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**ANALYSIS OF GAIN AND NOISE FIGURE IN
DIFFERENT CONFIGURATIONS OF EDFA**

MASTER OF SCIENCE

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YEMİN METNİ

Yüksek Lisans tezi olarak sunduđum “Analysis of Gain and Noise Figure in Different Configurations of EDFA” başlıklı bu çalışmanın, bilimsel ahlak ve geleneklere uygun şekilde tarafımdan yazıldığını, yararlandığım eserlerin tamamının kaynaklarda gösterildiğini ve çalışmanın içinde kullandıkları her yerde bunlara atıf yapıldığını belirtir ve bunu onurumla doğrularım.

Tarih ve İmza

ONAY

Tezimin kağıt ve elektronik kopyalarının İstanbul Arel Üniversitesi Fen Bilimleri Enstitüsü arşivlerinde aşağıda belirttiğim koşullarda saklanmasına izin verdiğimi onaylarım:

- Tezimin tamamı her yerden erişime açılabilir.

Tarih ve İmza

ÖZET

Bu çalışmada, Erbiyum Katkılı Fiber Yükselteçlerde (EDFA) kullanılan pompalama sinyalinin (1480 nm) yönünün sistemden elde edilen kazancın ve oluşan gürültü faktörünün üzerindeki etkisi incelenmiştir.

Bu tezde 5 bölüm bulunmaktadır. Bölüm-1'de fiberlerin ve optik haberleşmenin tarihçesine kısa bir bakış yapılmıştır. Bölüm-2'de Optik Haberleşme sistemlerinin genel yapısı, kullanılan cihaz ve malzemeler anlatılmıştır. Özellikle SDH sisteminin ve EDFA'nın kullanım alanı olan WDM sisteminin çalışma prensipleri, data kapasitesi, çalıştığı band aralığı anlatılmıştır. Bölüm-3'de EDFA sisteminin matematiksel teorisi anlatılmıştır. İlk kısımda EDFA'nın üç seviyeli temel denklem oranı, iki seviyeli temel denklem oranı, kesişim (overlap) faktörü, ömür zamanı (lifetimes), bant genişliği ve kendiliğinden yükseltilmiş emisyon (ASE) anlatılmıştır. İkinci kısımda EDFA sistemlerindeki kazanç, kazancın fiber uzunluğu ile değişimi, gürültü ve kaskat EDFA anlatılmıştır. Bölüm-4'de bu teze özgün olarak anlatılan yeni önerilmiş EDFA konfigürasyonlarının çözümleri MATLAB programı kullanılarak nümerik olarak incelenmiş olup, elde edilen sonuçlar karşılaştırmalı olarak yorumlanmıştır. Bölüm-5 ise sonuç kısmını içermektedir.

Elde edilen sonuçlardan görülmüştür ki, 1480 nm dalgaboyunda ileri, geri ve iki yönlü olarak pompalanmış tek geçişli ikili katmanlı ve çift geçişli tek katmanlı EDFA konfigürasyonlarında simüle edilmiş, pompalama yönünün gürültü faktörüne, sinyal kazancına ve gücüne olan etkisi incelenmiştir. Sonuç olarak, ileri-ileri pompalama yönlü çift geçişli tek katmanlı EDFA konfigürasyonunda yapılan pompalamanın daha yüksek çıkış sinyal gücü ve kazancı verdiği ve iki yönlü pompalamanın gürültü seviyesinin diğer önerilen pompalama konfigürasyonlarına göre daha düşük olduğu görülmüştür.

ABSTRACT

In this study our main objective is to design new EDFA configurations to obtain higher gain and lower NF values using an input signal -35 dBm at the wavelength of 1550 nm and the pump power 14 mW at the wavelength of 1480 nm. Utilizing Giles and Desurvire model, we proposed miscellaneous SP and DP EDFA configurations different in the means of pump signal direction where the two level system model equations are solved numerically in Matlab. The physical properties of the simulated EDFA configurations such as gain, noise factor, population density and amplified spontaneous emission were studied under various pumping directions.

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I would like to say thank you to my wife Çağla, for her encouragements, all her support during my MSc. without whom I wouldn't be writing these lines.

CONTENTS

ÖZET-----	I
ABSTRACT-----	II
ACKNOWLEDGEMENTS-----	III
LIST OF ABBREVIATIONS-----	VII
LIST OF TABLE-----	X
LIST OF FIGURE-----	XI
LIST OF APPENDIX-----	XIV

CHAPTER-1

A BRIEF HISTORY OF OPTICAL COMMUNICATION

1.1 Optical Fiber History-----	1
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CHAPTER-2

OPTICAL COMMUNICATION

2.1 Introduction-----	3
2.2 Optical Communication Theory and Devices-----	3
2.2.1 Optical Source-----	4
2.2.1.1 Light-Emitting Diodes (LEDs)-----	4
2.2.1.2 Lasers-----	4
2.2.2 Optical Detectors-----	5
2.2.2.1 Photoconductors-----	5
2.2.2.2 Photodiodes-----	6
2.2.2.3 Phototransistors-----	6
2.2.3 Optical Communication Systems-----	7
2.2.3.1 Fibre Distributed Data Interface (FDDI)-----	7
2.2.3.2 SONET and SDH-----	7
2.2.3.3 Wavelength Division Multiplexing (WDM)-----	9
2.2.3.4 Free Space Optics (FSO)-----	12
2.2.4 Optical Passive Components-----	12
2.2.4.1 Fiber-----	12
2.2.4.2 Couplers-----	13
2.2.4.3 Isolators and Circulators-----	14
2.2.4.4 Filters-----	14

CHAPTER-3
ERBIUM DOPED FIBER AMPLIFIERS

3.1	Introduction	16
3.2	EDFA Basics	17
3.2.1	Three-Level System For EDFAs	17
3.2.2	The Overlap Factor and A_{eff}	20
3.2.3	Lifetimes	21
3.2.4	Linewidths and Broadening	22
3.2.5	Two-Level System for EDFAs	23
3.2.6	Amplified Spontaneous Emission	26
3.3	Modelling and Complex Effects	27
3.3.1	Gain for EDFA	27
3.3.2	Gain as Function of Fiber Length	29
3.3.3	Noise in EDFA	30
3.4.4	EDFA Cascade	35

CHAPTER-4

4.1	Introduction	36
4.2	Single Pass Edfa Configurations	37
4.2.1	Setup, Formulation and Results for Configuration-1 (Forward-Forward Pump)	38
4.2.2	Setup, Formulation and Results for Configuration-2 (Forward-Backward Pump)	43
4.2.3	Setup, Formulation and Results for Configuration-3 (Backward-Backward Pump)	47
4.2.4	Setup, Formulation and Results for Configuration-4 (Backward-Forward Pump)	50
4.3	Double Pass Edfa Configurations	54
4.3.1	Setup, Formulation and Results for Configuration-5 (Forward Pump)	54
4.3.2	Setup, Formulation and Results for Configuration-6 (Forward-Forward Pump)	59

4.3.3 Setup, Formulation and Results for Configuration-7 (Backward Pump) -----	63
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CHAPTER-5

5.1 Conclusion -----	68
REFERENCES -----	70
APPENDIX -----	83
RESUME -----	131

LIST OF ABBREVIATIONS

EDFA	: Erbium doped fiber amplifier
SDH	: Synchronous Digital Hierarchy
PDH	: Plesiochronous Digital Hierarchy
SONET	: Synchronous Optical Network
WDM	: Wavelength Division Multiplexing
DWDM	: Dense Wavelength Division Multiplexing
ETSI	: European Telecommunications Standards Institute
VC	: Virtual Container
TU	: Tributary Unit
TUG	: Tributary Unit Group
C	: Container
AU	: Administrative Unit
AUG	: Administrative Unit Group
STM:	: Synchronous Transport Module
STS	: Synchronous Transport Signal
η_{SP}	: The spontaneous emission factor
B_0	: The optical bandwidth in the frequency domain over which the ASE power is being measured
P_{in}	: The signal input power
P_p	: Pump power
P_s	: Signal power
P_s^-	: Backward signal power
P_s^+	: Forward signal power
P_p^-	: Backward pump power
P_p^+	: Forward pump power
IP	: Internet Protocol
G	: Gain of the amplifier
\tilde{F}	: Noise figure
NF	: Noise figure
B_e	: Electrical bandwidth of the detector

Γ_s	: Signal Over-lap factor
Γ_p	: Pump Over-lap factor
Γ_{21}	: The transition probability from level 2 to level 1
Γ_{32}	: The transition probability from level 3 to level 2
σ_e	: Emission cross-sections
σ_a	: Absorption cross-sections
σ_p	: Pump cross-section
σ_s	: Signal cross-section
$\sigma_s^{(a)}$: Signal absorption cross section
$\sigma_s^{(e)}$: Signal emission cross section
$\sigma_p^{(a)}$: Pump absorption cross section
$\sigma_p^{(e)}$: Pump emission cross section
$g^*(\lambda)$: Inverted gain coefficient
$\alpha(\lambda)$: Small signal absorption coefficient
α_s	: Small signal absorption coefficient
α_p	: Small pump absorption coefficient
ϕ_p	: Pump flux
ϕ_s	: Signal flux
N_1	: The populations of level 1
N_2	: The populations of level 2
N_3	: The populations of level 3
N	: The total population density
τ_2	: The lifetime of level 2
τ_r	: Total lifetime
τ_{nr}	: The non-radiative lifetime
ρ	: Erbium ion density per unit volume
R	: Pumping rate
A_{eff}	: Fiber effective area
EDF	: Erbium doped fiber

ASE	: Amplified spontaneous emission
NF	: Noise Figure
h	: Planck constant
ν	: Frequency
$\Delta\nu$: Bandwidth
SNR	: Signal-to-noise ratio
OSNR	: The optical signal-to-noise ratio
L	: Length
$g(\lambda)$: The gain coefficient
Er^{3+}	: Three level Erbium ion
${}^4I_{13/2}$: Metastable state (level 2 transition)
${}^4I_{15/2}$: Ground state (level 1 transition)
${}^4I_{11/2}$: Level 3 transition
s_i	: Several signals
p_i	: Several pump
ν_s	: Signal frequency
ν_p	: Pump frequency
ρ	: Er^{3+} ion density per unit volume
R_{Loss}	: Percent of the reflected signal
C	: Circulator
W_{12}	: Up stimulated transition rates
W_{21}	: Down stimulated transition rates

LIST OF TABLE

Table 2.1 VC Types and capacity (ITU-T G.707/Y.1322 (01/2007))-----	8
Table 2.2 SDH hierarchical bit rates (ITU-T G.707/Y.1322 (01/2007)) -----	9
Table 2.3 Transmission windows used in optical fibers-----	11
Table 4.1 Parameters of the Single Pass EDFA-----	37
Table 4.2 SP EDFA results for the proposed configurations-----	53
Table 4.3 Parameters of the DP EDFA-----	54
Table 4.4 DP EDFA results for the proposed configurations-----	67

LIST OF FIGURE

Figure 2.1 Optical Transmission-----	3
Figure 2.2 Stimulated emission in a two level atom-----	5
Figure 2.3 Photoconductive Detector-Principle -----	6
Figure 2.4 SDH multiplexing structure as defined by the European Telecommunications Standards Institute where VC-Virtual Container,TU- Tributary Unit,TUG-Tributary Unit Group,C-Container,AU-Administrative Unit,AUG-Administrative Unit Group,STM-Synchronous Transport Module--	8
Figure 2.5 Block diagram of a DWDM system-----	10
Figure 2.6 Schematic of a step index optical fibre-----	12
Figure 2.7 Optical Couplers-----	13
Figure 2.8 Isolator and Circulator-----	14
Figure 2.9 Filter-----	15
Figure 3.1 Simplified three level energy diagram of Er^{3+} for the amplifier model. The transition rates between levels 1-3 and 1-2 are proportional to the populations in those levels and to the product of the pump flux ϕ_p - pump cross-section σ_p and signal flux ϕ_s - signal cross-section σ_s , respectively. The spontaneous transition rates of the ion (including radiative and nonradiative contributions) are given by Γ_{32} and Γ_{21} -----	17
Figure 3.2 Example of a radial distribution of the erbium ion density in a single-mode fiber and the equivalent “flat top” distribution, which has a constant ion density N stretching from $r=0$ to $r=R$ -----	21
Figure 3.3 Broadening-----	23
Figure 3.4 EDFA gain performance as a function of the input signal powers in dBm, at wavelength 1549.2 nm, at saturation for pump powers of 40, 65, 100 mW-----	28
Figure 3.5 Curves of gain G versus pump power P_p -----	28
Figure 3.6 Signal gain at 1530 nm (left) and 1550 nm (right) for 1480 and 980 nm pumping of erbium-doped Al-Ge silica fiber, as a function of fiber amplifier length. The launched pump power is 40 mW and the launched signal power is -40 dBm-----	29

Figure 3.7 Signal gain at 1530 nm (left) and 1550 nm (right) for 1480 nm and 980 nm pumping of erbium-doped Al-Ge silica fiber, as a function of fiber amplifier length. The launched pump power is 10 mW and the launched signal power is -40 dBm. From numerical simulations-----	30
Figure 3.8 An EDFA amplifies an input signal, and along with the amplified signal there is a background ASE that constitutes the noise of the amplifier. Any ASE not coincident with the signal wavelength can be filtered using an optical filter. However, ASE within the signal band cannot be filtered and constitutes the minimum noise added by the amplifier-----	31
Figure 3.9 (a) noise figure and (b) amplifier gain as a function of the length for several pumping levels-----	33
Figure 4.1 Configuration 1: Forward – Forward pump scheme for double stage SP EDFA-----	38
Figure 4.2 Population Density of Configuration-1-----	40
Figure 4.3 The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-1-----	41
Figure 4.4 Noise Figure of configuration-1-----	42
Figure 4.5 The forward travelling ASE of configuration-1-----	42
Figure 4.6 The backward travelling ASE of configuration-1-----	43
Figure 4.7 Forward-Backward pump scheme of configuration-2-----	43
Figure 4.8 Population density of configuration-2-----	44
Figure 4.9 The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-2-----	45
Figure 4.10 Noise Figure of configuration-2-----	45
Figure 4.11 The forward travelling ASE of configuration-2-----	46
Figure 4.12 The backward travelling ASE of configuration-2-----	46
Figure 4.13 Backward-Backward pump scheme of configuration-3-----	47
Figure 4.14 Population density of configuration-3-----	47
Figure 4.15 The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-3-----	48
Figure 4.16 Noise Figure of configuration-3-----	48
Figure 4.17 The forward travelling ASE of configuration-3-----	49
Figure 4.18 The backward travelling ASE of configuration-3-----	49
Figure 4.19 Backward-Forward pump scheme of configuration 4-----	50

Figure 4.20	Population density of configuration 4-----	51
Figure 4.21	The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at z=0 and z=15 m in configuration-4-51	
Figure 4.22	Noise Figure of configuration-4-----	52
Figure 4.23	The forward travelling ASE of configuration-4-----	52
Figure 4.24	The backward travelling ASE of configuration-4-----	53
Figure 4.25	Configuration 5-----	55
Figure 4.26	Population density of configuration 5-----	56
Figure 4.27	Signal gain as a function of EDFA length at configuration-5-----	57
Figure 4.28	Noise Figure of configuration-5-----	57
Figure 4.29	The forward travelling ASE of configuration-5-----	58
Figure 4.30	The backward travelling ASE of configuration-5-----	58
Figure 4.31	Configuration-6-----	59
Figure 4.32	Population density of configuration 6-----	60
Figure 4.33	Signal gain as a function of EDFA length at configuration-6-----	61
Figure 4.34	Noise Figure of configuration-6-----	61
Figure 4.35	The forward travelling ASE of configuration-6-----	62
Figure 4.36	The backward travelling ASE of configuration-6-----	62
Figure 4.37	Configuration-7-----	63
Figure 4.38	Population density of configuration-6-----	64
Figure 4.39	Signal gain as a function of EDFA length at configuration-7-----	65
Figure 4.40	Noise Figure of configuration-7-----	65
Figure 4.41	The forward travelling ASE of configuration-7-----	66
Figure 4.42	The backward travelling ASE of configuration-7-----	67

LIST OF APPENDIX

A.1 Matlab code for configuration-1-----	83
A.1.1 Spedfa1(y) for configuration-1-----	83
A.1.2 Spedfa2(y) for configuration-1-----	84
A.1.3 Solution for configuration-1-----	85
A.2 Matlab code for configuration-2-----	89
A.2.1 Spedfa1(y) for configuration-2-----	89
A.2.2 Spedfa2(y) for configuration-2-----	90
A.2.3 Solution for configuration-2-----	91
A.3 Matlab code for configuration-3-----	96
A.3.1 Spedfa1(y) for configuration-3-----	96
A.3.2 Spedfa2(y) for configuration-3-----	97
A.3.3 Solution for configuration-3-----	98
A.4 Matlab code for configuration-4-----	103
A.4.1 Spedfa1(y) for configuration-4-----	103
A.4.2 Spedfa2(y) for configuration-4-----	104
A.4.3 Solution for configuration-4-----	105
A.5 Matlab code for configuration-5-----	110
A.5.1 Spedfa(y) for configuration-5-----	110
A.5.2 Dpedfa(y) for configuration-5-----	111
A.5.3 Solution for configuration-5-----	112
A.6 Matlab code for configuration-6-----	117
A.6.1 Spedfa(y) for configuration-6-----	117
A.6.2 Dpedfa(y) for configuration-6-----	118
A.6.3 Solution for configuration-6-----	119
A.7 Matlab code for configuration-7-----	124
A.7.1 Spedfa(y) for configuration-7-----	124
A.7.2 Dpedfa(y) for configuration-7-----	125
A.7.3 Solution for configuration-7-----	126

CHAPTER-1

A BRIEF HISTORY OF OPTICAL FIBERS

1.1 OPTICAL FIBER HISTORY

The basic concept of amplifying a traveling optical wave was first introduced in 1962 by Geusic and Scovil (**J. E. Geusic and H. E. D. Scovil, 1962**). In 1963, the utilization of optical fibers in communication systems was proposed for the first time by a Japanese scientist, Jun-ichi Nishizawa, at Tohoku University (**Nishizawa Jun-ichi and Suto Ken, 2004; Sendai New, 2009**). One year later, optical fiber amplifiers were invented in 1964 by E. Snitzer working for American Optical Company. He demonstrated a neodymium doped fiber amplifier at $1.06\ \mu\text{m}$ where the fiber had a core of $10\ \mu\text{m}$ with a 0.75 to 1.5 mm cladding. The fiber has 1 m of length, and was wrapped around a flashlamp that excited the neodymium ions (**C. J. Koester and E. Snitzer, 1964; S. Sudo, 1997; Becker, Olsson and Simpson, 1999; E. Snitzer and R. Woodcock, 1965**). Shortly after, the first operational fiber-optical data transmission system was developed by German physicist Manfred Börner at Telefunken Research Labs in Ulm in 1965 and the first patent application for this technology was done in 1966 (**Börner Manfred, 1967**). Fibers became a practical communication medium when the researchers Charles K. Kao and George A. Hockham from the British company Standard Telephones and Cables (STC) proposed for the first time that attenuation could be reduced below 20 decibels per kilometer (dB/km) (**Hecht Jeff, 1999**). They observed that the reason for the high attenuation level in fibers was caused by impurities that could be eliminated, rather than by fundamental physical effects such as scattering. They systematically and successfully developed the theory for the light-loss properties in optical fibers, and discovered the right material to use for such fibers — silica glass with high purity and this discovery earned Kao the Nobel Prize in Physics in 2009 (**Press Release - Nobel Prize in Physics, 2009**). Just after Kao's discovery, the attenuation limit of 20 dB/km was first achieved in 1970, by researchers Robert D. Maurer, Donald Keck, Peter C. Schultz, and Frank Zimar from American glass maker Corning Glass Works.

By doping silica glass with titanium, they achieved an attenuation of 17 dB/km in a fiber communication line. A few years later, they produced a fiber with only 4 dB/km attenuation where germanium dioxide is used as the core dopant **(1971–1985 Continuing the Tradition, General Electric Company, 2012)**.

Single mode fiber amplifiers doped with rare earth ions were first demonstrated in 1983 by Broer and Simpson at Bell Telephone Laboratories. The purpose of their study was to understand the physics of fundamental relaxation mechanisms of rare earth ions in amorphous hosts **(J. Hegarty, M. M. Broer, B. Golding, J. R. Simpson and J. B. MacChesney, 1983; M. M. Broer, B. Golding, W. H. Heammerle and J. R. Simpson, 1986)**. In 1986, AT&T Bell Labs started the research and in subsequent years many groups around the world contributed to fast development of practical Erbium Doped Fiber Amplifiers (EDFAs). In 1989, newly developed InGaAsP laser diodes were used for the first time to pump EDFA at 1480nm. Without laser diode pump sources, the utilization of EDFAs in actual systems could never have been possible **(M. Digonnet, 1992; Russell Philip, 2003)**. Again in 1989, the first undersea test of erbium doped fiber amplifiers in a fiber optic transmission cable occurred. After 1989, EDFAs became catalyst for the new generation high capacity undersea and terrestrial fiber optic links and networks. **(N. Edagawa, K. Mochizuki and H. Wakabayashi, 1989)**. In conjunction with recent advances, the optical amplifiers offer solutions to the high capacity needs of nowadays voice and data transmission applications **(Becker, Olsson and Simpson, 1999; Russell Philip, 2003; Kuroda, 2012)**.

CHAPTER-2

OPTICAL COMMUNICATION

2.1 INTRODUCTION

This chapter is devoted to review the fundamentals of optical communication theory and devices where optical sources, optical detectors, optical communication systems and optical passive components are explained.

2.2 OPTICAL COMMUNICATION THEORY AND DEVICES

Figure 2.1 shows a general optical communication system which consists of mainly three components; transmitter, channel and the receiver. In the transmitter part, basically, the electrical signal in form of a serial bit stream is presented to a modulator that encodes the data appropriately. A light source, la-

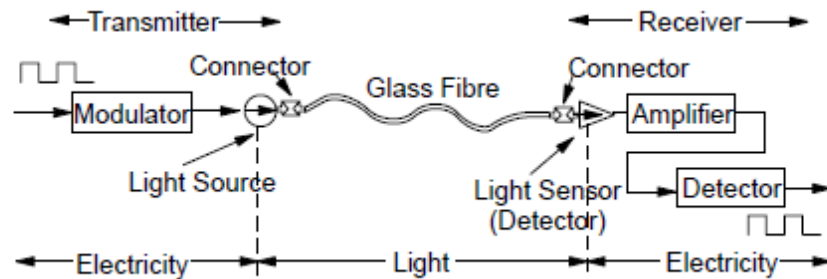


Figure 2.1 Optical Transmission (Harry J.R. Dutton, 1998).

ser or Light Emitting Diode – LED, driven by the modulator then sends the optical bits into the fibre transmission channel medium. In the channel, the light travels down the fibre where it may experience dispersion due to the different wavelengths in the optical wave packet. In the receiver part, the light is fed to a detector and converted back to the electrical signal in form of a serial bit stream. The signal is then amplified and fed to another detector, which isolates the individual state changes and their timing. It then decodes the sequence of state changes and reconstructs the original bit stream (Jagtar, 2011; B.P. Lathi, 1989; Harry J.R. Dutton, 1998).

2.2.1 OPTICAL SOURCE

2.2.1.1 Light-Emitting Diodes (LEDs)

Light-emitting diodes (LEDs) have been utilized in electronic equipment as indicator lights for decades due to their small size, durability and energy efficiency. (S. Nakamura, T. Mukai, and M. Senoh, 1994; N. Narendran, Y. Gu, J.P. Freyssonier-Nova, and Y. Zhu, 2005). In addition to this, LEDs offer a vast amount of new possibilities for product design, as compared to the traditional light sources (E.F. Schubert and J.K. Kim, 2005). One of the problems with controlling the light output from LEDs is that the technology itself has some inherent nonlinearities where both the amount of current and the temperature of the device will change the properties of the resulting illumination (Andres Thorseth, 2011). In its simplest form, an LED is a forward-biased p–n junction where radiative recombination of electron-hole pairs in the depletion region generates light. Some of the generated light escapes from the device and can be coupled into an optical fiber where this emitted light is incoherent having a relatively wide spectral width (30-60 nm) and a relatively large angular spread. (Govind P. Agrawal, 2002; J. Gower, 1993).

2.2.1.2 Light Amplification by the Stimulated Emission of Radiation (Lasers)

According to the emission theory of Einstein, energy in the form of a photon can be absorbed or emitted through carrier transitions between different energy levels where a monochromatic light wave travelling through the atoms with two energy levels having energy difference equal to the energy of the incident photon could induce the transition of atoms from a higher level to a lower energy level accompanied by emission of photons having exactly the same energy as the injected ones. Here, it is assumed that the population density in the upper level is bigger than the population density in the lower level. This is illustrated in Figure 2.2 (Xing, Cheng, 2011).

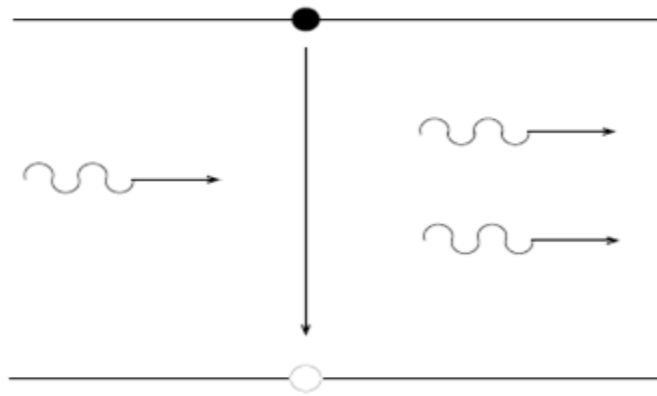


Figure 2.2: Stimulated emission in a two level atom. (Xing, Cheng, 2011).

Lasers can be classified according to their gain (amplifying material) medium such as gas lasers, dye lasers, solid state lasers, semiconductor lasers etc. (A. Yariv, 1989; E. Hecht, 2002). Solid state lasers use crystals as their gain medium where flashlamps having the appropriate emission wavelength are commonly placed inside the laser cavity and provide pumping light incident on the crystal. Thus, these kind of lasers are sometimes named as the optically pumped lasers. Ruby laser is the first functional solid state laser in the history and widely studied after that (Xing, 2011; T. H. Maiman, 1960).

2.2.2 OPTICAL DETECTORS

2.2.2.1 Photoconductors

Photoconductors are the simplest optical detectors consisting of a piece of (undoped) semiconductor material with electrical contacts attached where voltage is applied across these contacts. When a photon arrives in the semiconductor it is absorbed and an electron/hole pair is created. Due to the electric field between the two contacts, electron and hole each migrates separately towards the positive and the negative contact, respectively. Thus the resistance of the device varies with the amount of light falling on it. (Harry J.R. Dutton, 1998).

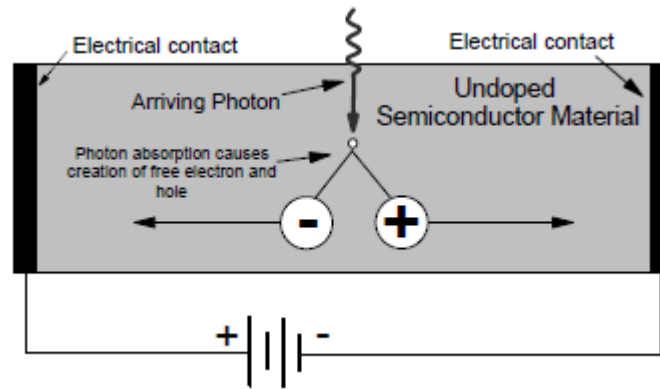


Figure 2.3: Photoconductive Detector-Principle (**Harry J.R. Dutton, 1998**).

2.2.2.2 Photodiodes

Photodiodes convert light directly to the electric current where an ideal (p-i-n) diode can convert one photon to one electron of current. This means that the output current obtained from such a device is very small and an external amplifier is needed before the signal is received (**Harry J.R. Dutton, 1998**).

Photodiodes are pn-junction diodes fabricated for the purpose of light detection having oppositely doped regions on a semiconductor substrate where these adjacent regions of opposite impurity doping result in the formation of a space charge region being free from charge carriers and having high impedance. Most pn junction photodiodes are fabricated using silicon or germanium and they exhibit high sensitivity for detecting visible and near wavelengths at room temperature (**Abid Kamran, 2011; Melchior, H, 1973**). When light falls on a pn-junction photodiode, the photons with higher energy than the band-gap energy of the material, generate electron-hole pairs. Photodiodes have two working modes; photoconductive or photovoltaic mode. Minimum dark current is seen in photovoltaic mode, whereas fast switching speed is seen in photodiodes when working in the photoconductive mode (**Wilson, J.S, 2003**).

2.2.2.3 Phototransistors

Phototransistors are photodiode-amplifier combinations integrated within a single silicon chip. These are combined to overcome the unity gain of

photodiodes. The typical gain of a phototransistor can range from 100 to over 1500. While the signal from a photodiode can always be amplified through use of an external op-amp or other circuitry, this approach is often not as practical or as cost-effective as the use of phototransistors. The phototransistor can be viewed as a photodiode whose output photocurrent is fed into the base of a conventional small-signal transistor. While not required for operation of the device as a photodetector, a base connection is often provided, allowing the option of using base current to bias the transistor. Phototransistors are often employed as the detector element for optoisolators and transmissive or reflective optical switches (<http://www.farnell.com/datasheets/1674282.pdf>).

2.2.3 OPTICAL COMMUNICATION SYSTEMS

2.2.3.1 Fibre Distributed Data Interface (FDDI)

FDDI was developed by the American National Standards Institute (ANSI) where originally it was proposed as a standard for fibre optical computer I/O channels. But later it has become a generalised standard for operation of a LAN at one hundred megabits per second. (**Harry J.R. Dutton, 1998**).

2.2.3.2 Synchronous Optical Network (SONET) and SDH

Synchronous Digital Hierarchy (SDH) is a multiplexing standard used all over the world except in the North America and Japan. The corresponding protocol for SDH in these areas is Synchronous Optical Networking (SONET) with relatively minor differences (**Alwayn, Vivek, 2004**).

SDH defines a multiplexing hierarchy, seen in Figure 2.4, that begins with a E-carrier link (see figure 2.4 and table 2.1) and ends up with a so called STM-N (see table 2.2) frame. (**European Telecommunications Standards Institute (ETSI), 2011**).

Table 2.2: SDH hierarchical bit rates (ITU-T G.707/Y.1322 (01/2007))

Synchronous digital hierarchy level	Hierarchical bit rate (kbit/s)
0	51 840
1	155 520
4	622 080
16	2 488 320
64	9 953 280
256	39 813 120
NOTE – The specification of levels higher than 256 requires further study.	

2.2.3.3 Wavelength Division Multiplexing (WDM)

WDM is the technology where multiple wavelengths of light (multiple channels) are launched into a single optical fibre with the advantage of no additional fibre link has to be installed, but rather modifications made to the network at its nodes, allowing for a more scaleable and easy upgradeable network. DWDM (Dense Wavelength Division Multiplexing) is a denser version of WDM resulting from advances made in the tuning of lasers and wavelength filtering (S.Kempainen, 1998). Due to the intensive research and development studies, the WDM technology is advancing fastly. (Ying Lu, Okan K.Ersoy, 2003; M. S. Ab-Rahman, and S. Shaari, 2009).

In the WDM based optical access networks, wavelength selective optical add/drop filters are required for adding and dropping a particular wavelength (M. S. Ab-Rahman, and S. Shaari, 2009). In these type of WDM optical network, DWDM technology is necessary for maximizing the limited transmission bandwidth where add/drop filter used in DWDM based optical networks should have a good reflection characteristic, a temperature stability, a narrow spectral bandwidth, and a low implementation cost (Ab-bou, F.M., H.Y. Wong, C.C. Hiew, A. Abid and H.T. Chuah, 2007). Due to these reasons, although many researchers have been proposed various technologies for implementation of the add/drop filters, their cost is too expensive to apply for DWDM based optical access networks. (P. S. Andre, J. L. Pinto, T. Almedia, and M. Pousa, 2002; M. S. Ab-Rahman, and S. Shaari, 2009). However “DWDM is the only technology that enables full network flexibility

and adaptability at speeds of 100G and beyond, quick service turnup to meet changing bandwidth requirements, and ultra-low latency connectivity. Facilitated by the platforms, carriers can enjoy more flexible transmission, quicker service provisioning, more reliable networks, and easier maintenance, to provide better services and generate more profits” (<http://www.huawei.com/>; <http://www.alcatel-lucent.com>).

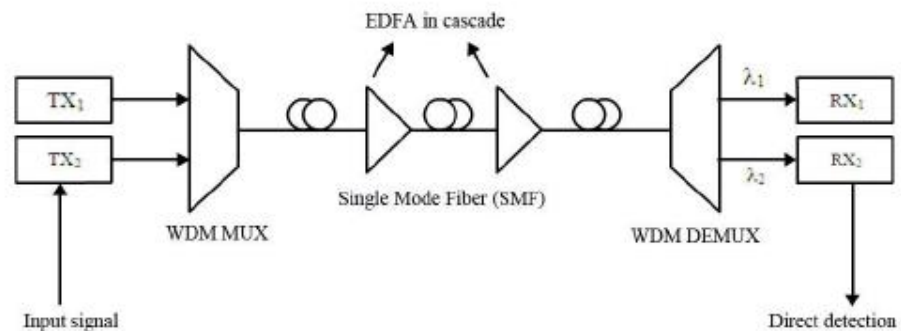


Figure 2.5: Block diagram of a WDM system (Perenyi Marcell, 2009)

WDM is basically an analogy of Frequency Division Multiplexing in the infrared domain where independent streams of data are modulated using different frequencies and sent through the same piece of fiber (see figure 2.6) (Perenyi Marcell, 2009; Achyut K. Dutta, Niloy K. Dutta, Masahiko Fujiwara, 2004; Krishna M. Sivalingam, Suresh Subramaniam, 2002). Multiplexing and demultiplexing optical signals is an essential component in WDM networks where optical signals must be split and joined regarding the frequency of the signal. There are two main types of demultiplexers, active and passive. Arrayed waveguide gratings, an example of a passive demultiplexer, can typically be also used as multiplexers (J.P. Laude and C-N. Zah, 1984; Arjen R. Vellekoop and Meint K. Smit, 1991). Acoustically tunable filters, an example of an active demultiplexer, have the ability to dynamically select multiple wavelengths (Perenyi Marcell, 2009; David A. Smith, Jane E. Baran, John J. Johnson and Kwok Wai Cheung, 1990).

At the receiver, several filters can be used to separate (demultiplex) the signals from each other (Perenyi Marcell, 2009; Achyut K. Dutta, Niloy K. Dutta,

Masahiko Fujiwara, 2004; Krishna M. Sivalingam, Suresh Subramaniam, 2002) in which demultiplexing can be done by diffraction based demultiplexers or interference based demultiplexers. In addition to these the most often used demultiplexing approach is the Arrayed Waveguide Grating (Govind P. Agrawal, 2002).

“Literature distinguishes dense and coarse WDM technologies depending on the spacing of the wavelength channels: the Dense WDM recommendation described in ITU-T G694.1 supports channel spacing values of 100, 50, 25 and 12.5 GHz with, respectively, allowing approximately 115, 229, 458 and 916 channels in the C and L bands. (table 2.3) The Coarse WDM scheme (ITU-T G694.2) defines 18 channels with channels spacing larger than 2 THz in the spectral bands by the letters O, E, S, C and L” (Spectral grids for WDM applications: DWDM frequency grid, ITU-T Recommendation G.694.1 June 2002; Spectral grids for WDM applications: CWDM frequency grid, ITU-T Recommendation G.694.2 December 2003)

Table 2.3: Transmission windows used in optical fibers (ITU-T Recommendation G.694.2)

Band	Description	Wavelength Range
O band	original	1260 to 1360 nm
E band	extended	1360 to 1460 nm
S band	short wavelength	1460 to 1530 nm
C band	conventional ("erbium window")	1530 to 1565 nm
L band	long wavelength	1565 to 1625 nm
U band	ultra long wavelengths	1625 to 1675 nm

DWDM refers originally to optical signals multiplexed within the 1550-nm band where erbium doped fiber amplifiers (EDFAs) are effective for wavelengths between approximately 1525-1565 nm (C band) or 1570-1610 nm (L band). EDFAs were originally developed to replace SONET/SDH optical-electrical-optical (OEO) regenerators since EDFAs, regardless of the modulated bit rate, can amplify any optical signal in their operating range. In terms of multi-wavelength signals (assuming that EDFA has enough pump signal energy available), it can amplify as many optical signals as can be

multiplexed into its amplification band. EDFAs therefore allow a single-channel optical link to be upgraded in bit rate by replacing only equipment at the ends of the link, while retaining the existing EDFA or series of EDFAs through a long haul route. Furthermore, single-wavelength links using EDFAs can similarly be upgraded to WDM links at reasonable cost where the EDFAs cost is thus leveraged across as many channels as can be multiplexed into the 1550-nm band (S. M. Nazmul Mahmud, Abdul Aoual Talukder, 2009)

2.2.3.4 Free Space Optics (FSO)

FSO systems use infra-red laser sources for the transmission of data between the transmitter and the receiver where they can transmit up to 1.25 Gbps over a maximum distance of 4 km. Since these systems use optical signals, it is not required to get radio spectrum licensing. FSO systems also have low installation costs. However, in poor weather conditions, they may shut down. Moreover, FSO systems are only useful in short distance private applications due to their point-to-point nature (Oladeji Akanbi, 2006; Carl Brannlund, 2008).

2.2.4 OPTICAL PASSIVE COMPONENTS

2.2.4.1 Fiber

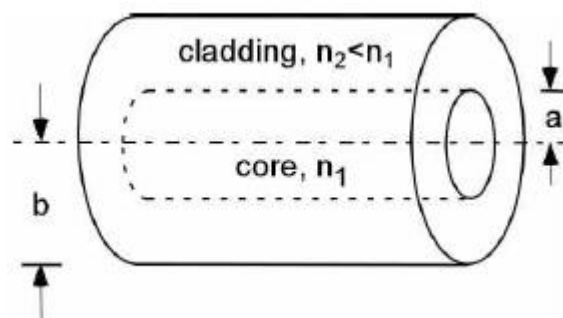


Figure 2.6: Schematic of a step index optical fibre. (Erji Mao, 2000).

An optical fiber is a cylindrical waveguide made of low-loss materials, such as silica glass, carries light along its length. The core in which the light

propagates and being guided is embedded in a cladding of slightly lower refractive index (see figure 2.6). Light rays coming at angles greater than the critical angle at the core-cladding interface undergo total internal reflection. Thus, these rays are guided and propagate inside the core (Erji Mao, 2000; Y. Weissman, 1992; Ankush Kumar, 2009). The cladding is usually coated with a tough resin buffer layer. In some cases this layer may be further surrounded by a jacket layer made of glass. These layers add only mechanical strength to the fiber and do not change to its optical wave guide properties. In order to reduce cross-talk between the fibers sometimes light-absorbing glass is utilized between the fibers in rigid fiber assemblies. (Light collection and propagation, National Instruments' Developer Zone, National Instruments Corporation, 2007; E. Hecht, 2002).

2.2.4.2 Couplers

Couplers are simple passive optical components used for splitting or combining signals where it consists of n input and m output ports. A $1 \times m$ coupler is called a splitter and an $n \times 1$ coupler is called a combiner. Figure 2.7, 2×2 coupler is described where a part of the first input signal is directed to the first output port and the rest to the second output port. In a similar way a part of the input second input signal is guided to both output ports. The fractions directed to output ports can be either equal or non-equal (Henrique, et al, 2002).

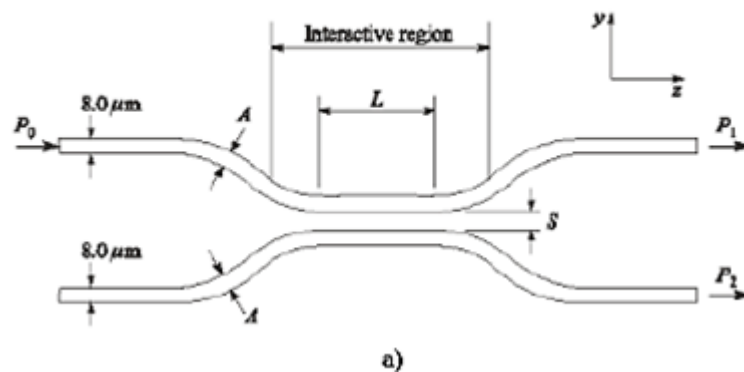


Figure 2.7: Optical Couplers (Henrique, et al, 2002).

2.2.4.3 Isolators and Circulators

Isolators (see figure 2.8a) are devices that allow transmission only in one direction and block the transmissions in the reverse direction. In order to prevent reflections from amplifiers or lasers. Typically the insertion loss, i.e. the loss in the forward direction is around 1 dB and the isolation, i.e. the loss in the reverse direction, is approximately 40 to 50 dB.

A circulator is a device similar to an isolator having multiple ports. Figure 2.8b) shows a circulator with input and output ports. A signal from each port is directed to the next adjoining port and blocked in all the other ports (see Figure 2.8c). Circulators can be used as a component in optical add/drop multiplexers and optical cross-connects (<http://www.lightreading.com>).

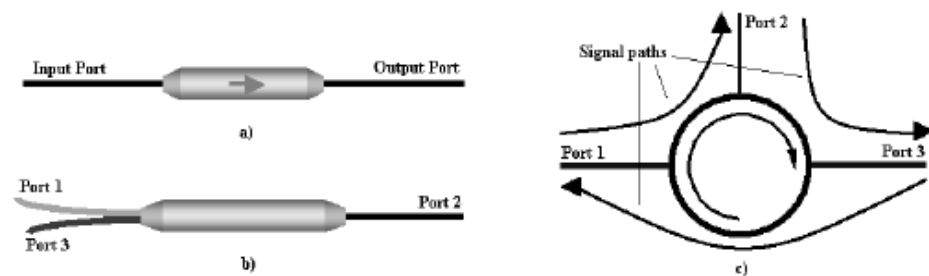


Figure 2.8: a) Isolator, b) Circulator, c) Logical scheme of a three port circulator (<http://www.lightreading.com>).

2.2.4.4 Filters

In order to filter or multiplex wavelength dependent we need to separate different frequencies from the signal. The principle idea for doing this depends on that some wavelengths are delayed in phase compared to other wavelengths. This is done by directing them through a longer path (**Henrique, et al, 2002**).

The key parameters of filters are insertion loss and passband flatness where insertion losses should be low and independent of polarization and temperature and passband should be flat and passband skirts should be as sharp as possible. As seen in figure 2.9t he flatter the passband and sharper the passband skirts,

we obtain smaller crosstalk energy passing through the adjacent channels (**R. Ramaswami, K. N. Sivarajan, 1998**).

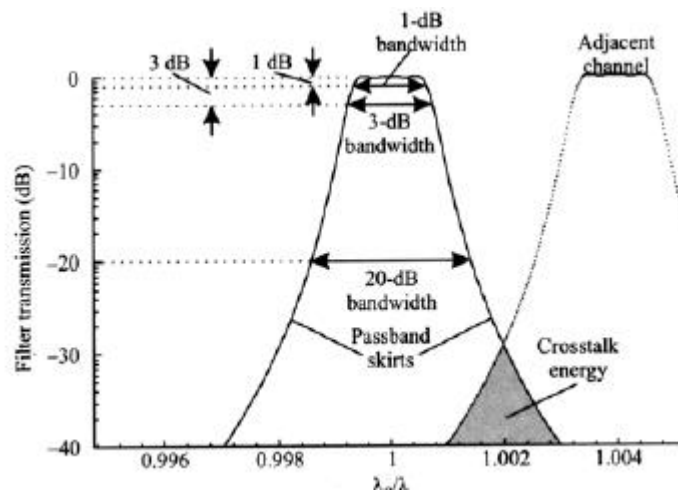


Figure 2.9: Filter (R. Ramaswami, K. N. Sivarajan, 1998).

CHAPTER-3

ERBIUM DOPED FIBER AMPLIFIERS

3.1 INTRODUCTION

The development of erbium doped fiber amplifiers (EDFAs), started in the mid 1980s, have been a major impetus on the growth of fiber communications with wavelength division multiplexing (WDM) and an important catalyst to the research on active-fiber technology in the third optical telecommunications window near 1.55 μm wavelength region where the loss of silica fibers is minimum (Mears, Reekie, Jauncey, and Payne, 1987; Morkel and Laming, 1989; M. Nakawaza, Y. Kimura and K. Suzuki, 1989; Giles and Desurvire, 1991; Fouli, 2002). EDFAs are now common components of lightwave transmission systems and have been widely used in optical communications (Giles and Desurvire, 1991; Fouli, 2002; Kuroda, 2012) due to the advantages they provide. It is possible to directly amplify optical data without conversion to electrical data by using EDFAs (Kuroda, 2012). Polarization independent high gain and low noise in the optical communication networks and providing a broadband amplification of radiation whose wavelength is in the so-called third window make EDFAs an important tool for building compact and practical devices for diverse applications in fiber-optic communication (Morkel and Laming, 1989; N. A. Olsson, 1989; Kemtchou, Duhamel and Lecoy, 1997).

“The erbium doped fiber systems results into important advantages for information processing and transmission like: possibility of easy integration, highly efficiency and gain, immunity to crosstalk, low noise and high saturation output power” (Agrawal, 1995 & 1997; Desurvire, 1995; Sterian, 2006).

Chapter 3 introduces basics, modeling and complex effects of EDFAs.

3.2 EDFA BASICS

3.2.1 Three-Level System for EDFAs

The general modeling of the erbium-doped fiber amplifier can be considered as a pure three level atomic system (Becker, Olsson and Simpson, 1999: 131; Simpson and Becker, 1987:12).

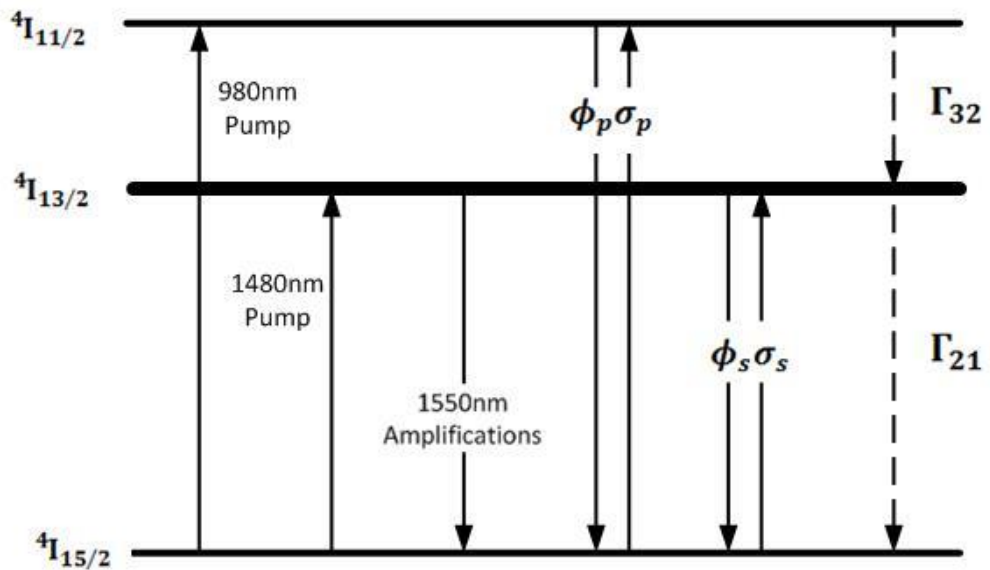


Figure 3.1: Simplified three level energy diagram of Er^{3+} for the amplifier model. The transition rates between levels 1-3 and 1-2 are proportional to the populations in those levels and to the product of the pump flux ϕ_p - pump cross-section σ_p and signal flux ϕ_s - signal cross-section σ_s , respectively. The spontaneous transition rates of the ion (including radiative and nonradiative contributions) are given by Γ_{32} and Γ_{21} (Muhyaldin, 2009; Becker, Olsson and Simpson, 1999: 132; Desurvire, 1994; Bjarklev, 1993).

For EDFAs, the stimulated emission is the main amplification mechanism where the population inversion is achieved by optical pumping. During this process, electrons that exist at higher energy levels are raised to the excited states by pump photons (Muhyaldin, 2009; Becker, Olsson and Simpson, 1999: 131; Desurvire, 1994; Bjarklev, 1993; Ghatak and Thyagarajan, 1998; Giles and Desurvire, 1991).

The configuration depicted in Figure 3.1 is known as the three level system model where the ground state is denoted by 1, an intermediate state labeled by 3 (into which energy is pumped), and another intermediate state by 2. State 2 often has relatively a longer lifetime for good amplifiers where it is referred as metastable level. For the considered model, state 2 is the upper level of the amplifying transition and state 1 is the lower level. The populations of the levels are labeled N_1 , N_2 and N_3 . The amplification is obtained in case of a population inversion between states 1 and 2 where at least half of the total population of erbium ions at level 1 needs to be excited to level 2 to have population inversion (**Becker, Olsson and Simpson, 1999: 131; Giles and Desurvire, 1991**).

“The incident light intensity flux at the frequency corresponding to the 1 to 3 transition (in number of photons per unit time per unit area) is denoted by ϕ_p and corresponds to the pump. The incident flux at the frequency corresponding to the 1 to 2 transition (in photons per unit time per unit area) is denoted by ϕ_s and corresponds to the signal field. The change in population for each level arises from absorption of photons from the incident light field, from spontaneous and stimulated emission, and from other pathways for the energy to escape a particular level. In particular, we write as Γ_{32} the transition probability from level 3 to level 2. This is the sum of the nonradiative and radiative transition probabilities, and in practice, for the most typical cases, is mostly nonradiative. Γ_{12} is the transition probability from level 2 to level 1. In the case of the $Er^{3+} \ ^4I_{13/2}$ (level 2) to $\ ^4I_{15/2}$ (level 1) transition, Γ_{21} is mostly due to radiative transitions. This is due to the fact that there are, for Er^{3+} , no intermediate states between levels 1 and 2 to which ions excited to level 2 can relax. It was defined $\Gamma_{21} = 1/\tau_2$, where τ_2 is the lifetime of level 2.”(**Becker, Olsson and Simpson, 1999: 133**)

The absorption cross section for the transition between state 1 to state 3 is denoted by σ_p , and the emission cross section for the transition between state 2 to state 1 is denoted by σ_s in Figure 3.1. Absorption and emission cross

sections are considered equal for transitions between individual nondegenerate states (**Bao and Hong Son, 2004; Becker, Olsson and Simpson, 1999: 133**).

“The rate equations for the population changes are written as”(**Becker, Olsson and Simpson, 1999: 133; Desurvire, 1994**)

$$\frac{dN_3}{dt} = -\Gamma_{32}N_3 + (N_1 - N_3)\phi_p\sigma_p \quad (3.1)$$

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + \Gamma_{32}N_3 - (N_2 - N_1)\phi_s\sigma_s \quad (3.2)$$

$$\frac{dN_1}{dt} = \Gamma_{21}N_2 - (N_1 - N_3)\phi_p\sigma_p + (N_2 - N_1)\phi_s\sigma_s \quad (3.3)$$

“In steady-state situation, the time derivatives will all be zero,

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} \quad (3.4)$$

and the total population N is given by”

$$N = N_1 + N_2 + N_3 \quad (3.5)$$

(Becker, Olsson and Simpson, 1999: 132,133)

“From Equation 3.1, the population of level 3 can be written as:

$$N_3 = \frac{1}{1 + \Gamma_{32}/\phi_p\sigma_p} N_1 \quad (3.6)$$

When Γ_{32} is large (corresponding to a speedy transition from level 3 to level 2) compared to the effective pump rate into level 3, then the value of $\phi_p\sigma_p$ and N_3 is very close to zero. Thus, the population of erbium ions is mostly in levels 1 and 2. From Equation 3.6, the population of level 2 can be written as:

$$N_2 = \frac{\left(\frac{\phi_p\sigma_p}{\Gamma_{32}}\right) + \phi_s\sigma_s}{\Gamma_{21} + \phi_s\sigma_s} N_1 \quad (3.7)$$

Then, from Equation 3.5, the populations N_1 , N_2 and population inversion ($N_2 - N_1$) can be derived as:” (Muhyaldin, 2009; Becker, Olsson and Simpson, 1999: 134)

$$N_2 - N_1 = \frac{\phi_p\sigma_p - \Gamma_{21}}{\Gamma_{21} + 2\phi_s\sigma_s + \phi_p\sigma_p} N \quad (3.8)$$

3.2.2 The Overlap Factor and A_{eff}

“In order to obtain the effective area of the absorption and emission cross sections, the transverse shape of the optical mode and its overlap with the transverse erbium ion distribution profile are very important since only the portion of the optical mode that overlaps with the erbium ion distribution will impact on absorption and emission. The overlap factor Γ is defined as a parameter to describe the relation between the optical mode and the erbium ion distribution.” (Xia, 2002; S. Park, Ahn, Ko, W. Lee, Oh, M. Lee and H. Park, 2013). “Generally, part of the optical mode will propagate in the cladding but erbium ions are typically doped in the core of the fiber. Therefore, the overlap factor is always less than 1” (Xia, 2002).

The effective cross-sectional area is decided by the shape of the erbium ion distribution and can be obtained by $A_{eff} = \pi R^2$, where R is the equivalent flat top radius of the erbium ion distribution. Since the actual transverse distribution of erbium ions is hard to obtain, A_{eff} is usually used to simplify the calculation in the mode. Figure 3.2 shows an example of an equivalent flat top distribution and the actual erbium ion distribution. The radius R of the flat top distribution is determined by the geometric profile of the actual erbium ion distribution”(Xia, 2002).

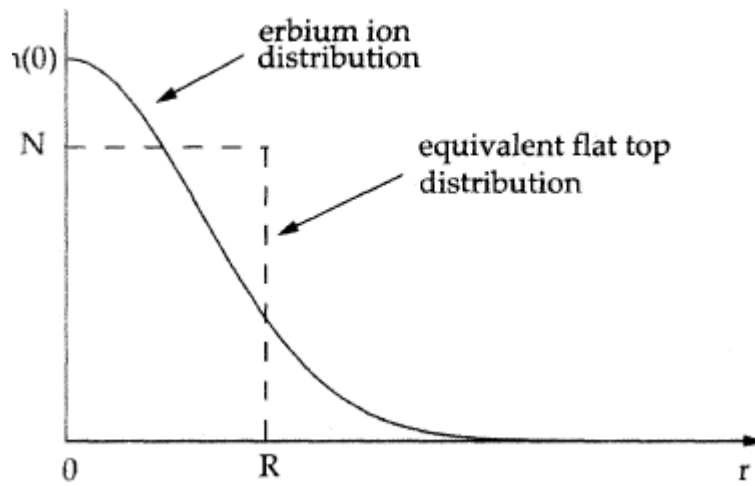


Figure 3.2: “Example of a radial distribution of the erbium ion density in a single-mode fiber and the equivalent “flat top” distribution, which has a constant ion density N stretching from $r=0$ to $r=R$.”(Xia, 2002; Becker, Olsson and Simpson, 1999: 142)

3.2.3 Lifetimes

“The lifetime of a level is inversely proportional to the probability per unit time that the ion will exit from that excited level. When there are several pathways for the population to decay, the total probability is the sum of the individual probabilities for each pathway. The two main pathways for decay are radiative and non-radiative, and hence the lifetime is given by,

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

where τ is the total lifetime, τ_r is the radiative lifetime, and τ_{nr} is the non-radiative lifetime. **(Desurvire, 1994)**” “The radiative lifetime arises from the fluorescence from an excited level to all the levels below it. Non-radiative lifetime depends largely on the glass composition and the coupling between the vibrations of the lattice ions and the states of the rare earth ions. **(Lidgard et al, 1991)**”

3.2.4 Linewidths and Broadening

“Linewidth represents a finite spectrum of the gain in the wavelength domain. This happens due to broadening of the energy states, i.e., each of the states actually is a collection of many closely spaced energy levels. The homogeneous, or natural, broadening arises from the lifetime and depends on both radiative and nonradiative processes **(Milonni, Eberly, 1988)**.” “Hence, the faster the lifetime the broader the state. The inhomogeneous broadening is a measure of various different sites in which an ensemble of ions can be situated. An inhomogeneous line is thus a superposition of a set of homogeneous lines. Such homogeneous and inhomogeneous lineshapes are shown in figure 3.3 respectively. In the presence of a strong signal that saturates the transition, the absorption or emission lineshapes will be affected in a different way, depending on whether the line is homogeneously or inhomogeneously broadened. In glasses, both the homogeneous and inhomogeneous broadening can be quite large, as compared to crystals **(Becker, Olsson and Simpson, 1999)**.” “In silica fibres where the photon energy is rather strong and electron-photon coupling strength is significant, the homogeneous broadening is quite large. The inhomogeneous broadening is also large due to multiplicity of sites and environments available to the ion **(Todorikki, Hirao and Soga, 1992)**.”

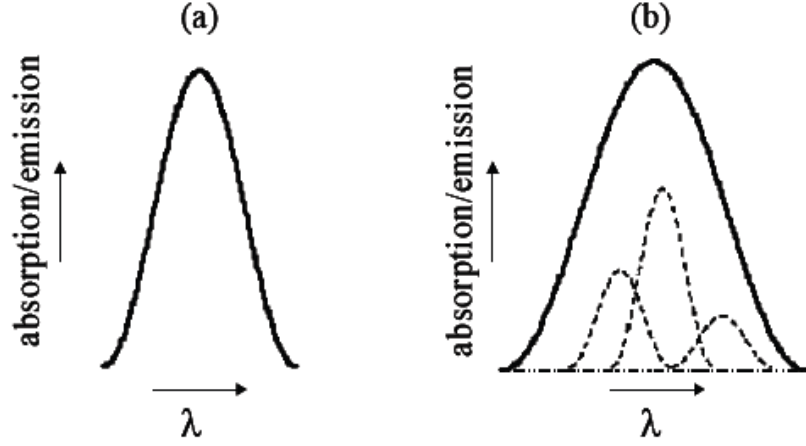


Figure 3.3: (a) A homogeneously broadened line for a collection of ions with identical transition wavelengths and lifetimes. (b) An inhomogeneously broadened line made up of a collection of homogeneously broadened lines with different centre wavelengths and linewidths. (**Becker, Olsson and Simpson, 1999**)

3.2.5 Two-Level System for EDFAs

“Having reduced the three-level system to an effective two-level system, we can write the rate equations so as to involve only the total population densities of multiplets 1 and 2.

$$\begin{aligned} \frac{dN_2}{dt} &= -\Gamma_{21}N_2 + (N_1\sigma_s^{(a)} - N_2\sigma_s^{(e)})\phi_s - (N_2\sigma_p^{(e)} - N_1\sigma_p^{(a)})\phi_p \\ \frac{dN_1}{dt} &= \Gamma_{21}N_2 + (N_2\sigma_s^{(e)} - N_1\sigma_s^{(a)})\phi_s - (N_1\sigma_p^{(a)} - N_2\sigma_p^{(e)})\phi_p \end{aligned} \quad (3.9)$$

Where $\sigma_s^{(a)}, \sigma_s^{(e)}, \sigma_p^{(a)}$ and $\sigma_p^{(e)}$ represent the signal and pump absorption and emission cross section, respectively.”(**Becker, Olsson and Simpson, 1999: 146; Pedersen, Bjarklev, Povlsen, Dybdal and Larsen, 1991; Song, Park, Lee and Kim, 2012**).“Since the total population density N is given by

$$N = N_1 + N_2 \quad (3.10)$$

We have

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} \quad (3.11)$$

and only one of the equations from system 3.9 is an independent equation. We can calculate N_2 , for example, in terms of the signal and pump intensities. N_1 is then simply given by $N - N_2$. It was found from equations 3.9, for the case of one pump field and one signal field, that the population density $N_2(z)$, as a function of position z along the fiber, is given by

$$N_2(z) = \frac{\frac{\tau\sigma_s^{(a)}}{h\nu_s} I_s(z) + \frac{\tau\sigma_p^{(a)}}{h\nu_p} I_p(z)}{\frac{\tau(\sigma_s^{(a)} + \sigma_s^{(e)})}{h\nu_s} I_s(z) + \frac{\tau(\sigma_p^{(a)} + \sigma_p^{(e)})}{h\nu_p} I_p(z) + 1} N \quad (3.12)$$

In general, we will assume that N is independent of z . The pump and signal propagation equations are then written, in a very similar fashion, as

$$\begin{aligned} \frac{dI_p(z)}{dz} &= (N_2\sigma_p^{(e)} - N_1\sigma_p^{(a)})I_p(z) \\ \frac{dI_s(z)}{dz} &= (N_2\sigma_s^{(e)} - N_1\sigma_s^{(a)})I_s(z) \end{aligned} \quad (3.13)$$

Stimulated emission from level 2 contributes to field growth, absorption from level 1 contributes to field attenuation. The equations needed to simulate the amplifying properties of the fiber are thus the population equation and the propagation equations, one for each field. The condition for population inversion, $N_2 - N_1 > 0$, in the presence of a small signal field, corresponds to the pump being greater than the threshold value:

$$I_{th} = \frac{h\nu_p}{(\sigma_p^{(a)} - \sigma_p^{(e)})\tau_2} \quad (3.14)$$

The pump threshold that corresponds to signal gain at the signal wavelength ($\frac{dI_s}{dz} > 0$) is slightly different is equal to

$$I_{th} = \frac{h\nu_p}{\tau_2} \frac{1}{\sigma_p^{(a)} \left(\frac{\sigma_s^{(e)}}{\sigma_s^{(a)}} \right) - \sigma_p^{(e)}} \quad (3.15)$$

The equations above can be easily generalized to the case of multiple signals and multiple pumps.”(Giles and Desurvire, 1991; Giles, Burrus, DiGiovanni, Dutta and Raybon, 1991; Becker, Olsson and Simpson, 1999: 147) “For the case of several signals s_i and several pump p_i , the population equation becomes

$$N_2(z) = \frac{\sum_{s_i} \frac{\tau \sigma_{s_i}^{(a)} I_{s_i}(z)}{h\nu_{s_i}} + \sum_{p_i} \frac{\tau \sigma_{p_i}^{(a)} I_{p_i}(z)}{h\nu_{s_i}}}{\sum_{s_i} \frac{\tau(\sigma_{s_i}^{(a)} + \sigma_{s_i}^{(e)})}{h\nu_{s_i}} I_{s_i}(z) + \sum_{p_i} \frac{\tau(\sigma_{p_i}^{(a)} + \sigma_{p_i}^{(e)})}{h\nu_{p_i}} I_{p_i}(z) + 1} N \quad (3.16)$$

The field propagation equations are identical to those of equations 3.13, with appropriate cross sections. Such multisignal system of equations will be used when computing, for example, the spectral distribution of the ASE or the amplification of multiple-signal channels in a WDM system.”(Becker, Olsson and Simpson, 1999: 147)

3.2.6 Amplified Spontaneous Emission

“Spontaneous emission is an important phenomenon in optical amplifiers. The excited erbium ion can spontaneously relax to the ground state and emit a photon that is unrelated to the input signal wavelength. In an EDFA, photons at random wavelengths are generated and propagate in both forward and backward directions. These photons can be further amplified along the rest of the EDF as signals and therefore, they are referred to as ASE (amplified spontaneous emission).” (Xia, 2002) “Spontaneous emission will result in randomly phased, incoherent radiation travelling in all direction. Therefore, those spontaneously generated photons which undergo gain in the fiber amplifier and travel in the same direction as the signal light, form a background noise that adds to the signal light. This background noise is referred to as amplified spontaneous emission. This is an inevitable phenomenon which degrade the signal-to-noise ratio (SNR) of the received signal.” (Heng Foo, 1999)

The basic element of ASE power is the equivalent noise power, which is defined as the power generated in a point of EDF by spontaneous emission at frequency ν and in a bandwidth of $\Delta\nu$. Since there are two independent polarizations for a given frequency, the equivalent noise power can be expressed as:”

$$P_{ASE}^0 = 2h\nu\Delta\nu \quad (3.17)$$

(Xia, 2002)

3.3 MODELING AND COMPLEX EFFECTS

3.3.1 Gain for EDFA

“Gain is the main characteristic of an amplifier. The EDFA gain is defined as the ratio of the output signal power to the input signal power as shown in Equation (3.18). It is calculated by integrating the gain coefficient $g(\lambda)$ over the length L of the erbium-doped fibre. The gain coefficient $g(\lambda)$ is calculated by summation of both the emission coefficient, $g^*(\lambda) = \Gamma_s N \sigma_e(\lambda)$, multiplied by the fractional populations of the ions in the excited state, N_2 , and the absorption coefficient, $\alpha(\lambda) = \Gamma_s N \sigma_a(\lambda) > 0$, multiplied by the fractional populations of the ions of the first excited and ground states of erbium, N_1 , the terms $g^*(\lambda)$ and $\alpha(\lambda)$ are shown in Equation (3.19)” (Muhyaldin, 2009; Zyskind and Nagel)

$$G(\lambda) = \frac{P_{out}}{P_{in}} = \int_0^L g(\lambda, z) dz \quad (3.18)$$

$$G(\lambda) = \int_0^L (g^*(\lambda)N_2(z) - \alpha(\lambda)N_1(z)) dz \quad (3.19)$$

“The spectra of the emission and absorption coefficients of an erbium doped Ge/Al/P silica fibre are shown in Figure 3.4. The gain coefficient can be expressed in units of dB/m. The terms mentioned are used in the numerical simulations, which focused on the analysis of the dynamic behaviour of cascaded EDFAs in WDM optical networks. These values are provided by Highwave-Technologies of France.” (Muhyaldin, 2009; www.highwave-tech.com, 2002)

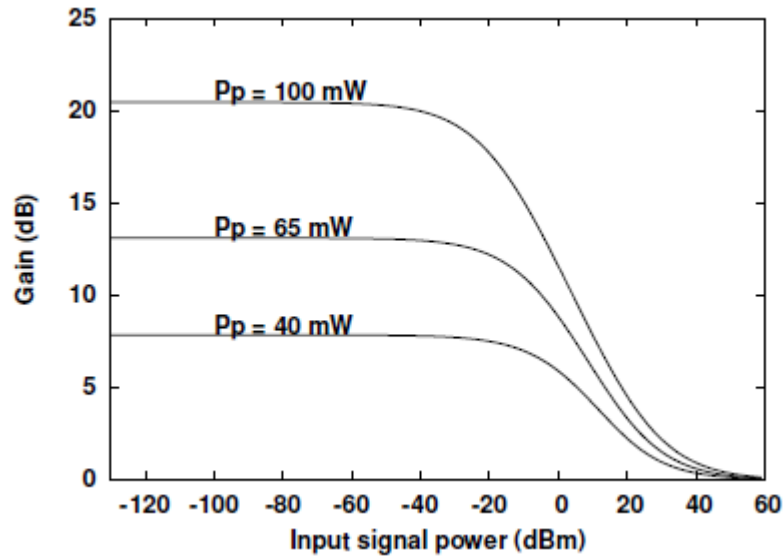


Figure 3.4: EDFA gain performance as a function of the input signal powers in dBm, at wavelength 1549.2 nm, at saturation for pump powers of 40, 65, 100 mW(Muhyaldin, 2009; www.highwave-tech.com, 2002)

“Figure 3.5 shows the curves of the gain G versus the pump power P_p , where we take the signal $P_s = 1 \mu\text{W}$, Er^{3+} ion concentration $N_{\text{Er}} = 1.0 \times 10^{26} \text{m}^{-3}$, Yb^{3+} ion concentration $N_{\text{Yb}} = 0, 2.0 \times 10^{27} \text{m}^{-3}$, and waveguide length $z = 1, 2, 3 \text{ cm}$.” (Wang, Sheng Ma, Li, Zhang, 2008)

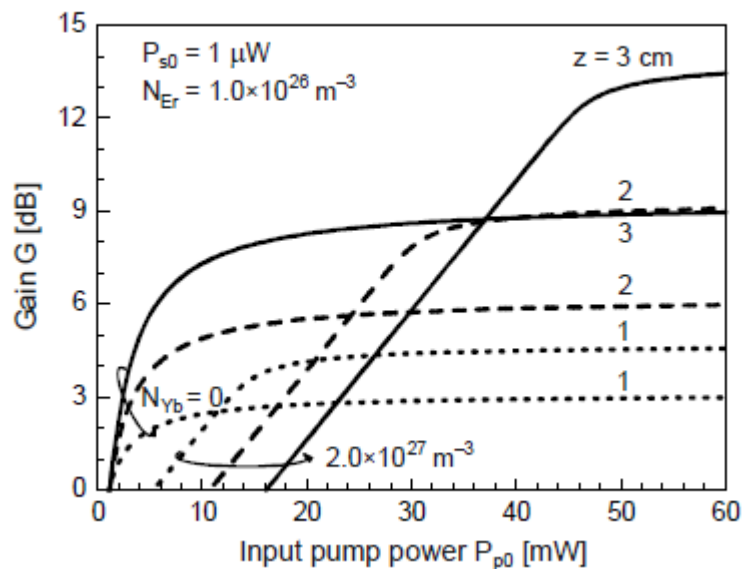


Figure 3.5: Curves of gain G versus pump power P_p (Wang, Sheng Ma, Li, Zhang, 2008).

3.3.2 Gain as Function of Fiber Length

“Figure 3.6 shows the signal gain at 1550 nm, for both 980 nm and 1480 nm pumping and 40 mW of pump power, as a function of the erbium-doped fiber length, for erbium-doped Al-Ge silica fiber. Interestingly, for the 1550 nm signal, the 1480 nm pump provides a higher gain than the 980 nm pump at equal pump powers. This was noted in previous simulations.” (Povlsen, Bjarklev, Lumholt, Vendeltrop-Pommer, Rottwitt and Rasmussen, 1991)

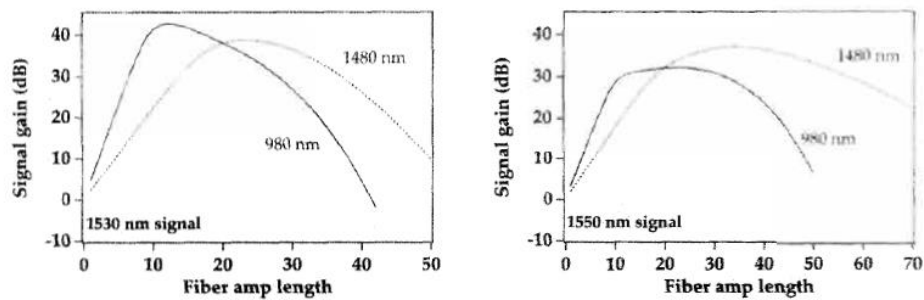


Figure 3.6: Signal gain at 1530 nm (left) and 1550 nm (right) for 1480 and 980 nm pumping of erbium-doped Al-Ge silica fiber, as a function of fiber amplifier length. The launched pump power is 40 mW and the launched signal power is -40 dBm (Povlsen et al, 1991).

“The 1480 nm pump can maintain the necessary inversion levels (≥ 0.40 for this particular fiber) over significantly longer lengths than the 980 nm pump. The reason for this is the higher quantum efficiency of 1480 nm pumping. This allows the signal to grow to a higher maximum value. The situation is reversed in the case of the 1530 nm signal. Since 1530 nm signal requires high inversions (≥ 0.53) and benefits from very high inversion levels, the 980 nm pump with its higher inversion capabilities can reach higher small signal gains than a 1480 nm pump, not with standing the greater quantum efficiency of latter. (Becker, Olsson and Simpson, 1999: 169) For higher input powers (e.g., -10 dBm), the fiber will be in a saturation regime where the inversion is reduced. In that case the higher quantum efficiency of the 1480 nm pump is the dominant factor and will give a higher gain at 1530 nm than the 980 nm pump. At high pump powers (for this particular fiber geometry) such as 40mW, the

maximum gain is achieved within a relatively broad range of fiber lengths. At low powers, the optimal length is in a much narrower range, as is shown in Figure 3.7.”(Becker, Olsson and Simpson, 1999: 169, Papannareddy, 2002:87)

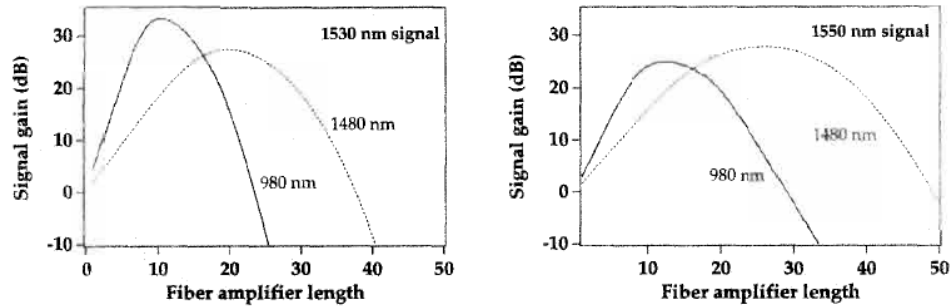


Figure 3.7: Signal gain at 1530 nm (left) and 1550 nm (right) for 1480 nm and 980 nm pumping of erbium-doped Al-Ge silica fiber, as a function of fiber amplifier length. The launched pump power is 10 mW and the launched signal power is -40 dBm. From numerical simulations(Becker, Olsson and Simpson, 1999: 169; Papannareddy, 2002:88).

3.3.3 Noise in EDFA

“Most, if not all, applications of photons and lightwave signals in communications, sensors, signal processing, etc., require the detection and subsequent conversion of the an electrical signal. In this process, the useful signal will be corrupted by noise and the ultimate sensitivity and performance of the system is limited by the noise characteristics.” (Becker, Olsson and Simpson, 1999: 201)“If EDFAs can compensate for the loss suffered while propagating through a fiber, the question that arises in one’s mind is whether it is possible to traverse an arbitrarily long distance in the fiber by periodic amplification along the fiber link provided that the dispersion effects do not limit the distance. This is, in fact, not possible, due to the addition of noise by each amplifier, as discussed below.

In an EDFA, population inversion between two energy levels of erbium ion leads to optical amplification by the process of stimulated emission. As

mentioned earlier, erbium ions occupying the upper energy level can also make spontaneous transitions to the ground state and emit radiation. This radiation appears over the entire fluorescent band of emission of erbium ions and travels in both the forward and backward directions along the fiber. Just like the signal, the spontaneous emission generated at any point along the fiber can be amplified as it propagates through the population-inverted fiber. The resulting radiation is called amplified spontaneous emission (ASE). This ASE, which has no relationship with the signal propagating through the amplifier, is the basic mechanism leading to noise in the optical amplifier. **(Thyagarajan and Ghatak, 2007)**

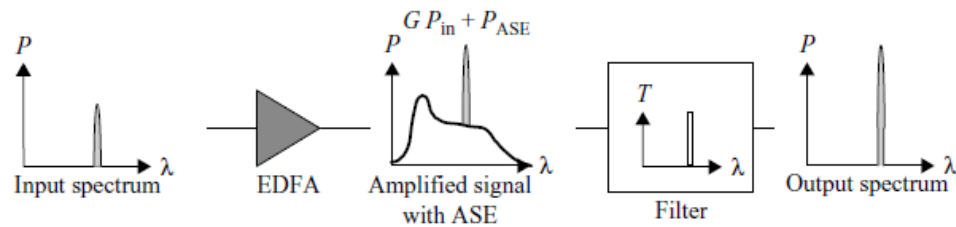


Figure 3.8: An EDFA amplifies an input signal, and along with the amplified signal there is a background ASE that constitutes the noise of the amplifier. Any ASE not coincident with the signal wavelength can be filtered using an optical filter. However, ASE within the signal band cannot be filtered and constitutes the minimum noise added by the amplifier.

Figure 3.8 shows the spectrum at the input of an EDFA and the output from the EDFA. At the output we have both the amplified signal and a background ASE. The ASE appearing in a wavelength region not coincident with the signal can be filtered using an optical filter as shown in the figure. On the other hand, the ASE that appears in the signal wavelength region cannot be separated and constitutes the minimum added noise from the amplifier.” **(Thyagarajan and Ghatak, 2007)**

“If P_{in} represents the signal input power (at frequency ν) into the amplifier and G represents the gain of the amplifier in linear units (the corresponding gain in decibels is given by $\tilde{G}=10\log G$), the output signal power is given by GP_{in} .

Along with this amplified signal, there is ASE power, which can be shown to be given by

$$P_{ASE} \approx 2\eta_{SP}(G - 1)h\nu B_0 \quad (3.20)$$

where B_0 is the optical bandwidth in the frequency domain over which the ASE power is being measured (which must be at least equal to the optical bandwidth of the signal), and the spontaneous emission factor η_{SP} is given by”

$$\eta_{SP} = \frac{N_2}{N_2 - N_1} \quad (3.21)$$

(Becker, P.C. 2002; Thyagarajan and Ghatak, 2007; Becker, Olsson and Simpson, 1999: 204)

“Here N_2 and N_1 represent the population densities (number of atoms per unit volume) in the upper and lower amplifier energy levels of erbium in the fiber. Minimum value for η_{SP} corresponds to a completely inverted amplifier for which $N_1 = 0$ (i.e., all atoms excited to the upper level) and thus $\eta_{SP} = 1$; for partial inversion, $\eta_{SP} > 1$.

“We can define the optical signal-to-noise ratio (OSNR) as the ratio of the output optical signal power to the ASE power:

$$OSNR = \frac{P_{out}}{P_{ASE}} = \frac{GP_{in}}{2\eta_{sp}(G - 1)h\nu B_0} \quad (3.22)$$

(Thyagarajan and Ghatak, 2007; Becker, Olsson and Simpson, 1999: 231; R. Tenc)

where P_{in} is the average power input into the amplifier (which is about half of the peak power in the bit stream, assuming equal probability of 1’s and 0’s).

“Amplifier noise is the ultimate limiting factor for system applications. For a lumped EDFA, the impact of ASE is quantified through the noise figure NF given by $NF = 2\eta_{sp}$. The spontaneous emission factor η_{sp} depends on the relative populations N_1 and N_2 of the ground and excited states as 4.21. Since EDFAs operate on the basis of a three-level pumping scheme, $N_1 \neq 0$ and $\eta_{sp} > 1$. Thus, the noise figure of EDFAs is expected to be larger than the ideal value of 3 dB” (Agrawal, 2002; S. B. Alexander, 1987; M. W. Maeda and D. A. Smith, 1991).

“The spontaneous-emission factor can be calculated for an EDFA by using the rate-equation model discussed earlier. However, one should take into account the fact that both N_1 and N_2 vary along the fiber length because of their dependence on the pump and signal powers; hence η_{sp} should be averaged along the amplifier length. As a result, the noise figure depends both on the amplifier length L and the pump power P_p , just as the amplifier gain does. Figure 3.9(a) shows the variation of NF with the amplifier length for several values of P_p/P_p^{sat} when a $1.53 \mu\text{m}$ signal is amplified with an input power of 1mW. The amplifier gain under the same conditions is also shown in Figure 3.9(b). The results show that a noise figure close to 3 dB can be obtained for a high-gain amplifier pumped such that $P_p/P_p^{sat} \gg 1$ ” (Agrawal, 2002; S. B. Alexander, 1987)

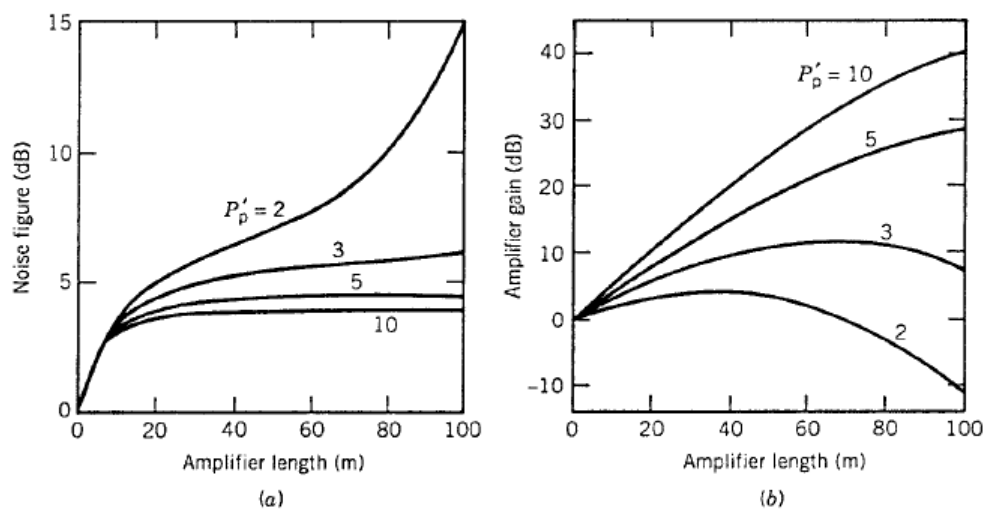


Figure 3.9: (a) noise figure and (b) amplifier gain as a function of the length for several pumping levels. (M. W. Maeda and D. A. Smith, 1991)

“The experimental results confirm that NF close to 3 dB is possible in EDFAs. A noise figure of 3.2 dB was measured in a 30 m long EDFA pumped at 0.98 μm with 11 mW of power” (T. Okoshi, 1985; Agrawal, 2002). “A similar value was found for another EDFA pumped with only 5.8 mW of pump power at 0.98 μm ” (Agrawal, 2002; T. G. Hodgkinson, R. A. Harmon, and D. W. Smith, 1987). “In general, it is difficult to achieve high gain, low noise, and high pumping efficiency simultaneously. The main limitation is imposed by the ASE traveling backward toward the pump and depleting the pump power. Incorporation of an internal isolator alleviates this problem to a large extent. In one implementation, 51 dB gain was realized with a 3.1 dB noise figure at a pump power of only 48 mW” (P. Poggiolini and S. Benedetto, 1994).

“The measured values of NF are generally larger for EDFAs pumped at 1.48 μm . A noise figure of 4.1 dB was obtained for a 60-m-long EDFA when pumped at 1.48 μm ” (T. Okoshi, 1985). “The reason for a larger noise figure for 1.48 μm pumped EDFAs can be understood from Figure 3.9(a), which shows that the pump level and the excited level lie within the same band for 1.48 μm pumping. It is difficult to achieve complete population inversion $N_1 \approx 0$ under such conditions. It is nonetheless possible to realize $NF < 3.5$ dB for pumping wavelengths near 1.46 μm . (Agrawal, 2002)

“Relatively low noise levels of EDFAs make them an ideal choice for WDM light wave systems. In spite of low noise, the performance of long-haul fiber-optic communication systems employing multiple EDFAs is often limited by the amplifier noise. The noise problem is particularly severe when the system operates in the anomalous-dispersion region of the fiber because a nonlinear phenomenon known as the modulation instability enhances the amplifier noise and degrades the signal spectrum” (S. Benedetto and P. Poggiolini, 1994; G. P. Agrawal, 1996; S. Ogita et al, 1990).

3.3.4 EDFA Cascade

“A serious problem facing wavelength division multiplexed networks with fiber amplifier cascades is transient cross saturation or gain dynamics of fiber amplifiers. Attention has been focused primarily on circuit-switched scenarios. When the number of WDM channels transmitted through a circuit-switching network varies, channel addition/removal will tend to perturb signals at the surviving channels that share all or part of the route. Power transients in the surviving channels can cause severe service impairment due to either inadequate eye opening or the appearance of optical nonlinear ties” (Ye Chen, 200; Y. Sun, et al, 1997).

“Signal power excursions more serious than those induced by channel addition/removal in circuit switched networks can arise when data on the WDM channels is highly variable in nature. Self-similar traffic can lead to large variation in EDFA gain” (Ye Chen, 2000).

“When self-similar packet traffic is directly transmitted in burst-mode on the WDM channels, as in the case of Internet Protocol (IP) over WDM, long inter-burst idle intervals may give enough time to fiber amplifiers to reach gains greatly exceeding the average values. This can in turn lead to significant variation in output power and optical OSNR. This effect accumulates along a cascade of fiber amplifiers in the same way as the fast power transients in the circuit-switching scenario. The effect of WDM traffic statistics on the output power and OSNR swings in a cascade of five EDFAs of standard design has been theoretically investigated in” (A. Bononi, L. Tancevski, and L.A. Rusch, 1998; L. Tancevski, et al 1999). “The results of the simulations indicate that substantial power and OSNR swings occur at the output of a cascade when highly variable burst-mode traffic is transmitted. Power swings in excess of 9 dB and OSNR swings of more than 4 dB were observed. The stabilization effect of clamping the gain of the first EDFA by all-optical feedback loop and letting the lasing power propagate through the cascade of six EDFAs has been studied in” (M. Karasek, et al, 2000).

CHAPTER-4

4.1 INTRODUCTION

In Single Pass EDFA (SP EDFA) and Double Pass EDFA (DP EDFA) applications, there are two types of pumping signal wavelengths being used; 980 nm and 1480 nm. The pumping at 980 nm provides lower noise figure than pumping at 1480 nm. On the other hand, 1480 nm pumping has higher quantum efficiency and thus provides higher output power and therefore it is preferred in booster type amplifiers even though the conventional SP EDFA and DP EDFA configurations pumped at 1480 nm have the disadvantages in the means of Noise Figure (NF). The main motivation of this thesis is to propose modified and extended SP EDFA and DP EDFA configurations to overcome the high NF problem for 1480 nm pumping level.

In this study we work in C-Band (1530-1570 nm). We use an input signal with the power -35 dBm at the wavelength $\lambda_s=1550$ nm. We utilize SP EDFA and DP EDFA in our configurations with different pumping directions w.r.t the direction of the input signal. For SP EDFA we propose 4 different pumping schemes:

- i. Forward-Forward pumping scheme
- ii. Forward-Backward pumping scheme
- iii. Backward-Backward pumping scheme
- iv. Backward-Forward pumping scheme

where two separate pump signals each of at 7 mW or a single pump signal at 14 mW with wavelength $\lambda_p=1480$ nm are used. In (i), two separate pump signals in the forward direction at 7 mW are applied on two different SP EDFA, i.e. the proposed configuration is composed of two different stages. In (ii), (iii), and (iv) same pump power is used with only direction differences depending on the configuration. For each proposed SP EDFA configuration we calculate the Gain, NF and PASE.

For DP EDFA we propose 3 different pumping schemes:

- i. Forward pumping scheme

- ii. Forward-Forward pumping scheme
- iii. Backward pumping scheme

where a single pump signal at 14 mW with wavelength $\lambda_p=1480$ nm is used in (i) and (iii), and two separate pump signals each of at 7 mW with wavelength $\lambda_p=1480$ nm are used in (ii). For each proposed DP EDFA configuration we calculate the Gain, NF and PASE.

4.2 SINGLE PASS EDFA CONFIGURATIONS

The parameter set used for the utilized SP EDFA in the calculations shown in Table 4.1 is mostly obtained from the published literature. Reference point of this thesis is the study of Hossain et al. where it is shown that for the input signal -35 dBm at the wavelength of 1550 nm and the pump power 14 mW at the wavelength of 1480 nm, the best gain value is 35.30 dB and the lowest NF value is 7 dB which are obtained at 30 meter of EDFA. Using the same parameters (signal power, signal wavelength, pump wavelength) we offer new configurations to obtain improved gain and decreased NF where the same total length of EDFA and the same total pump power are used. Thus, without increasing the total cost (utilizing same total length of EDFA and same total pump power) we aim to increase the performance of EDFA system in the means of gain and NF. In our SP EDFA configurations we use two stages of EDFA with equal length. The first stage (EDFA L1 – 15 m) and the second stage (EDFA L2 – 15m) are pumped with the pump signal at different directions w.r.t. the input signal for each configuration proposed.

Table 4.1: Parameter set of the SP EDFA.

EDFA L1	15 m	h	6.626068×10^{-34} J.s
EDFA L2	15 m	ν_s	193.45×10^{12} Hz
τ	0.0102 seconds	ν_p	202.40×10^{12} Hz
$\sigma_s^{(a)}$	$2.910556 \times 10^{-25} m^2$	A	$1.633 \times 10^{-11} m^2$
$\sigma_s^{(e)}$	$4.118853 \times 10^{-25} m^2$	$\Delta\nu$	3100 GHz
$\sigma_p^{(a)}$	$2.787671 \times 10^{-25} m^2$	α_s	0.20 dB/km
$\sigma_p^{(e)}$	$0.810563 \times 10^{-25} m^2$	α_p	0.24 dB/km
P_p^+	7 mW	ρ	300 ppm
P_p^-	7 mW	Γ_s	0.74
P_s	-35 dBm	Γ_p	0.77

4.2.1 Setup, Formulation and Results for Configuration-1 (Forward-Forward Pump)

The first setup is shown in Figure 4.1. As seen in the figure, the proposed SP EDFA configuration is composed of two stages (EDFA L1 and EDFA L2) where each of them has 15 m length. The input signal (P_s) is sent directly to EDFA L1. In this configuration, there are two separate pump signals applied at two different points in the forward direction (w.r.t. the direction of input signal). The first and the second pump signals at 7 mW are applied separately on EDFA L1 and EDFA L2, respectively, in the forward direction.

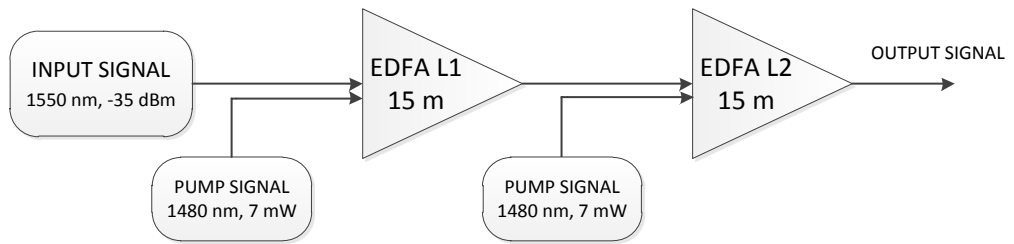


Figure 4.1: Configuration 1: Forward – Forward pump scheme for double stage SP EDFA.

According to Giles and Desurvire model explained in Chapter 3, when pumping at 1480 nm, it is necessary to form a system model for EDFA using the energy levels ${}^4I_{13/2}$ and ${}^4I_{15/2}$ where their population densities are denoted as N_1 and N_2 , respectively. The population densities are calculated as below:

$$N_1 = \rho \frac{1 + W_{21}\tau}{1 + (W_{12} + W_{21})\tau + R\tau} \quad (4.1)$$

$$N_2 = \rho \frac{R\tau + W_{12}\tau}{1 + (W_{12} + W_{21})\tau + R\tau} \quad (4.2).$$

The value of W_{12} , W_{21} and R can be calculated as:

$$R = \frac{P_p^+ \Gamma_p \sigma_p^{(a)}}{hV_p A} \quad (4.3)$$

$$W_{12} = \frac{\sigma_s^{(a)} \Gamma_s}{hV_s A} (P_s^+ + P_{ASE}^+ + P_{ASE}^-) \quad (4.4)$$

$$W_{21} = \frac{\sigma_s^{(e)} \Gamma_s}{hV_s A} (P_s^+ + P_{ASE}^+ + P_{ASE}^-) \quad (4.5).$$

In Giles and Desurvire model, the two level system model is given as below:

$$\frac{dP_p^+}{dz} = P_p^+ \Gamma_p (\sigma_p^{(e)} N_2 - \sigma_p^{(a)} N_1) - \alpha_p P_p^+ \quad (4.6)$$

$$\frac{dP_s^+}{dz} = P_s^+ \Gamma_s (\sigma_s^{(e)} N_2 - \sigma_s^{(a)} N_1) - \alpha_s P_s^+ \quad (4.7)$$

$$\frac{dP_{ASE}^+}{dz} = P_{ASE}^+ \Gamma_s (\sigma_s^{(e)} N_2 - \sigma_s^{(a)} N_1) + 2\sigma_s^{(e)} N_2 \Gamma_s hV_s \Delta\nu - \alpha_s P_{ASE}^+ \quad (4.8)$$

$$\frac{dP_{ASE}^-}{dz} = -P_{ASE}^- \Gamma_s (\sigma_s^{(e)} N_2 - \sigma_s^{(a)} N_1) + 2\sigma_s^{(e)} N_2 \Gamma_s hV_s \Delta\nu + \alpha_s P_{ASE}^- \quad (4.9).$$

NF is generated by spontaneous emission and number of spontaneous photons is given by

$$\eta_{SP} = \frac{\eta N_2}{\eta N_2 - N_1} \quad (4.10)$$

where

$$\eta = \frac{\sigma_s^{(e)}}{\sigma_s^{(a)}} \quad (4.11).$$

The NF of a high gain SP EDFA is calculated as;

$$NF = 2\eta_{SP} \quad (4.12).$$

The differential equations (4.6), (4.7), (4.8) and (4.9) are coupled equations. First, we solve equations (4.6), (4.7) and (4.8) from 0 to 15 m (from the beginning to the end of EDFA L1 in Figure 4.1) using ode45() function in Matlab. For EDFA L1 calculations from 0 to 15 m, we do not consider P_{ASE}^- , (Eq. 4.9) where $P_p^+(z=0) = P_{p_initial}$ (initial pump power to SP EDFA), $P_s(z=0) = P_{s_initial}$ (initial signal power to SP EDFA) and $P_{ASE}^+(z=0) = 0$ are taken as the initial boundary values. Once we calculate P_p^+ , P_s and P_{ASE}^+ , again using ode45() function, this time we calculate the whole set of equation from

$z=15$ to $z=0$ including P_{ASE}^- with $P_{ASE}^-(z = 15) = 0$, $P_{ASE}^+(z = 15) = P_{ASE}^+_{z=15}$, $P_s(z = 15) = P_{s_{z=15}}$, $P_p^+(z = 15) = P_{p_{z=15}}^+$ where $P_{ASE}^+_{z=15}$, $P_{s_{z=15}}$ and $P_{p_{z=15}}^+$ are the final values obtained from the EDFA L1 calculations. Then, the evaluated input signal obtained as an output signal from the end of EDFA L1 is directly sent into EDFA L2. The residue pump signal obtained at the end of EDFA L1 is added to the second pump signal and sent into EDFA L2. Same procedure is followed for calculating P_p^+ , P_s , P_{ASE}^+ and P_{ASE}^- in EDFA L2 calculations as done in EDFA L1.

Figure 4.2 shows the upper population density N_2 and ground state population density N_1 in per cubic meter as a function of position along a 30 m length.

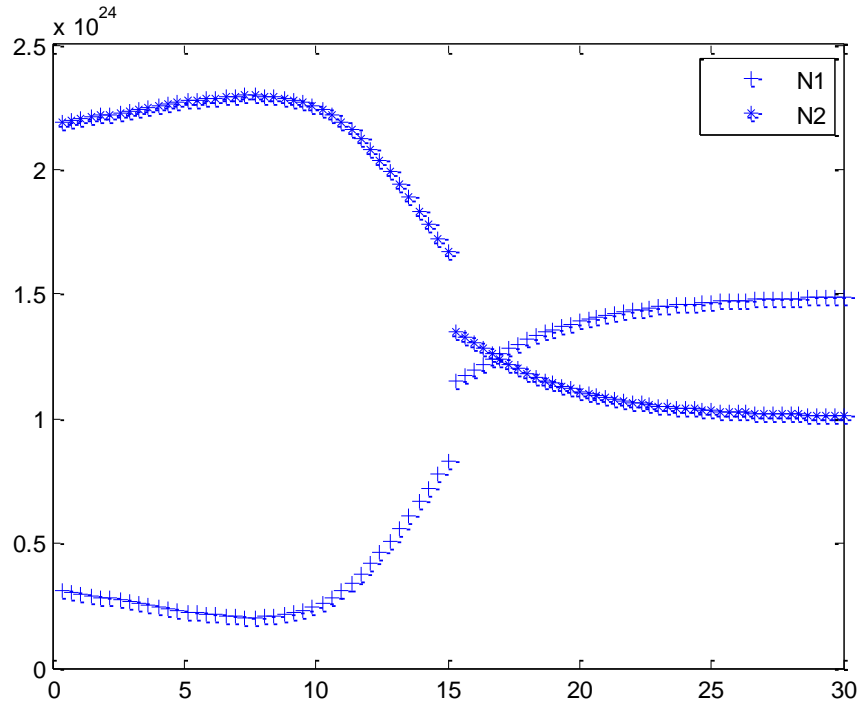


Figure 4.2: Population Density of Configuration 1.

From this figure, after 17 meter length, upper state population is less than the ground state population. For this reason, if we use an EDFA of length more than 17 meter, the portion of the EDFA that exceeds this length remains unpumped. This unpumped portion of the EDFA absorbs the signal and degrades the system performance. If an EDFA of length less than 17 meter is used for the proposed configuration-1, then a portion of the pump power will remain unused which could provide more population inversion and hence the

increment of the gain. For these reasons, an EDFA length of 17 meter is an optimized length for configuration-1.

Figure 4.3 shows the signal gain as a function of EDFA length for configuration-1. Referring to Figure 4.3, signal gain increases upto the length of 17 meter and after this point the gain starts decreasing which justifies the findings in Figure 4.2.

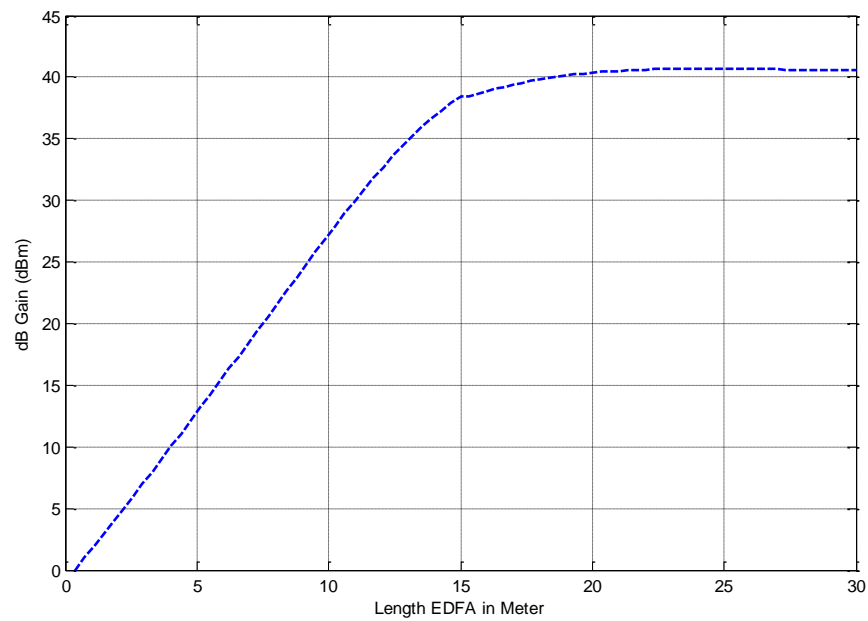


Figure 4.3: The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-1.

In Figure 4.4 the NF of configuration-1 is depicted.

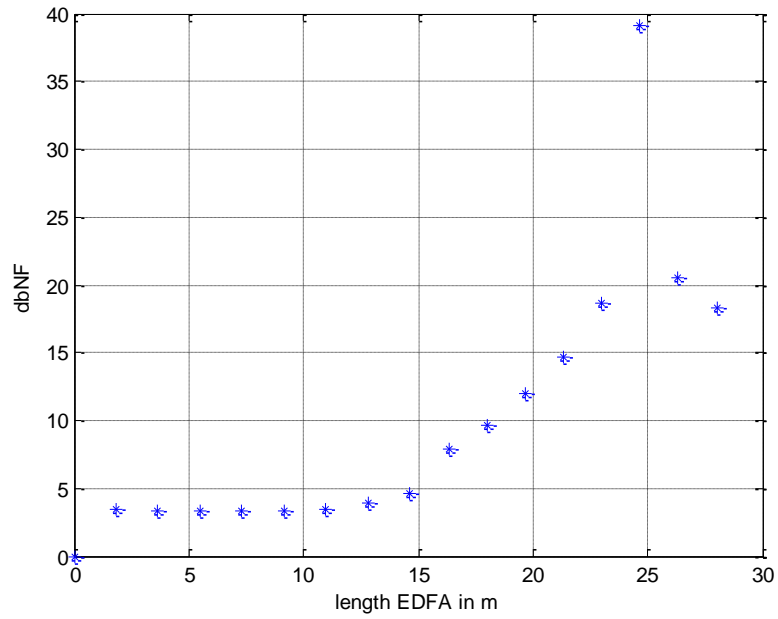


Figure 4.4: Noise Figure of configuration-1.

Figure 4.5 shows the forward and backward travelling ASE as a function of position along the combined length of EDFA L1 and EDFA L2.

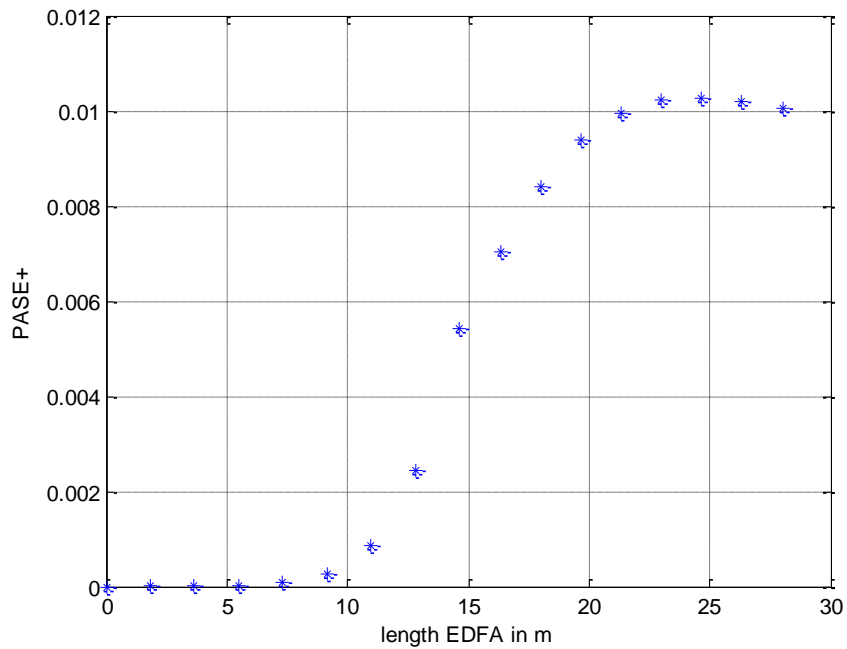


Figure 4.5: The forward travelling ASE of configuration-1.

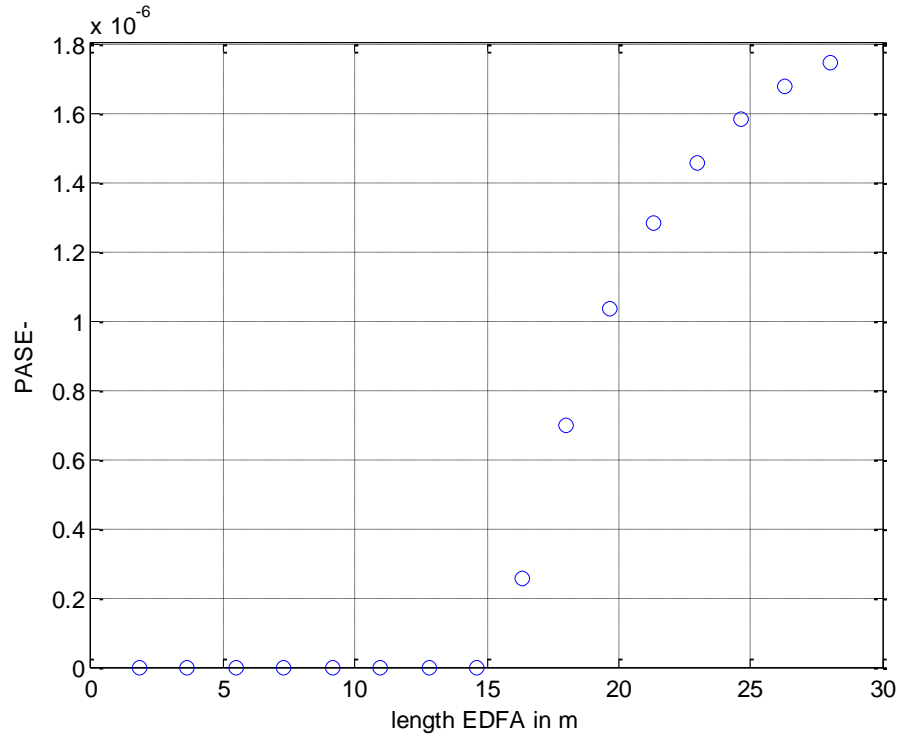


Figure 4.6: The backward travelling ASE of configuration-1.

4.2.2 Setup, Formulation and Results for Configuration-2 (Forward-Backward Pump)

The second setup is shown in figure 4.7. In this configuration, we use two stages of SP EDFA (EDFA L1, EDFA L2) where each of them has 15 m length. The input signal (P_s) is sent directly into EDFA L1. We also use two pump signals as in the previous case applied at two different points. This time one is in the forward direction and the second one is in the backward direction (with respect to input signal) as seen in the figure 4.7. The first pump signal at 7mW is applied on EDFA L1 in the forward direction and the second pump signal at 7mW is applied on EDFA L2 in the backward direction.

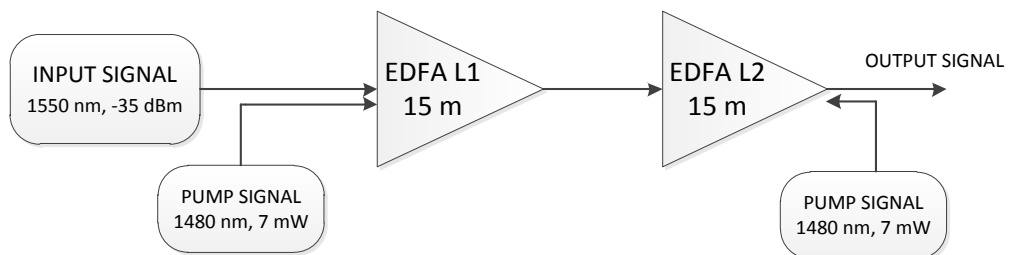


Figure 4.7: Forward-Backward pump scheme of configuration 2.

In this configuration for the evaluation of N_1 , N_2 , W_{12} , W_{21} , P_p^+ , P_s^+ , P_{ASE}^+ , P_{ASE}^- and NF the Eqs. (4.1), (4.2), (4.4), (4.5), (4.6), (4.7), (4.8), (4.9) and (4.12) can be used. The only additional equations in this configuration will be for the calculation of pumping rate (instead of Eq. (4.3)) and for the spatial evolution of P_p^- term which are given as below;

$$R = \frac{P_p^- \Gamma_p \sigma_p^{(a)}}{hV_p A} \quad (4.13)$$

$$\frac{dP_p^-}{dz} = -P_p^- \Gamma_p (\sigma_p^{(e)} N_2 - \sigma_p^{(a)} N_1) + \alpha_p P_p^- \quad (4.14)$$

where P_p^- is the pump signal applied on the EDFA L2 in the backward direction.

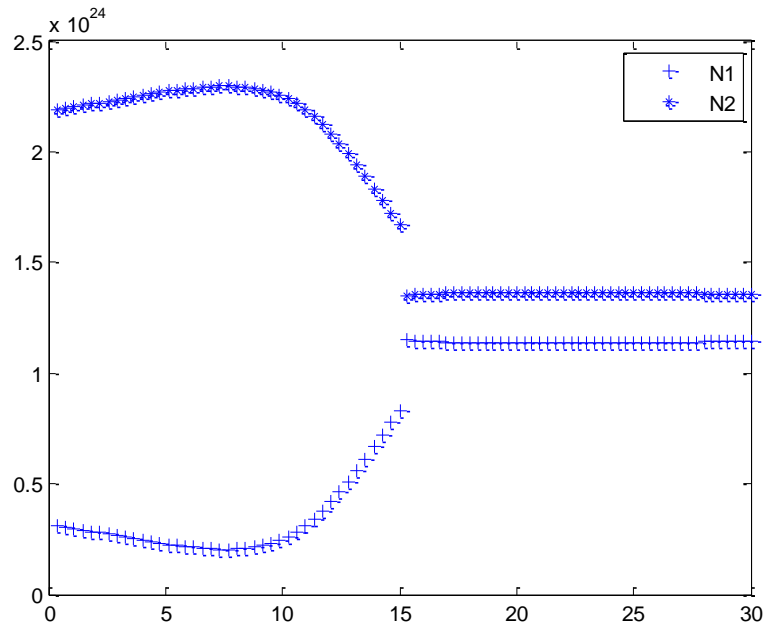


Figure 4.8: Population density of configuration-2.

Figure 4.8 shows the population density in per cubic meter in the upper state and ground state as a function of position along EDFA L1 and EDFA L2.

Figure 4.9 shows the dbgain along the length of two stages of EDFA. Referring to Figure 4.9, signal gain increases upto the length of 30 meter and after the 30 meter it begins to reduce.

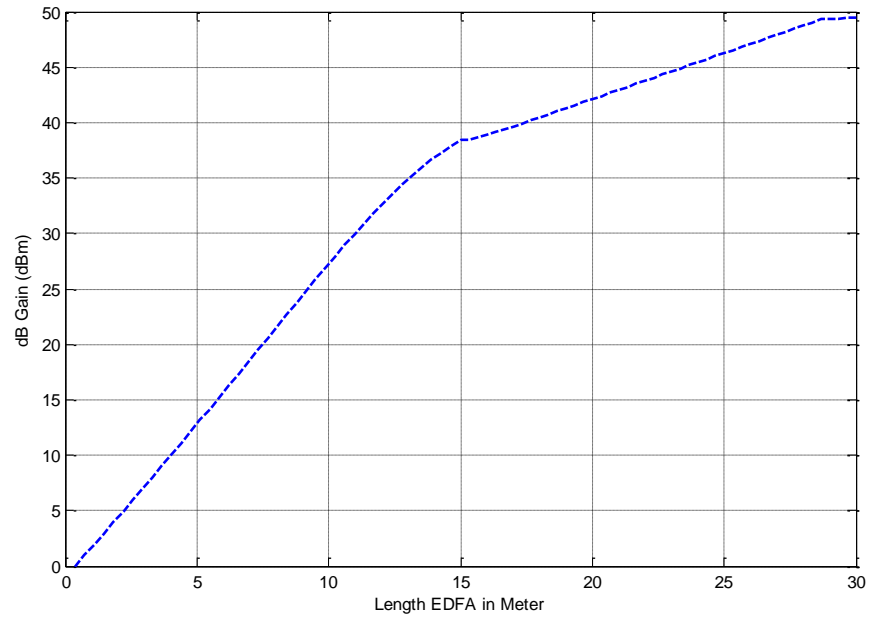


Figure 4.9: The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-2.

Figure 4.10 shows NF in dB as a function of 30 m long EDFA at 1550 nm signal wavelength.

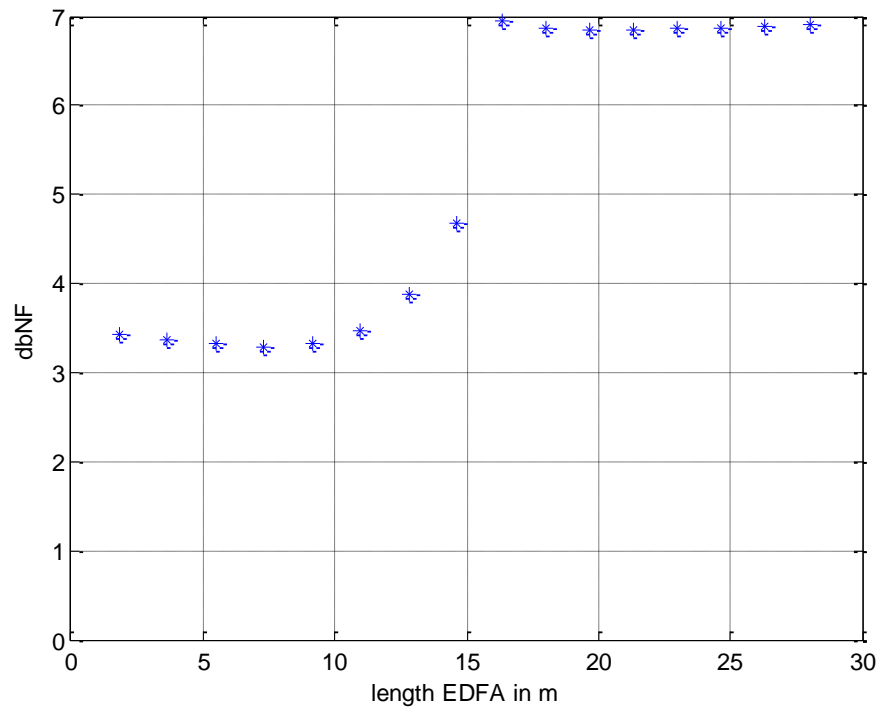


Figure 4.10: Noise Figure of configuration-2.

Figures 4.11 and 4.12 show the forward and backward travelling ASE as a function of position along 30 m long SP EDFA, respectively.

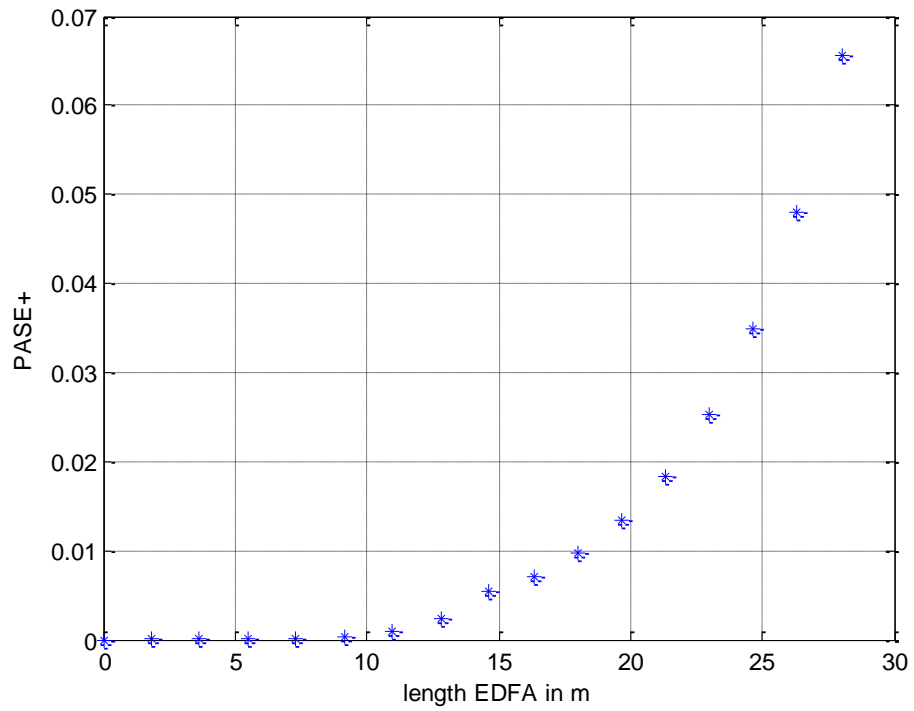


Figure 4.11: The forward travelling ASE of configuration-2.

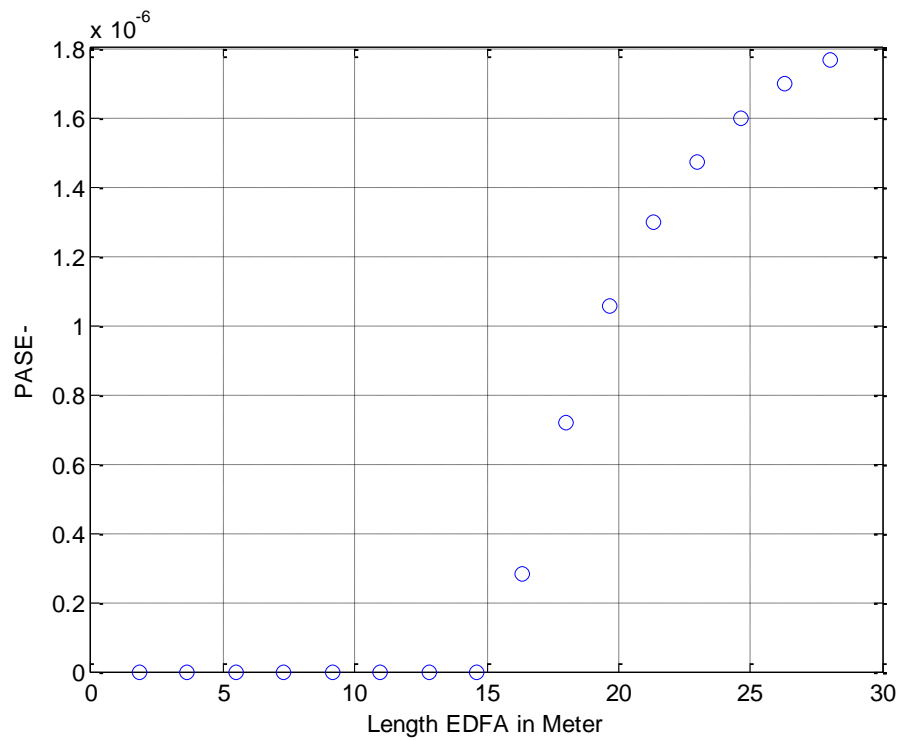


Figure 4.12: The backward travelling ASE of Configuration-2.

4.2.3 Setup, Formulation and Results for Configuration-3 (Backward-Backward Pump)

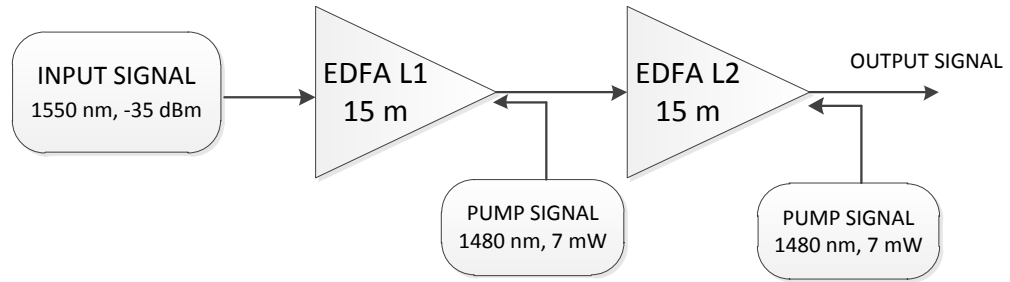


Figure 4.13: Backward-Backward pump scheme of configuration 3.

The third setup is shown in Figure 4.13. In this configuration, we use two stages of SP EDFA (EDFA L1, EDFA L2) where each of them has 15 m length. The input signal (P_s) is sent directly into EDFA L1. We also use two pump signals applied at two different points in the backward direction with respect to input signal. The first backward pump signal at 7mW is applied on EDFA L1 and second backward pump signal at 7mW is applied on EDFA L2.

Figure 4.14 shows the population density in per cubic meter in the upper state and ground state as a function of position along a 30 m long.

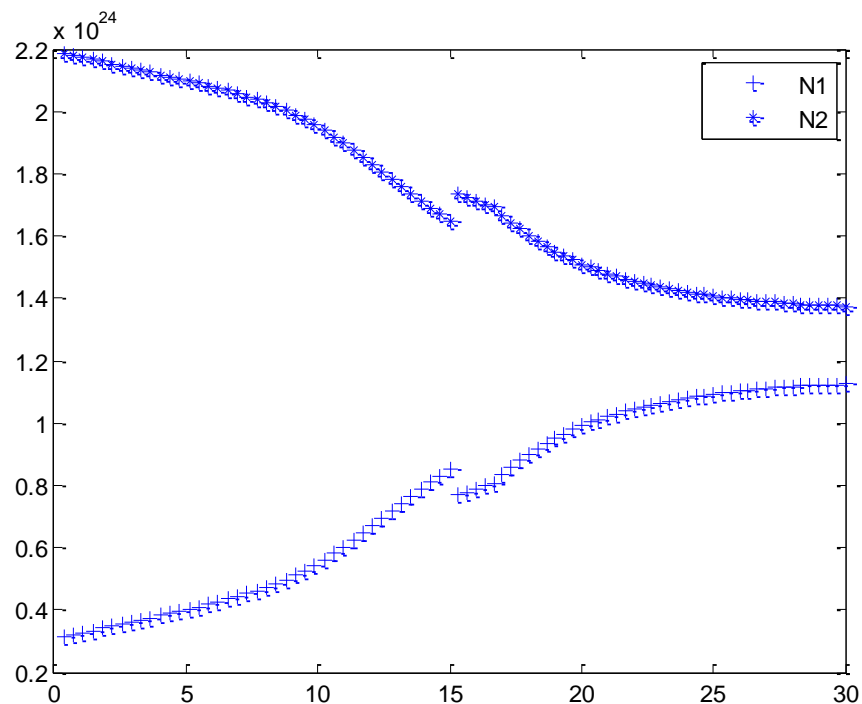


Figure 4.14: Population density of configuration-3.

Figure 4.15 shows the dbgain along the length of two stages of EDFA. Referring to Figure 4.15, signal gain increases upto the length of 30 meter and after the 30 meter it begins to reduce.

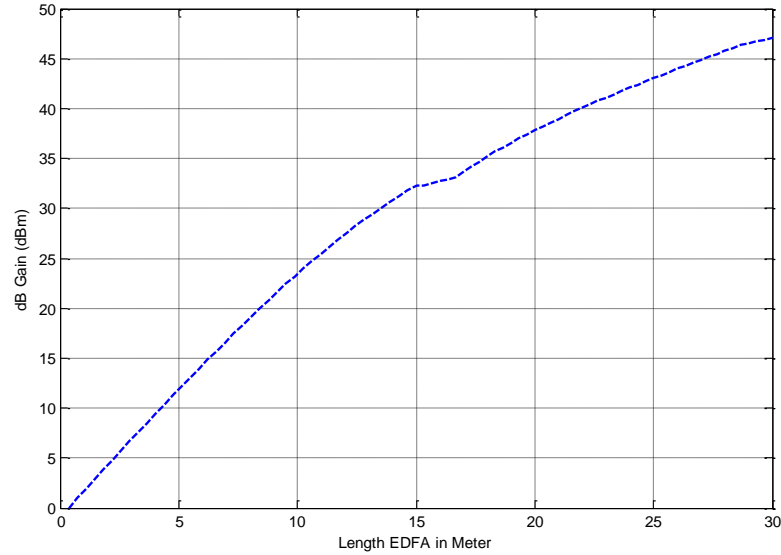


Figure 4.15: The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-3.

Figure 4.16 shows NF in dB as a function of 30 m long EDFA at 1550 nm signal wavelength.

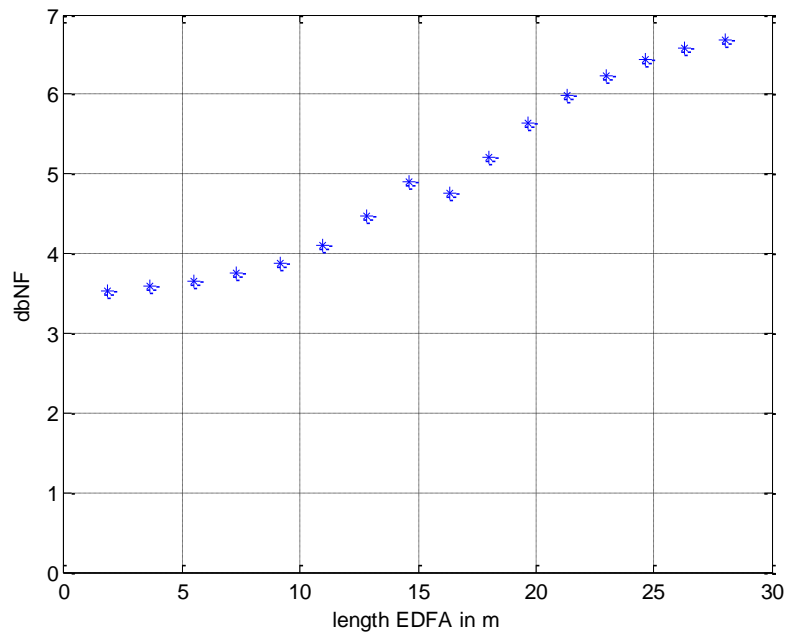


Figure 4.16: Noise Figure of configuration-3.

Figure 4.17 and Figure 4.18 show the forward and backward travelling ASE as a function of position along 30 m long SP EDFA, respectively.

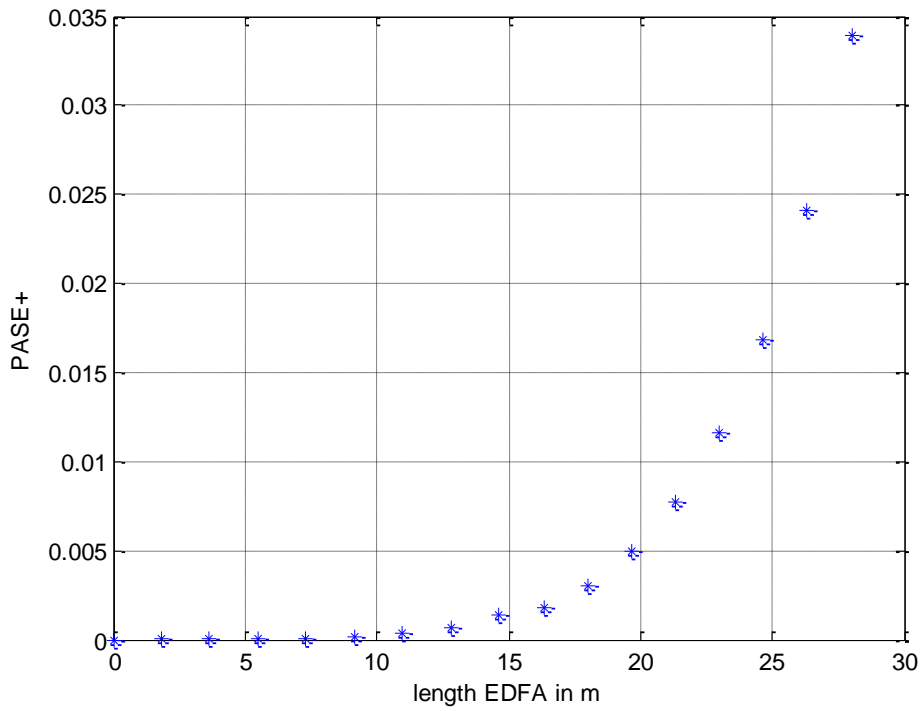


Figure 4.17: The forward travelling ASE of configuration-3.

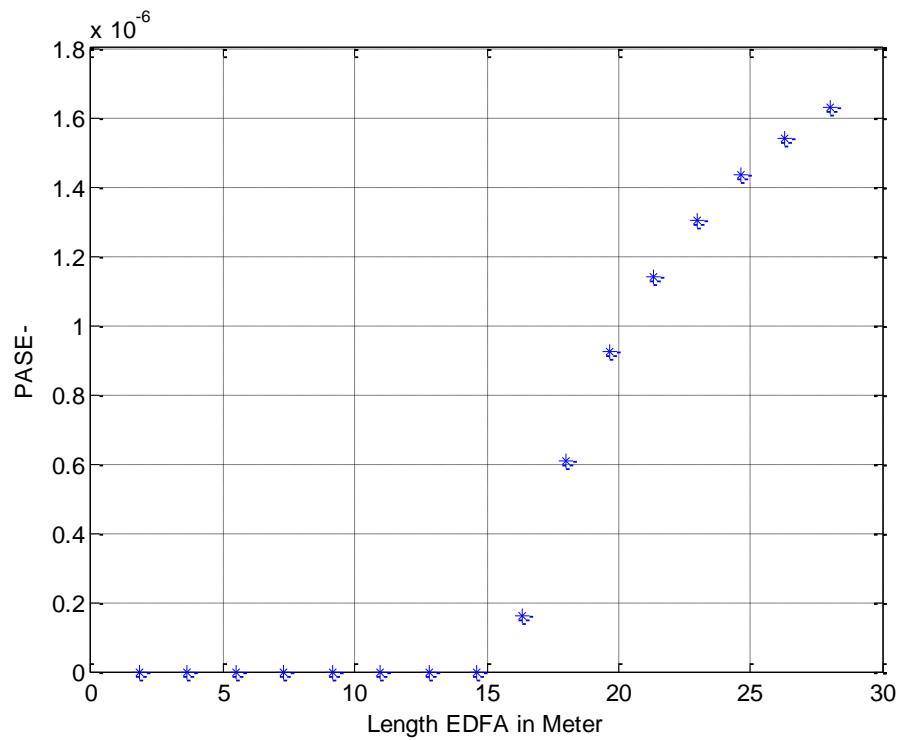


Figure 4.18: The backward travelling ASE of configuration-3.

4.2.4 Setup, Formulation and Results for Configuration-4 (Backward-Forward Pump)

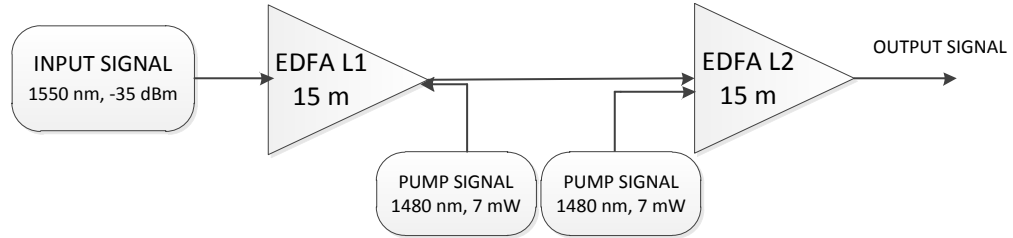


Figure 4.19: Backward-Forward pump scheme of configuration 4

The fourth setup is shown in Figure 4.19. In this configuration, we use two stages of SP EDFA (EDFA L1, EDFA L2) where each of them has 15 m length. The input signal (P_s) is sent directly into EDFA L1. We also use two pump signals applied at two different points in the forward direction and backward direction (with respect to input signal). The first pump signal at 7mW is applied on EDFA L1 in the backward direction and the second pump signal at 7mW is applied on EDFA L2 in the forward direction.

Figure 4.20 gives the population density in per cubic meter in the upper state and ground state as a function of position. It is seen Figure 4.20 that after 20,67 meter, upper state population is less than the ground state population. For this reason, if we use an EDFA of length more than 20,67 meter, the portion of the EDFA that exceeds this length remains unpumped. This unpumped portion of the EDFA absorbs the signal and degrades the system performance. If an EDFA of length less than 20,67 meter is used for the proposed SP EDFA configuration then a portion of the pump power will remain unused which could cause more population inversion and hence the increment of the gain. For these reasons an EDFA length of 20,67 meter is chosen as an optimized length for the SP EDFA configuration.

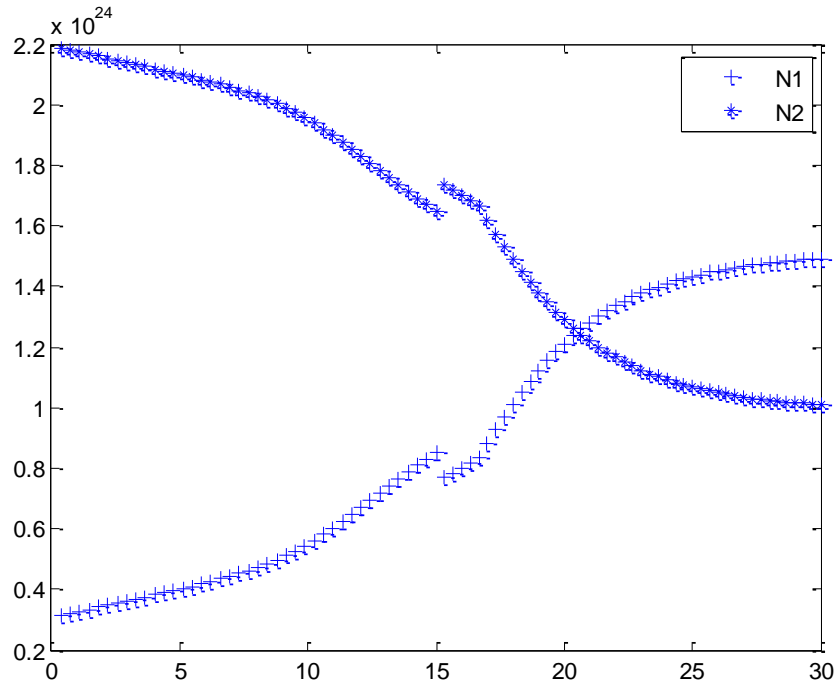


Figure 4.20: Population density of configuration-4.

Figure 4.21 shows the dbgain along the length of two stages of EDFA. Referring to Figure 4.21, signal gain increases upto the length of 20,67 meter and after the 20,67 meter it begins to reduce.

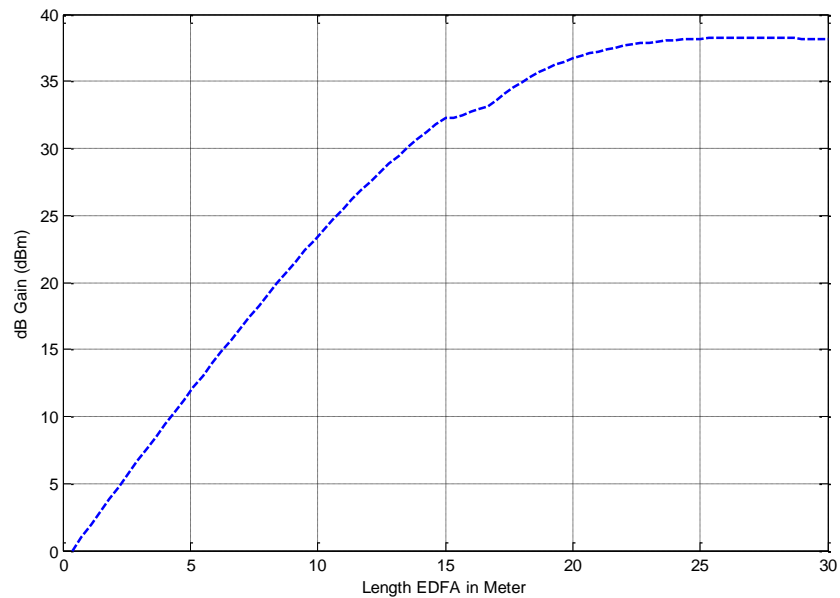


Figure 4.21: The signal gain as a function of EDFA length with 1550 nm input signal and 7mW pump signals applied at $z=0$ and $z=15$ m in configuration-4.

Figure 4.22 shows NF in dB as a function of 30 m long EDFA at 1550 nm signal wavelength.

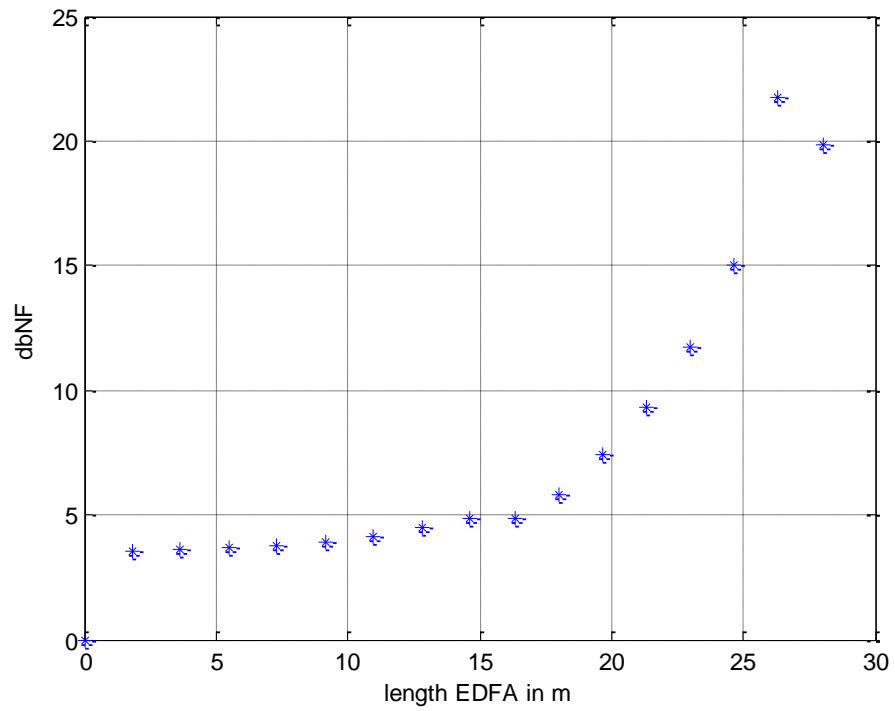


Figure 4.22: Noise Figure of configuration-4.

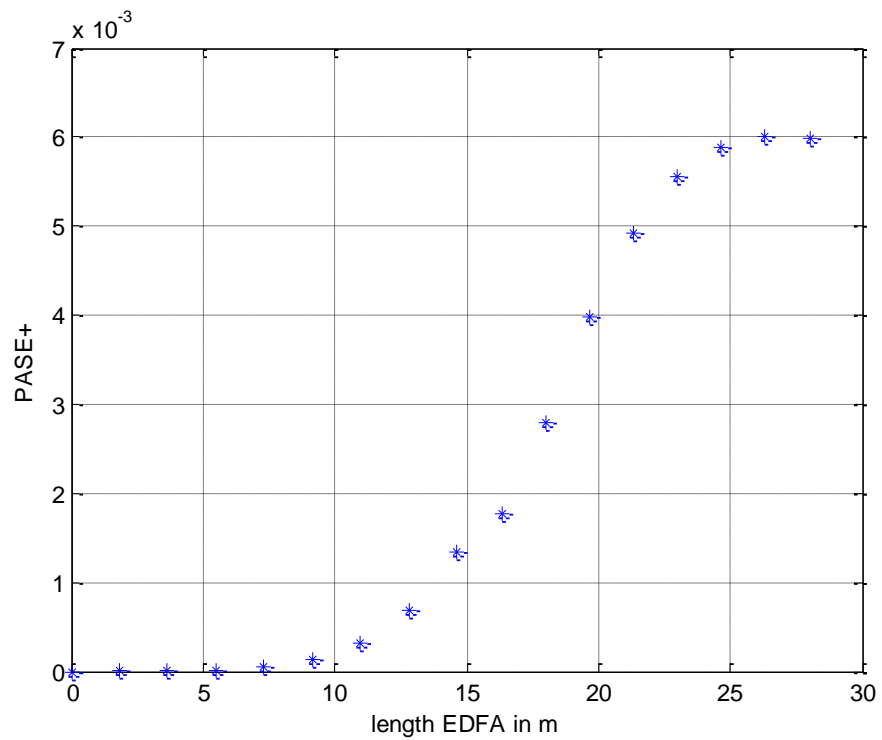


Figure 4.23: The forward travelling ASE of configuration-4.

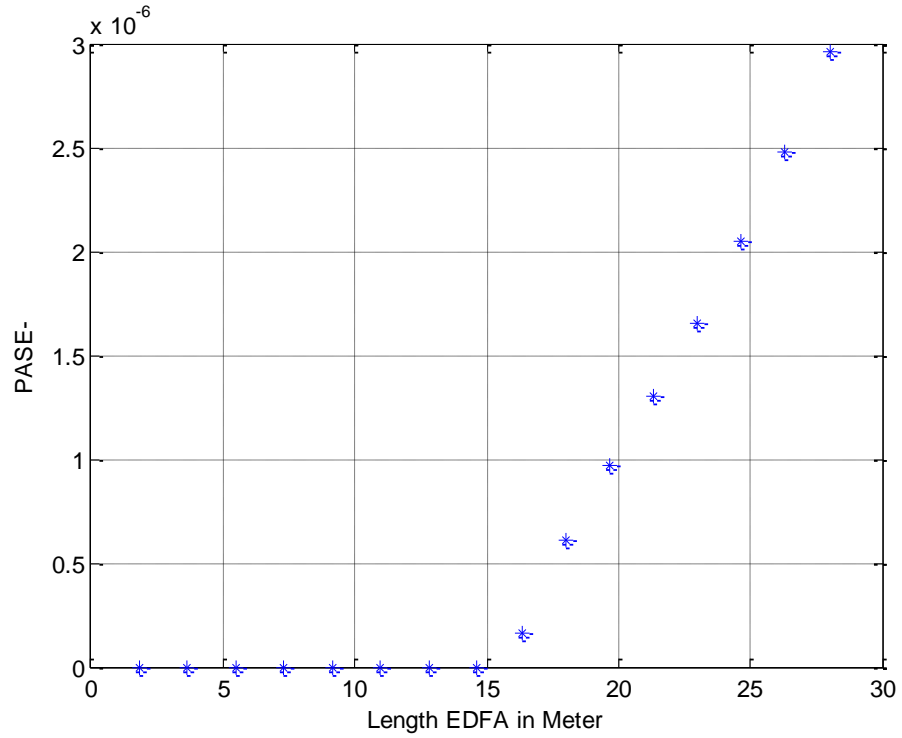


Figure 4.24: The backward travelling ASE of configuration-4.

Figure 4.23 and Figure 4.24 show the forward and backward travelling ASE as a function of position along 30 m long SP EDFA, respectively.

In Table 4.2 given below population density, gain, NF, PASE+ and PASE- results found for the proposed SP EDFA configurations are tabulated.

	N1-N2	GAIN	NF	PASE+	PASE-
Configuration-1 (Forward-Forward)	17 m	39,39 dB	15 dB	0,00825	6,25E-07
Configuration-2 (Forward-Backward)	30 m	49,80 dB	7 dB	0,07	1,80E-06
Configuration-3 (Backward-Backward)	30 m	47,08 dB	7 dB	0,035	1,79E-06
Configuration-4 (Backward-Forward)	20,67 m	37,08 dB	17,5 dB	0,0042	1,10E-06

Table 4.2: SP EDFA results for the proposed configurations.

4.3 DOUBLE PASS EDFA CONFIGURATIONS

The parameters of the utilized DP EDFA are shown in Table 4.3. In our DP EDFA configurations we use two stages of EDFA with equal length. We choose $\lambda_s=1550$ nm, the power for the input signal is fixed at 35 dBm. R_{Loss} 10% is considered in this work.

EDFA L	15 m	h	6.626068×10^{-34} J.s
τ	0.0102 seconds	ν_s	193.45×10^{12} Hz
$\sigma_s^{(a)}$	$2.910556 \times 10^{-25} m^2$	ν_p	202.40×10^{12} Hz
$\sigma_s^{(e)}$	$4.118853 \times 10^{-25} m^2$	A	$1.633 \times 10^{-11} m^2$
$\sigma_p^{(a)}$	$2.787671 \times 10^{-25} m^2$	$\Delta\nu$	3100 GHz
$\sigma_p^{(e)}$	$0.810563 \times 10^{-25} m^2$	α_s	0.20 dB/km
P_p^+, P_p^-	7 mW	α_p	0.24 dB/km
P_s^+	-35 dBm	ρ	300 ppm
R_{Loss}	0.1	Γ_s	0.74
Γ_p	0.77		

Table 4.3: Parameters of the DP EDFA

4.3.1 Setup, Formulation and Results for Configuration-5 (Forward Pump)

The modelling setup is shown in Figure 4.25. A 14mW forward pump signal with respect to the direction of the input signal has been used to design the DP EDFA in configuration-5.

The input signal is sent to the port 1 of the circulator (C), and obtained as the output from port 2. After this point, the signal obtained from port 2 and the pump signal are sent directly together into EDFA L. A mirror with reflection loss R_{Loss} , is used as a reflector at the end of EDFA L. It basically reflects the amplified signal back into the EDFA together with the pump signal for the second round (double pass) of amplification in the opposite direction. Thus, the pump signal is in the same direction (forward) with the input signal at the two stages of amplification. The output of EDFA L after second amplification (DP EDFA) enters as input to the port 2 of the circulator, which then obtained as the output signal from the 3rd port of the circulator.

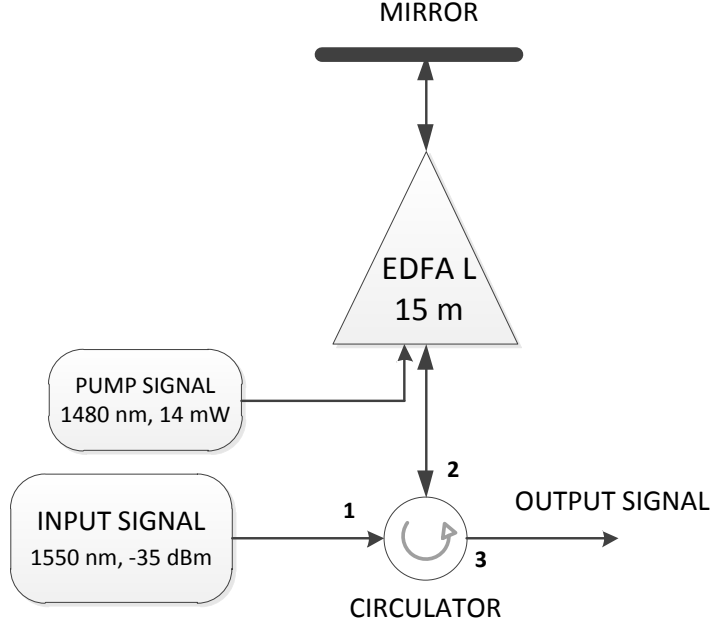


Figure 4.25: Configuration-5.

As explained in the previous sections, according to Giles and Desurvire, we need a system model with two energy levels in pumping at 1480 nm. The population densities N_1 , N_2 and the value of R for these two energy levels can be calculated using Eqs. (4.1), (4.2) and (4.3).

The equations to calculate W_{12} and W_{21} of SP EDFA given by equations (4.4) and (4.5) are modified by considering the reflected backward signal power P_s^- of DP EDFA to calculate the W_{12} and W_{21} as

$$W_{12} = \frac{\sigma_s^{(a)} \Gamma_s}{h\nu_s A} (P_s^+ + P_{ASE}^+ + P_s^- + P_{ASE}^-) \quad (4.15)$$

$$W_{21} = \frac{\sigma_s^{(e)} \Gamma_s}{h\nu_s A} (P_s^+ + P_{ASE}^+ + P_s^- + P_{ASE}^-) \quad (4.16)$$

According to Giles and Desurvire model $\frac{dP_p^+}{dz}$, $\frac{dP_s^+}{dz}$, $\frac{dP_{ASE}^+}{dz}$, $\frac{dP_{ASE}^-}{dz}$ and Noise figure NF will be calculated using equations (4.6), (4.7), (4.8), (4.9) and (4.12) where z is the coordinate along the EDFA. At $z=0$ (at the beginning of EDFA), $P_s^+ = P_{S_{initial}}^+$ (initial signal power at the input of the DP EDFA).

Different than the SP EDFA, we have P_s^- term in DP EDFA case due to the mirror reflection as explained above which is calculated as

$$\frac{dP_s^-}{dz} = -P_s^- \Gamma_s (\sigma_s^{(e)} N_2 - \sigma_s^{(a)} N_1) + \alpha_s P_s^- \quad (4.17)$$

At $z=L$ (at the end of EDFA),

$$P_s^- = G_{firstpass} P_s^+_{initial} (1 - 0.01xR_{Loss}) \quad (4.18)$$

where $G_{firstpass}$ is the gain of the signal after the first pass through the DP EDFA.

Figure 4.26 shows the upper population density N_2 and ground state population density N_1 in per cubic meter as a function of position along a 30 m length.

From this figure, after 20,67 meter length, upper state population is less than the ground state population. For this reason, if we use an EDFA of length more than 20,67 meter then the portion of the EDFA that exceeds 20,67 meter remains unpumped. This unpumped portion of the EDFA absorbs the signal and degrades the system performance. If an EDFA of length less than 20,67 meter is used for the proposed remotely pumped DP EDFA configuration then a portion of the pump power will remain unused which can causes more population inversion and hence the increment of the gain. For these reasons an EDFA length of 20,67 meter is chosen as an optimized length for the proposed remotely pumped DP EDFA configuration.

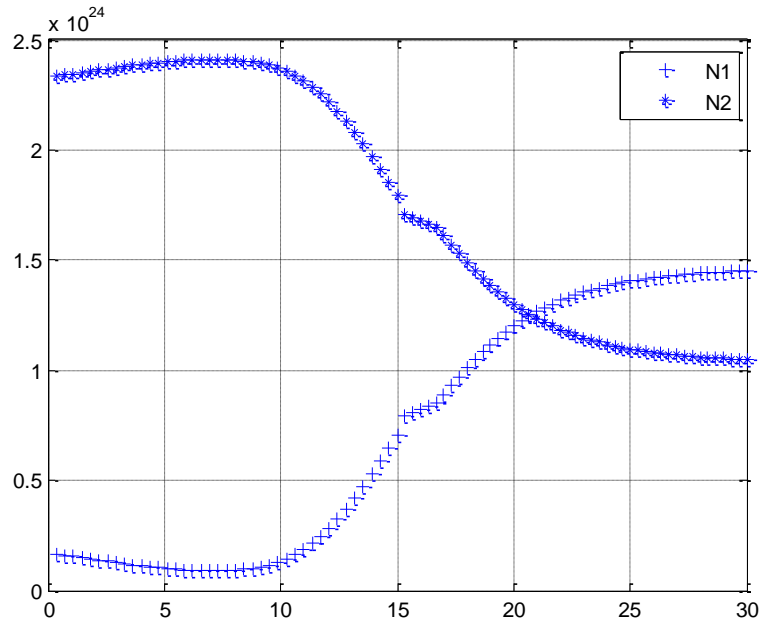


Figure 4.26: Population density of configuration-5.

Figure 4.27 shows the signal gain as a function of EDFA length at 1550 nm using 14 mW of pump power and injected signal power of -35 dBm. Referring to Figure 4.27, signal gain increases upto the length of 20,67 meter. This justifies the findings in Figure 4.26.

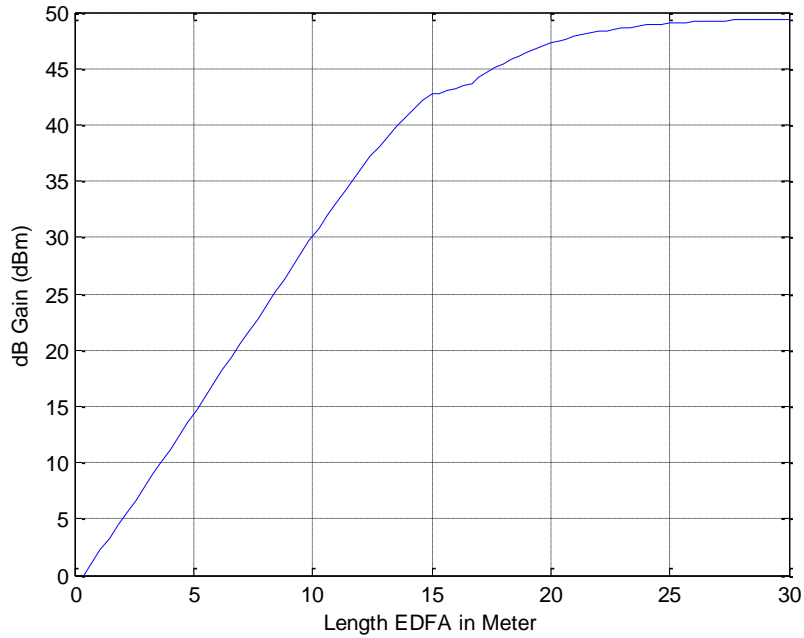


Figure 4.27: Signal gain as a function of EDFA length at configuration-5.

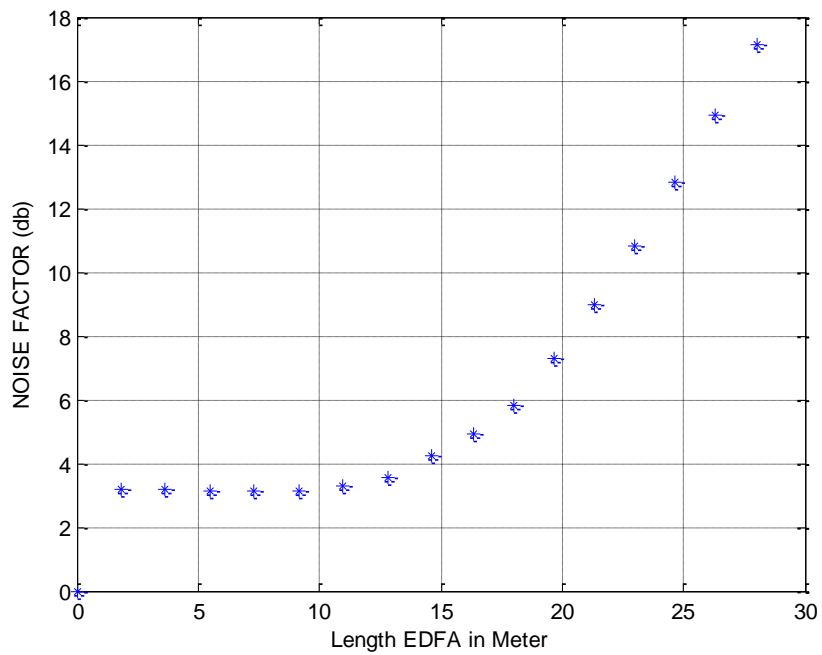


Figure 4.28: Noise Figure of configuration-5.

Figure 4.28 shows NF in dB as a function of 30 m long EDFA at 1550 nm signal wavelength.

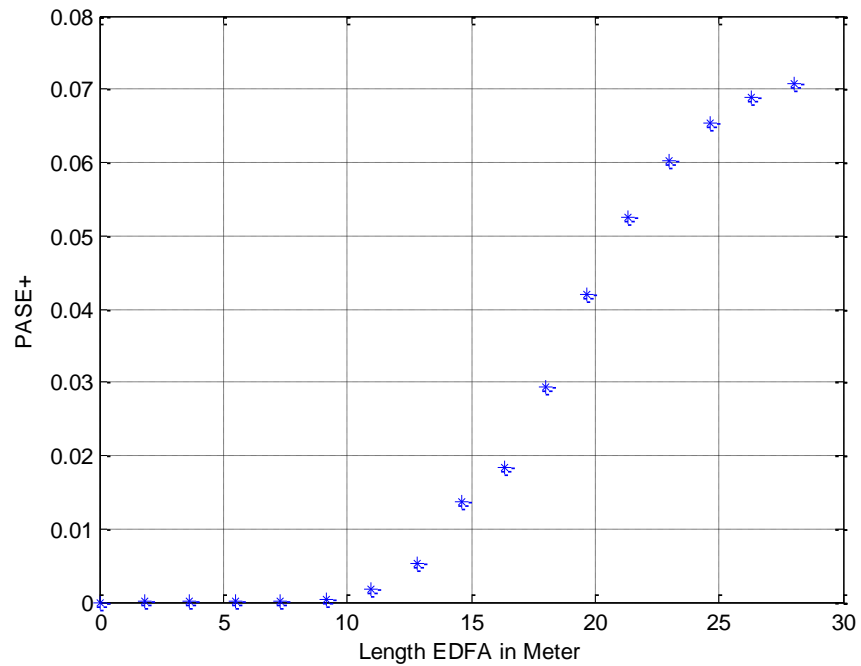


Figure 4.29: The forward travelling ASE of configuration-5.

Figure 4.29 shows the forward travelling ASE as a function of position along 30 m long DP EDFA, respectively.

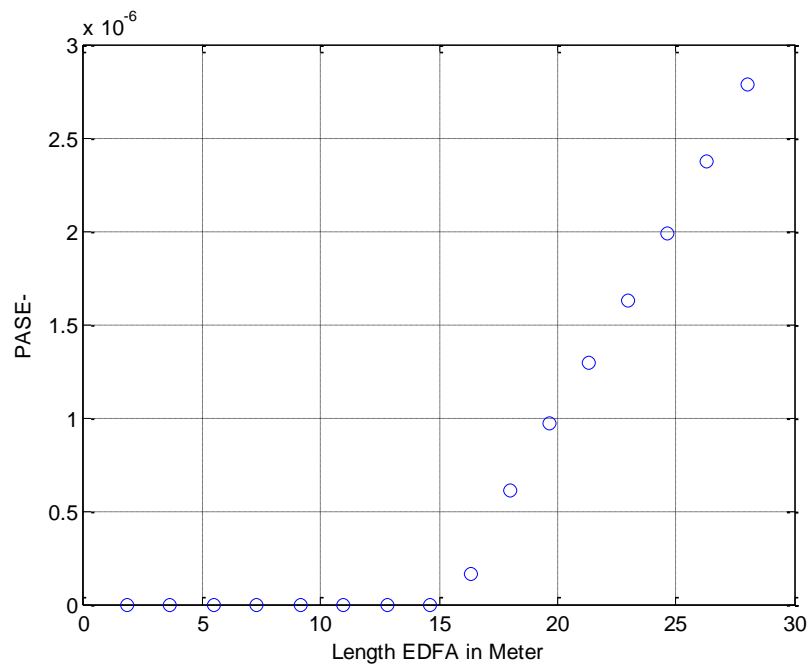


Figure 4.30: The backward travelling ASE of configuration-5.

Figure 4.30 shows the forward travelling ASE as a function of position along 30 m long DP EDFA, respectively.

4.3.2 Setup, Formulation and Results for Configuration-6 (Forward-Forward Pump)

The setup for configuration-6 is shown in Figure 4.31. In this configuration we divide the 14 mW pump signal into two 7 mW forward pump signals. The first forward pump signal with respect to the direction of the input signal sent directly into EDFA L together with the input signal obtained from the port 2 of the circulator. The second forward pump signal is sent into the EDFA L in the same direction with respect to the direction of the mirror reflected signal. Thus, different than configuration-5, in configuration-6 only the half of the pump signal is reflected together with the one time amplified input signal and the other half of the pump signal is directly sent with the same direction (forward) into EDFA L for the second time amplification of the reflected signal.

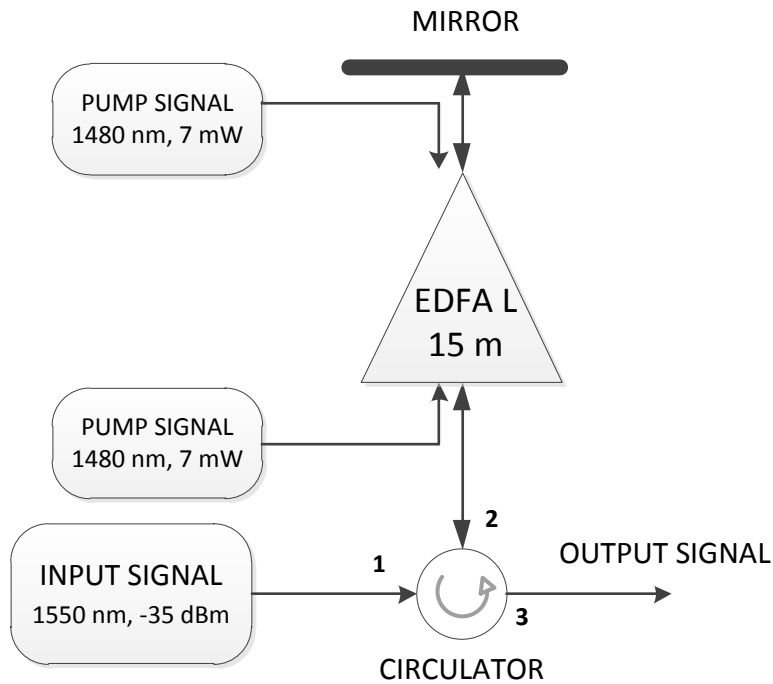


Figure 4.31: Configuration-6.

The population densities N_1, N_2 and the values of W_{12} , W_{21} and R can be calculated as in Eqs. (4.1), (4.2), (4.16), (4.17) and (4.3), respectively.

As explained in the previous section for configuration-5, the Giles and Desurvire model $\frac{dP_p^+}{dz}$, $\frac{dP_s^+}{dz}$, $\frac{dP_{ASE}^+}{dz}$, $\frac{dP_{ASE}^-}{dz}$, $\frac{dP_s^-}{dz}$ and Noise Figure NF will be calculated using equations (4.6), (4.7), (4.8), (4.9), (4.17) and (4.12), respectively.

Figure 4.32 shows the population density in per cubic meter in the upper state and ground state as a function of position along DP EDFA where 0-15m resembles the first pass and 15-30m resembles the second pass of the input signal through EDFA.

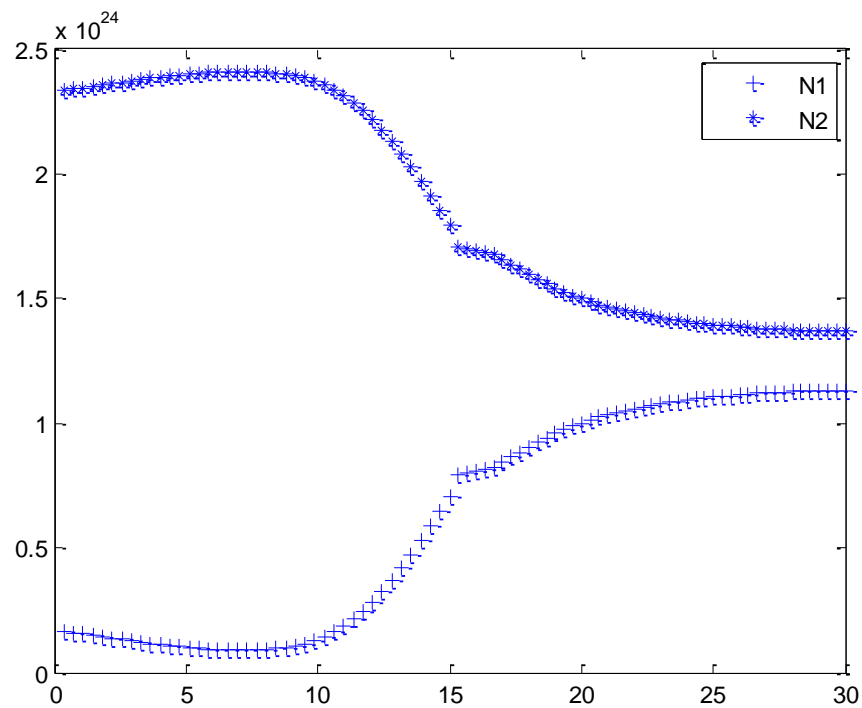


Figure 4.32: Population density of configuration-6.

Figure 4.33 shows the signal gain as a function of EDFA length at 1550 nm using 7 mW of pump Powers in the forward direction. The advantage of configuration-6 comparing to configuration-5 is the increment of signal gain up to 30 meter while the Noise Figure is kept almost constant after 16 meter (second pass of the signal through EDFA).

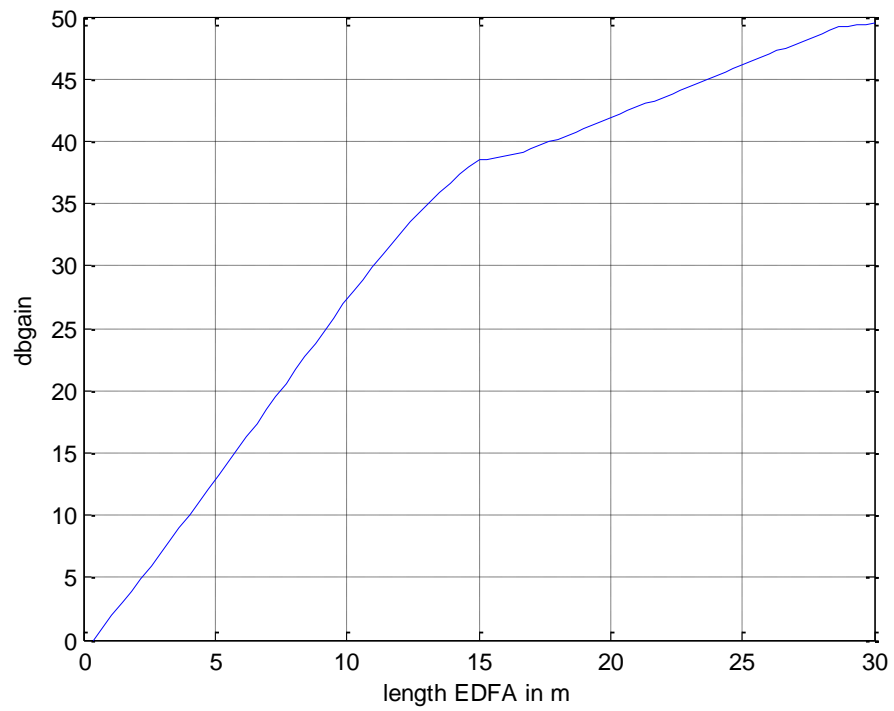


Figure 4.33: Signal gain as a function of EDFA length at configuration-6.

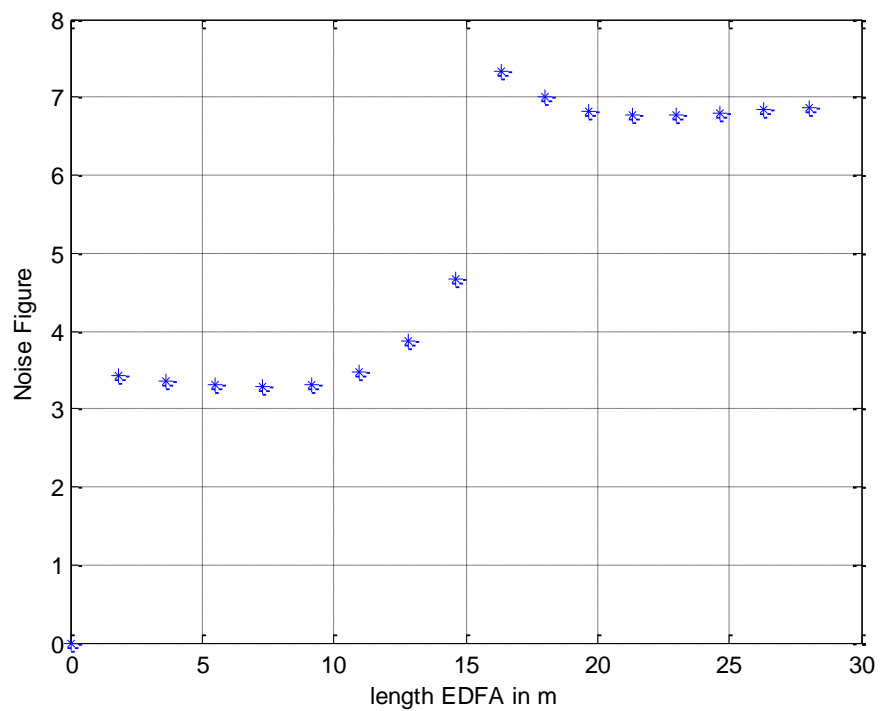


Figure 4.34: Noise Figure of configuration-6.

Figure 4.34 shows NF in dB as a function of 30 m long EDFA at 1550 nm signal wavelength.

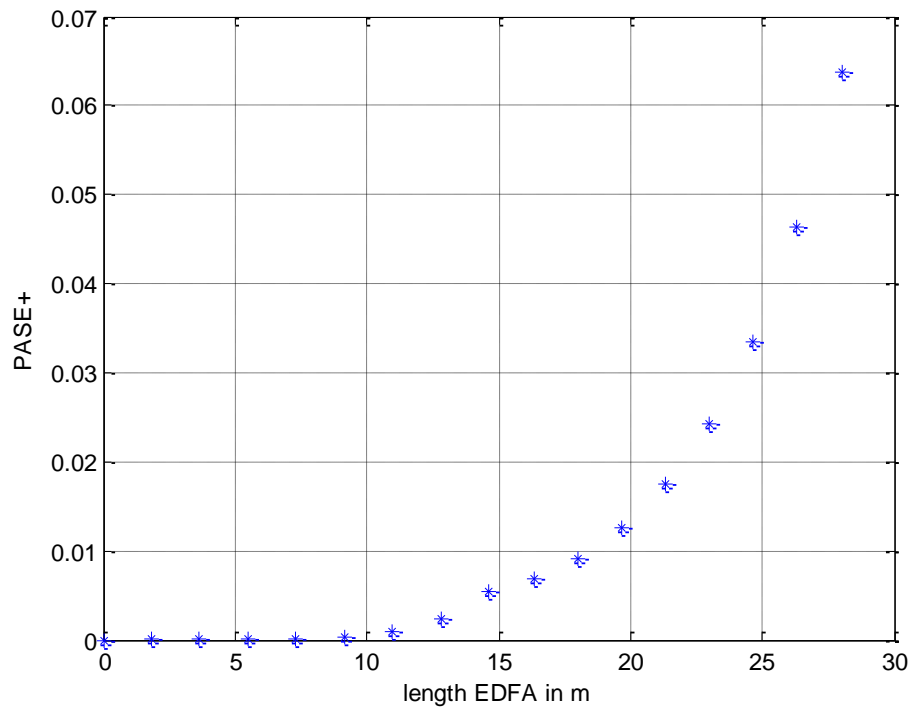


Figure 4.35: The forward travelling ASE of configuration-6.

Figure 4.35 shows the forward travelling ASE as a function of position along 30 m long DP EDFA, respectively.

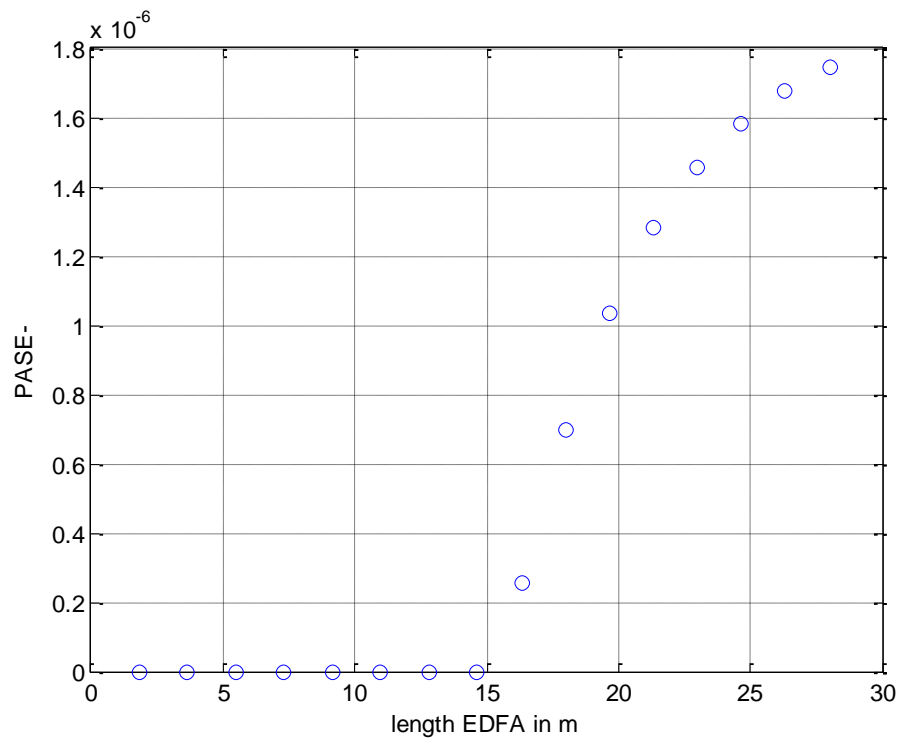


Figure 4.36: The backward travelling ASE of configuration-6.

Figure 4.36 shows the forward travelling ASE as a function of position along 30 m long DP EDFA, respectively.

4.3.3 Setup, Formulation and Results for Configuration-7 (Backward Pump)

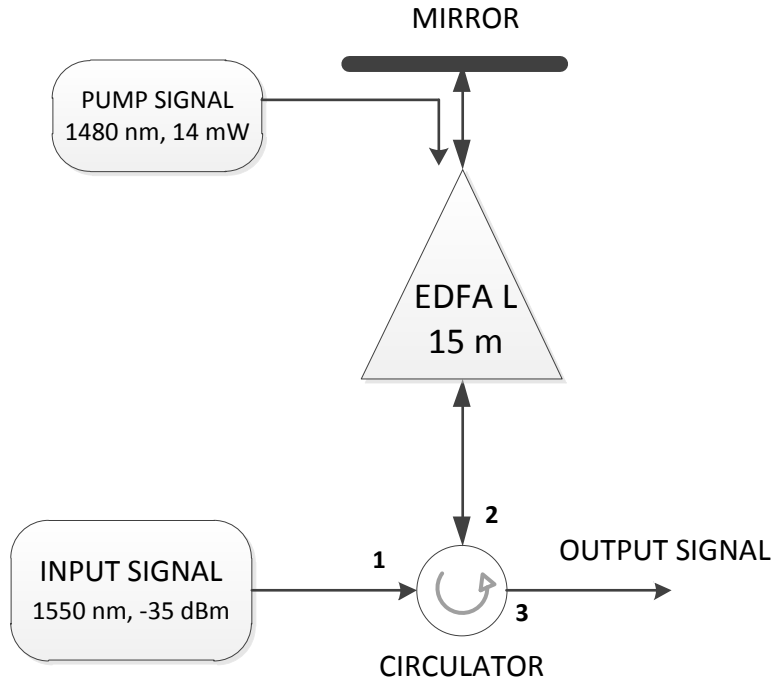


Figure 4.37: Configuration-7.

The setup of configuration-7 is shown in Figure 4.37. A 14mW backward pump signal with respect to the direction of the input signal has been used to design the DP EDFA.

As explained for configuration-6, here the population densities N_1 , N_2 and the values of W_{12} , W_{21} and R can be calculated as in Eqs. (4.1), (4.2), (4.16), (4.17) and (4.13), respectively. And also for the Giles and Desurvire model, as explained in configuration-5 and configuration-6, $\frac{dP_p^-}{dz}$, $\frac{dP_s^+}{dz}$, $\frac{dP_{ASE}^+}{dz}$, $\frac{dP_{ASE}^-}{dz}$, $\frac{dP_s^-}{dz}$ and NF will be calculated using equations (4.14), (4.7), (4.8), (4.9), (4.17) and (4.12), respectively.

From this figure, after 19,33 meter length, upper state population is less than the ground state population. For this reason, if we use an EDFA of length more than 19,33 meter then the portion of the EDFA that exceeds 19,33 meter remains unpumped. This unpumped portion of the EDFA absorbs the signal and degrades the system performance. If an EDFA of length less than 19,33 meter is used for the proposed remotely pumped DP EDFA configuration then a portion of the pump power will remain unused which can causes more population inversion and hence the increment of the gain. For these reasons an EDFA length of 19,33 meter is chosen as an optimized length for the proposed remotely pumped DP EDFA configuration.

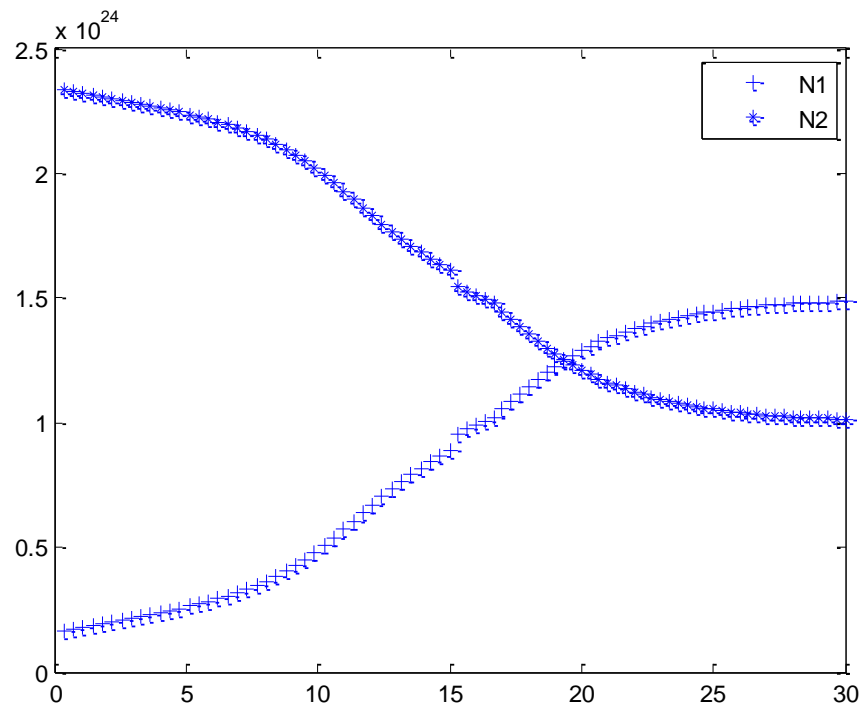


Figure 4.38: Population density of configuration-7.

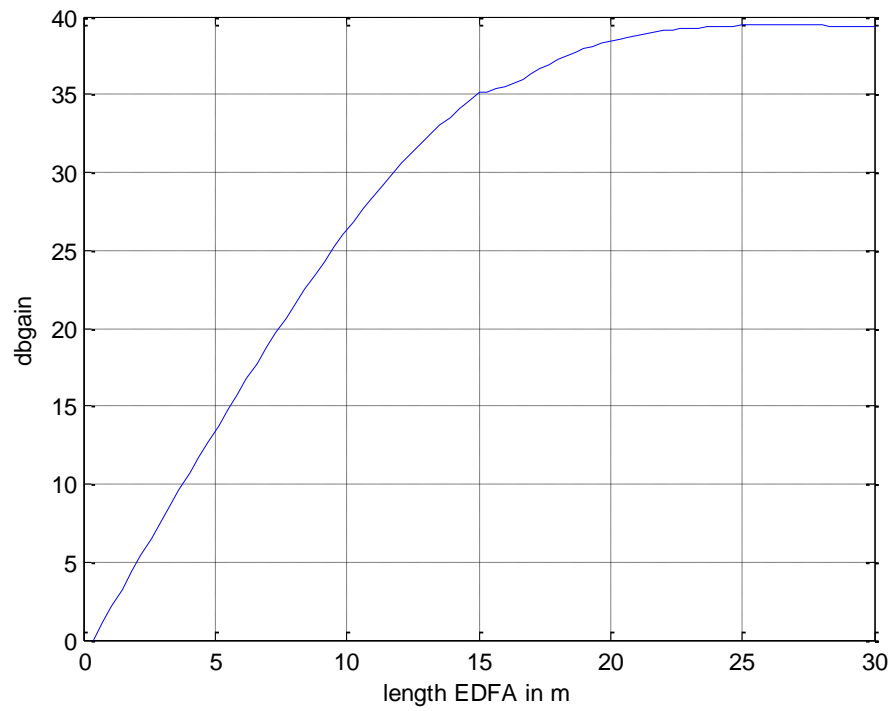


Figure 4.39: Signal gain as a function of EDFA length at configuration-7.

Figure 4.39 shows the signal gain as a function of EDFA length at 1550 nm using 14 mW of pump powers in the backward direction.

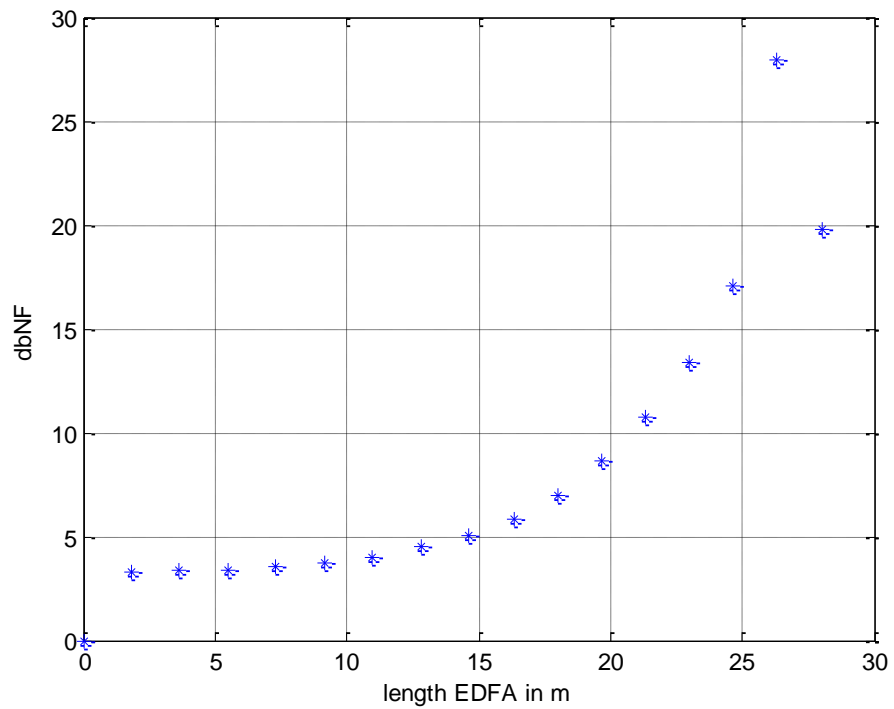


Figure 4.40: Noise Figure of Configuration-7.

As seen in figure 4.38, since N_1 gets bigger than N_2 after 19,33 meters, the signal doesn't get amplified and this is justified in figure 4.39. The signal is amplified maximum up to around 40 dBm. In figure 4.40 the NF is close to 9 dB around 19,33 meters, but it increases gradually up to 30 dB after 19,33 meters. Thus, the Configuration-6 has a better performance than Configuration-7 (and Configuration-5) in the means of higher output power and lower NF.

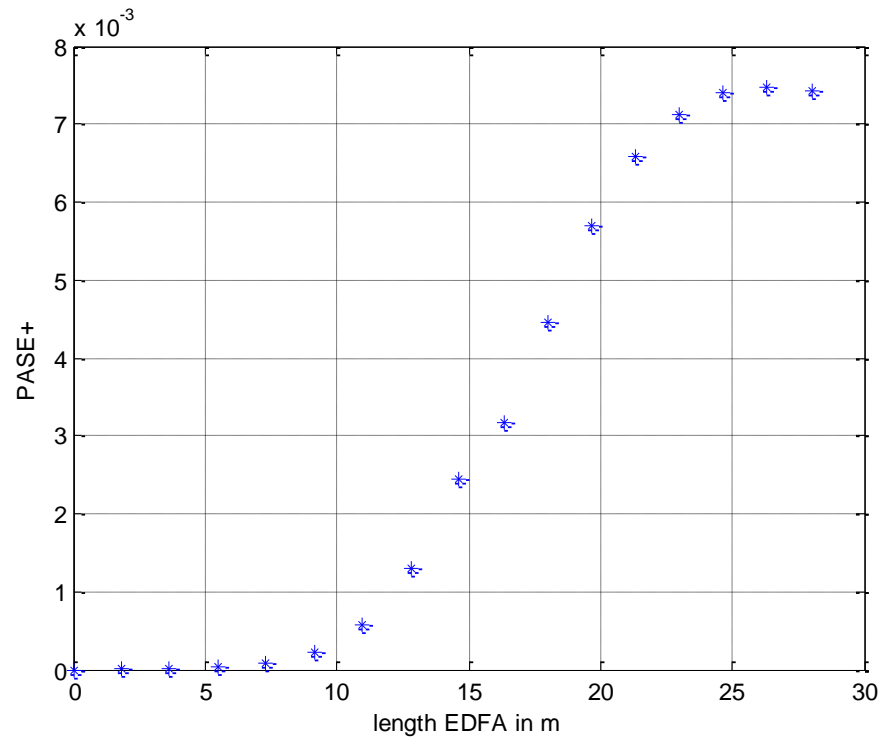


Figure 4.41: The forward travelling ASE of configuration-7.

Figure 4.41 show the forward travelling ASE as a function of position along 30 m long DP EDFA.

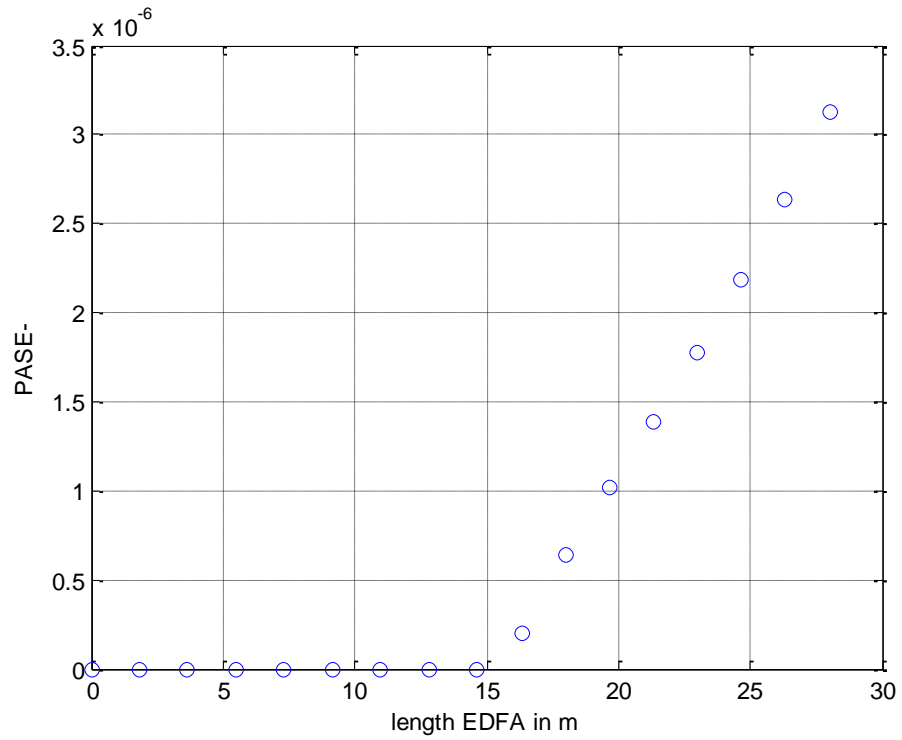


Figure 4.42: The backward travelling ASE of configuration-7.

Figure 4.41 shows the backward travelling ASE as a function of position along 30 m long DP EDFA.

In Table 4.4 given below population density, gain, NF, PASE+ and PASE- results found for the proposed DP EDFA configurations are tabulated.

	N1-N2	GAIN	NF	PASE+	PASE-
Configuration-5 (Forward)	20,67 m	47,66 dB	8.1 dB	0,042	2,30E-06
Configuration-6 (Forward-Forward)	30 m	49,90 dB	7 dB	0,07	1,80E-06
Configuration-7 (Backward)	19,33 m	38.09 dB	16 dB	0,0056	1,02E-06

Table 4.4: DP EDFA results for the proposed configurations.

CHAPTER-5

5.1 CONCLUSION

In this study our main objective is to design new EDFA configurations to obtain higher gain and lower NF values using the design parameters of the study done by Hossain et al. where it is shown that for the input signal -35 dBm at the wavelength of 1550 nm and the pump power 14 mW at the wavelength of 1480 nm, the highest gain and the lowest NF values found are 35,30 dB and 7 dB, respectively. To achieve a better performance than these values, we propose different SP and DP EDFA configurations.

As explained in section 4.2, we have four SP configurations different in the means of pump signal direction with two EDFA stages. According to the results in Table 4.2, the highest gain and the lowest NF values are obtained in configuration-2 where we have pump signals in the forward and the backward direction. The first pump signal at 7mW is sent into the first stage in the forward direction and the second pump signal at 7mW is sent into the second stage in the backward direction. Thus, the best performance in the means of gain and NF among the proposed SP configurations is obtained for the Forward-Backward pumping scheme.

As explained in section 4.3 we proposed three DP EDFA configurations different in the means of pump signal direction. According to the results in Table 4.4, the highest gain and the lowest NF values are obtained in configuration-6 where we have two pump signals at 7 mW both are in the forward direction. Thus, the best performance in the means of gain and NF among the proposed DP configurations is obtained for the Forward-Forward pumping scheme.

In conclusion, the following observations can be made: The best SP scheme is configuration-2 and the best DP scheme is configuration-6. If we compare these best schemes with each other, configuration-6 is more advantageous than configuration-2 in the means of cost since we use only 15 meters of EDFA in

DP scheme (we use 30 meters of EDFA in SP scheme). Thus, the best performance in the means of gain, NF and the system cost is obtained for configuration-6. Besides, comparing configuration-6 with the literature, although configuration-6 shows same performance in the means of NF (7 dB) and cost (15 meters), it is much better in the means of gain results (49,90 dB>35,30 dB). This shows the importance and the effect of the pump signal direction in EDFA applications.

As a future project, triple pass configurations (SP+SP+SP, SP+DP) using different pump signal directions should be investigated. In addition the effect of pumping direction for 980 nm pump signal needs to be also further investigated and should be understood for the proposed SP and DP EDFA configurations (and also future proposed triple pass configurations) in this study.

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APPENDIX

A.1 Matlab code for configuration-1

A.1.1 Spedfa1(y) for configuration-1

```
function dydz=spedfa1(y)
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
```

```
dydz=dydz';
return
```

A.1.2 Spedfa2(y) for configuration-1

```
function dydz=spedfa2(y)
Pp=y(1,1);
Ps=y(2,1);
PASE_plus=y(3,1);
PASE_minus=y(4,1);
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
```

```

dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;
dydz=dydz';
return

```

A.1.3 Solution for configuration-1

```

clear all
format long
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmap=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[7e-3 3.16228e-7 0];
nu=sigmase/sigmasa;
spdistancearray=[0 15];
dpdistancearray=[15 30];

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa1(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[7e-3 3.16228e-7 0]);
end
sizey=size(y);

```

```

array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminussp=size(PASEplussp);
PASEminussp=zeros(sizePASEminussp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;

A=y;%%%%%%%%%%
sizeA=size(A);

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa2(y);
    [z,y] = ode45(bistabilityWrapper, dpdistancearray,[7e-3 A(sizeA(1),2)
A(sizeA(1),3)]);
end
sizey=size(y);
array3=ones(sizey(1),1);
dbgaindp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

PASEplusdp=y(:,3);

```



```

PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;

B=y;%%%%%%%%%%
sizeB=size(B);

sizedp=size(dbgaindp);
sp1=sizedp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);
N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);
Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);
NF=zeros((sp1+dp1),1);

%%%%%%%%%%Connective
Part%%%%%%%%%
for i=1:1:sp1
    dbgain(i)=dbgainsp(i);
    distancearray(i)=spstepsize*i;
    N1(i)=N1sp(i);
    N2(i)=N2sp(i);

```

```

PASEplus(i)=PASEplusp(i);
PASEminus(i)=PASEminusp(i);
Psfull(i)=Pssp(i);
Ppfull(i)=Ppsp(i);
NF(i)=NFsp(i);
end
for i=(sp1+1):1:(sp1+dp1)
    dbgain(i)=dbgaindp(i-sp1);
    distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);
    N1(i)=N1dp(i-sp1);
    N2(i)=N2dp(i-sp1);
    PASEplus(i)=PASEplusdp(i-sp1);
    PASEminus(i)=PASEminusdp(i-sp1);
    Psfull(i)=Psdp(i-sp1);
    Ppfull(i)=Ppdp(i-sp1);
    NF(i)=NFdp(i-sp1);
end

dbNF=10*log10(NF);
sampledistancearray=zeros(25,1);
sampledbgain=zeros(25,1);
sampleN1=zeros(25,1);
sampleN2=zeros(25,1);
samplePASEplus=zeros(25,1);
samplePASEminus=zeros(25,1);
samplePs=zeros(25,1);
samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);

```

```

samplePASEplus(i)=PASEplus(i*5);
samplePASEminus(i)=PASEminus(i*5);
samplePs(i)=Psfull(i*5);
samplePp(i)=Ppfull(i*5);
sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('length EDFA in
m'),ylabel('dbgain')
figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('length
EDFA in m'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'*'),grid on,xlabel('Length
EDFA in Meter'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),legend('Ps','Pp');
figure,plot(sampledistancearray,sampledbNF,'*'),grid on,xlabel('length EDFA
in m'),ylabel('dbNF')
figure,plot(z,y(:,1:2)),grid on,xlabel('length EDFA in m'),ylabel('Power in
mW'),legend('Pp','Ps');

```

A.2 Matlab code for configuration-2

A.2.1 Spedfa1(y) for configuration-2

```

function dydz=spedfa1(y)
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);
t=0.0102;

```

```

sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz=dydz';
return

```

A.2.2 Spedfa2(y) for configuration-2

```

function dydz=spedfa2(y)
Pp=y(1,1);
Ps=y(2,1);
PASE_plus=y(3,1);
PASE_minus=y(4,1);

```

```

t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=-Pp*gammap*(sigmape*N2-sigmapa*N1)+alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;
dydz=dydz';
return

```

A.2.3 Solution for configuration-2

```

clear all
format long

```

```

t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[7e-3 3.16228e-7 0];
nu=sigmase/sigmasa;
spdistancearray=[0 15];
dpdistancearray=[15 30];

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa1(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[7e-3 3.16228e-7 0]);
end
sizey=size(y);
array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminussp=size(PASEplussp);

```

```

PASEminusp=zeros(sizePASEminusp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;

A=y;%%%%%%%%%%%%%%
sizeA=size(A);

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa2(y);
    [z,y] = ode45(bistabilityWrapper, dpdistancearray,[7e-3 A(sizeA(1),2)
A(sizeA(1),3)]);
end
sizey=size(y);
array3=ones(sizey(1),1);
dbgaindp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
W21=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

PASEplusdp=y(:,3);
PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;

B=y;%%%%%%%%%%%%%%
sizeB=size(B);

```

```

sizesp=size(dbgainssp);
sp1=sizesp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);
N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);
Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);
NF=zeros((sp1+dp1),1);

%%%%%%%%%% Connective Part
%%%%%%%%%%
for i=1:1:sp1
    dbgain(i)=dbgainssp(i);
    distancearray(i)=spstepsize*i;
    N1(i)=N1ssp(i);
    N2(i)=N2ssp(i);
    PASEplus(i)=PASEplussp(i);
    PASEminus(i)=PASEminussp(i);
    Psfull(i)=Pssp(i);
    Ppfull(i)=Ppsp(i);
    NF(i)=NFsp(i);
end
for i=(sp1+1):1:(sp1+dp1)
    dbgain(i)=dbgaindp(i-sp1);
    distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);

```



```

N1(i)=N1dp(i-sp1);
N2(i)=N2dp(i-sp1);
PASEplus(i)=PASEplusdp(i-sp1);
PASEminus(i)=PASEminusdp(i-sp1);
Psfull(i)=Psdp(i-sp1);
Ppfull(i)=Ppdp(i-sp1);
NF(i)=NFdp(i-sp1);
end

dbNF=10*log10(NF);
sampledistancearray=zeros(25,1);
sampledbgain=zeros(25,1);
sampleN1=zeros(25,1);
sampleN2=zeros(25,1);
samplePASEplus=zeros(25,1);
samplePASEminus=zeros(25,1);
samplePs=zeros(25,1);
samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);
    samplePASEplus(i)=PASEplus(i*5);
    samplePASEminus(i)=PASEminus(i*5);
    samplePs(i)=Psfull(i*5);
    samplePp(i)=Ppfull(i*5);
    sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('length EDFA in
m'),ylabel('dbgain')

```

```

figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('length
EDFA in m'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'*'),grid on,xlabel('Length
EDFA in Meter'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),legend('Ps','Pp');
figure,plot(sampledistancearray,sampledBNF,'*'),grid on,xlabel('length EDFA
in m'),ylabel('dbNF')
figure,plot(z,y(:,1:2)),grid on,xlabel('length EDFA in m'),ylabel('Power in
mW'),legend('Pp','Ps');

```

A.3 Matlab code for configuration-3

A.3.1 Spedfa1(y) for configuration-3

```

function dydz=spedfa1(y)
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;

```

```

deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=((((sigmasa* gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=((((sigmase* gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=-Pp*gammap*(sigmapa*N2-sigmase*N1)+alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz=dydz';
return

```

A.3.2 Spedfa2(y) for configuration-3

```

function dydz=spedfa2(y)
Pp=y(1,1);
Ps=y(2,1);
PASE_plus=y(3,1);
PASE_minus=y(4,1);
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;

```

```

A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;
dydz=dydz';
return

```

A.3.3 Solution for configuration-3

```

clear all
format long
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;

```

```

AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[7e-3 3.16228e-7 0];
nu=sigmase/sigmaasa;
spdistancearray=[0 15];
dpdistancearray=[15 30];

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa1(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[7e-3 3.16228e-7 0]);
end
sizey=size(y);
array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmaasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmaapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminussp=size(PASEplussp);
PASEminussp=zeros(sizePASEminussp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;

A=y;%%%%%%%%%%%%%%
sizeA=size(A);

for i=1:1:500

```

```

bistabilityWrapper = @(z,y) spedfa2(y);
[z,y] = ode45(bistabilityWrapper, dpdistancearray,[7e-3 A(sizeA(1),2)
A(sizeA(1),3)]);
end
sizey=size(y);
array3=ones(sizey(1),1);
dbgaindp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
W21=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

PASEplusdp=y(:,3);
PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;

B=y;%%%%%%%%%%%%%%
sizeB=size(B);

sizesp=size(dbgainsp);
sp1=sizesp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);

```

```

N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);
Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);
NF=zeros((sp1+dp1),1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Connective
Part%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:1:sp1
    dbgain(i)=dbgainsp(i);
    distancearray(i)=spstepsize*i;
    N1(i)=N1sp(i);
    N2(i)=N2sp(i);
    PASEplus(i)=PASEplussp(i);
    PASEminus(i)=PASEminussp(i);
    Psfull(i)=Pssp(i);
    Ppfull(i)=Ppsp(i);
    NF(i)=NFsp(i);
end
for i=(sp1+1):1:(sp1+dp1)
    dbgain(i)=dbgaindp(i-sp1);
    distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);
    N1(i)=N1dp(i-sp1);
    N2(i)=N2dp(i-sp1);
    PASEplus(i)=PASEplusdp(i-sp1);
    PASEminus(i)=PASEminusdp(i-sp1);
    Psfull(i)=Psdp(i-sp1);
    Ppfull(i)=Ppdp(i-sp1);
    NF(i)=NFdp(i-sp1);
end

dbNF=10*log10(NF);

```

```

sampledistancearray=zeros(25,1);
sampledbgain=zeros(25,1);
sampleN1=zeros(25,1);
sampleN2=zeros(25,1);
samplePASEplus=zeros(25,1);
samplePASEminus=zeros(25,1);
samplePs=zeros(25,1);
samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);
    samplePASEplus(i)=PASEplus(i*5);
    samplePASEminus(i)=PASEminus(i*5);
    samplePs(i)=Psfull(i*5);
    samplePp(i)=Ppfull(i*5);
    sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('length EDFA in
m'),ylabel('dbgain')
figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('length
EDFA in m'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'*'),grid on,xlabel('Length
EDFA in Meter'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),legend('Ps','Pp');

```



```

figure,plot(sampledistancearray,sampledBNF,'*'),grid on,xlabel('length EDFA
in m'),ylabel('dbNF')
figure,plot(z,y(:,1:2)),grid on,xlabel('length EDFA in m'),ylabel('Power in
mW'),legend('Pp','Ps');

```

A.4 Matlab code for configuration-4

A.4.1 Spedfa1(y) for configuration-4

```

function dydz=spedfa1(y)
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);

t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
%rho=2e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));

```

```

R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=-Pp*gammap*(sigmape*N2-sigmapa*N1)+alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmaasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz=dydz';
return

```

A.4.2 Spedfa2(y) for configuration-4

```

function dydz=spedfa2(y)
Pp=y(1,1);
Ps=y(2,1);
PASE_plus=y(3,1);
PASE_minus=y(4,1);
t=0.0102;
sigmaasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmaasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));

```

```

W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=-Pp*gammap*(sigmapa*N2-sigmapa*N1)+alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmaasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;

dydz=dydz';
return

```

A.4.3 Solution for configuration-4

```

clear all
format long
t=0.0102;
sigmaasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[7e-3 3.16228e-7 0];

```

```

nu=sigmase/sigmaasa;
spdistancearray=[0 15];
dpdistancearray=[15 30];

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa1(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[7e-3 3.16228e-7 0]);
end
sizey=size(y);
array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmaasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminusp=size(PASEplussp);
PASEminusp=zeros(sizePASEminusp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;

A=y;%%%%%%%%%%%%%%
sizeA=size(A);

for i=1:1:500
    bistabilityWrapper = @(z,y) spedfa2(y);
    [z,y] = ode45(bistabilityWrapper, dpdistancearray,[7e-3 A(sizeA(1),2)
A(sizeA(1),3)]);
end
sizey=size(y);
array3=ones(sizey(1),1);

```

```

dbgaindp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

PASEplusdp=y(:,3);
PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;

B=y;%%%%%%%%%%
sizeB=size(B);

sizesp=size(dbgainsp);
sp1=sizesp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);
N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);
Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);

```

```

NF=zeros((sp1+dp1),1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Connective
Part%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:1:sp1
    dbgain(i)=dbgainsp(i);
    distancearray(i)=spstepsize*i;
    N1(i)=N1sp(i);
    N2(i)=N2sp(i);
    PASEplus(i)=PASEplusp(i);
    PASEminus(i)=PASEminusp(i);
    Pfull(i)=Pssp(i);
    Ppfull(i)=Ppsp(i);
    NF(i)=NFsp(i);
end
for i=(sp1+1):1:(sp1+dp1)
    dbgain(i)=dbgaindp(i-sp1);
    distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);
    N1(i)=N1dp(i-sp1);
    N2(i)=N2dp(i-sp1);
    PASEplus(i)=PASEplusdp(i-sp1);
    PASEminus(i)=PASEminusdp(i-sp1);
    Pfull(i)=Psdp(i-sp1);
    Ppfull(i)=Ppdp(i-sp1);
    NF(i)=NFdp(i-sp1);
end

dbNF=10*log10(NF);
sampledistancearray=zeros(25,1);
sampledbgain=zeros(25,1);
sampleN1=zeros(25,1);
sampleN2=zeros(25,1);
samplePASEplus=zeros(25,1);
samplePASEminus=zeros(25,1);

```

```

samplePs=zeros(25,1);
samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);
    samplePASEplus(i)=PASEplus(i*5);
    samplePASEminus(i)=PASEminus(i*5);
    samplePs(i)=Psfull(i*5);
    samplePp(i)=Ppfull(i*5);
    sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('length EDFA in
m'),ylabel('dbgain')
figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('length
EDFA in m'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'*'),grid on,xlabel('Length
EDFA in Meter'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),legend('Ps','Pp');
figure,plot(sampledistancearray,sampledbNF,'*'),grid on,xlabel('length EDFA
in m'),ylabel('dbNF')
figure,plot(z,y(:,1:2)),grid on,xlabel('length EDFA in m'),ylabel('Power in
mW'),legend('Pp','Ps');

```

A.5 Matlab code for configuration-5

A.5.1 Spedfa(y) for configuration-5

```
function dydz=spedfa(y)
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);

t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
```



```
dydz=dydz';
return
```

A.4.1 Dpedfa(y) for configuration-5

```
function dydz=dpedfa(y)
Pp=y(1,1);
Ps=y(2,1);
PASE_plus=y(3,1);
PASE_minus=y(4,1);
Ps_minus=y(5,1);
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
%rho=2e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus+Ps_minus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus+Ps_minus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
```

```

N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmapa*N2-sigmaa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmaa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmaa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmaa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;
dydz(5)=-Ps_minus*gammas*(sigmase*N2-sigmaa*N1)+alfas*Ps_minus;
dydz=dydz';
return

```

A.5.3 Solution for configuration-5

```

clear all
format long
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[14e-3 3.16228e-7 0];
nu=sigmase/sigmasa;
spdistancearray=[0 15];
dpdistancearray=[15 30];

```

```

for i=1:1:500
    %spedfa(y);
    bistabilityWrapper = @(z,y) spedfa(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[14e-3 3.16228e-7 0]);
end
sizey=size(y);
array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminusp=size(PASEplussp);
PASEminusp=zeros(sizePASEminusp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;

A=y;%%%%%%%%%%
sizeA=size(A);
Ps_minus_Initial= A(sizeA(1),2)*(1-0.01*0.1); %Ps_minus initial with
reflection loss
for i=1:1:500
    %dpedfa(y);
    bistabilityWrapper = @(z,y) dpedfa(y);
    [z,y] = ode45(bistabilityWrapper, dpdistancearray,[A(sizeA(1),1)
A(sizeA(1),2) A(sizeA(1),3) 0 Ps_minus_Initial]);
end
sizey=size(y);
array3=ones(sizey(1),1);

```

```

dbgaindp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4)+y(:,5));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4)+y(:,5));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

PASEplusdp=y(:,3);
PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;

B=y;%%%%%%%%%%
sizeB=size(B);
sizedp=size(dbgaindp);
sp1=sizedp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);
N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);
Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);
NF=zeros((sp1+dp1),1);

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Connective

Part%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i=1:1:sp1

 dbgain(i)=dbgainsp(i);

 distancearray(i)=spstepsize*i;

 N1(i)=N1sp(i);

 N2(i)=N2sp(i);

 PASEplus(i)=PASEplussp(i);

 PASEminus(i)=PASEminussp(i);

 Psfull(i)=Pssp(i);

 Ppfull(i)=Ppssp(i);

 NF(i)=NFsp(i);

end

for i=(sp1+1):1:(sp1+dp1)

 dbgain(i)=dbgaindp(i-sp1);

 distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);

 N1(i)=N1dp(i-sp1);

 N2(i)=N2dp(i-sp1);

 PASEplus(i)=PASEplusdp(i-sp1);

 PASEminus(i)=PASEminusdp(i-sp1);

 Psfull(i)=Psdp(i-sp1);

 Ppfull(i)=Ppdp(i-sp1);

 NF(i)=NFdp(i-sp1);

end

dbNF=10*log10(NF);

sampledistancearray=zeros(25,1);

sampledbgain=zeros(25,1);

sampleN1=zeros(25,1);

sampleN2=zeros(25,1);

samplePASEplus=zeros(25,1);

samplePASEminus=zeros(25,1);

samplePs=zeros(25,1);

```

samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);
    samplePASEplus(i)=PASEplus(i*5);
    samplePASEminus(i)=PASEminus(i*5);
    samplePs(i)=Psfull(i*5);
    samplePp(i)=Ppfull(i*5);
    sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('Length EDFA in
Meter'),ylabel('dB Gain (dBm)')
%figure,plot(sampledistancearray,sampledbgain,'*'),grid on,xlabel('length
EDFA in m'),ylabel('dbgain')
figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),grid on,legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('Length
EDFA in Meter'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'o'),grid on,xlabel('Length
EDFA in Meter'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),grid on, legend('Ps','Pp');
figure,plot(sampledistancearray,sampledbNF,'*'),grid on,xlabel('Length EDFA
in Meter'),ylabel('NOISE FACTOR (db)')

```

A.6 Matlab code for configuration-6

A.6.1 Spedfa(y) for configuration-6

```
function dydz=spedfa(y)
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);

t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
```

dydz=dydz';

return

A.6.2 Dpedfa(y) for configuration-6

function dydz=dpedfa(y)

Pp=y(1,1);

Ps=y(2,1);

PASE_plus=y(3,1);

PASE_minus=y(4,1);

Ps_minus=y(5,1);

t=0.0102;

sigmasa=2.910556003e-25;

gammas=0.74;

gammap=0.77;

sigmase=4.118853202e-25;

sigmapa=2.787671233e-25;

sigmape=0.810563905e-25;

h=6.626068e-34;

Vs=193.45e12;

Vp=202.4e12;

A=1.633e-11;

deltav=3100e9;

alfas=1.0233e-3;

alfap=1.028e-3;

rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus+Ps_minus));

W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus+Ps_minus));

R=((Pp*gammap*sigmapa)/(h*Vp*A));

N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));


```

N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=-Pp*gammap*(sigmapa*N2-sigmapa*N1)+alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmaasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;
dydz(5)=-Ps_minus*gammas*(sigmase*N2-sigmaasa*N1)+alfas*Ps_minus;
dydz=dydz';
return

```

A.6.3 Solution for configuration-6

```

clear all
format long
t=0.0102;
sigmaasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[7e-3 3.16228e-7 0];
nu=sigmase/sigmaasa;
spdistancearray=[0 15];
dpdistancearray=[15 30];

```

```

for i=1:1:500
    %spedfa(y);
    bistabilityWrapper = @(z,y) spedfa(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[7e-3 3.16228e-7 0]);
end
sizey=size(y);
array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminusp=size(PASEplussp);
PASEminusp=zeros(sizePASEminusp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;
A=y;%%%%%%%%%%
sizeA=size(A);
Ps_minus_Initial= A(sizeA(1),2)*(1-0.01*0.1);
for i=1:1:500
    bistabilityWrapper = @(z,y) dpedfa(y);
    [z,y] = ode45(bistabilityWrapper, dpdistancearray,[7e-3 A(sizeA(1),2)
A(sizeA(1),3) 0 Ps_minus_Initial]);

end
sizey=size(y);
array3=ones(sizey(1),1);
dbgaindp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4)+y(:,5));

```

```

W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4)+y(:,5));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

```

```

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

```

```

PASEplusdp=y(:,3);
PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;
B=y;%%%%%%%%%%
sizeB=size(B);
%B=y(45,:);

```

```

sizesp=size(dbgainsp);
sp1=sizesp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

```

```

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);
N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);
Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);

```

```

NF=zeros((sp1+dp1),1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Connective
Part%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:1:sp1
    dbgain(i)=dbgainsp(i);
    distancearray(i)=spstepsize*i;
    N1(i)=N1sp(i);
    N2(i)=N2sp(i);
    PASEplus(i)=PASEplusp(i);
    PASEminus(i)=PASEminusp(i);
    Pfull(i)=Pssp(i);
    Ppfull(i)=Ppsp(i);
    NF(i)=NFsp(i);
end
for i=(sp1+1):1:(sp1+dp1)
    dbgain(i)=dbgaindp(i-sp1);
    distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);
    N1(i)=N1dp(i-sp1);
    N2(i)=N2dp(i-sp1);
    PASEplus(i)=PASEplusdp(i-sp1);
    PASEminus(i)=PASEminusdp(i-sp1);
    Pfull(i)=Psdp(i-sp1);
    Ppfull(i)=Ppdp(i-sp1);
    NF(i)=NFdp(i-sp1);
end

dbNF=10*log10(NF);
sampledistancearray=zeros(25,1);
sampledbgain=zeros(25,1);
sampleN1=zeros(25,1);
sampleN2=zeros(25,1);
samplePASEplus=zeros(25,1);
samplePASEminus=zeros(25,1);

```

```

samplePs=zeros(25,1);
samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);
    samplePASEplus(i)=PASEplus(i*5);
    samplePASEminus(i)=PASEminus(i*5);
    samplePs(i)=Psfull(i*5);
    samplePp(i)=Ppfull(i*5);
    sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('length EDFA in
m'),ylabel('dbgain')
figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('length
EDFA in m'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'o'),grid on,xlabel('length
EDFA in m'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),legend('Ps','Pp');
figure,plot(sampledistancearray,sampledbNF,'*'),grid on,xlabel('length EDFA
in m'),ylabel('dbNF')

```

A.7 Matlab code for configuration-7

A.7.1 Spedfa(y) for configuration-7

```
function dydz=spedfa(y)
%y=[10 0.001 0 0];
Pp=y(1);
Ps=y(2);
PASE_plus=y(3);

t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12=(((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus));
W21=(((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));
N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=-Pp*gammap*(sigmape*N2-sigmapa*N1)+alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
```

```

sigmasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz=dydz';
return

```

A.7.2 Dpedfa(y) for configuration-7

```

function dydz=dpedfa(y)
%y=[10 0.001 0 0];
Pp=y(1,1);
Ps=y(2,1);
PASE_plus=y(3,1);
PASE_minus=y(4,1);
Ps_minus=y(5,1);
t=0.0102;
sigmasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
A=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;

W12((((sigmasa*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus+Ps_minus));
W21((((sigmase*gammas)/(h*Vs*A))*(Ps+PASE_plus+PASE_minus+Ps_minus));
R=((Pp*gammap*sigmapa)/(h*Vp*A));

```

```

N1=(rho*((1+W21*t)/(1+(W12+W21)*t+R*t)));
N2=(rho*((R*t+W12*t)/(1+(W12+W21)*t+R*t)));
dydz(1)=Pp*gammap*(sigmape*N2-sigmaapa*N1)-alfap*Pp;
dydz(2)=Ps*gammas*(sigmase*N2-sigmaasa*N1)-alfas*Ps;
dydz(3)=PASE_plus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav-alfas*PASE_plus;
dydz(4)=-PASE_minus*gammas*(sigmase*N2-
sigmaasa*N1)+2*sigmase*N2*gammas*h*Vs*deltav+alfas*PASE_minus;
dydz(5)=-Ps_minus*gammas*(sigmase*N2-sigmaasa*N1)+alfas*Ps_minus;
dydz=dydz';
return

```

A.7.3 Solution for configuration-7

```

clear all
format long
t=0.0102;
sigmaasa=2.910556003e-25;
gammas=0.74;
gammap=0.77;
sigmase=4.118853202e-25;
sigmaapa=2.787671233e-25;
sigmape=0.810563905e-25;
h=6.626068e-34;
Vs=193.45e12;
Vp=202.4e12;
AA=1.633e-11;
deltav=3100e9;
alfas=1.0233e-3;
alfap=1.028e-3;
rho=2.5e24;
y=[14e-3 3.16228e-7 0];
nu=sigmase/sigmaasa;
spdistancearray=[0 15];

```



```

dpdistancearray=[15 30];

for i=1:1:500

    bistabilityWrapper = @(z,y) spedfa(y);
    [z,y] = ode45(bistabilityWrapper, spdistancearray,[14e-3 3.16228e-7 0]);
end
sizey=size(y);
array1=ones(sizey(1),1);
dbgainsp=10*log10(y(:,2)/3.16228e-7);
W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));
N1sp=(rho*(array1+W21*t))./(array1+(W12+W21)*t+R*t);
N2sp=(rho*(R*t+W12*t))./(array1+(W12+W21)*t+R*t);
PASEplussp=y(:,3);
sizePASEminusp=size(PASEplussp);
PASEminusp=zeros(sizePASEminusp(1),1);
Pssp=y(:,2);
Ppsp=y(:,1);
nuSPsp=(nu*N2sp)./(nu*N2sp-N1sp);
NFsp=2*nuSPsp;
A=y;%%%%%%%%%%%%%%
sizeA=size(A);
Ps_minus_Initial= A(sizeA(1),2)*(1-0.01*0.1); %Ps_minus initial with
reflection loss
for i=1:1:500

    bistabilityWrapper = @(z,y) dpedfa(y);
    [z,y] = ode45(bistabilityWrapper, dpdistancearray,[A(sizeA(1),1)
A(sizeA(1),2) A(sizeA(1),3) 0 Ps_minus_Initial]);
end
sizey=size(y);
array3=ones(sizey(1),1);
dbgaindp=10*log10(y(:,2)/3.16228e-7);

```

```

W12=((sigmasa*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4)+y(:,5));
W21=((sigmase*gammas)/(h*Vs*AA))*(y(:,2)+y(:,3)+y(:,4)+y(:,5));
R=((y(:,1)*gammap*sigmapa)/(h*Vp*AA));

N1dp=(rho*(array3+W21*t))./(array3+(W12+W21)*t+R*t);
N2dp=(rho*(R*t+W12*t))./(array3+(W12+W21)*t+R*t);

PASEplusdp=y(:,3);
PASEminusdp=y(:,4);
Psdp=y(:,2);
Ppdp=y(:,1);
nuSPdp=(nu*N2dp)./(nu*N2dp-N1dp);
NFdp=2*nuSPdp;

B=y;%%%%%%%%%%
sizeB=size(B);
%B=y(45,:);

sizesp=size(dbgainsp);
sp1=sizesp(1);
spstepsize=(spdistancearray(2)-spdistancearray(1))/sp1;
sizedp=size(dbgaindp);
dp1=sizedp(1);
dpstepsize=(dpdistancearray(2)-dpdistancearray(1))/dp1;

dbgain=zeros((sp1+dp1),1);
distancearray=zeros((sp1+dp1),1);
N1=zeros((sp1+dp1),1);
N2=zeros((sp1+dp1),1);
PASEplus=zeros((sp1+dp1),1);
PASEminus=zeros((sp1+dp1),1);

```

```

Psfull=zeros((sp1+dp1),1);
Ppfull=zeros((sp1+dp1),1);
NF=zeros((sp1+dp1),1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Connective
Part%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:1:sp1
    dbgain(i)=dbgainsp(i);
    distancearray(i)=spstepsize*i;
    N1(i)=N1sp(i);
    N2(i)=N2sp(i);
    PASEplus(i)=PASEplusp(i);
    PASEminus(i)=PASEminusp(i);
    Psfull(i)=Pssp(i);
    Ppfull(i)=Ppsp(i);
    NF(i)=NFsp(i);
end
for i=(sp1+1):1:(sp1+dp1)
    dbgain(i)=dbgaindp(i-sp1);
    distancearray(i)=spdistancearray(2)+dpstepsize*(i-sp1);
    N1(i)=N1dp(i-sp1);
    N2(i)=N2dp(i-sp1);
    PASEplus(i)=PASEplusdp(i-sp1);
    PASEminus(i)=PASEminusdp(i-sp1);
    Psfull(i)=Psdp(i-sp1);
    Ppfull(i)=Ppdp(i-sp1);
    NF(i)=NFdp(i-sp1);
end

dbNF=10*log10(NF);
sampledistancearray=zeros(25,1);
sampledbgain=zeros(25,1);
sampleN1=zeros(25,1);
sampleN2=zeros(25,1);

```

```

samplePASEplus=zeros(25,1);
samplePASEminus=zeros(25,1);
samplePs=zeros(25,1);
samplePp=zeros(25,1);
sampledbNF=zeros(25,1);

for i=1:1:16
    sampledistancearray(i)=distancearray(i*5);
    sampledbgain(i)=dbgain(i*5);
    sampleN1(i)=N1(i*5);
    sampleN2(i)=N2(i*5);
    samplePASEplus(i)=PASEplus(i*5);
    samplePASEminus(i)=PASEminus(i*5);
    samplePs(i)=Psfull(i*5);
    samplePp(i)=Ppfull(i*5);
    sampledbNF(i)=dbNF(i*5);
end

figure,plot(distancearray,dbgain),grid on,xlabel('length EDFA in
m'),ylabel('dbgain')
figure,plot(distancearray,N1,'+')
hold on
plot(distancearray,N2,'*'),legend('N1','N2')
figure,plot(sampledistancearray,samplePASEplus,'*'),grid on,xlabel('length
EDFA in m'),ylabel('PASE+')
figure,plot(sampledistancearray,samplePASEminus,'o'),grid on,xlabel('length
EDFA in m'),ylabel('PASE-')
figure,plot(sampledistancearray,samplePs,'*')
hold on
plot(sampledistancearray,samplePp,'o'),legend('Ps','Pp');
figure,plot(sampledistancearray,sampledbNF,'*'),grid on,xlabel('length EDFA
in m'),ylabel('dbNF')

```

VITA

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