

Figure 3.1 illustrates the flowchart of the general research work of the proposed single and double pass SHFA. Three essential sections were discussed in this section: investigation, optimization and improvement. The investigation study is started with the determination of the amplification bandwidth of the proposed amplifier in the absence of the input signal power. Then the optimization at first is achieved thorough the variation of pump power for the used pump power units. After the optimum amplification bandwidth was achieved, an optimization in the input signal power is presented in the presence of the input signal power for the widest flatness gain bandwidth. Finally, the improvement key was achieved by choosing a proper pump wavelength of the Raman pump unit in order to avoid the overlapping in the amplification bandwidth and prevent the gain saturation in the second amplifier due to the cascading process.

3.3 The Input Parameters of SHFA

The experimental input parameters of the proposed SHFA can be classified into three categories: input signal power, input signal wavelength, and the value of the pump powers used for EDFA and RFA.

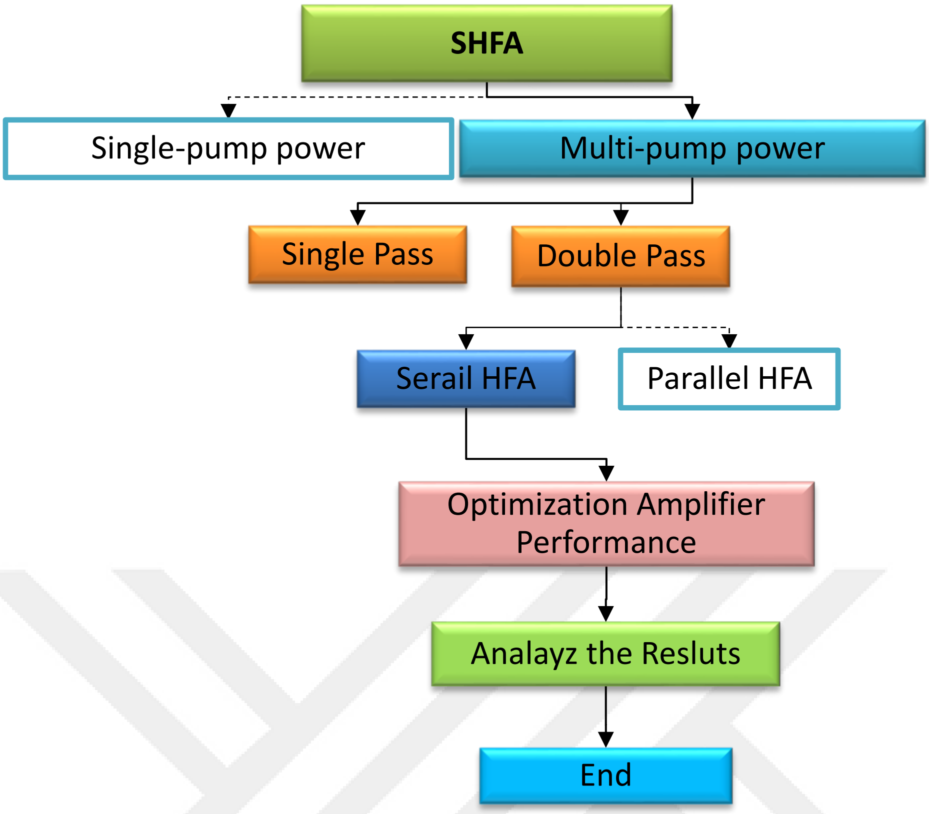

Figure 3.1 Flowchart of the general research work.

3.3.1 Input Signal Power

For the whole experiment study, the input signal power is achieved by the tunable laser source (TLS) with a power variation between -30 and -5 dBm in 5 dBm step. The variation of the input signal power is an important so that the proposed amplifier can be tested under three different input power regions: small input signal power regime, moderate input signal power regime, and large input signal power regime. Both of overall gain spectrum and gain dynamic range are tested under the input signal power variation.

3.3.2 Input Signal Wavelength

The wavelength of the input signal is also varied between 1520 and 1620 nm to measure the overall gain spectrum and to determine the flatness gain bandwidth of the proposed amplifier. In addition, the flatness gain spectrum is recorded at different input signal power regions.

3.3.3 Pump Power Level

Two pump power units are used in the proposed amplifier: erbium and Raman pump units of 1480 and 1495 nm respectively. Maximum Raman pump powers of 475 and 300 mW were used for single and double pass SHFA respectively. While an optimization is made for erbium pump power so that the widest flatness amplification band is achieved for these two amplifiers.

3.4 The Performance Parameters Of SHFA

For the SHFA, the performance parameters are considered as the efficiency and the quality of such type of amplifier design. Because the complex contribution of two different gain media (linear erbium gain and nonlinear Raman gain) within the SHFA, the performance parameters were used to optimize such gains contribution. Below is the definition of the performance parameter of the proposed amplifier:

3.4.1 Gain Level

The gain level as a factor (unit less) is defined as the ratio of the output signal to the input signal [77] and it is considered as one of the most important parameters in the amplifier:

$$G = \frac{Pout}{Pin} \tag{3.1}$$

Where: *G* is the gain, *Pout* and *Pin* are the output and the input signals power, respectively. While the gain level in dB can be expressed as

$$G_{dB} = Pout_{dBm} - Pin_{dBm} \tag{3.2}$$

The total gain of SHFA is given by [78]:

$$G_{SHFA} = G_{EDFA} * G_{RFA} \tag{3.3}$$

Where G_{SHFA} is SHFA gain factor, G_{RFA} is the RFA gain factor; G_{EDFA} is the EDFA gain factor. In the same way the SHFA gain can be expressed in (dB) as:

$$G_{SHFA}(dB) = G_{EDFA}(dB) + G_{RFA}(dB) \tag{3.4}$$

3.4.2 Average Gain Level

The average gain of the SHFA is defined as the summation of the gain level values within the spectrum bandwidth ($\lambda_1 - \lambda_n$) of the amplifier at different input signal wavelength to the number of the gain at these wavelengths [46]:

$$G_{av} = \frac{G_{(\lambda 1)} + G_{(\lambda 2)} + \ \ldots . + G_{(\lambda n)}}{n} \tag{3.5}$$

Where: G_{av} is the amplifier average gain, $G_{(\lambda 1)}$ is the gain at λ1 and n is the wavelength numbers within the spectrum bandwidth.

3.4.3 Gain Difference (dB)

The gain difference is so important in order to determine the flatness gain bandwidth of the amplifier and it can be expressed as:

$$G_{diff} = G_{max} - G_{min} \tag{3.6}$$

Where: G_{diff} in dB is gain difference, G_{max} and G_{min} are maximum and minimum gains in dB, respectively.

3.4.4 Flatness Gain Bandwidth

The flatness gain bandwidth is one of the most important performance parameters of the amplifier that is because it is measure the effective spectrum bandwidth of the amplifier. In addition, it is defined as the gain spectrum bandwidth at which the maximum gain difference should not exceeds 3 dB. Figure 3.2 illustrated the Flatness gain bandwidth reported by [79].

3.4.5 Gain Dynamic Range (dB)

The overall gain saturation for a certain wavelength could suffers from gain saturation with the increment of the input signal power at the optimum pump power values (large input signal regime). Therefore, the gain dynamic range is defined as the input signal power range at which the maximum gain difference should not exceeds 3 dB. After this critical point (input power value) the overall gain tends to be saturated in a linear function. Figure 3.3 illustrated the gain dynamic range reported by [79].

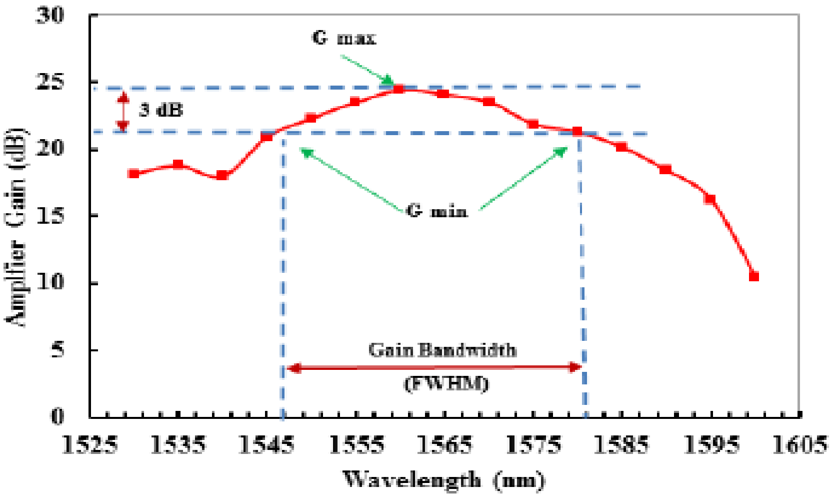

Figure 3.2 Flatness gain bandwidth reported by [79].

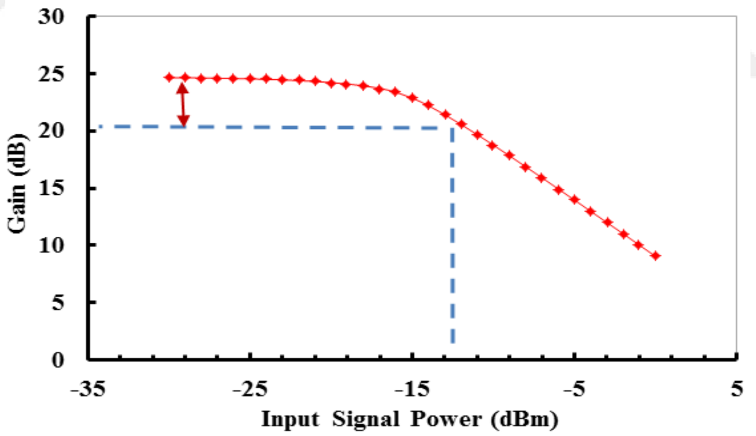

Figure 3.3 Gain dynamic range reported by [79].

3.4.6 Noise Figure Level (dB)

The noise figure (NF) is defined as the noise added into the inserted input signal power after the amplification process inside the optical amplifier. Since two amplifier types of erbium and Raman are used in the SHFA. Therefore, the NF of these two amplifiers should be expressed. The NF of the EDFA is expressed by Beker et al. 1999:

$$NF_{EDFA}(dB) = 10log\frac{P_{ASE_{(E)}}}{hvG_{EDFA}B_0} + \frac{1}{G_{EDFA}} \tag{3.7}$$

where $P_{ASE_{(E)}}$ is the amplified spontaneous emission power of the erbium, h is the Planck's constant, v is the frequency of the input signal in Hz, G_{EDFA} is the EDFA gain, and B_0 is the bandwidth of the amplification band in Hz.

In this context, the NF of the RFA is expressed by Bristiel et al. 2004 under the same parameters that related to Raman gain, amplified spontaneous emission for Raman, and the bandwidth of the Raman amplifier:

$$NF_{RFA}(dB) = 10log\frac{2P_{ASE_{(R)}}}{hvG_{RFA}B_0} + \frac{1}{G_{RFA}} \tag{3.8}$$

The NF of the single pass SHFA is given by [125]:

$$NF_{SHFA} = NF_1 + \frac{NF_2 - 1}{G_1} \tag{3.9}$$

Where NF_{SHFA} is the SHFA noise figure, $NF_1$is the first amplifier stage noise figure, $NF_2$is second amplifier stage noise figure and G_1 is the amplifier stage gain. Equation (3.9) illustrates that the overall NF of the SHFA is dominated by first amplifier noise since the NF of the second amplifier is divided on the gain factor of the first amplifier [80].

3.5 Experimental Components

The setup of the proposed SHFA is experimentally demonstrated. Therefore, it is important to list the optical components that used along the experiment works. Table 3.1 listed the optical component which are used in measuring, monitoring, and collecting the data for the entire work.

Table 3.1 specifications of the experimental components.

Components	Specifications
Erbium Doped Fiber-M5 (EDF)	Numerical Aperture 0.21 - 0.24 Absorption (dB/m) 5 – 7 @980nm 16.0 – 20.0 @1531nm Attenuation (dB/km) ≤10 @1200nm
Tunable Laser Sources (TLS)	Resolution accuracy ± 5% Wavelength resolution 0.001 nm Maximum power wavelength +14.5 dBm Relative wavelength accuracy ≤ ± 0.01 nm Wavelength range 1480-1620 nm Power: form –30 to –5dBm
Laser Diode Driver with TEC (CLD105)	Control Range 1 to 1.5A
Erbium pump unit	Operating wavelength: 1480 nm Power: up to 40 mW
Dispersion Compensation Fiber (DCF)	Model number DCM-80 Designed for SMF-28, (ITU G.652) Chromatic Dispersion -1360±10 ps/nm Fiber Length 6.8km Insertion Loss 9.0 ± 0.5dB
Raman pump unit	Operating wavelength: 1495 nm. Power: up to 475 mw
OSA	Measurement wavelength range 600 to 1750 nm Wavelength linearity ± 0.01 nm (1520-1580 nm) Wavelength reproducibility ±0.005 (for one minute) Maximum wavelength resolution 0.03nm
WDM/WSC	Wavelength: 1480 nm / C+L-band Wavelength: 1495 nm / L-band
VOA	Operating Range: 1520-1600 nm
Optical Fiber Isolators	Center wavelength: 1550nm Isolation bandwidth: $\pm 50nm$ insertion loss: 0.6dB
3-Ports Circulator	Operating Wavelength 1460nm-1620nm Isolation (dB) Port 2 to Port 1: 50dB minimum Insertion Loss (dB) Port 1 to Port 2: 0.8dB maximum Return Loss (dB) 55dB minimum

3.6 Pump Power Optimization

The optimization in the pump power is required so that widest flatness gain bandwidth, good average gain level, lower noise figure, and lower gain difference are achieved. To achieve such optimization, low input signal power is used in order to make sure that there is no saturation effect could take place. Therefore –30 dBm of the input signal power is used and the spectrum of the overall gain is recorded. Maximum Raman pump powers of 475 and 300 mW are used for single and double pass SHFA respectively. These powers are used to achieve the maximum Raman gain. An optimization is used for erbium pump power so that the flat and wide spectrum could be achieved for both amplifier configurations.

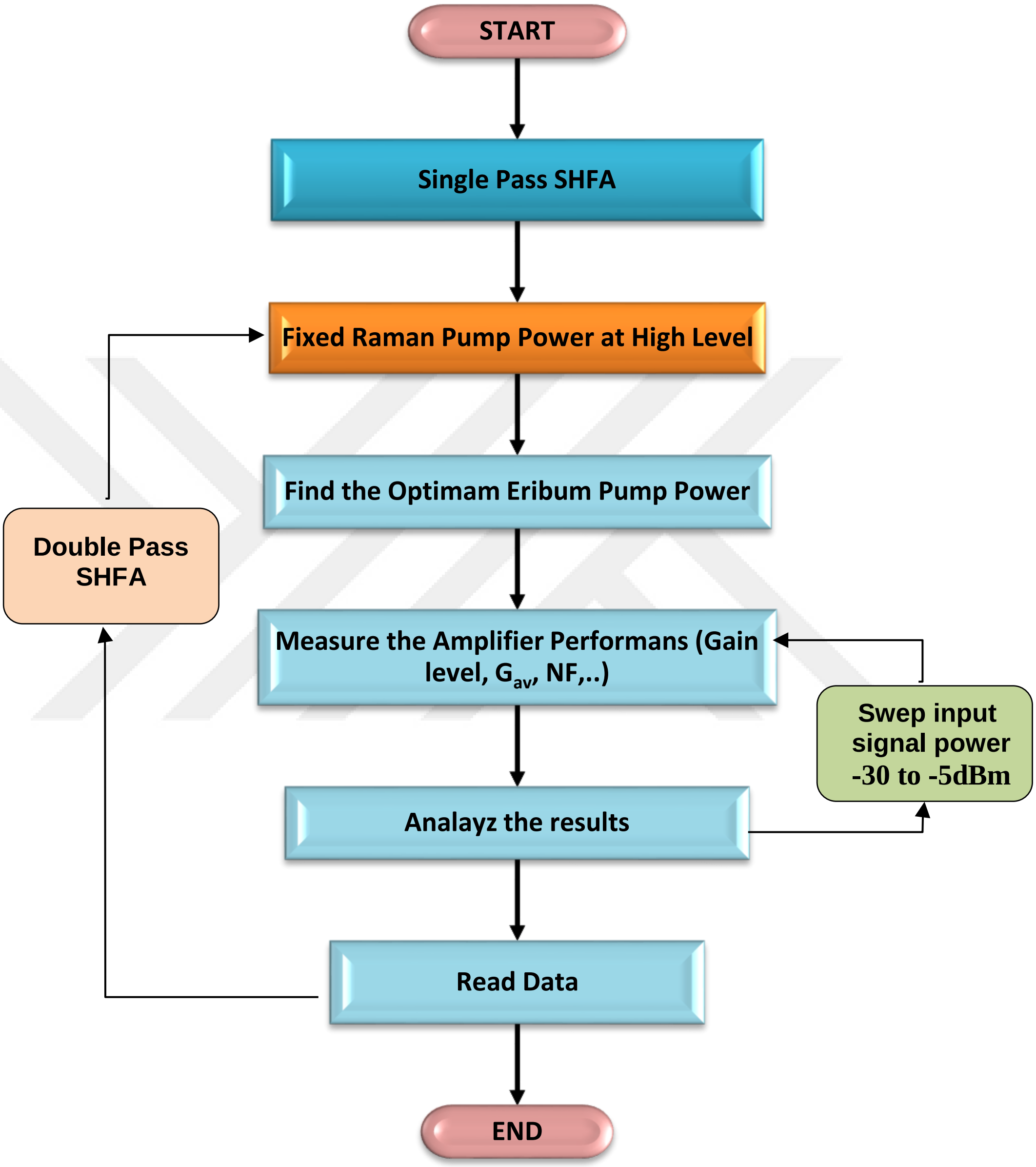

Figure 3.4 Characteristics flowchart of the prposed SHFA

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.

4.2 Expiremental Setup of Single Pass SHFA

Figure 4.1 illustrates the experimental configuration of the proposed SHFA. Tunable source laser (TSL) that has wavelength range of 150 nm (1480-1630nm) and maximum power of 14 dBm is used as an input signal. The Variable optical attenuator (VOA) is used after TSL to control the inserted input signal power into the amplifier. To extract the residual pump power after the EDF and to prevent any feedback into TSL, an optical circulator is used. The EDFA consists of 3 m of EDF (cut-off wavelength: 300 nm, Er doping radius: 1.9 μm, and Er^3 ion concentration: 440 ppm), which is backward pumped by 1480 nm. While RFA is performed by 7 km of DCF (a nonlinear coefficient of 14.5×10^{-10} W^{-1}, dispersion parameter of −110 ps/nm/km, total loss of 4.4 dB, and effective area of 18.5 μm^2), which is also backward pumped by Raman pump unit of 1495 nm.

A wave selective coupler (WSC) is used to extract the residual Raman pump power that is reflected into DCF via pump reflector to achieve high pump efficiency. The wavelength of the Raman pump unit at 1495nm is too important so it can provide peak gain at L-band region (1595, 1st order Raman scattering) in addition to tail gain in shorter wavelength (until 1570 nm) as the bandwidth of the Raman peak gain is normally 40 nm. This tail gain can assist the tail gain comes from EDFA and both can contribute to achieve wide gain flatness. The input signal from TSL is first attenuated by VOA and then inserted into EDFA. The amplified signal is inserted to RFA for the second amplification stage. In cascading process, it is known that the first amplifier could saturate the second amplifier. Therefore, two different peak amplifications bandwidth (1530-1565 nm for EDFA, and 1570-1615 nm for RFA) are used to prevent such saturation problem which caused by the overlapping of the amplification bands. Both of input and the amplified signal in addition to the noise figure are measured at the output using an optical spectrum analyzer.

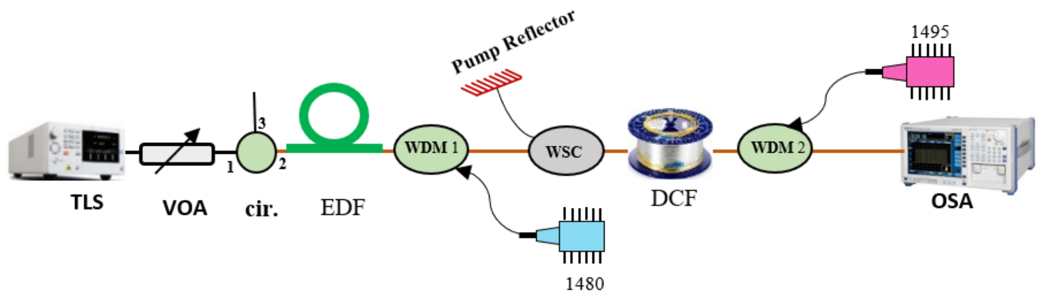

Figure 4.1 Experimental Setupe of Single pass SHFA

4.3 Experimental Results For Single Pass SHFA

The emission peak of the proposed SHFA is illustrated in figure 4.2 in the lack of TSL power. In general, measuring such peak emission because it is reflecting the overall gain bandwidth in the presence of the inputs signal power. Since EDFA gain is higher than RFA gain, therefore, an optimization was done as illustrated in figure 4.2a. Maximum Raman pump power of 475 mW was used with the variation of 1480 nm to specify the wide amplification bandwidth. The results illustrate that the optimal 1480 nm pump power was 40 mW that can achieve wide emission amplification peak band flatness. The flatness is determined as the peak difference should not exceed 3-dB. When the pump power was increased more, higher peak gain was observed at c-band region which related to EDFA, and no flatness peak gain was recorded. On the other side, figure 4.2b shows the effect of the pump power units on the amplification bandwidth. Obviously, by making 1495 nm off, no amplification peak band was observed in L-band region and only an EDFA's amplification band from 1530-1565 nm was achieved. This is because when 1495 nm was off, no peak gain at 1595 nm could be achieved. Therefore, only the tail peak gain of the EDFA was appeared at L-band region. While, by making 1480 nm off, no peak gain at C-band region was observed and the appeared peak gain was only at 1595 nm which related to Raman pump unit of 1495nm, and the low peak gain recorded at C-band region is related to the tail gain provided by the 1495 nm.

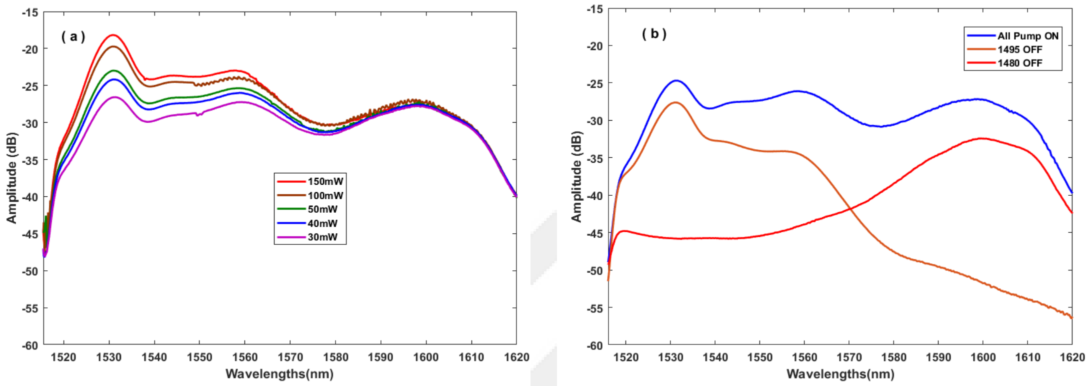

Figure 4.2 a) Amplification peak gain at 1495of 475 mW and at different 1480 pump powers. b) at optimal pump powers with different conditions.

The overall gain spectrum and the measured noise figure of the proposed amplifier was illustrated in figure 4.3. At the optimal pump power units (475 and 40 mW for 1495 and 1480 nm respectively), a broadly gain flatness bandwidth of 81 nm (1525–1606 nm), which has gain variation less than 3dB and an average gain level of 25 dB was obtained for a small input signal power of -30 dBm, as illustrated in figure 3a. The achieved flatness gain bandwidth can be attributed to the contribution of EDFA and RFA amplification bandwidth bands (figure 4.2a) which is obtained after carefully choosing of both of pump powers and wavelength. In another word, low EDFA pump power and high Raman pump power was used to achieve flat amplification peak since the Erbium gain is higher than the Raman gain. In addition, the Raman pump unit wavelength was chosen at 1495nm to prevent the overlapping between EDFA and RFA and to prevent the saturation in RFA. Clearly, low noise figure values lower than 5 dB were presented at small input signal power within the flatness gain bandwidth. That is because the noise figure is more affected by the first amplifier (EDFA) in the SHFA [13] and under low input signal power, no saturation could occur in EDFA. To show the effect of the gain saturation on the overall gain spectrum, the proposed amplifier is tested under large input signal power of -5 dBm, as shown in figure 4.3b. wider flatness gain bandwidth of 100 nm (1520-1620 nm) was obtained but in the expense of gain level that observed at 14 dB. Under such large input signal power, EDFA suffers from deep saturation but the amplified signal after EDFA can resulted in RFA saturation. Higher noise figure values were observed at large input signal power within the entire flatness bandwidth because both amplifiers suffer from saturation due to large input signal power that reduced the gain and increased the noise level at the amplified signal.

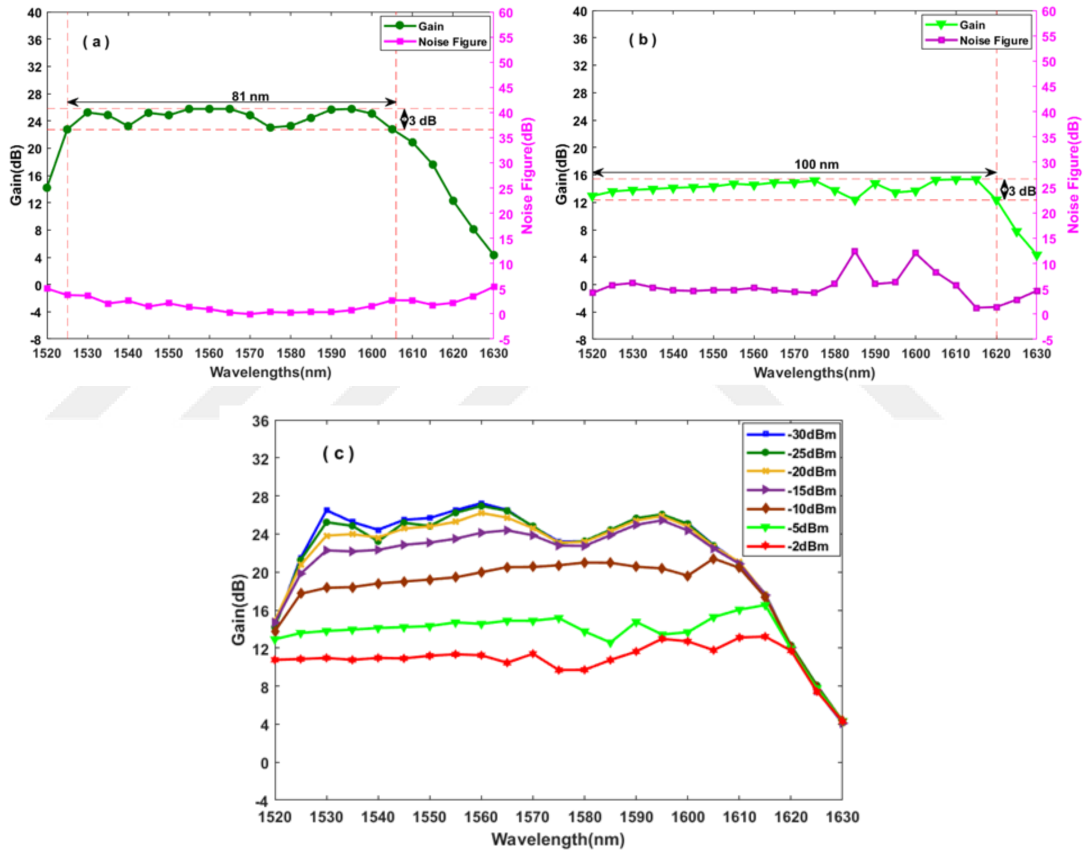

Figure 4.3 Overall gain spectrum and noise figure (a): at signal power of -30 dBm (b): at signal power of -5 dBm (c): at different input signal powers.

Figure 4.3c shows the overall gain spectrum at different input signal power ranges from -30 to -5 dBm with step of 5 dBm. Almost same flatness gain bandwidth was recorded for input signal power values -30, -25, -20, and -15 dBm with small gain level decrement. The decrement in the gain level for these different input signal power values was less than 3 dB which illustrate that the proposed amplifier can work without saturation until -15 dBm. Wider flatness gain bandwidth was recorded beyond -15 dBm but in the large degradation in the gain level value due to the saturation process

Figure 4.4 shows the spectrum of the input and the amplified signal spectrum which measured by OSA at small input signal power of -30 dBm using different input signal wavelength within the flatness gain bandwidth. The results were conducted to make sure that the proposed amplifier could achieve a significant optical signal to noise ratio (OSNR), high gain, and low noise level. Obviously, high OSNR, high gain level, and low noise level were observed for all selected signal wavelength that prove the flatness gain bandwidth, gain level, and the noise figure conducted in figure 4.4.

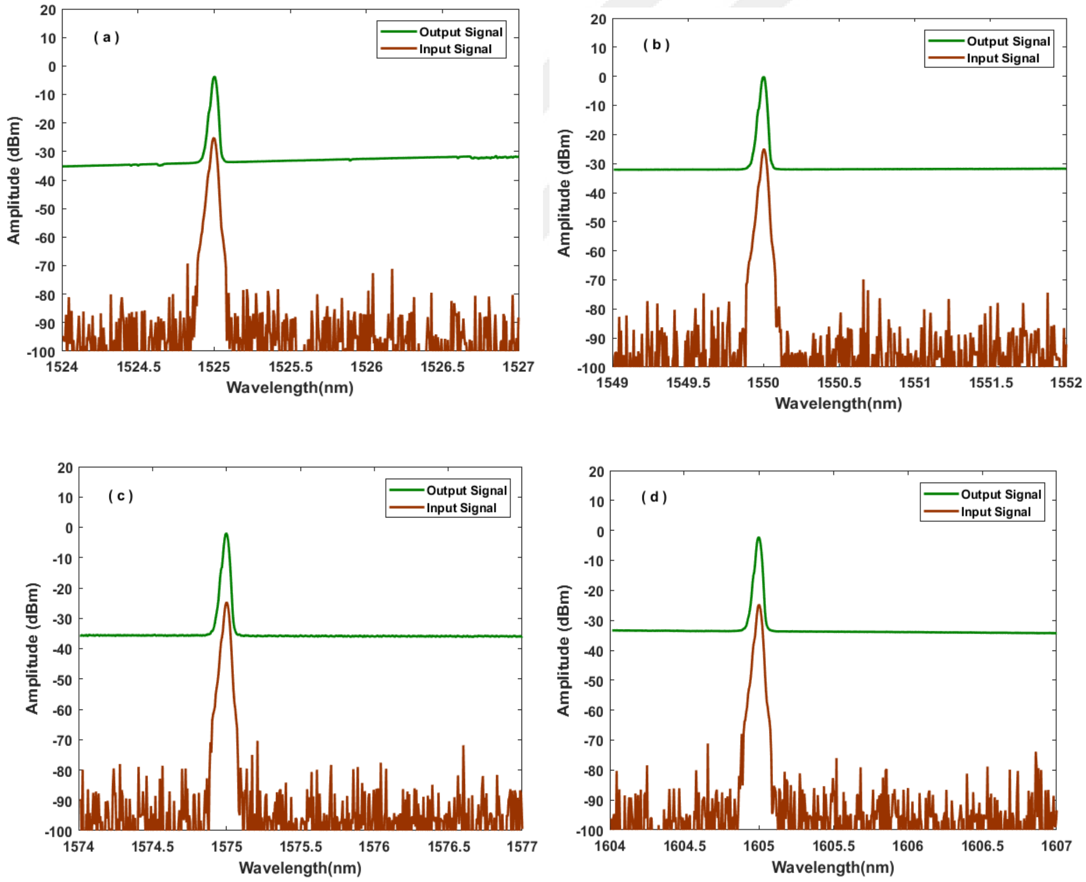

Figure 4.4 Output spectrum of the input and the amplified signals at different wavelengths

The gain dynamic range is also investigated in our proposed amplifier. This range is defined as the input signal power values at which the gain variation should not exceed 3 dB. Figure 4.5 shows the gain level as a function of input signal power for different input signal wavelength within the flatness gain bandwidth range.

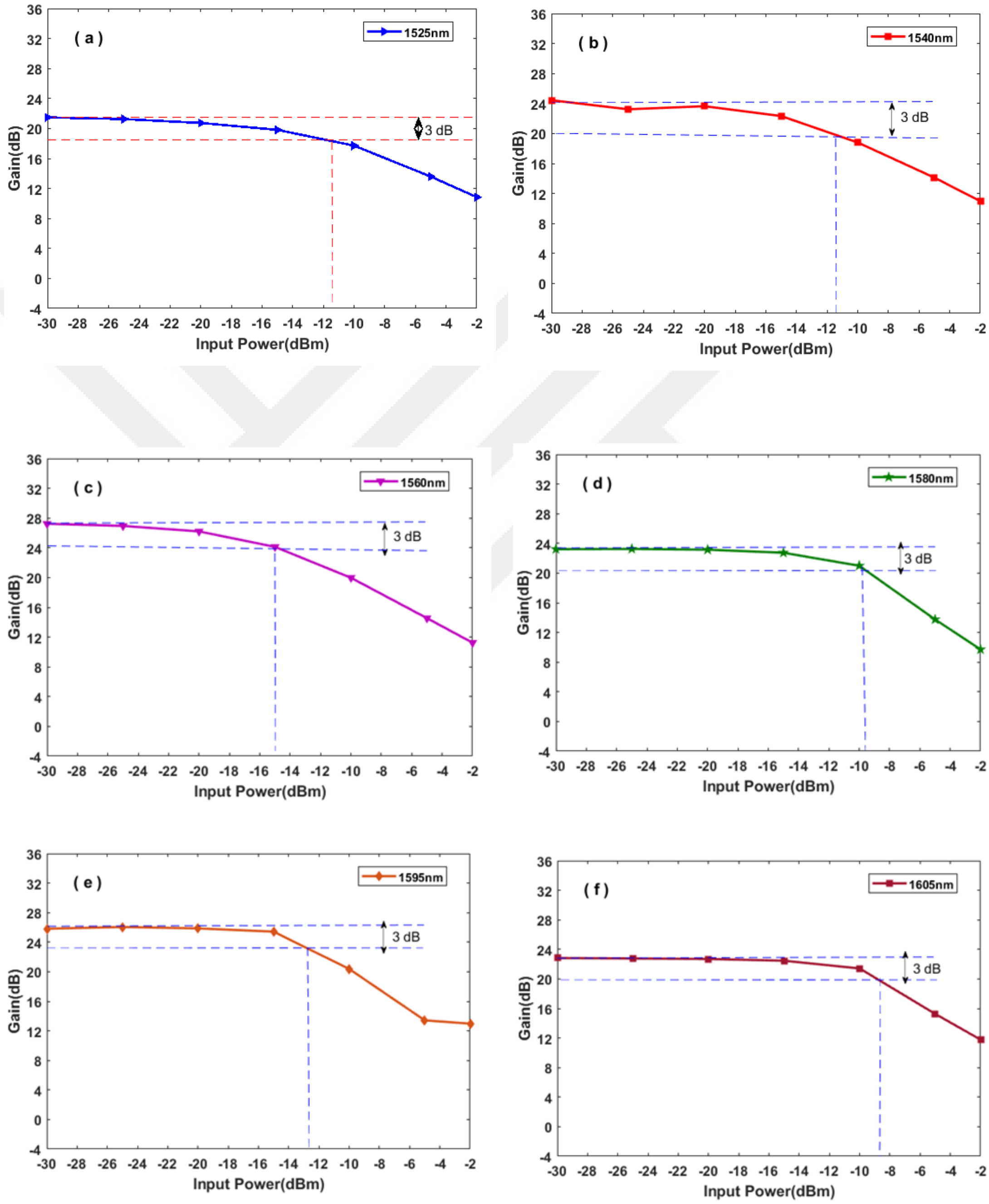

Figure 4.5 Gain dynamic range at different input signal wavelengths.

The input signal was varied from -30 to -2 dBm at 5 dBm steps. Starting with 1525 and 1540 nm (figure 4.5 a, b), the gain was saturated at -11.5 dBm. At these wavelengths erbium gain is more effective than Raman gain since the Raman peak gain is quit far. Therefore, the overall gain saturation is more affected by the erbium gain saturation. Early saturation was recorded at input signal wavelength of 1560 nm and the observed saturation power was -15 dBm (figure 4.5c). This is because this wavelength is laying in the central wavelength of the erbium emission peak bandwidth. Move away to L-band region at 1580 nm (figure 4.5d), wider dynamic range was observed, and the saturation power was at -9 dBm. The reason behind that can be attributed to the input signal wavelength which is outside of the peak gain of both of erbium and Raman amplifiers.

When the input signal wavelength was tuned to 1595 nm (figure 4.5e) narrower gain dynamic range was recorded, and the gain was saturated at -12.5 dBm. This can be attributed to the central of the Raman peak gain bandwidth at 1595 nm. Finally, as the input signal wavelength tuned to 1605 nm, the gain was saturated at -9 dBm that exhibit wider gain dynamic range as this wavelength is at the falling edge of the Raman peak gain. The results specify that the gain dynamic range is highly affected by the Raman gain rather than erbium gain until the individual amplifier suffer from deep saturation.

4.4 Experimental Setup Of Double Pass SHFA

The experimental setup of the proposed double pass SHFA is illustrated in figure 4.6. The input signal is achieved via Tunable source laser (TSL) with 150 nm (1480-1630nm) wavelength range and a maximum power of 14 dBm. The variation of the input signal is controlled by the Variable optical attenuator (VOA) so that low, moderate, and large input signal power can be obtained. The optical circulator is used for a unidirectional for both the input and the amplified signal powers. The EDFA block is formed by a pump power unit of 1480 nm with a pump power value of 30 mW along with a wavelength division multiplexer (WDM) to pump a 3m of normal EDF type (Er doping radius: 1.9 µm, cut-off wavelength: 300 nm, and Er^3 ion concentration: 440 ppm). To reduce the competition of the amplified spontaneous emission, a wave selective coupler (WSC) is used to extract the residual 1480 nm pump power out of the amplifier. While a pump power unit of 1495 nm with a pump power value of 300 mW is used along with WDM to pump a 7 km of DCF (a nonlinear coefficient of 14.5 $\times 10^{-10}$ W^{-1}, dispersion parameter of −110 ps/nm/km, total loss of 4.4 dB, and effective area of 18.5 μm^2), forming RFA block. Another WSC and a pump reflector is used with RFA block to extract and reflect the residual Raman pump power to the Raman gain media and to enhance the pump efficiency.

Due the cascading process in double pass SHFA, the central peak of the amplification bands for EDFA and RFA should be carefully chosen in order to avoid the gain saturation due to large input signal power regime. The achieved input signal from the TSL is firstly controlled by VOA and inserted into the amplifier via an optical circulator. First amplification is happened within EDFA block, and the amplified signal is inserted into RFA block for the second amplification. Another circulator is used after RFA block to achieve double pass amplification process. Now the amplified signal after RFA block is reinserted into RFA and then into EDFA to be recorded at the output side via an optical spectrum analyzer.

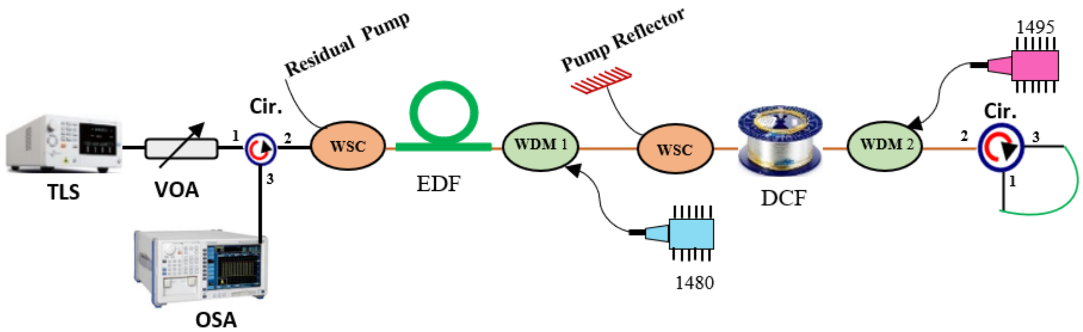

Figure 4.6 Experimental setup of the proposed double pass SHFA amplifier

4.5 Double Pass SHFA Experimental Results

Figure 4.7 shows the amplification band of the double pass SHFA in the absence of input signal power. An optimization process is made at the maximum 1495 nm of 300 mW and with a variation of 1480 nm pump power as illustrated in figure 4.7a. This optimization is done to achieve the optimal flatness amplification bandwidth of the proposed amplifier. The flatness is defined as the maximum peak difference should not exceeds 3 dB. Determining the flat amplification band in the absence of input signal power is important because it is reflecting the flatness gain bandwidth of the amplifier in the presence of input signal power. The results show that the optimum 1480 nm pump power was 30 mW. Increasing 1480 nm pump power more, higher gain was recorded at C-band region which related to EDFA peak gain, and no flatness amplification band will be achieved. Therefore, a 1480 nm pump power is chosen to be fixed at 30 mW for the entire experiment. In addition, figure 2b illustrates the pump power units' effect on the achieved amplification band.

Clearly, by making 1480 nm off, no amplification band is recorded at C-band region and a restively low amplification band is observed at L-band region (at 1595 nm: the 1st order Raman scattering introduced by 1495 nm pump power). This is due to when the 1480 nm was off, an EDF is working as an absorber section and due to the double pass propagation through EDF, C-band wavelengths were totally absorbed by EDF. While, since L-band wavelengths' a bit far from the absorption peak of the EDF, the amplification band was partially absorbed by EDF. While by making 1495 nm off, the amplification bandwidth was observed only at C-band region (the emission peak of the EDFA) and no amplification band was recorded at L-band region due to the absence of Raman peak gain.

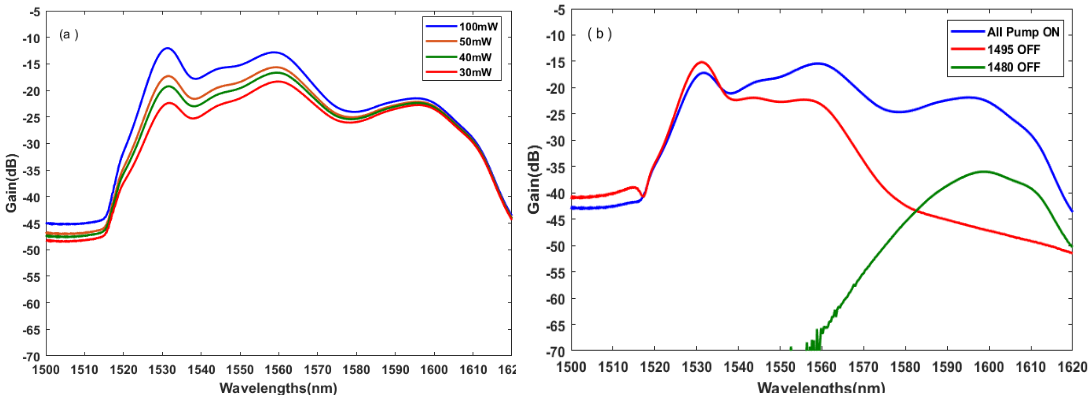

Figure 4.7 a) Amplification bandwidth at 1495 of 300 mW vs. 1480 pump power. b) Amplification bandwidth under different conditions.

Figure 4.8 shows spectrum of the overall gain and the recorded noise figure. Under the optimum pump power values of 30 and 300 mW for 1480 and 1495 respectively, a wide gain flatness bandwidth of 77 nm (1524-1607 nm) and an average gain level of 28 dB is achieved at low input signal power of -30 dBm as shown in figure 4.8a. This wide flatness bandwidth of the gain is achieved due to the contribution of the RFA and EDFA amplifications' bands.

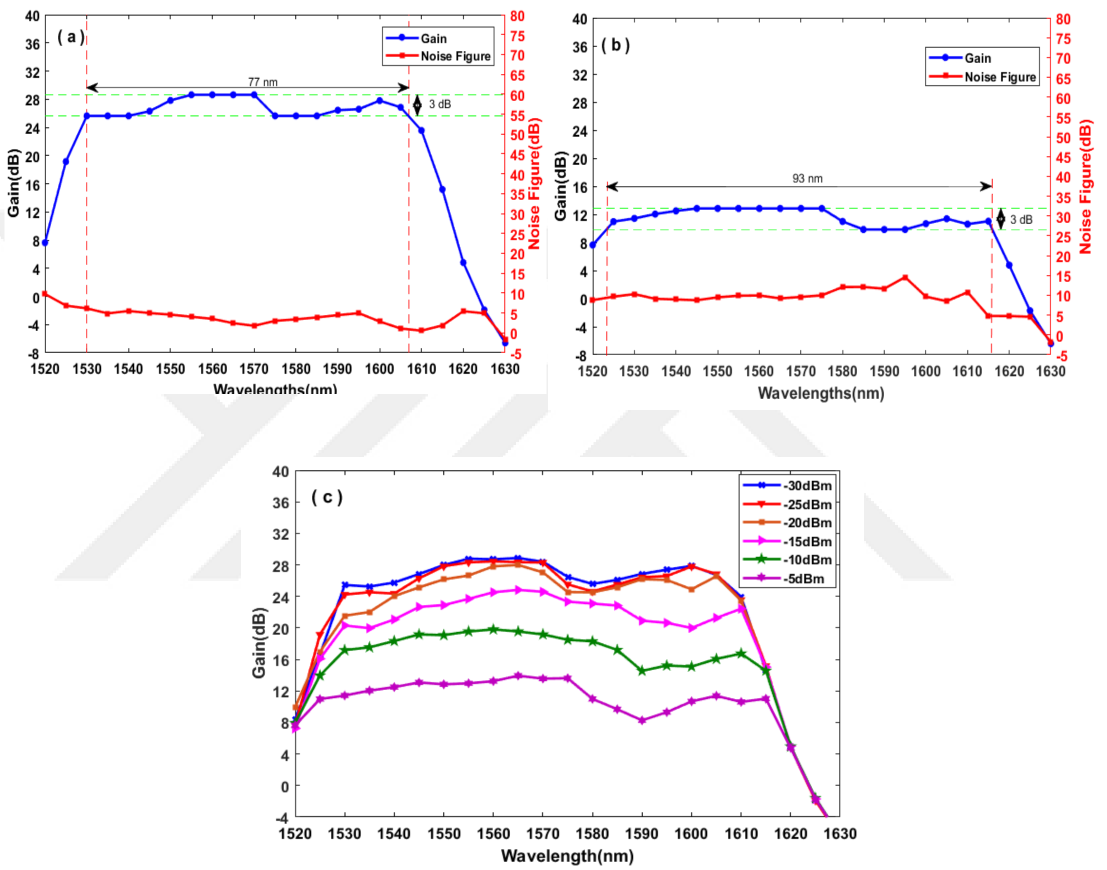

Figure 4.8 Gain spectrum (a): at small input signal power of -30 dBm (b): at large input signal power of -5 dBm (c): at different input signal powers

The amplification bands of these two amplifiers were chosen to avoid the overlapping that may causes gain saturation in the second amplifier due to large input signal power regime. In another word, the central wavelength of the Raman peak gain was chosen to be far from the central peak gain of the erbium. Hence, no overlapping could be occurring and at the same time the tail gain of the two amplifiers can be accumulated and boost each other to achieve wide bandwidth. In addition, it is known that erbium gain is higher that the Raman gain. Therefore, low erbium pump power was used to minimize the gain spectrum at C-band region. While high Raman pump power is used to increase the gain spectrum at L-band region. Within the entire flatness bandwidth, low noise figure values were recorded (almost 5 dB). The reason behind that can be attributed to the low noise figure of EDFA under low input signal regime since the overall noise figure is highly affected by the first amplifier stage [5].

The proposed amplifier is also tested under large input signal power regime to show the effect of gain saturation on the amplifier performance as shown in figure 4.8b. broader gain flatness bandwidth of 93 nm between 1524 and 1617 nm with an average gain level of 11 dB is obtained. The degradation in the average gain level is because the deep saturation of both amplifiers and the double pass amplification process. In addition, higher noise figure values were recorded within the entire flatness bandwidth due to the same reasons. More experimental results were conducted at different input signal power values. Figure 4.8c illustrates the overall gain spectrum as a function of input signal power. The input signal power value was varied from -30 to -5 dBm with a step of 5 dBm. Obviously, wider flatness bandwidth was recoded with the increment of the input signal power value but in the expense of gain level value due the saturation effect.

The spectrum of the input and the amplified signal were measured by OSA at different wavelength and at low input signal power of -30 dBm as illustrated in figure 4.9. The results showed that the achieved optical signal to noise ratio of the amplified signals, level gain, and the noise level are significant. Therefore, according to the recorded spectrums, the proposed amplifier could be involved in real time optical communication system.

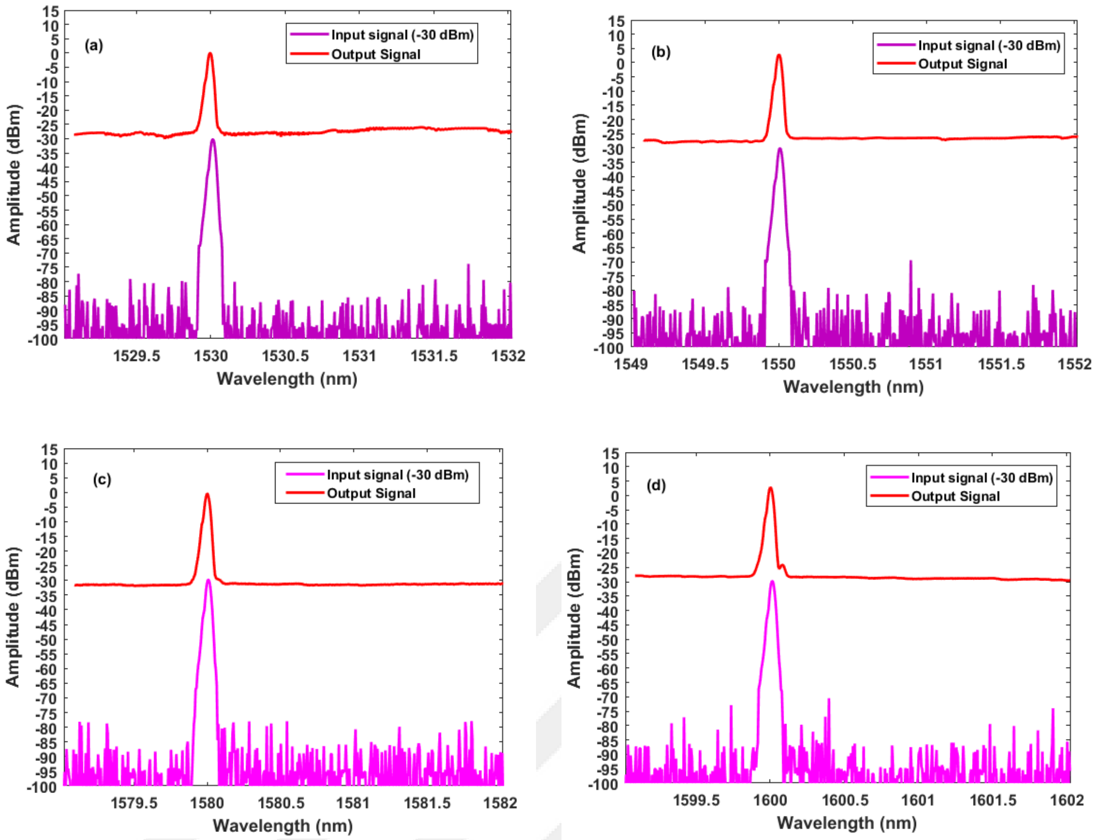

Figure 4.9 Output spectrum of the input and the amplified signals at different wavelengths.

Figure 4.10 illustrates the gain dynamic range of the proposed amplifier which is defined as the range of the input signal power in which the gain difference should not exceeds 3 dB. Different input signal wavelength values within the range of the flatness gain bandwidth were used. In the C-band region, 1530-1560, at which EDFA is more effective, the recorded input power value that caused gain saturation was -20 dBm (figure 4.10a-c). At the input signal wavelength of 1570, slightly wider gain dynamic range was recorded and the input signal power that causes a gain saturation was -19 dBm (figure 4.10d). This slight enhancement in the gain dynamic range (1 dB) can be attributed to the contribution of the tail gain of the Raman in this wavelength. Wider gain dynamic range values were recorded at longer input signal wavelength (1590 and 1600 nm) and the saturation input signal power was -17 dBm (figure 4.10e, f). This is because at these wavelengths, the overall gain saturation is mainly depending on the Raman gain saturation which is saturated after EDF gain saturation.

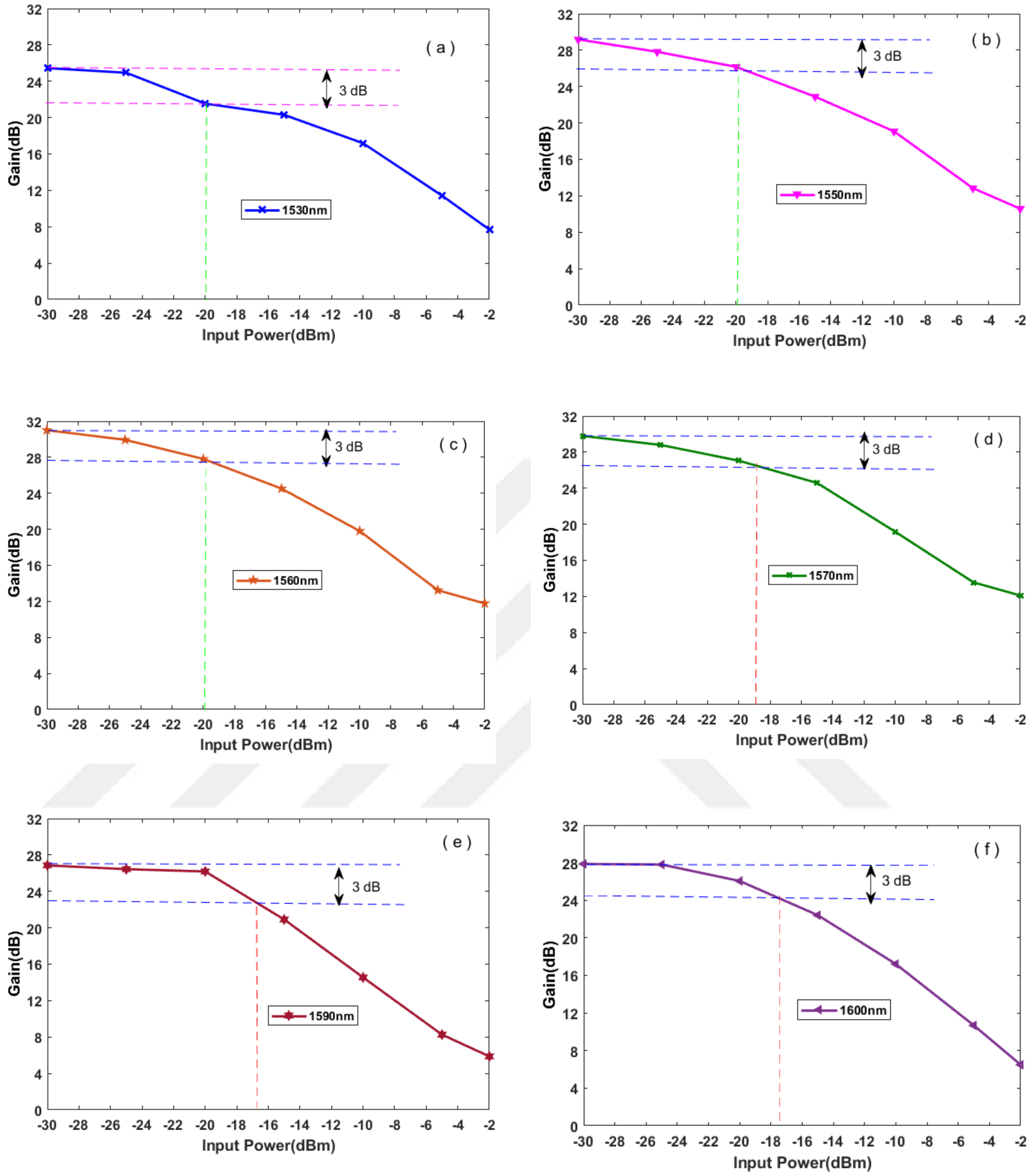

Figure 4.10 Gain dynamic range at different input signal wavelengths.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

An experimental demonstration of SHFA is presented in this study. The spectrum of the overall gain and the noise figure is recorded for low and large input signal powers. Under the optimum conditions, a wide flatness gain bandwidth of 81nm (1525-1606 nm) and 100 nm (1520-1620 nm) were achieved for low and large input signal powers respectively. The wide flatness bands were obtained due to two reasons: an optimization in EDFA gain and the careful choosing of Raman pump unit wavelength at 1495nm so that the Raman gain was forced to be far from the erbium gain to avoid the effect of the gain saturation in SHFA. The spectrum of the amplified signals was recorded within the amplification bandwidth and results show an excellent OSNR. The gain dynamic range was tested within the amplification bandwidth to show the input signal power range of the proposed amplifier.

In addition, an efficient wide band flat gain bandwidth based on double pass SHFA is experimentally demonstrated. The overall gain spectrum and the noise figure are tested under small and large input signal power. With an optimal condition, a flat gain bandwidth of 77 nm between 1530 and 1607 is achieved for small input signal power. The proposed amplifier is tested under large input signal power regime and the results illustrated wider flatness gain bandwidth of 93 nm from 1524 to 1617 nm. Two major parameters were behind the obtained flatness gain bandwidth; the optimization in the erbium gain that give flat amplification band and the wavelength of the Raman pump unit. A significant optical signal to noise ratios of the amplified signal were achieved for the whole flatness gain bandwidth. Finally, good gain dynamic ranges were recorded at different signal wavelength within the entire gain bandwidth.

For future work, a SHFA in which a double pass RFA and single pass EDFA could be a good idea to achieve high gain level in addition to low Raman pump power could be obtained. High Raman gain in double pass amplification can be achieved since Raman gain illustrates high saturation power related to the inserted input signal.

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