Department of Electrical and Computer Systems Engineering

Technical Report
MECSE-35-2004

EDFA MATLAB SIMULINK MODEL

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A N EDFA USING MATLAB SIMULINK

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Abstract

Optical fibre amplifiers are dominating the loss compensation in fibre optic communications systems, especially the Erbium doped types for communication spectrum based on silica fibres. Several models have been developed for such photonic amplification devices. However there is no comprehensive and models developed in MATLAB SIMULINK platform. This report describes in details the development of a SIMULINK model for EDFAs operating under steady state and dynamic condition.

The equations that govern the pump and signal propagation in the doped fibre are derived and tabulated with corresponding amplifier parameters. The model blocks are then described under the SIMULINK environment. Simulation results are compared with experimental values and their close agreements indicate the validity of the SIMULINK EDFA models.

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1   Introductory remarks

Since 1989 the rare-earth metal doped fibres have been exploited as the optical amplification medium and laser sources, both in experimental and theoretical aspects. It is no doubt that the Erbium-doped fibre amplifiers (EDFA) are the amplifying devices employed in commercial optical transmission systems. Several models have also been reported and developed for the design and system simulation.

The mathematical laboratory MATLAB has also been progressively developd and improved ove the last two decades. It has now been considered as the standard mathematical tool boxes in teaching and R&D laboratories around the world. Recently it has added the SIMULINK toll boxes. This gives an additional and powerful toll for simulation of physical systems. The Laboratory for Optical Communications and Applied photonics of Monash university has developed several packages under MATLAB and SIMULINK for simulation of photonic devices and optical communications system for both research and training purposes.

This report thus describes the comprehensive and successful implementation of the EDFA over the SIMULINK MATLAB 7 R14. The report has been organized as follows:

➢ The fundamental and theoretical expressions for representing the optical amplification and the rate of transitions of the erbium ions and lightwaves propagation over the amplifying medium are described in section 2. Both forward and backward pumping configurations are given.

➢ Section 3 gives an account of the SIMULINK models for the amplifiers in the steady state and dynamic environments.

➢ Section 4 then illustrates the samples of the SIMULINK simulator;

➢ Section presents details of the simulation results to iluustrate the validity of the developed models and confirm them with experimental data obtained from EDFA constructed in the laboratory as well as those specified by commercial manufacturers.

The SIMULINK models are proven to be user-friendly and ease for use. It would be a good tool for teaching graduates at advanced levels in the field of photonics and optical communications.

2   Fundamental and Theoretical Issues of EDFAs

The basic theoretical development of the Erbium-Doped Fiber Amplifier (EDFA) is described as a preparation of the EDFA simulation modeling development. Several technical terms such as Pumping Scheme, Population inversion factor, ASE noise, etc, are explained and defined.

2.1   EDFA Configuration

Erbium-doped Fiber Amplifier mainly constructed by a short length of optical fiber whose core has been doped with less than around 0.1% erbium, an optically active rare earth element which has many unique intrinsic properties for optical amplification, Ref [6]. The optical fiber used is named Erbium-Doped Fiber. The optical amplifier engineer will choose appropriate erbium-doped fiber during the Erbium-Doped Fiber Amplifier development. Different doped fiber have different characteristic of the absorption and emission factors, which will be identified and discussed in a later section.

An EDFA consists of an erbium-doped silica fiber, and other photonic components such as the pump source, the optical isolators, the WDM coupler etc. as shown in Figure 1. An enhanced EDFA Module consists of an erbium-doped fiber, a wavelength dependent coupler (WSC) , a polarization insensitive optical isolator (OI). An optical filter may be required to improve EDFA performance [12] depending on specific applications. The optical filter is used to reduce the amplified spontaneous emission (ASE) noise and protect the amplifier from saturation cause by ASE accumulated in an in-line-amplification system. The OI is used for achieving a stable amplified operation to prevent spurious oscillations and reflection. The pump source is used for pumping the erbium ions to upper energy level, several proper pumping wavelength laser diodes exist at the present. Both 1480 nm and 980 nm pumping laser diodes can provide an high pump gain, the investigating of those two pumping wavelength will be described in later section. The WSC/WDM is used to combine the pump sources and the incoming signal. The pump lightwaves are guided and propagating along the EDF length and the depleted erbium ions then rise to an excited state by absorption the energy. As the signal propagates through the EDF, it stimulates emission of light from the

excited ions, thus the signal is amplified. The tap coupler is used as a separator taping the pumping power in order to protect the receiver, normally used in pre-amplifier.

Two pumping configurations can be used in EDFAs, the backward pumping and dual backward and forward pumping as shown in Figure 2.
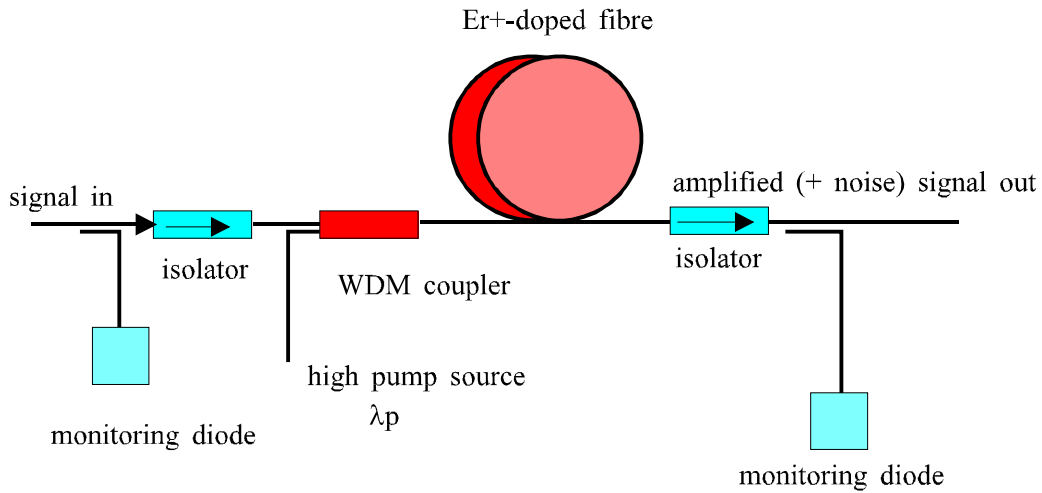
Figure 1 Standard forward pumped EDFA, extracted from Ref [10].
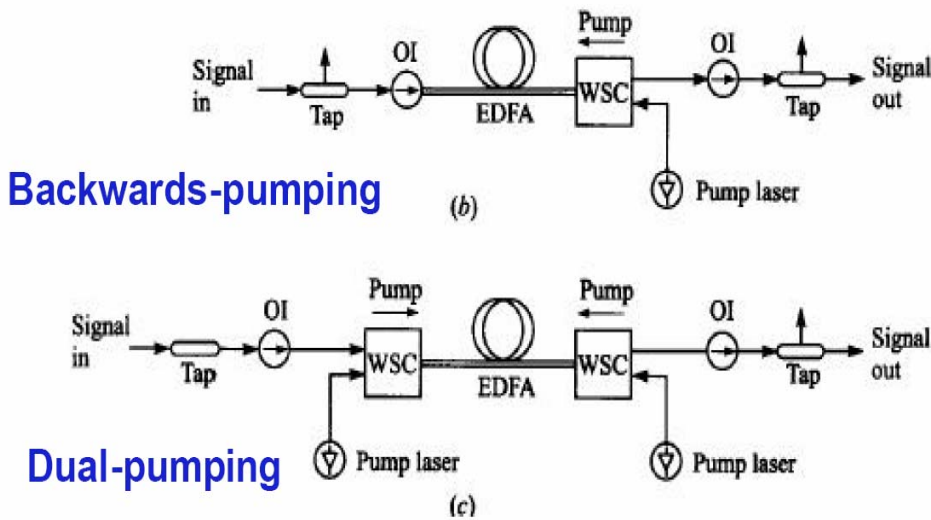
Figure 2 Backwards-pumping and dual pumping, taken from ref [10] permission pending

The only difference of the three configurations is the pumping propagation direction. As the name of the configuration; in forwarding pumping, the signal light co-propagates with the pump light, whereas in backward pumping it counter-propagates relative to the pump light, dual dumping would pump bi-directional. Considering the noise performance, the forward pumping can produce optical amplification with low noise, but may offer lower amplification gain due to fluctuation of the pump power and signal power. On the other hand, the backward

pumping may be effective for high power output but it suffers higher ASE noise. Thus there is an enhanced model in which bi-directional pumping or dual pumping can be combined.

3   EDFA operational principles

The basic operation principles of EDFA is that the Erbium ions which can exist in several energy states. When they are a high energy state, a photons could be stimulated it to give up some of its energy (as light) and return to a lower-energy (more stable state), thence photonic amplification [13].

3.1.1   Pump Wavelength and Absorption Spectrum

The pump wavelength can be either 980nm or 1480nm due to the availability of these lasers sources. Why most of EDFAs are using those two as their pumping wavelength but the others? Before we go to the answer, let's see the Energy levels of the triply ionized erbium ion, Er+, the absorption band of Er+ and the pump efficiency

(a)

20

energy levels

(x10³ cm⁻²)

$^2H_{11/2}$

$^4S_{3/2}$

$^4F_{9/2}$

$^4I_{11/2}$

$^4I_{13/2}$

514   532   667   800   980   1480   1550 nm

0 $^4I_{15/2}$

(b)
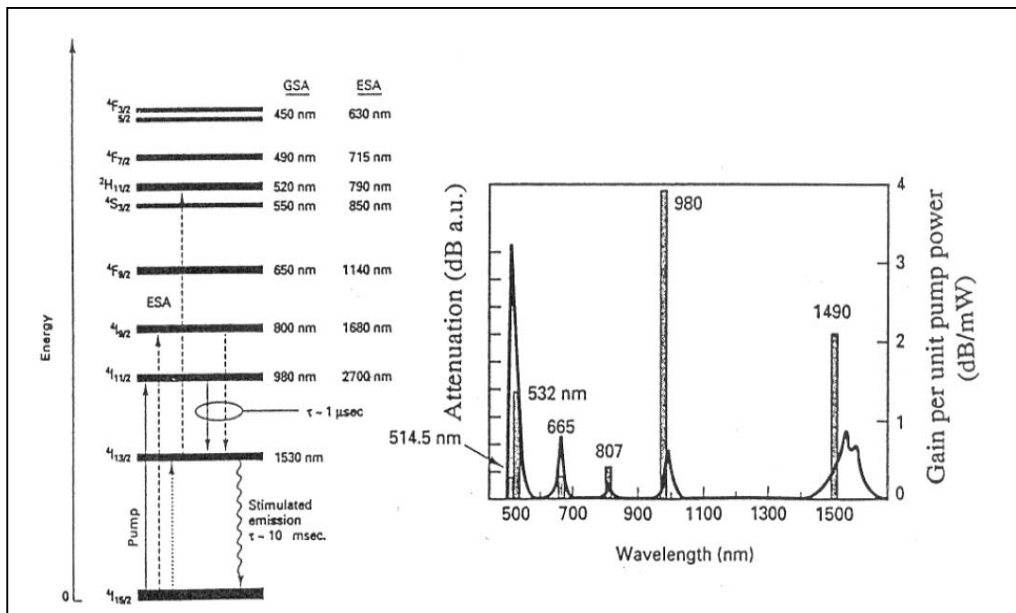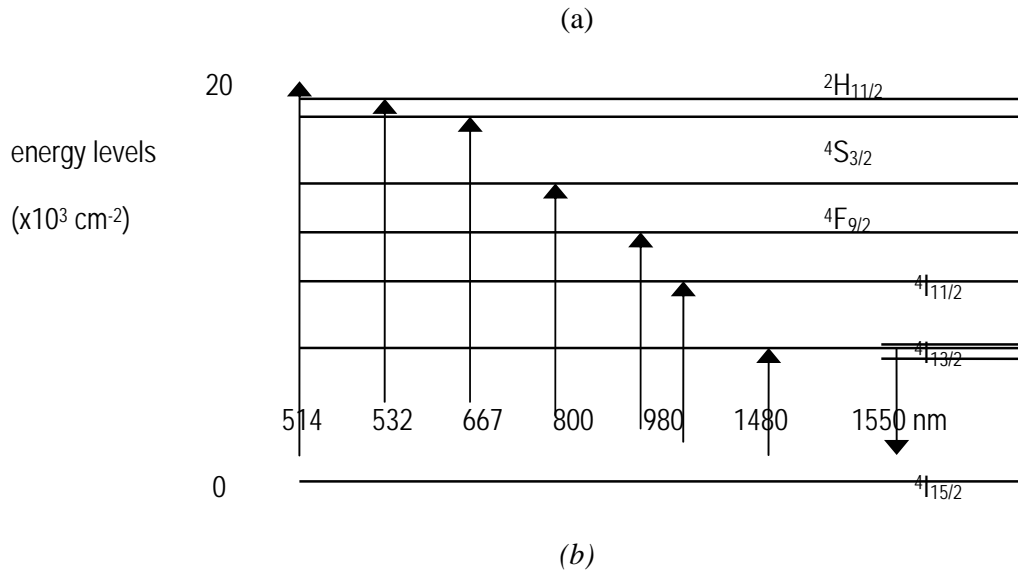
Figure 3 Erbium ion energy levels and pump spectra (a) details and (b) simplified model.

There are serval states to which the erbium ions could be pumped using sources of different wavelengths such as those operating at 1490nm, 980nm and 800nm. However, in real lightwave systems, the pump wavelength must provide a high power to achieve high gain per pump. The commonly available laser diodes can operate at 800nm, 980 nm and 1480 nm, but the pump efficiency can go more than 1dB/mW with low attenuation depending on the pump frequency. The only pump wavelength laser sources that can give a high pumping efficiency with lower attenuation are those operating at 980nm or 1490nm. In the practice the 980nm pumping source is commonly used due to its high gain coefficient (4dB/mW). The model given in this report employes both of 980nm and 1480nm pumping sources. The different effect of those two wavelength sources is mainly caused by the absorption and emission factor.

3.1.2   Pump Mechanism

Amplification mechanism is the key for developing the EDFA simulation model. The optical amplification gain is supplied by the excited erbium ions (Er+) when the amplifier is pumped to achieve population inversion. Depending on the energy states of dopant, pumping schemes can be classified as a two or three scheme. The main difference between the two level and three level pumping schemes is related to energy state occupied by stimulated-emission event. In the case of a three-level scheme, the lower level is ground, whereas it is an excited state with a fast relaxation time in the two-level scheme.

As shown in Figure 4, Erbium ions are pumped to an upper energy level by the absorption of lightwave energy from the pump source at either 980 or 1480nm to regain the equilibrium distribution [12].

Stage 1
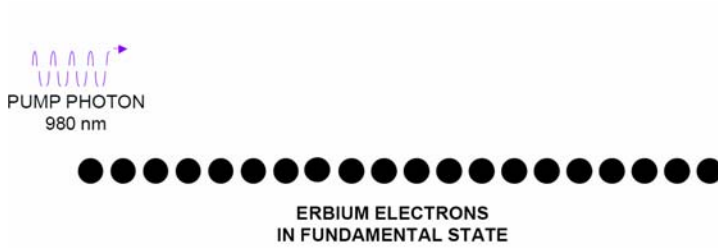
Figure 4 The pump photon start propagating through the Erbium fiber, all the erbium electrons now are lay on the fundamental state (Ground state). Taken from ref [4] Permission Pending

Stage 2
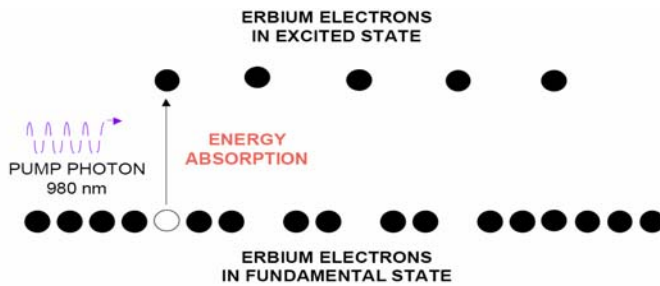
Figure 5 the erbium electrons which are pumped to higher-level energy states extracted from [10] .

Stage 3
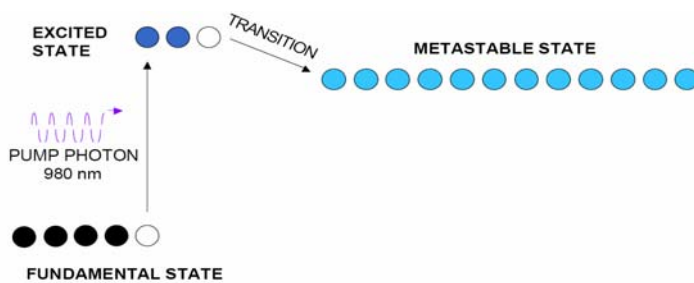
Figure 6 the erbium electrons now revert to lower states (metastable state) spontaneously after some mean lifetimes t – 1msec (spontaneous emission), Taken from ref [10] Permission Pending

Stage 4
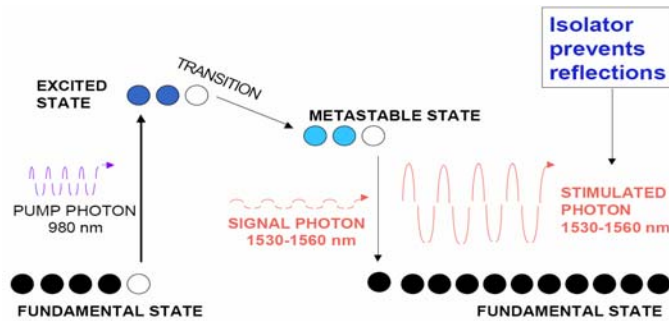
Figure 7 (b) the erbium electron revert to the fundamental state spontaneously (spontaneous emission) and stimulated to do so by some incident photons (Signal) of exactly the energy corresponding to the drop too lower state (Stimulated emission), extracted from ref [10].

Coherence of pump sources and signals means the incident photon and the stimulated one have the same frequency, phase, propagation direction and polarization [14]. The optical gain is achieved when the population inversion reaches sufficiency high level at which the absorption from the ground state is considerably reduced. This can be readily achieved with available pump lasers because the meta-stable state exists in Er^{3+} thus rendering the population inversion possible. In addition the photon lifetime from the meta-stable state to fundamental state must be longer than that from excited state to metastable state, normally around 10 ~ 10.5 msec, the lifetime from excited state to meta-stable state is normally about 1ms. Therefore the ions are accumulated in the metastable, hence the ion population in excited stated is negligibly small. This fact is critical in the design of the simulator.

3.1.3   Amplifier Noises

During the signal amplification process, noises are generated. The dominant amplification noise source is the ASE noise (amplifier stimulated emission noise). When ions are on transition from the excited state to the fundamental state, some excited erbium ions decay to the fundamental state with spontaneous emission before amplifying the injecting signal photons. Thus photons are emitted with random phase and direction [12].
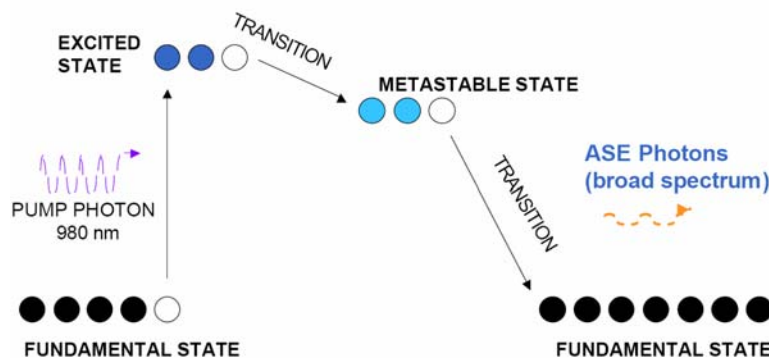
The ASE spectral range is very while and cover almost the C- and L- bands covering the gain spectrum of the amplifier as shown in *Figure 9.*
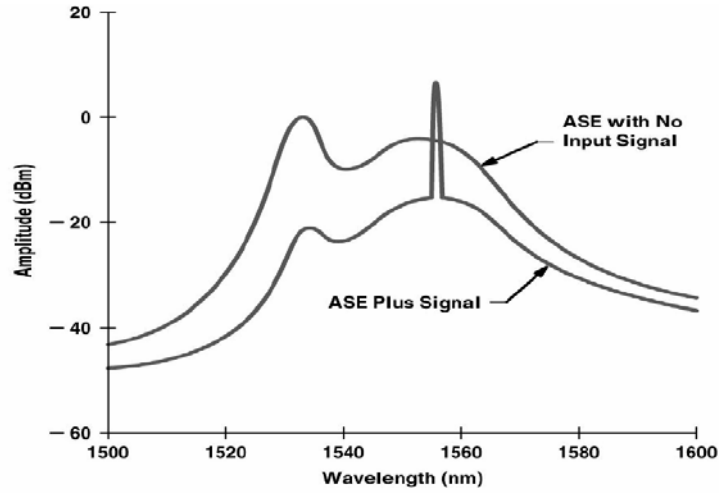
(a)
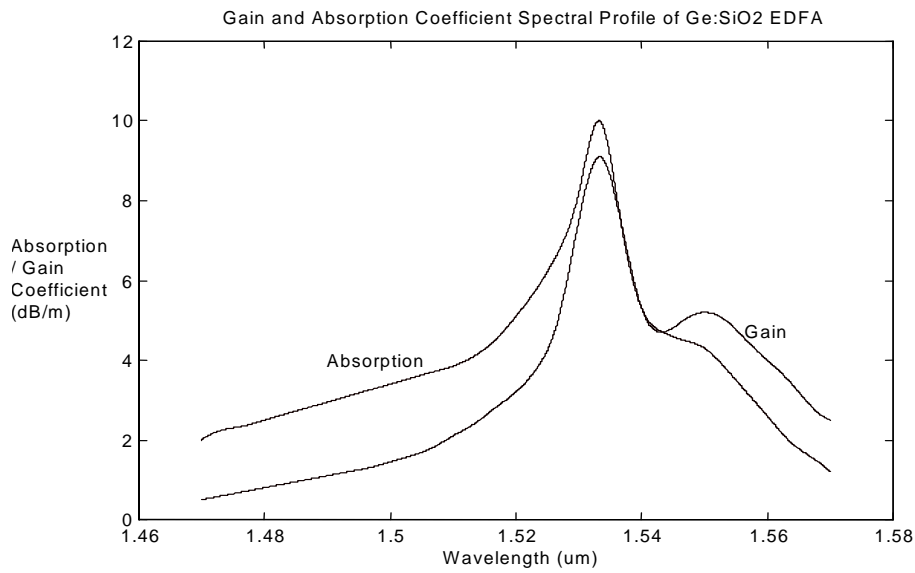
(b)

Figure 9 (a) ASE noise spectrum, taken from Ref [10] (b) absorption and gain spectra.

It will reduce the available gain for the signal field. Figure 9 shows the saturated gain has been reduce by the ASE. That is due to the incoherence of the excited erbium ions with the signal photons. The ASE noises cause degradation to the signal and noise ratio (SNR).
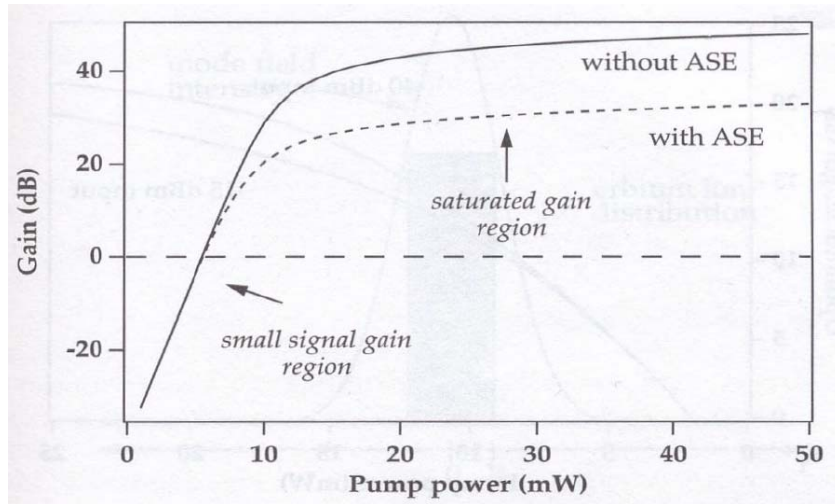
Figure 10 Optical gain reduction by the ASE, extracted from Ref[10]

EDFAs are employed in long haul transmission systems, the ASE level grows after a cascade of amplifiers and begins to saturate the optical amplifiers, hence reduce the signal gain. This is because total power almost equal to the pump power plus the ASE power.

3.1.4 Amplifier Gain Modulation

Gain modulation of EDFAs can provide an attractive approach for implementing status and control communication in modern dense wavelength division multiplexing (DWDM) communication networks. The desired control signal is imposed as amplitude over modulation on the payload communication signals propagating down the system, via modulation of the EDFA pump power [2]. We report herewith in this document the impacts of pump modulation and signal modulation effect on EDFA gain.

3.2 EDFAs in long-haul transmission systems

Optical amplifiers can be employed with three different types for optical transmission systems as a booster-amplifier, an in-line amplifier regenerator and as an optical pre-amplifier at the receiver as shown in **Figure 11**.

Booster OA   **In-line OA1**   **Optical pre-Amp**
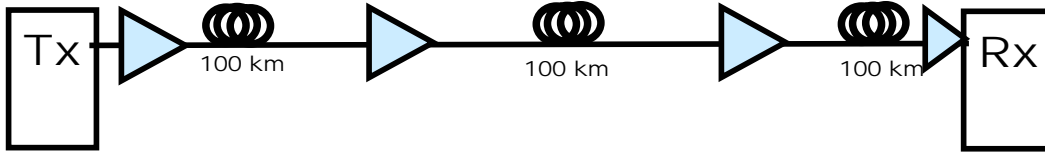
Figure 11 The employment of three type of amplifiers and related monitoring equipment.

- The booster amplifier increase and provide a high optical power signal prior to transmission. In long-haul optical communication system the use of a booster amplifier can increase the link power budget and reduce the number of regenerators required.

- In-line optical amplifiers: The main function of in line amplifier is to compensate for the fibre loss of the fibre span or the dispersion compensating fibres thereby overcoming the need for O/E regeneration.

- Optical Preamplifier – the main function of the optical preamplifier is to increase the power level of a signal before detection and hence the receiver sensitivity.

4   EDFA Simulation Model

In this section, the mathematical expressions for developing EDFA simulation model are described. In general the simulation models can be classified in both the steady state and dynamic models and/or perturbation modes [6]. In this report, only the first two models are used for EFDAs simulation. The models of single EDFA are investigated; a cascade of EDFAs can be implemented without difficulty and left for users to construct.

4.1   Amplifier parameters

A number of parameters can calrify the principles of the simulation model as shown in **Table 1** and **Table 2**.

Physical Meaning	Expression	Symbol & Unit
Erbium-Doped Fiber Parameters (Part I)		
Core radius of Erbium-Doped Fiber		r (um)
Core area of EDF		A (m^2)
Overlap factor of EDFA at Wavelength(λ)		Γ_λ
Ion density of Erbium-Doped Fiber		ρ (ions/m^3)
Florescence lift time of EDFA		τ (msec)
Absorption cross-section at Wavelength(λ)		σ_λ^α (m^2)
Emission cross-section at Wavelength (λ)		σ_λ^e (m^2)

Physical Meaning	Expression	Symbol & Unit
Absorption coefficient at wavelength(λ)	$\rho \; \Gamma_\lambda \; \sigma_\lambda^\alpha$	α_λ (m^{-1})
Absorption over length L at wavelength (λ)	$\alpha_\lambda \times$ L	
Plank Constant	6.626e-34	h (J.s)
Speed of light		c (msec^{-1})

Table 1 Erbium-Doped fiber parameters

Physical Meaning	Expression	Symbol & Unit
Erbium-Doped Fiber Parameters (Part II)		
Length of the Erbium fiber		L (m)
Population density in fundamental state		n_1(ions/m^3)
Population density in excited state (assume 980nm pump)		n_3(ions/m^3)
Population density in meta-stable state		n_2(ions/m^3)
Signal power		P$_{in}$ (mW)
Pump power		P$_{out}$ (mW)
Signal power in simulation	$N_s = \dfrac{P_{signal}^{in} c}{h \lambda_s}$	N$_s$ (photons/sec)
Pump power in simulation	$N_p = \dfrac{P_{pump}^{in} c}{h \lambda_p}$	N$_p$ (photons/sec)

Table 2 Glossary of EDFA parameters

Bononi and Rusch have developed a dynamic model based on the one-dimensional ordinary non-linear differential equation for the time-dependent population of excited stat erbium ions in EDFAs.' [3]. With the three level states, the amplification in erbium-doped fiber is based on the stimulated erbium ions; thus the state population would have discrepancy. Simplifying the schemes to be a 3-level pumping, the three populations of erbium atoms are: ground State (the fundamental state with population density n_1), level state 2 (the excited state population density, also called meta-stable sate with signal frequency n_2) and level state 3 (the excited state population with pump frequency n_3). The rate equation for these three states can be defined and given as [6], [13]

Ground State 1 population:

$$\frac{\partial n_1}{\partial t} = -W_{1-3} * n_1 - W_{1-2} * n_1 + W_{2-1} * n_2 + \frac{n_2}{\tau_{2-1}} + W_{3-1} n_3 + \frac{n_3}{\tau_{3-2}} \tag{1.1}$$

State 2 population:

$$\frac{\partial n_2}{\partial t} = W_{1-2} * n_1 - W_{2-1} * n_2 + W_{3-2} * n_3 - \frac{n_2}{\tau_{2-1}}$$ (1.2)

and finally the state 3 population equation:

$$\frac{\partial n_3}{\partial t} = W_{1-3} * n_1 - W_{3-2} * n_3 + W_{3-1} * n_3 - \frac{n_3}{\tau_{3-2}}$$ (1.3)

Physical Meaning	Symbol	Expression	Comment
Transition rate from state 1 to state 2	W_{1-2}	$W_{1-2} = \dfrac{\Gamma_s \sigma_{1-2} N_s}{A}$	Transition associate by the signal
Transition rate from state 1 to state 3	W_{1-3}	$W_{1-3} = \dfrac{\Gamma_p \sigma_{1-3} N_p}{A}$	Transition associate by the pump (980nm)
Transition rate from state 2 to state 1	W_{2-1}	$W_{2-1} = \dfrac{\Gamma_s \sigma_{2-1} N_s}{A}$	Transition associate by the signal (C-band) 1525 – 1565 nm (L-band) 1566 – 1605 nm
Transition rate from state 3 to state 2	W_{3-2}	$W_{3-2} = \dfrac{\Gamma_p \sigma_{3-2} N_p}{A}$	Transition associate by the pump (980nm)
Transition rate from state 3 to state 1	W_{3-1}	$W_{3-1} = \dfrac{\Gamma_p \sigma_{3-1} N_p}{A}$	Transition associate by the pump (980nm)

Table 3 Transition rates between States of a stimulated Er^{3+} ion.

The transition from state 3 to 2 (W_{3-2}) is much more influential on the EDFA gain than the transition down to the fundamental state (W_{3-1}).The transition rate W_{3-1} can be neglected. The transition W_{1-3} is associated with the pump source. Furthermore we can refer to **Figure 8**, the florescence life time for transition (W_{3-2}) is short enough (1 µsec) compared with that of the transition (W_{2-1}) (10msec), thus the erbium ions can be accumulated in State 2. Hence, the transition rate W_{1-3} should very close to transition W_{3-2} due to the shorter life time. We thus have $W_{3-2} \cong W_{1-3}$. Substituting this into (1.2) we have

$$\frac{\partial n_2}{\partial t} = W_{1-2} * n_1 - W_{2-1} * n_2 + W_{1-3} * n_3 - \frac{n_2}{\tau_{2-1}}$$ (1.4)

In fact, n_3, n_2 and n_1 are independent. However as mentioned above the erbium ions are accumulated in upper State 2; the population density in n_3 thus can be negligible. The total population density ρ of the fiber is a constant value. Therefore if $n_3 \approx 0$, then n_1 and n_2 are

no longer independent with each other and under the constraint that the sum of the two equals the total erbium ions with the fiber $n_1 + n_2 = \rho$. In particular, the population are functions of both time and linear distance along the erbium-doped fiber[3], [13], [6] .

Furthermore, the relationship between the input power and the population have to determined next. The following diagram will illustrate how the input power evolute along the EDF.
Amplification
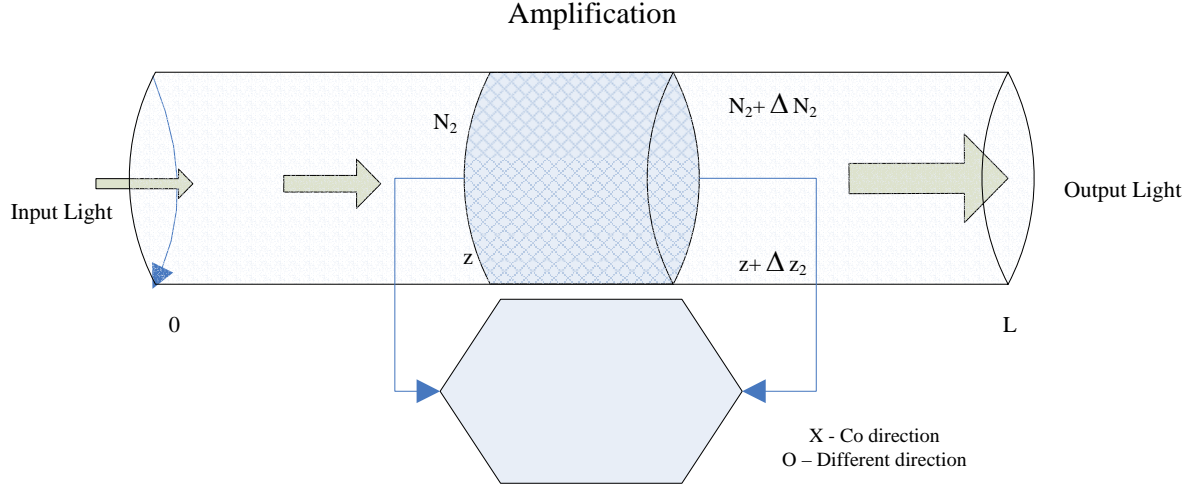
Figure 12 Power evolution of the signal under the amplification process along EDF.

Refer to Figure 12, the input light is amplified along the distance during the time. Hence the optical power through the erbium-doped fiber is determined [2] by

$$\frac{\partial P_p}{\partial z} = -\Gamma_p * \sigma_{1-3} n_1 * P_p - \gamma_p * p_p \tag{1.5}$$

$$\frac{\partial P_s}{\partial z} = -\Gamma_s * \sigma_{1-2} n_1 * P_s + \Gamma_s * \sigma_{2-1} n_2 * P - \gamma_s * p_s \tag{1.6}$$

where γ denotes the scattering and other losses of the EDF. As shown in *Figure 2*, X means the co-directional photon. O is the photon simulation in different direction, hence generating noises, reflection power and scattering.

5   EDFAs dynamic model

In our simulator the EDFAs dynamic modelling is focused rather than the steady state modelling as *"EDFAs with high output powers for multiple channel optical network are strongly saturate and the resultant effective time constant are reduce to the order of tens of microsecond which is 1000 times shorter than its lift time."* [6].   The time dependent problem is especially important in the optical network where the optical channels are constantly reconfigured. Dynamic modelling can predicts the EDFA gain more accurately during multi-channel amplification. This section describes the essential Bononi-Rusch approach; and

develops it to accommodate time varying pump and communication signal. Multi-channel amplification modelling principle also will be considered in this section.

First, we note that from 1.1 – 1.6 are typically solved by obtaining the population in different state. As the transition rate $W_{1-2} = \dfrac{\Gamma_s \sigma_{1-2} N_s}{A}$, $W_{1-3} = \dfrac{\Gamma_p \sigma_{1-3} N_p}{A}$ and $W_{2-1} = \dfrac{\Gamma_s \sigma_{2-1} N_s}{A}$, Substituting into (1.5 and 1.6), we have

$$\frac{\partial P_p}{\partial z} = -W_{1-3} * n_1 * A - \gamma_p * p_p \tag{1.7}$$

$$\frac{\partial P_s}{\partial z} = -W_{1-2} * n_1 * A + W_{2-1} * n_2 * A - \gamma_p * p_p \tag{1.8}$$

Multiplying eq. (1.4) by the fibre effective core area and substituting (1.7) and (1.8) [11]. We have

$$\frac{\partial N_2}{\partial t} = P_s(0,t) * (1 - e^{G_s}) + P_s(0,t) * (1 - e^{G_p}) - \frac{N_2}{\tau} - \gamma_p * p_p - \gamma_s * p_s \tag{1.9}$$

where G_s and G_p are the amplification gains of the power evolution respectively. The increment of the power along the EDFA is non-linear and assumed varied exponentially, we have [1]

$$P_p(L,t) = P_p(0,t) e^{\frac{\Gamma_p \sigma_{1-3}}{A} N_2 - \Gamma_p \sigma_{1-3} \rho L - \gamma_p} \tag{1.10}$$

$$P_s(L,t) = P_s(0,t) e^{\frac{\Gamma_s(\sigma_{1-2}+\sigma_{2-1})}{A} N_2 - \Gamma_s \sigma_{1-2} \rho L - \gamma_s} \tag{1.11}$$

Assuming $\gamma = 0$ leading to

$$G_p = \frac{\Gamma_p(\sigma_{1-3} + \sigma_{3-1})}{A} N_2 - \Gamma_p \sigma_{1-3} \rho L \tag{1.12}$$

$$G_s = \frac{\Gamma_s(\sigma_{1-2} + \sigma_{2-1})}{A} N_2 - \Gamma_s \sigma_{1-2} \rho L \tag{1.13}$$

The different spectral input channel will have different EDFA gain due to the wavelength dependence of the absorption and emission cross sections and the overlap factor.

For the 3-level schemes (980nm pump) σ_{1-2} and σ_{2-1} are the absorption and emission factors respectively at the signal wavelength and σ_{1-3} and σ_{3-1} correspond to the pump wavelength, σ_{3-1} is assumed to be negligible over the short transition time.

For the 2-level scheme, the pump source is normally operating in the spectral region 1480nm – 1490nm, the rate equations are similar to those obtained for the 3-level scheme, but the absorption and emission factor [σ_{1-3} σ_{3-1}] have to be matched with the correspondent wavelength. Rewrite these matrices to [σ_a σ_e]. The [σ_a σ_e] for the pump wavelength is [σ_{a_p} σ_{e_p}], with σ_{e_p} is non zero and refers to the spectrum of absorption and emission factors.

For multi-channel amplification, the modelling equations are integrated and summarised as

$$\frac{\partial N_2}{\partial t} = \sum_{\lambda_o}^{\lambda_n} P_\lambda(0,t) * (1 - e^{G_\lambda}) - \sum_{\lambda_o}^{\lambda_n} \gamma_\lambda * p_\lambda - \frac{N_2}{\tau} \tag{1.14}$$

2.2 EDFA steady state modelling principles

'*It is well known that one of the advantages of EDFA is its slow dynamics as a result of the long spontaneous lift time of around 10msec*'. This is also the reason why steady state models plays an important role in the dynamic analysis of EDFAs properties for system applications [5]. The EDFA steady state modelling has been widely used. An EDFA operates in a steady state condition when $\frac{\partial N_2}{\partial t} = 0$, that is when there are no population increment and the EDFA gain reaches the saturation mode. Thus in order to model the EDFA in steady state, we have

$$0 = \sum_{\lambda_o}^{\lambda_n} P_\lambda^{saturation}(0,t) * (1 - e^{G_\lambda^{saturation}}) - \sum_{\lambda_o}^{\lambda_n} \gamma_\lambda * p_\lambda^{saturation}(0,t) - \frac{N_2^{steady-state}}{\tau} \tag{1.15}$$

which ca be simplified to

$$P_p(L,t) = \sum_{\lambda_0}^{\lambda_n} P_{\lambda_p}^{steady}(0,t) e^{\frac{\Gamma_p \sigma_{a\lambda p}}{A} N_2^{steady} - \Gamma_p \sigma_{a\lambda p} \rho L - \gamma_p} \tag{1.16}$$

$$P_s(L,t) = \sum_{\lambda_0}^{\lambda_n} P_{\lambda_s}^{Steady}(0,t) e^{\frac{\Gamma_s (\sigma_{a\lambda s} + \sigma_{e\lambda s})}{A} N_2^{steady} - \Gamma_s \sigma_{a\lambda s} \rho L - \gamma_s} \tag{1.17}$$

This model thus can predict the onset of steady state of the amplification gains and pump absorption in an optical amplifier containing an arbitrary number pumps and signal for co- and contra-propagating scenario.

5.1 Population inversion factor

Population inversion indicates the number of ions inverted from State 1 to State 2 excited by the pumping energy. In order to obtain the amplification gain, the number of photons gained simulated emission from the metastable state to the fundamental state must be greater than

those of the absorption from the fundamental state to state 2. This condition implies that the population in metastable state must be maintained at a greater level than that of fundamental state. The degree of population inversion can thus be expressed by population inversion factor n_{sp}[13] as

$$n_{sp} = \frac{N_2}{N_2 - \dfrac{\sigma_e}{\sigma_a} N_1} \tag{1.18}$$

where n_{sp} is related to the pump and signal power and is the key factor of the amplifying spontaneous emission noise (ASE).

5.2   Amplifier Noises

In the previous section, the production of the ASE photons is described. The noise statistics of the amplified lightwaves follows a Gaussian distribution. By considering noise as random variable generated by various independent sources, thus it can be assumed that in general the probability density function of their sum also approaches Gaussian. The effect of amplifier noise can therefore be modelled as a Gaussian random process with a noise variance.

5.2.1   ASE Noise model

The ASE noise as a random noise can be modelled by generating complex spectral components whose real and imaginative random variables are Gaussian with variance P_{ase} corresponding to the average noise. The ASE noise spectral power can be estimated over a bandwidth Δf as

$$P_{ase} = n_{sp}(G-1)hf_s\Delta f = N_0\Delta f \tag{1.19}$$

where it is assumed that a sufficiently large bandwidth on ASE detection is used and sensitive within the spectral region 1480nm – 1605nm, G is the small signal amplification gain. To model the ASE noise, a Gaussian wave with ASE mean power and variance are used, which are described in the next section.

5.2.2   Other noise sources

In practice, an optical BPF is usually incorporated in the EDFA to reduce the ASE noise contribution. ASE induced noise are contributed by two noise sources:

- Spontaneous-spontaneous beat noise

    Sp-Sp beat noise is caused by the self interference of the generated spontaneous photons and given as:

$$P_{sp-sp} = 2n_{sp}^2(G-1)^2 e^2\Delta f \tag{1.20}$$

- Signal-spontaneous beat noise

S-sp beat noise is produced by the beating between the signal photons and those of the spontaneous emission and given as

$$P_{s-sp} = 4e^2 \frac{P_{in}}{hf} n_{sp} (G-1)G \tag{1.21}$$

The signal S-sp term dominates the ASE noise, thus we have

$$N_{s-sp} = 4e^2 N_{in} n_{sp} (G-1)G \tag{1.22}$$

6   EDFA simulation model

This section gives the evaluation of the numerical data resulting from our EDFA simulator and EDFA Module, experimental results are compared with those generated by our models. The principal advantage of the Simulink EDFA simulator is its versatility and ease of use. These results are by no means exhaustive.

7   EDFA simulation: the MatLab Simulink model

According to the simulation modelling principle from the previous chapter, here we will focus on how to implement EDFA simulation on MatLab Simulink. This section documents the Simulink simulation design and developments, explaining how each of the blocks within the simulator are brought together. *Figure 13* and *Figure 14* illustrates the EDFA Simulator and EDFA Modules and associated monitoring equipment. The explorer views of the subsystem within the Simulink Model are available to user on request.

3.1 Simulator Design Outline

Simulink can be easier for a user unfamiliar with the programmer's methods or general programming techniques, i.e. operators or system technicians. This reduces the likelihood of human induced error when modeling the system of choice, important in the rapidly changing area of information transmission.

The Simulink simulation model in this project basically derived into two parts: 1) EDFA Simulator. 2) EDFA Module. EDFA Simulator is simulating the details of amplification along the Erbium-Doped fiber in order to investigating and scoping how the signal can be pumped along the fiber, also observing the effect in gain modulation during the amplification. EDFA simulator development is base on the EDFA dynamic modelling. And EDFA module is used with the whole optical system simulation for predicting the amplification output and its noise scoping. EDFA Module development is base on the EDFA Steady State modelling. Thus the function of those two simulations is different. EDFA model can be easily combined with transmitter simulator and fiber simulator to form an optical communication link.
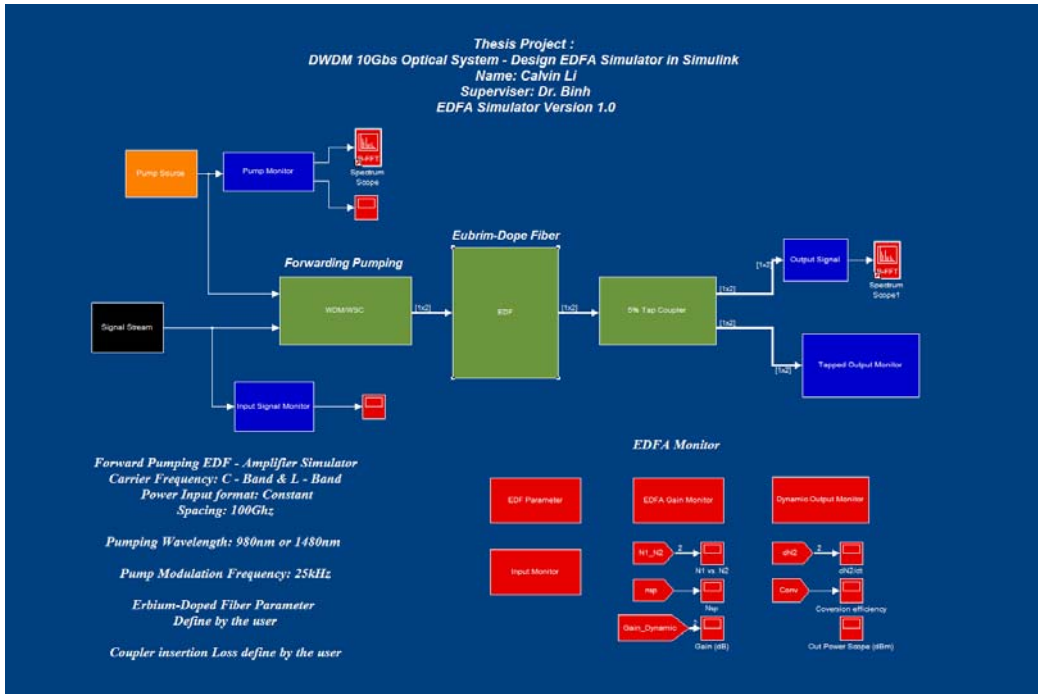
Figure 13 The EDFA Simulator Model: amplifier general layout.

Figure 14 EDFA Module amplifier and monitoring systems.

7.1   Simulator Design Process

Intrinsically, Mat Lab Simulink is a very powerful design tool. However, this also means many different factors need consideration to accurately model a system. Little experience with complex system modeling meant that a knowledge base of the system needed to be developed step by step. Therefore derive the simulator prototype into number of small task will simplify the design process, pending time. Thus, initially the first task of the thesis will focus on how to simulate the pumping schemes of the Erbium-doped fiber; which this is the primary goal that have to be achieved; and this also mainly part of our simulator. The simulator is divided into a number of stages. The following flow-chart will easy to briefing the design process:
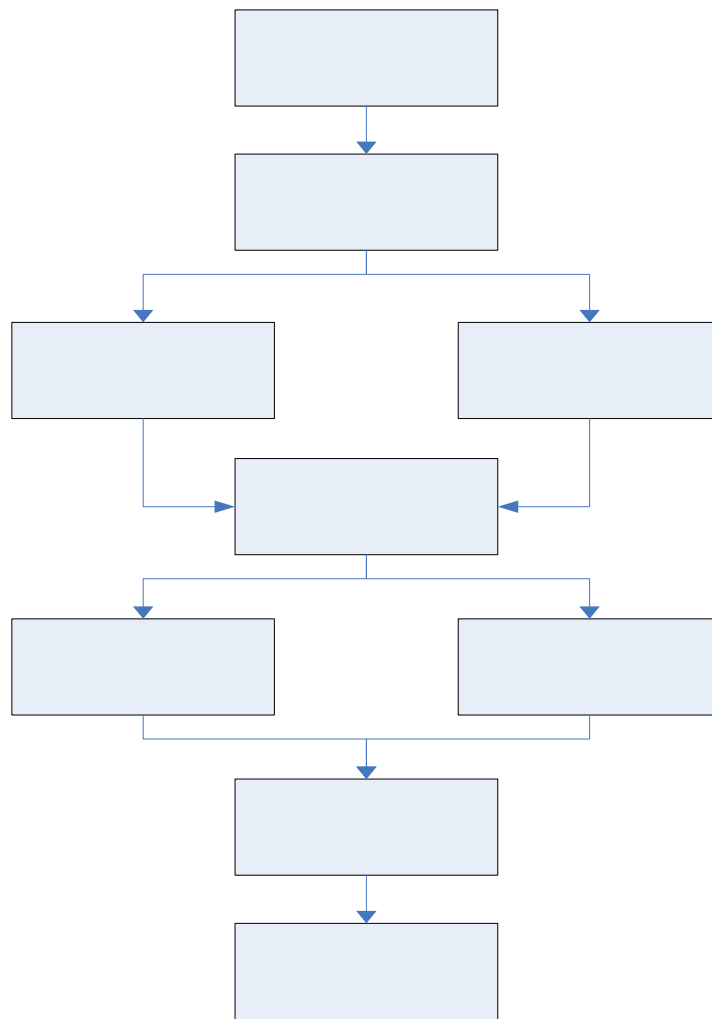
Figure 15 Simulation Design Flow Chart

7.2   Simulator Requirement

In this section, the requirement related to the basic issues such as software compatibility and simulation efficiency on the MatLab Simulink software are described. First, the EDFA Simulink simulation is designed based on MatLab Simulink MatLab 7. Running the simulator

in MatLab Simulink will be the first requirement. As there are many versions of Mat Lab Simulink are available, thus running the Simulator in the incorrect version may cause bug/hang or jams.

Second, the blocksets included in the Simulink library must be included and activated. Running without a relevant blockset libraries initialized upon the user's platform, the Simulink simulation can be opened. The following specific blocksets are needed to assure the operation are: Simulink DSP blockset, Simulink Sink, Simulink Communications Blockset and the Simulink Extras Blockset.

7.3   Simulator Design Assumptions

7.3.1   Sampling time Assumption

In designing the simulator it is decided that a discrete rather than continuous sampling method is employed, primarily for practical reasons. In particular a discrete sampling system would decrease the processing power required to execute simulations and reduce execution time.

In accordance with the sampling theorem previously outlined all data was sampled at or above the Nyquist frequency. That is all sampling was performed at least twice the highest frequency within the simulator (the sampling frequency applied on this project was up to seven times of the highest frequency). The use of discrete sampling periods helps to ensure synchronization of the various system components as the data signal was propagated, an important consideration in optical systems. Consideration of optical transmission system parameters shows the highest frequency to be that of the carrier waveform. For the purpose of this project the carrier frequency was defined in C-band and L-band, which is around 0.2PHz. Thus sampling within the system needed to occur at seven times of this rate, approximately 1.4 PHz (Peta-Hz) in order to ensure signal aliasing issues did not arise and given more accurate result. All blocksets require a discrete sampling time at which to generate data. Unfortunately this sampling rate is very high and may cause slowness in the execution time.

7.3.2   Signal streams

Signal stream in EDFA simulator are not defined during the simulation, the EDFA simulator assumes the average signal power. Thus the signal stream simulating in EDFA simulator would be a constant value with superimposed noise on Gaussian pulses. Hence the determination in the output power also is the average signal power.

Signal stream in EDFA Module is developed as the PSK (Phase shift key) modulation signal with Gaussian noise. The carrier is defined to be a 192.5 THz sine waveform. The data stream is assumed at 10 Gb/s binary pulse.

7.3.3 EDFA Simulink Simulation model assumption

In the development of the EDFA Dynamic Gain simulator, a number of assumptions have been made.

- ✓ As the pumping wavelength 980nm and 1480nm can provide a high gain amplification and lower noise. So we assume the EDFA will be pump with either 980nm ad 1480nm.

- ✓ Due to the transient lifetime from excited state to metastable state is short enough. Thus we assume the erbium atom operate in only two levels relevant for the amplification process;

- ✓ The area of the erbium-doped active region is small compared to that of the optical mode at each wavelength of interest. This assumption for the erbium-doped core allows us to treat the overlap factor to be a constant value, independent of energy level and optical power;

- ✓ As the amplified spontaneous emission is randomly generated, thus in the simulator we assume the stimulated ions are propagating in one direction to estimate the average mean ASE noise power; and

- ✓ No reflection occur during the amplification process.

EDFA steady state Gain Modelling assumptions are also made

- ✓ As the pumping wavelength 980nm and 1480nm can provide a high gain amplification and lower noise. So we assume the EDFA is pumped with either 980nm or 1480nm source.

- ✓ Due to the transient lifetime from excited state to metastable state is short. Thus we again assume two levels operation of the dped ions.

- ✓ As excited state absorption only affects the pump absorption along the fiber. Thus it can be neglected.

- ✓ The response of each individual ion in the collection is equally broadened, at a picosecond time scale.

- ✓ Amplified spontaneous emission (ASE) noise is assumed to be small so that it does not saturate the EDFA amplifier.

- ✓ The area of the erbium-doped active region is small compared to that of the optical mode at each wavelength of interest. This assumption for the erbium-doped core

allows the assumption of constant overlapping factor and independent of the energy level.

✓ As in the steady state model, thus the population increment delta N_2 will be assumed to be zero

7.3.4 System Initialisation

To correctly operate the simulator an initialization process is required. Written as an M-file this loads parameters and variables required for the simulator operation. Titled initialization's the user needs to run this file before starting the Simulink simulation. Failing to do so will result in an error warning. It is within the initialization file that the user can modify system parameters. There are several data to be defined in the initialization file, the following table, **Table 4** gives the input data that can be defined before the simulation. **Table 5** gives the glossary for input signals.

Physical Meaning	Symbol defined in Initialize file
Erbium-Doped Fiber Parameters	
Core radius of Erbium-Doped Fiber	r (um)
Overlap factor of EDFA at Wavelength(k)	Gamma
Ion density of Erbium-Doped Fiber	p
Peak absorption on 1530nm	Peak_absorsion
Peak absorption on 980nm	Peak_absorsion_pump
Length of the fiber	L (m)

Table 4 Parameter set for the Erbium-doped fiber

EDFA Input initialize	Symbol defined in Initialize file
Input signal power	Signal_Power (dBm)
input Pump Power	Pump_Power (mW)
Input wavelength	Index
Pump wavelength	pump_wavelength
Number of channel input	N
Pump Modulation Index	mod
Pump Modulation frequency	Mod_freq

Table 5 Input parameter set

The use of the initialization file simplifies operation for users. All variable parameters are contained here and automatically updated in the Simulink platform upon execution (saved in to the MatLab memory called "workspace"). Not incorporating the initialization file would have required the user to input the same variable in multiple blocks increasing errors and complicating the operation of the simulator.

7.4   EDFA Simulator Modelling

The EDFA simulator is combined with various segments as referred in the prototype of *Figure 13*. Each block presents different segment of the EDFA simulator. For example, the input signal stream is represented by a block, which named [Signal Stream]; and each block consist more than one subsystem inside, to check the design inside just by double clicking the block. The EDFA in the Simulink simulation is implemented as those subsystems and they are called from a main program. The following are the input and output ports in the EDFA simulator & EDFA Module:

7.4.1   Using the EDFA Simulator

Input:

Signal Stream - Power of signal (include C- Band & L – Band signal)

Pump source - Power of the Pump (Include pump modulation, 980nm pump source and 1480 pump source)

Output:

All the Output displayer have been put into the block named ### Monitor and you can check the output value by open the open the Monitor block.

- ✓ EDF Parameter (EDF Parameters Monitor) – the parameter of the Erbium-Doped fiber such as radius, ions density etc.)

- ✓ EDFA Gain Monitor – Dynamic Gain and Steady State gain scope. (All the Gain data have been put in order (Ascent)

- ✓ EDFA Dynamic Gain Monitor – Output Signal power, output pump power, Average ASE power, Noise figure, SNR, Other noise power)

Also scopes displays the evolution of the signal. So now, let's explain segment by segment.
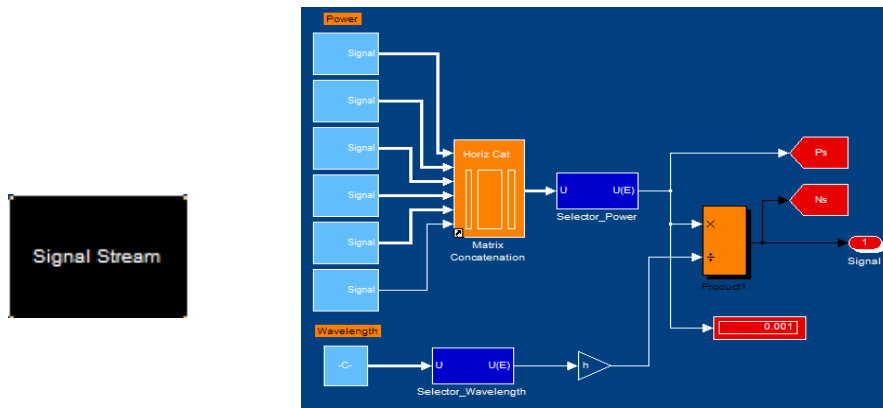
7.4.2   Signal Data Stream Modelling

Figure 16 Signal Stream Prototype

As illustrated in ***Figure 16***, the signal stream basically modelling the C-Band and L-band signal. As we assume the system using 100 GHz spacing (0.8nm), C-band is assumed from 1525nm -1565nm. Thus there are around 51 channels can be used as a carriers over this band. That we can see in ***Figure 16*** there are five signal power block with heavy line except the last. The heavy lines are multi-dimensional vector time series associated with 10 channels each signal block. The wavelength section uses for convert the signal power for Unit (mW) into photons. The input signal power of each channel has been define as a constant mean power.
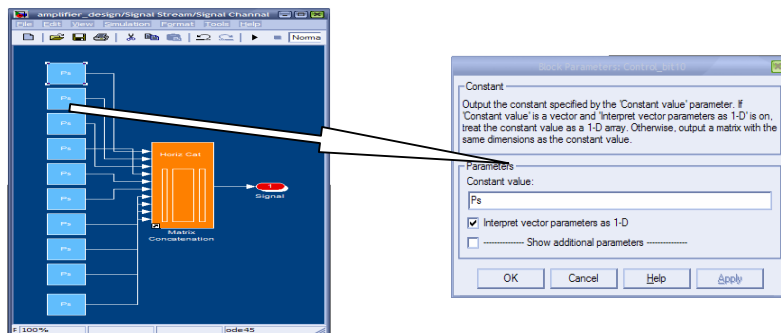
Figure 17 Signal Block Prototype

The value of the mean signal power is defined in file [Simulation_initailise.m]. The signal carrier frequency is ultra-high, around 192.5 THz. If we inject a signal generator with a real 192.5 THz signal (eg. A sinuous wave with 192.5 THz), the Simulink generates the output based on each sampling point of this signal wave; and it may take a long time (maybe more than two days!) to generate output result, which is, naturally very inconvenient. In the other hand, predict the average output power after the amplifier is good enough for the design the amplifier. Therefore an average mean input signal power can be used under our consideration.

Pump power also has been set as a constant mean power for simulation. In the previous section, we have identified that there are three different EDFA configurations: Forwarding Pump, Back warding Pump and Dual Pumping. Only the forwarding pumping is described in this section as the others can follow with ease. The SIMULINK model for the pump source is shown in ***Figure 18***.
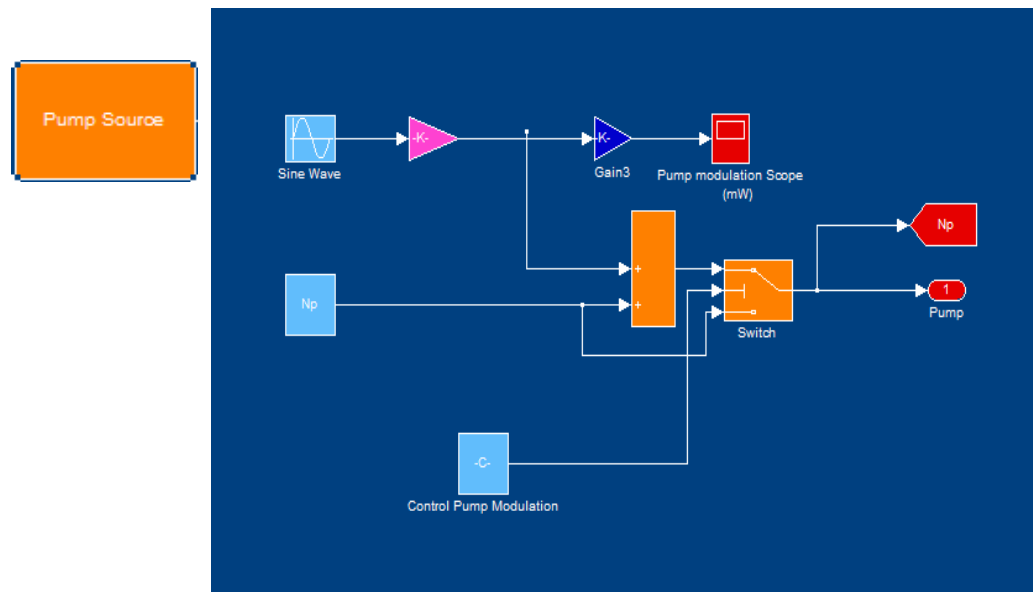

Figure 18 Pump Source Prototype

7.5.1   Pumping Wavelength

As described above there are two wavelengths pumping can give a high amplifier gain, in our simulation the wavelength modeling is implemented within the initialization file. The following is the instruction code for setting the event when different wavelength propagating through the EDFA.

Algorithm:

31

According to the absorption and emission characteristic, the absorption and emission of the fiber will be changed with different wavelength propagating. The absorption factor is normally given by the fiber manufacturer or measured.

7.5.2   Pump Modulation

Pump modulation can be added and its effects on gain modulation can be insvestigated. Freeman and Conradi use a dimensionless number called "modulation index" to measure the power in the modulated signal [2]. Using this definition, the input pump time series has the form $P_p(0,t) = P_p(0) + P_p(0)m_p \cos \omega t$ where $P_p^{0}(0)$ mean the initialise pump power (in Watts), $m_{p \text{ is}}$ the modulation index. As the mean pump power is given here of a constant value, this is added to the term $m_p P_p^{0}(0) \cos wt$ at the summation box, which illustrated in *Figure 19*.
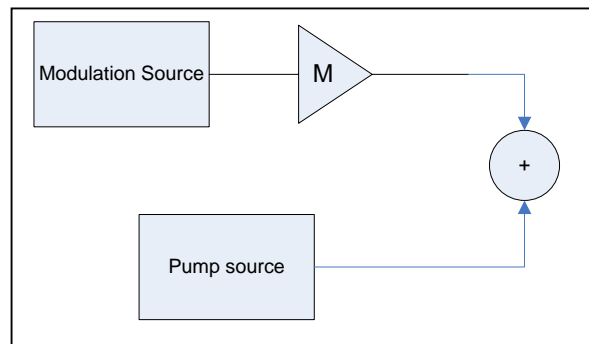
Figure 19 Pump Modulation module.

$P_p(0)m_p \cos \omega t$ is the output of the sine wave generator in *Figure 19*. The gain labelled with [-M-] is the modulation index m_p. N_p is the constant mean pump power; here the unit of the pump power is in photons/sec. The method for converting Watts to Photons/sec was listed in previous section.

7.5.3   EDF Modelling

We have described the theoretical EDF modelling. This section gives the Simulink simulation model design. The Simulink simulation models are based on the rate euetions given in Section 2. The characteristic of the EDF depends on two factors: EDFA gain characteristic and ASE noise characteristic. The gain characteristic will depends on the absorption and emission factor for different wavelength. Due to the fact that, different erbium-doped fiber provides different Absorption and emission characteristic, therefore, simulate the Absorption and emission spectrum would be our first step.

The existing absorption spectrum given in [16],[2],[6] and [7] can be used. The absorption spectrum can be illustrated in *Figure 20*.
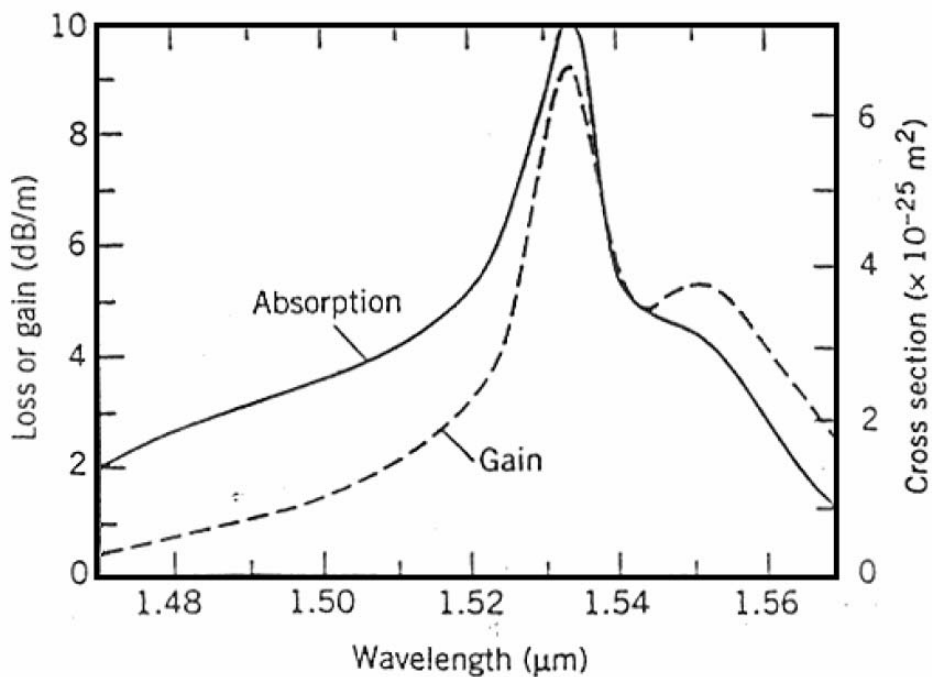
Figure 20 Absorption and Emission Spectrum taken from ref [4.

Although all the data from those references are different, yet the slopes of those spectrums are quite similar. According to this assumption, take normalize will be the first choose to simulate the spectrum. The following is the normalize spectrum simulation.
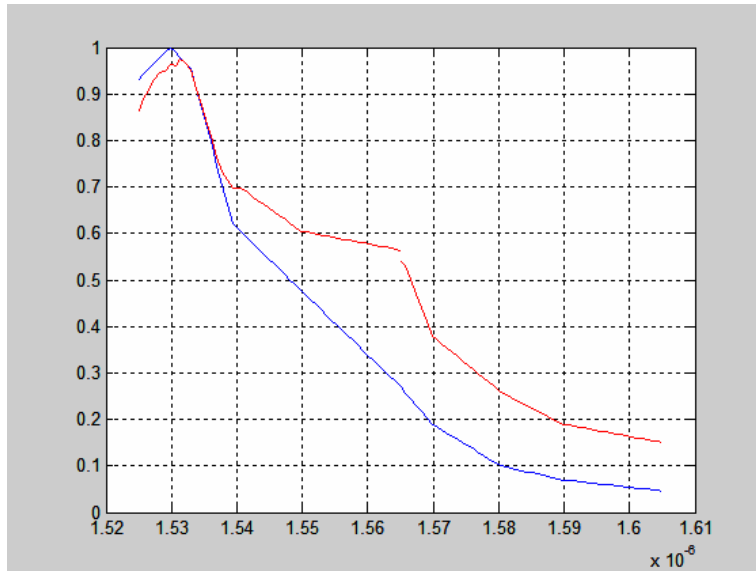
Figure 21 The absorption and emission factor Normalize spectrum (C-band & L- band)

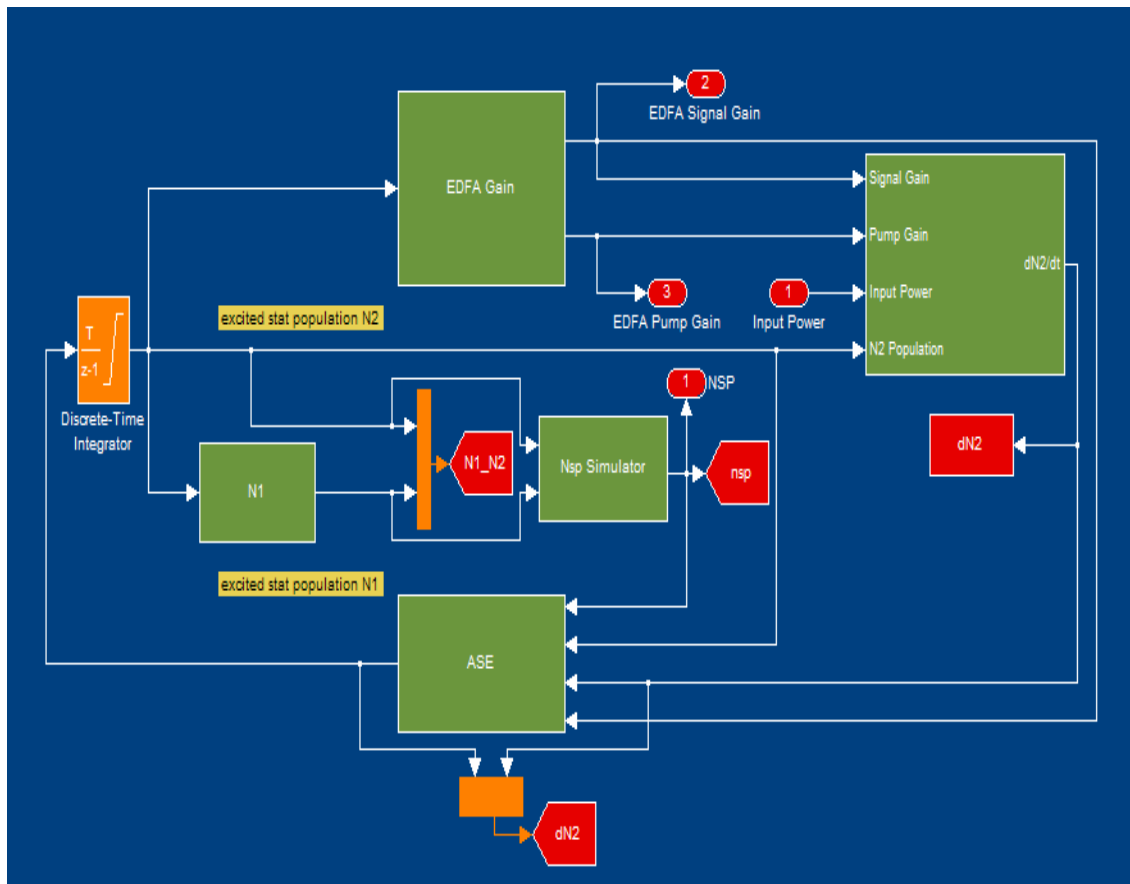The EDF simulation can be start after this spectrum. **Figure 22** illustrates the prototype of EDF simulation.

Figure 22 EDF Simulation Prototype

7.5.4 EDFAs Dynamic Gain Model

The equations for solving the dynamic gain model have been described in the above section. This section will describe how all the block gathering. As we mention in Section 4, the gain the EDFA is base on the equations $G_p = \dfrac{\Gamma_p(\sigma_{1-3} + \sigma_{3-1})}{A} N_2 - \Gamma_p \sigma_{1-3} \rho L - \gamma_p G_p$ and

$G_s = \dfrac{\Gamma_s(\sigma_{1-2} + \sigma_{2-1})}{A} N_2 - \Gamma_s \sigma_{1-2} \rho L - \gamma_s G_s$. In our simulation the Simulink Model representing these expressions are given in *Figure 23*.
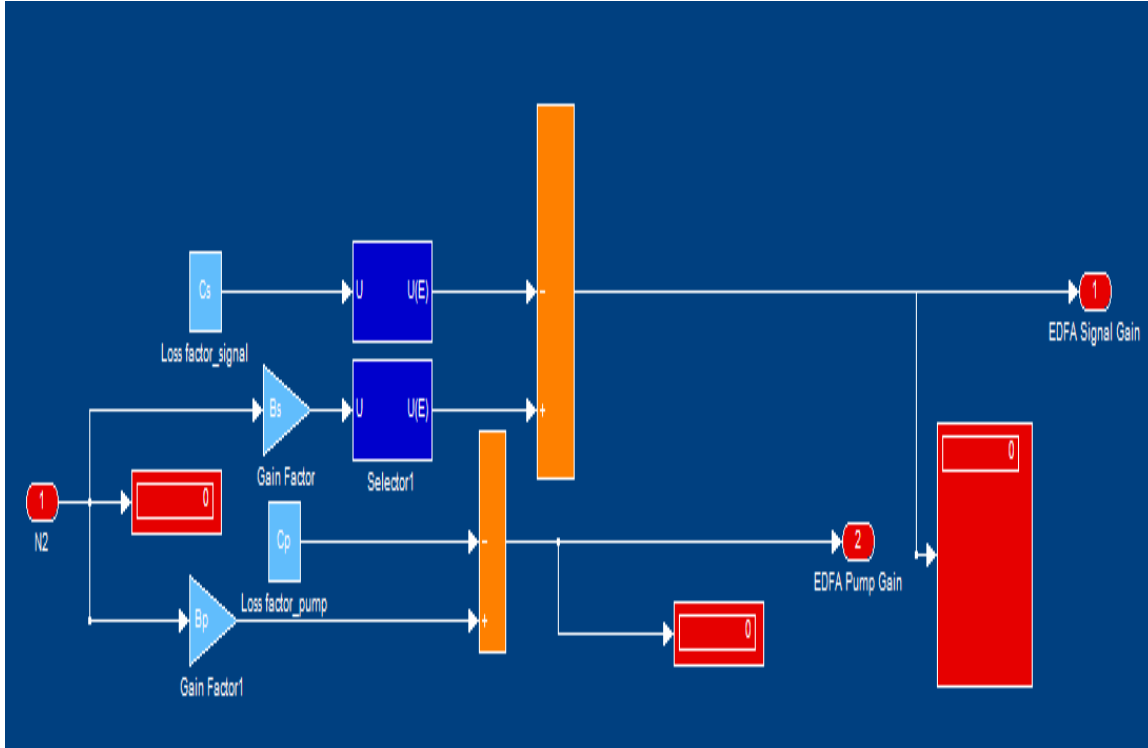
Figure 23 EDFAs Dynamic Gain Modelling corresponding to Figure 22.

In *Figure 23*, B_s and B_p will be the matrix of $\dfrac{\Gamma(\sigma + \sigma)}{A}$, and C_s and C_p will the matrix of $\Gamma \sigma \rho L - \gamma G$. Due the characteristic of the absorption and emission, different wavelength signal propagating through the EDF would cause the change of the absorption and emission factor. So C_s and B_s is an memory that store all the absorption and emission value, the following selector is an artificial intelligent block which can selector the corespondent value for matching the wavelength. Selector block work by outputting with a selected reference index form the B_s matrix, like $[Bs_1 \quad Bs_2 \quad Bs_3 \quad \cdots \quad Bs_{51}]$ Selected [index 1] => Output – B_{s1} . Accordingly the absorption and emission factor changes in different wavelength.
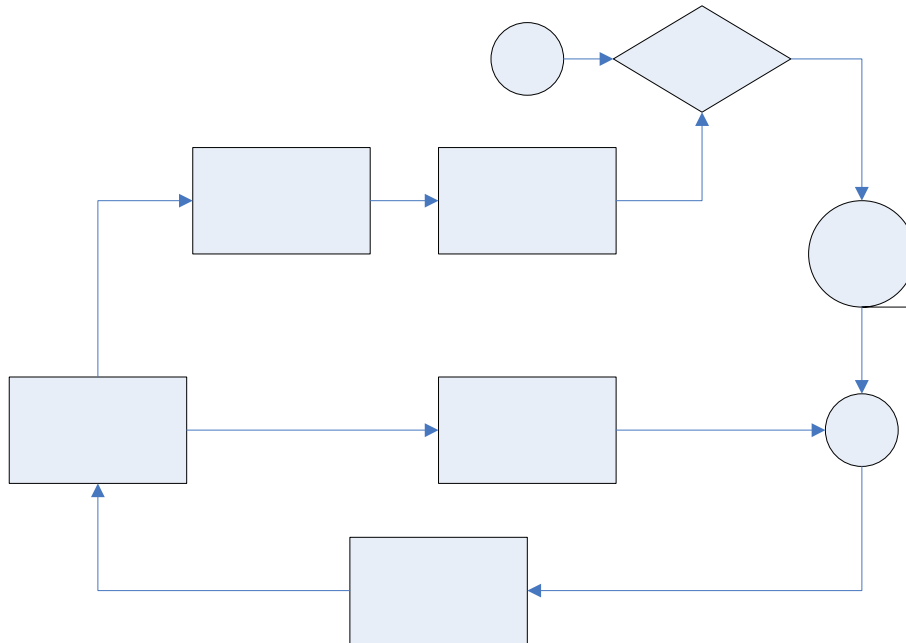
Figure 24 dN₂ / dt simulation block diagram

AS shown in the block diagram of ***Figure 24***, the loop continues the execution til the difference of the input power and output power is the same as that of N_2/τ, that means N_2 is saturated. Thus the gain remains in the steady state. The data inside the discrete time integrator block is setting the step time for each increment; here we set 3.25e-7 as the sampling step. The output of the model is given in ***Figure 25***
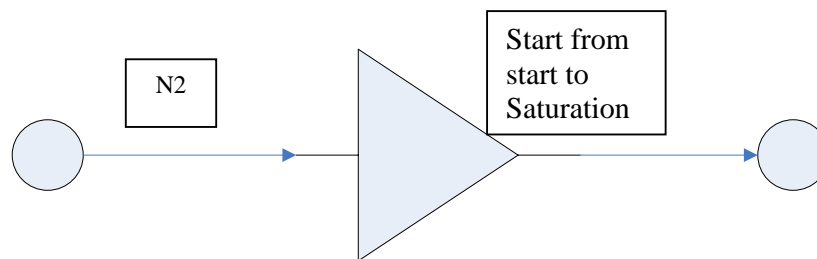

Figure 25 Output algorithm

Discrete Time
Integration

7.5.5 EDFAs steady state Gain Model

In steady state, d N_2 / dt = 0, the Simulink Model can be illustrated as in **Figure 26**.
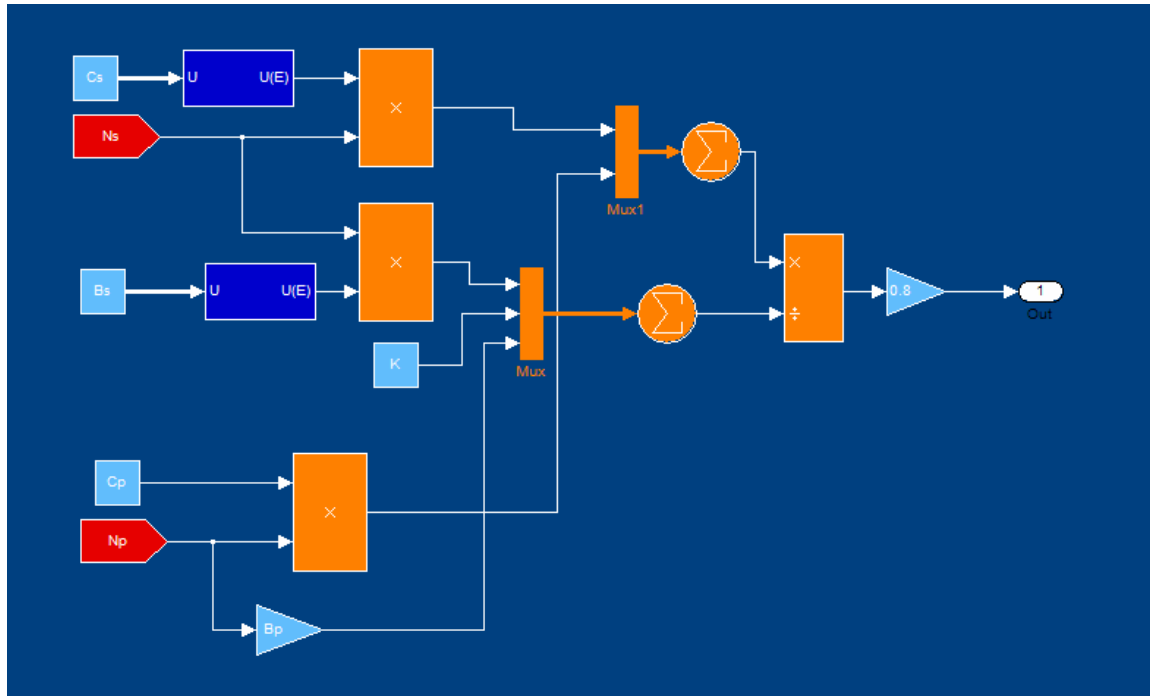
Figure 26 EDFA Steady State N_2 Model.

The signal gain here is equal to B_s * N_2 (Saturate) – C_s, the pump Gain here is equal to B_p * N_2 (Saturate) – $C_{p\ the}$ Simulink development is similar to EDFA Dynamic model. The output would be the same as given in **Figure 25**.

7.5.6 *Population inversion factor Modelling*

- N_1 simulation.

    Recalling the three state populations, and the assumption of N_3 to be zero. The relation between N_1 and N_2 is then $N_1 = N_{total} – N_2$.
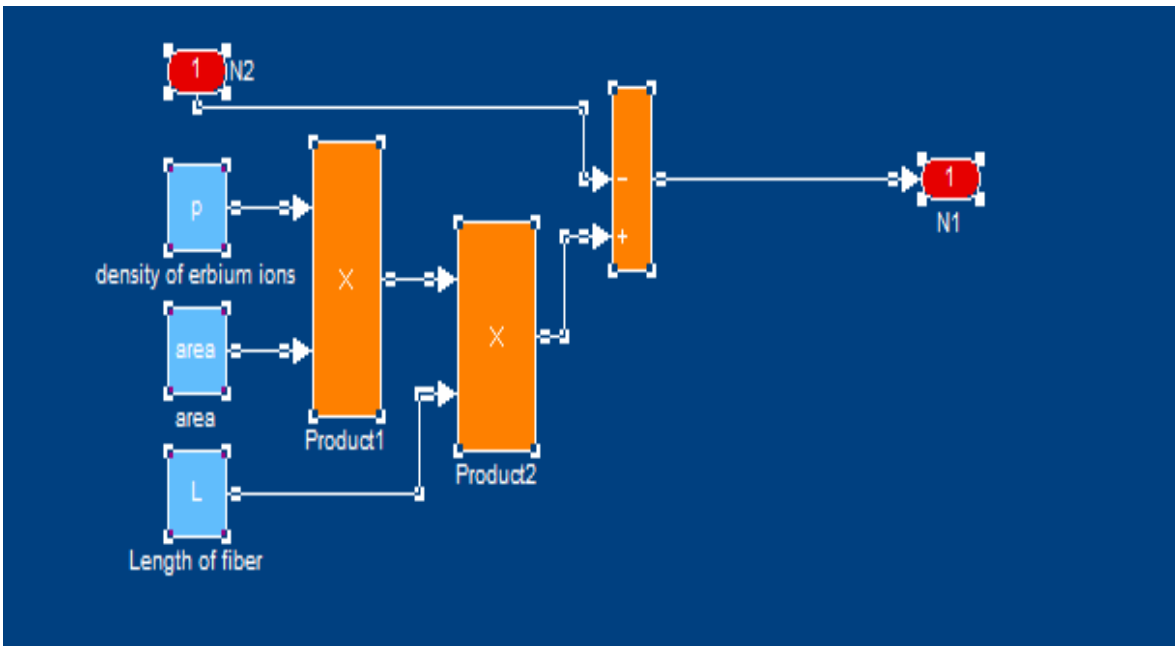
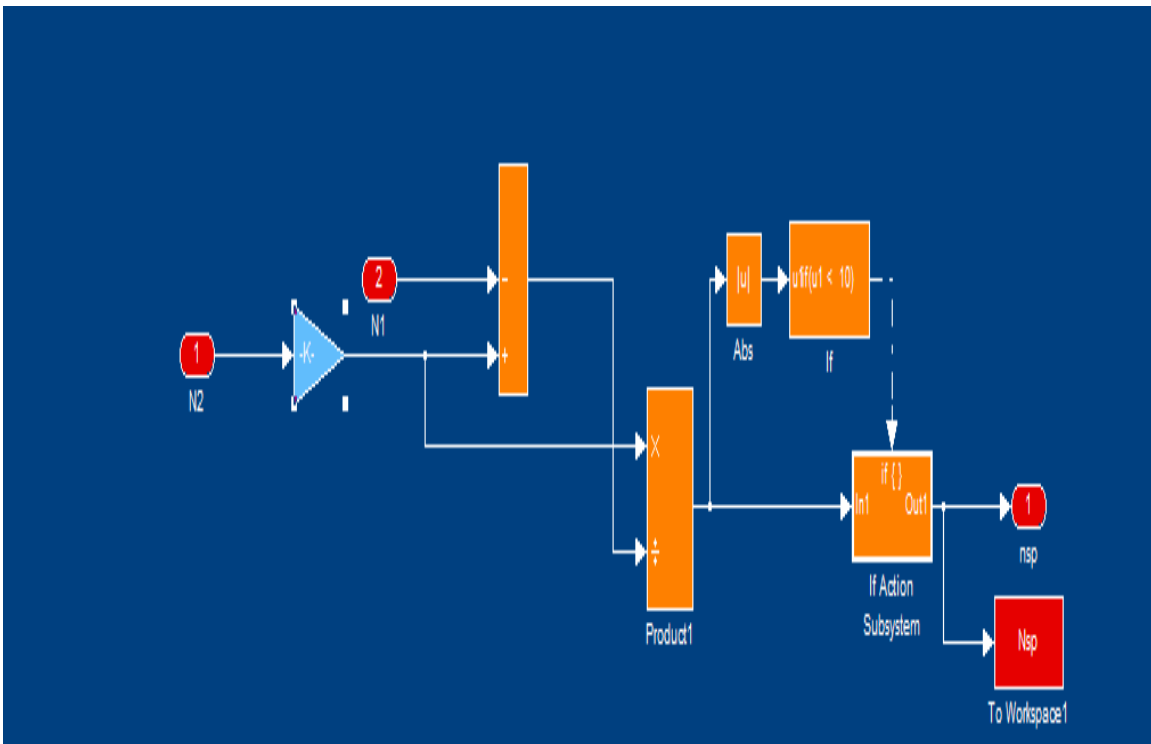*Figure 27 Representation of N_1 in the Simulator*

- N_{sp} simulation

Figure 28 Representation of n_{sp} in the simulator

According to the population inversion factor equation, N_1 would equal to N_2. This would lead the result approaching infinite. Therefore the [if statement] could make the result limited under 10. Also the population inversion factor would greater than 10 in practice.

7.5.7 Amplifier noise Modelling

In the previous section we have mentioned the method for simulate the amplification noise. Therefore, to simulate the ASE noise, determine the average mean ASE power will the first action. For the dynamic gain modelling in Simulink, the process derived into three section time:

Figure 29 Amplification population in sequential process

Thus calculation for determining the ASE is conducted in three different statements. In the simulation, the following is the algorithm for simulate the ASE mean power.

$G < 1$

$G = 1$

$G > 1$
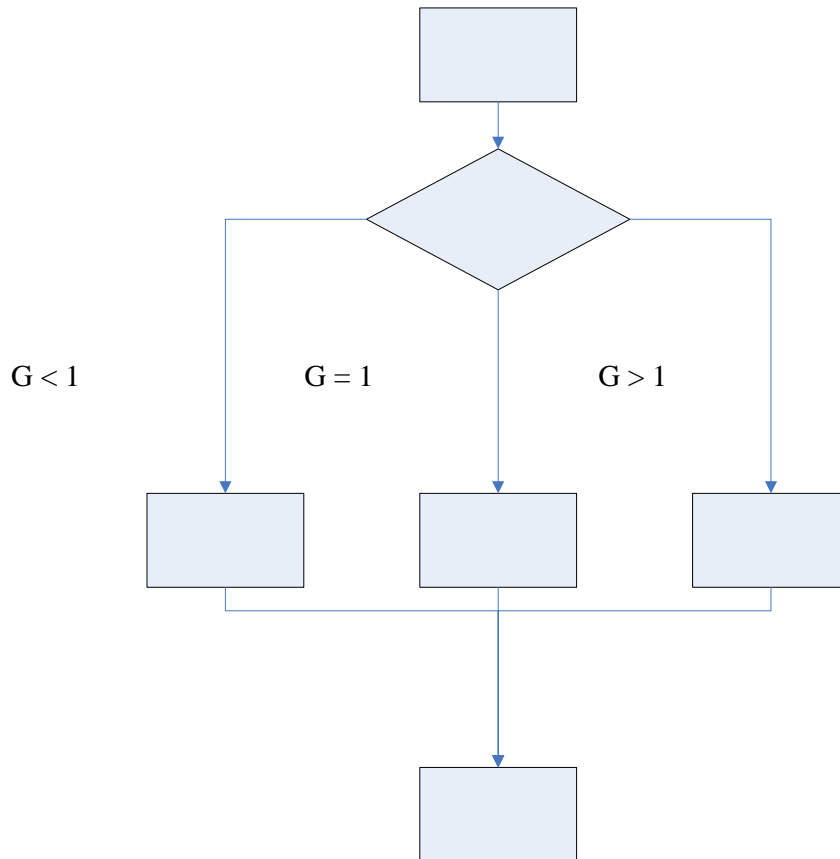
N2 <

Figure 30 Modeling flow chart for the ASE noise power.

After the determination of the ASE mean power, the Gaussian assumption of the ASE mean power is used and set the variance to model the ASE power and the number of randomly generated photons as shown in *Figure 31* and *Figure 32*.
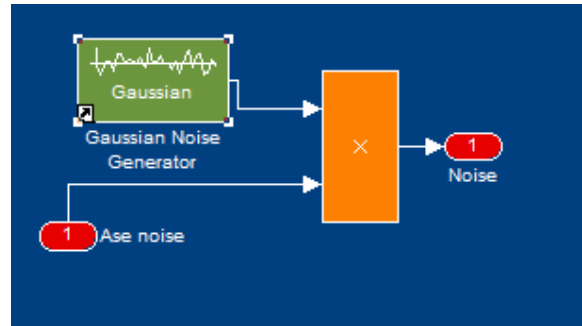
Figure 31 ASE Model.

8 **Simulink EDFA Simulator: Execution procedures**

The simulator consists of three major parts, the initialization file [EDFA_initialisation.m], EDFA Simulator [EDFA_simulator.mdl] and EDFA Module [EDFA_module.mdl].

Steps for executing a simulation:

1. Access MatLab 7.0 R14 or any latest version. Open the initialization file from its stored disk, using file, then open, as per normal.

2. The step upon brings the MatLab coded initialization file on screen. Refer to the appendices for a hard copy of this file. This file allows the user to define all variables pertaining to the optical simulator. The user is free to modify any value within this file. The file has been commented so as to instruct the user and future designers of the simulators operation.

3. To run a simulation, enter the required parameter values, then from the debug menu select save and run. This will run the file and load the relevant values into both the MatLab workspace and the Simulink simulator. The simulator should also open in the Simulink workspace. To analyze the initialized system, simply open the Input Monitor block and EDF Parameter, the initialize input will presenting there.

4. To inspect the result of EDFA simulator, double click the Output Monitor block or either opens the Scope for see the dynamic evolution. Indeed, all results are saved in to the workspace for further investigation.

5. To inspect the results of the EDFA Module, scopes are popped up automatically, if not, just doodle click the scope.

Notes: as EDFA module can combine with other simulation block, thence the input data stream can be replaced by any other device simulator block. To increase the execution time,

the run type in [normal mode], [accelerating mode],[from outside] in the option menu can be changed.

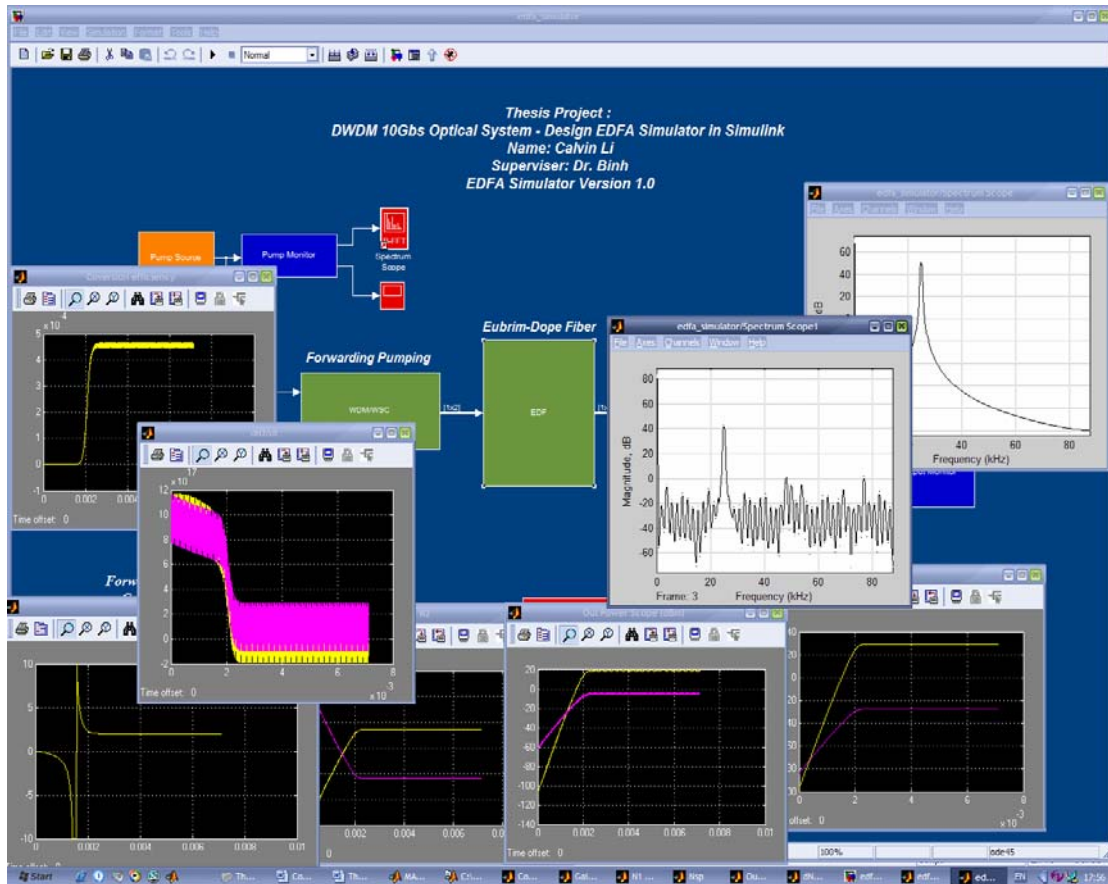Typical simulator screen shots of the SIMULINK EDFA simulator are given in *Figure 32* and Figure 33.

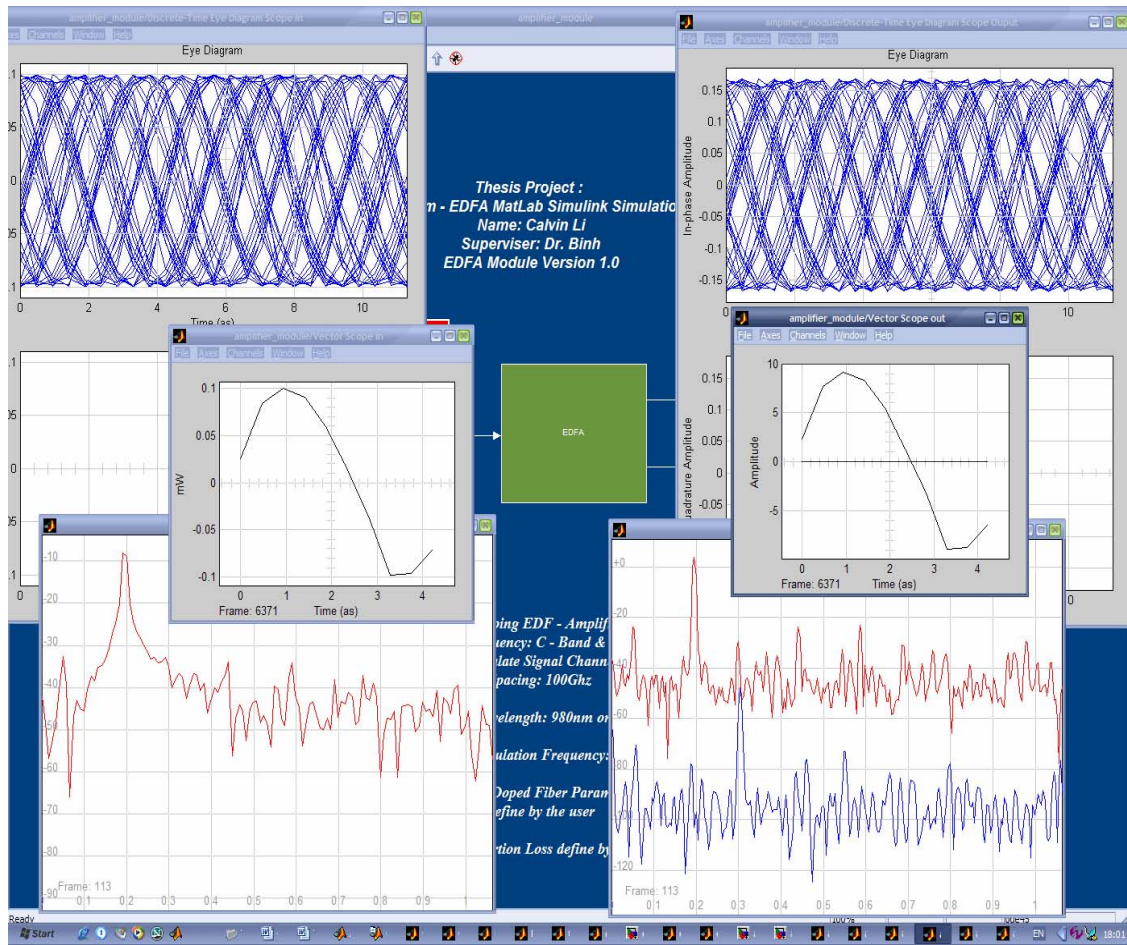*Figure 32: Samples of the screen shots of the EDFA Simulator*

Figure 33 *Samples of the screen shot of the EDFA Simulator*

The simulated results are based on practical EDFA parameters constructed in our laboratory and some commercial amplifiers operating in the C-band. Table 4 gives a set of the parameters employed in the simulator and the power generated at the output of the EDFA is plotted verus the input signal power with the wavelength of the input channel as a parameter is given in *Figure 34* . The saturation is on set at around -14 dBm as expected.

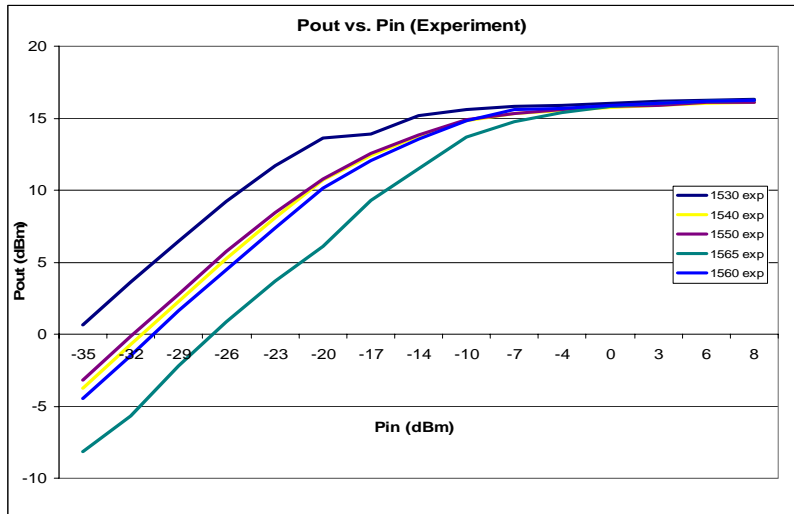| Single Channel	C-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Pump Power(mW)	195	Peak Absorption:	6.09 dB/m	at 1530 nm
Without Gain Modulation			5.24 dB/m	at 979 nm

Table 6 *EDFA Simulator parameters.*

Figure 34 (a) Experimental results: EDFA output power versus input power level with channel wavelength as a parameter.
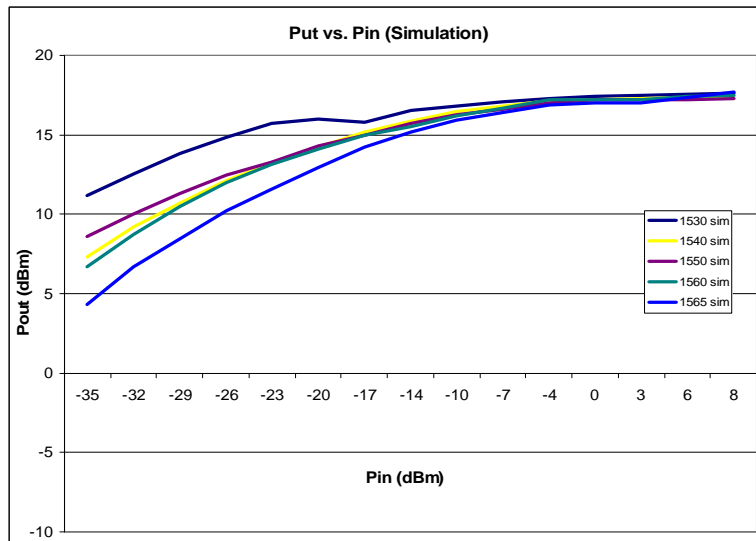

Figure 34(b) Simulation Results: EDFA output power is plotted against the input signal level with the input channel wavelength as a parameter.
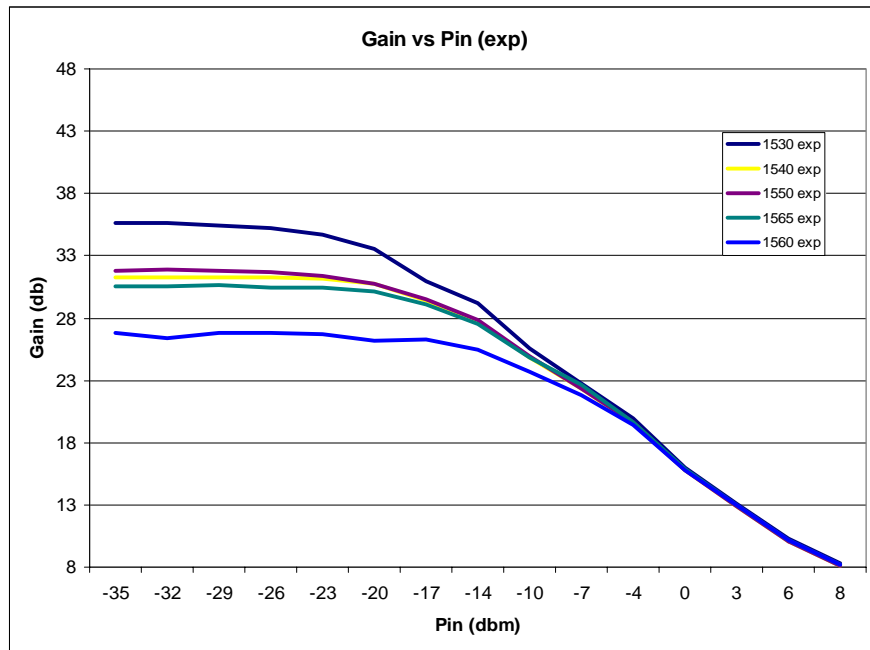
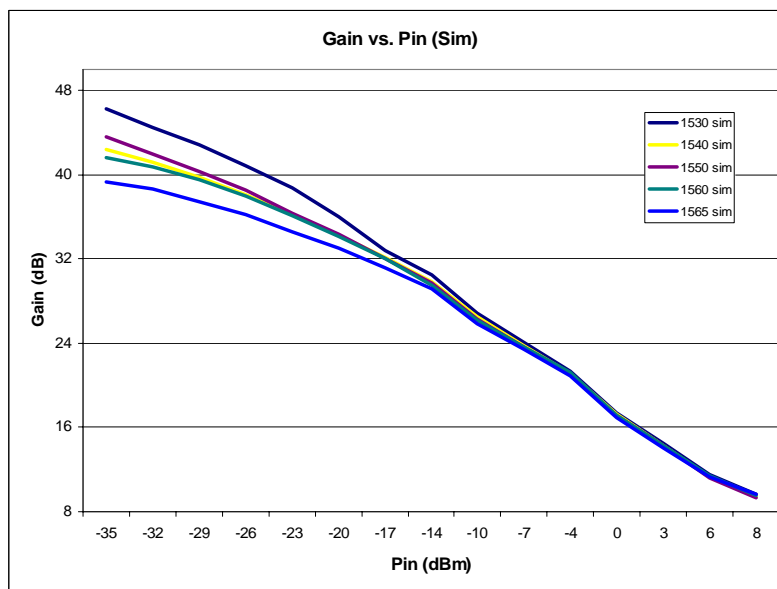*Figure 35 (a) Experimental results of the amplification gain.*

Figure 35(b) Simulation Result of amplification gain

The EDFA gain obtained from the simulation agrees with those of the experiment, the only discrepancy is during low signal input power, this might due the internal setting of the commercial device, which is unknown, all the other factors such as the absorption and emission spectrum in the commercial EDFA may be slightly different from the simulator.
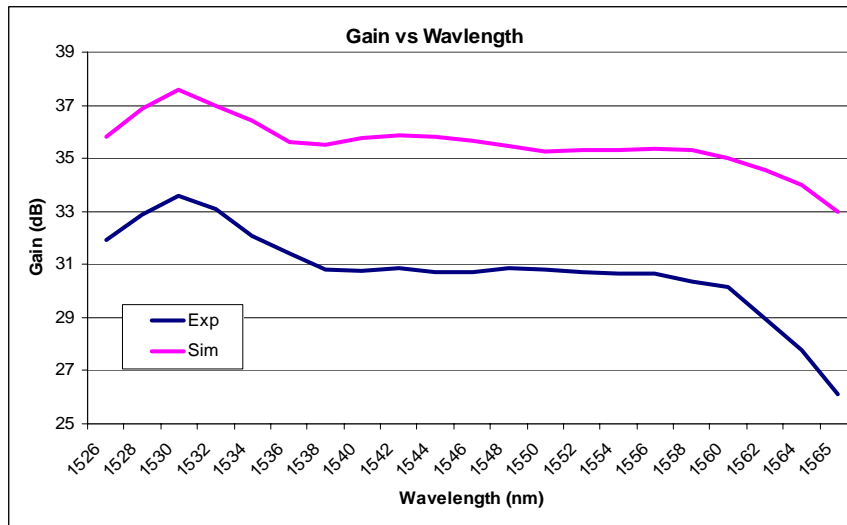
Table 7 EDFA Simulator Parameters

Single Channel	C-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		

| EDF length(m) | 16 | Cut off Wavelength | 940nm | |
| Pump Power(mW) | 195 | Peak Absorption: | 6.09 dB/m | at 1530 nm |
| Signal Input Power (dBm) | -20 | | 5.24 dB/m | at 979 nm |
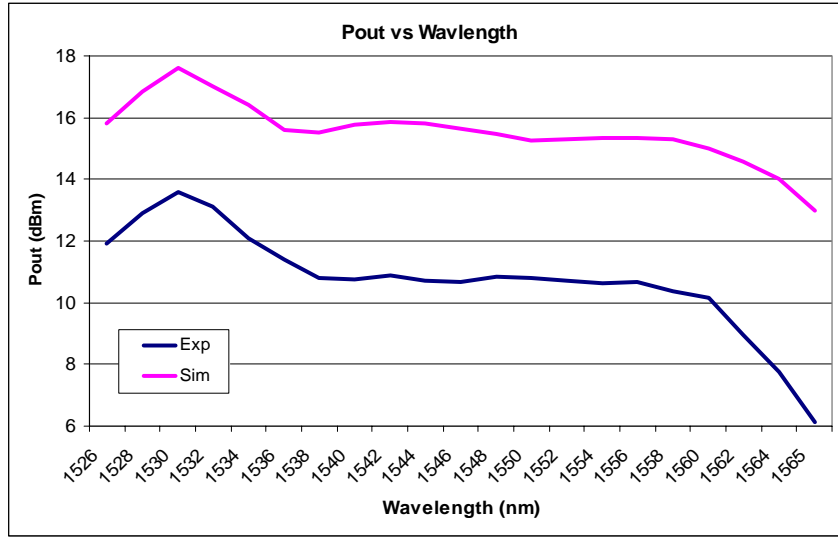
(a)

(b)

Figure 36 Spectral propertes of (a) Output signal power (b) EDFA Gain

The spectral gain is dependent on the stimulation emission factor. As the population inversion rate changes with the signal wavelength, the gain is peaked at 1528 nm.

Table 8 EDFA Simulator testing Parameter

| Single Channel	C-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Signal Wavelength	1565	Peak Absorption:	6.09 dB/m	at 1530 nm
Signal Input Power (dBm)	-20		5.24 dB/m	at 979 nm
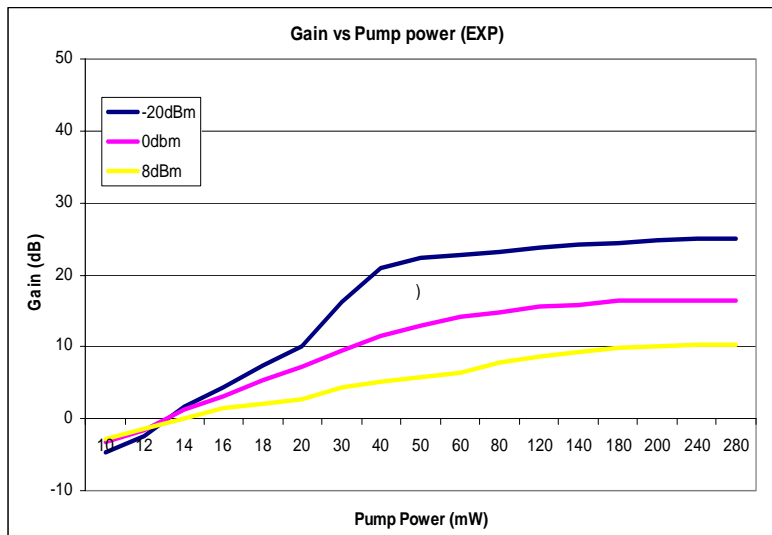
(a)
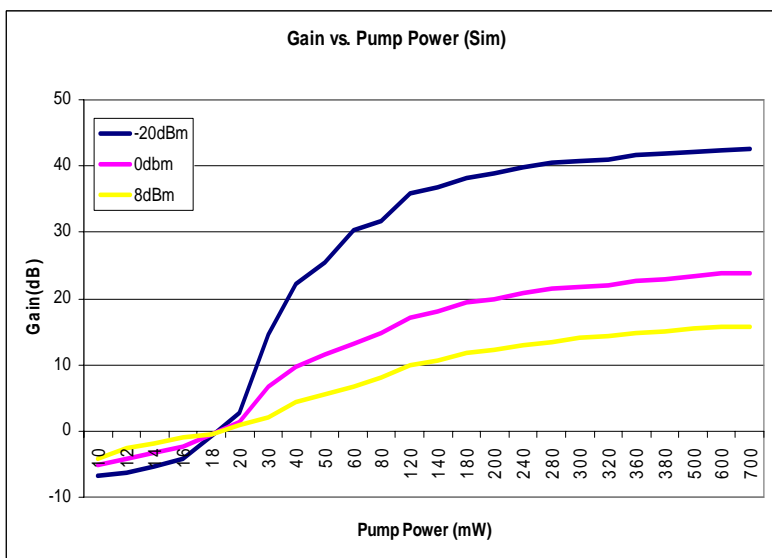
(b)

Figure 37 Pump power plotted against the amplification gain with the signal power as a parameter (a) and (b).

Gain does not increase infinitely with the increasing pump power, as the ions density in erbium-doped fiber is constant. Thus the pump power pump just produces the energy pumping ions to the higher energy state. Thus if all the ions have been pumped to the high state, then even more pump power, the number of simulated photons still remain the same, hence the gain saturation as illustrated.
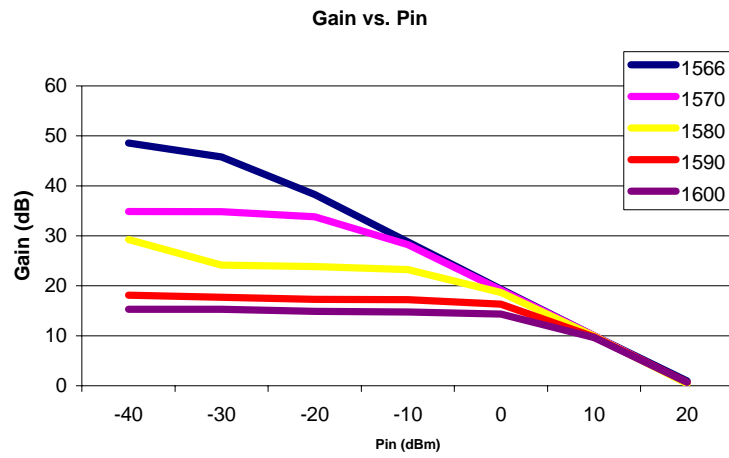
8.1 Amplification in the L-band

Table 9 EDFA Simulator testing Parameter

Signal Channel	L-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Pump Power(mW)	195(22.9dBm)	Peak Absorption:	6.09 dB/m	at 1530 nm
Without Gain Modulation			5.24 dB/m	at 979 nm
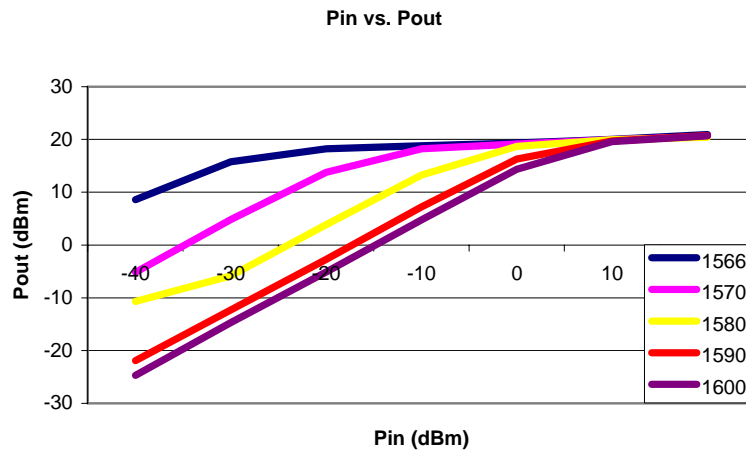
(a)

(b)

Figure 38 EDFA gain versus input signal power level for L-band (a) output power versus input level (b) gain against input power level.

We can compare the L-Band signal with the C-band signal and tabulated as shown in **Table 10** and the gain is plotted over the C- and L-bands *as in Figure 39.*

Table 10

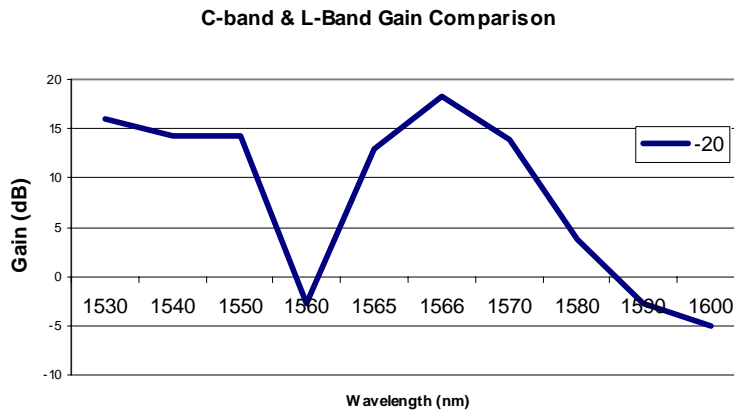| Signal level/wavelength	1530	1540	1550	1560	1565
-20	16.01	14.22	14.3	-2.709	12.97
	1566	1570	1580	1590	1600
-20	18.24	13.8	3.838	-2.709	-5.115

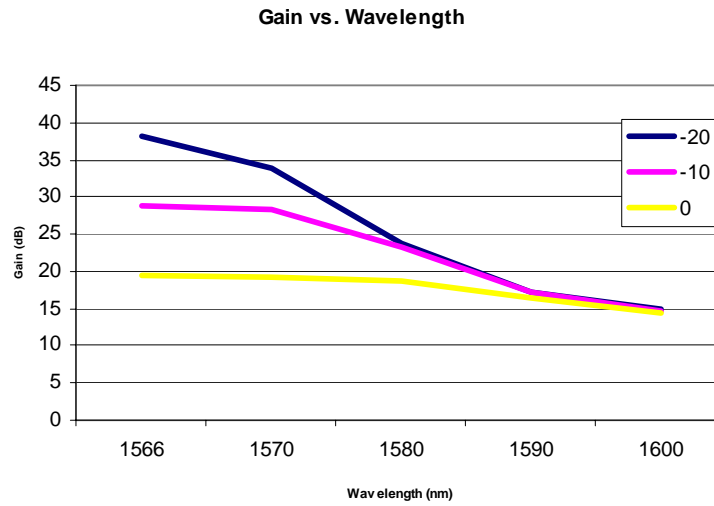*Figure 39 EDFA gain spectrum*

Gain vs. Wavelength

Figure 40 L-band gain spectrum

The pump power is varied and the EDFA gain in the L-band is plotted in **Figure 40** with the parameters of the amplifier are given in *Table 11*.

Table 11 EDFA Simulator testing Parameter

Single Channel	C-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Signal Wavelength	1565	Peak Absorption:	6.09 dB/m	at 1530 nm
Signal Input Power (dBm)	-20		5.24 dB/m	at 979 nm

Operating Wavelength = 1565nm
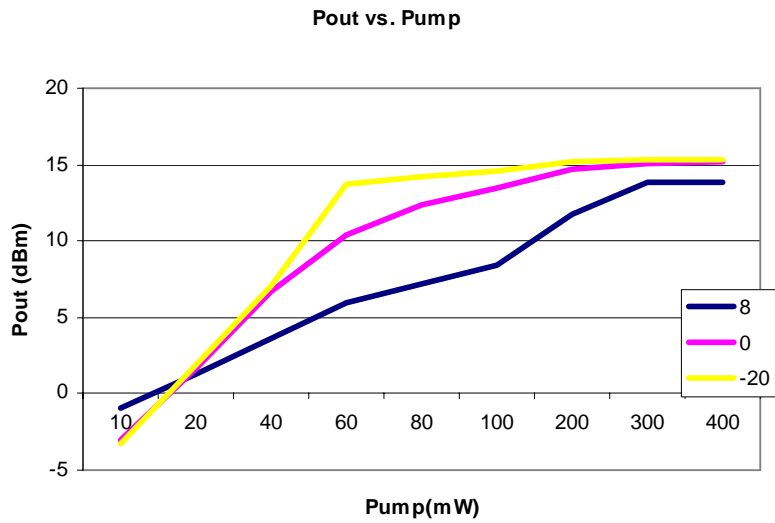
Pout vs. Pump

Figure 41 Output power of the EDFA as a function of the pump power with input power level as a parameter.
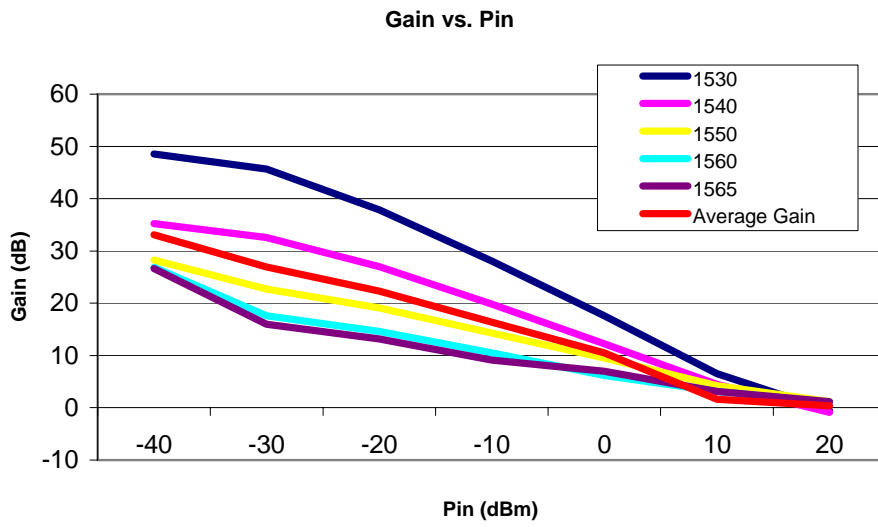
8.1.1 Multi-channel operation of EDFA
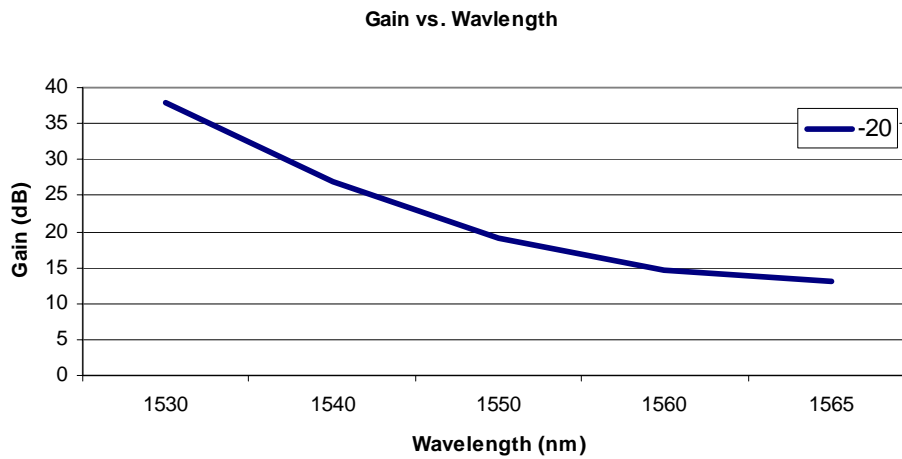
Table 12 EDFA Simulator testing Parameters for results of **Figure 42**.

Multi-Channel	C-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Pump Power(mW)	195	Peak Absorption:	6.09 dB/m	at 1530 nm
Without Gain Modulation			5.24 dB/m	at 979 nm

Pout vs. Pin

a)

Gain vs. Pin


(b)

Gain vs. Wavlength
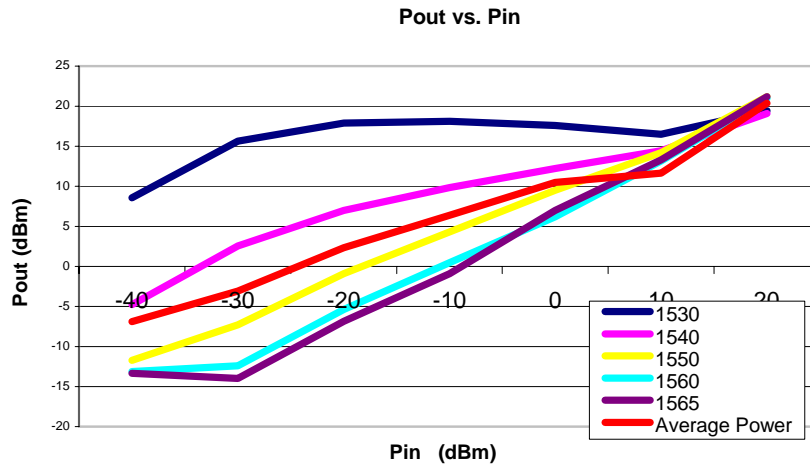
(c)

Figure 42 EDFA characteristics (a) Output power as a function of input signal power level for different channel wavelengths (b) gain variation as a function of input level and (c) gain spectra.

8.1.2   ASE measurement

Table 13 EDFA Simulator parameters for the ASE simulation results of Figure 43

Signal Channel	C-Band	EDF Parameter		
Pump Wavelength(nm)	980	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Pump Power(mW)	195(22.9dBm)	Peak Absorption:	6.09 dB/m at 1530 nm	
Without Gain Modulation			5.24 dB/m at 979 nm	
Signal Power(dBm)	-20			
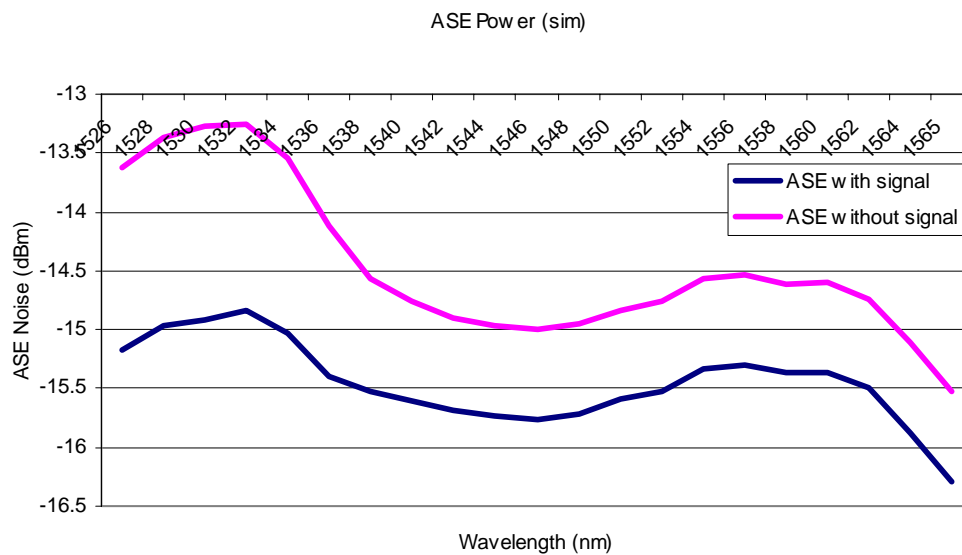
(a)

ASE Effect on Gain Saturation
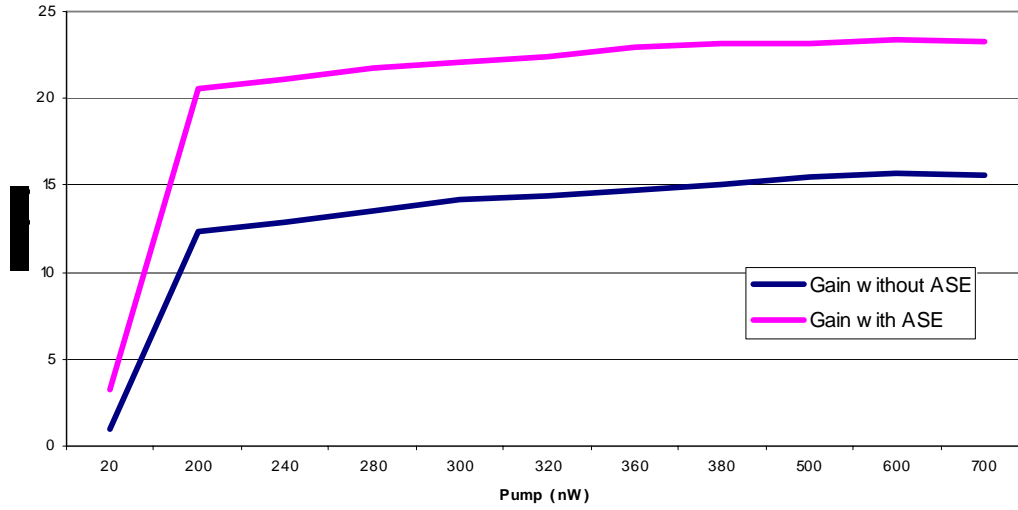
(b)

Figure 43 ASE noise (a) spectral property and (b) as a function of pump power.

8.1.3   Pump Wavelength Testing

Table 14 EDFA Simulator testing parameters used for Figure 44

Result of EDFA Amplifier		EDF Parameter		
Pump Wavelength(nm)	1480	MFD = 5.9um at 1550nm		
EDF length(m)	16	Cut off Wavelength	940nm	
Pump Power(mW)	195	Peak Absorption:	6.09 dB/m	at 1530 nm
Signal Input Power (dBm)	-20		5.24 dB/m	at 979 nm

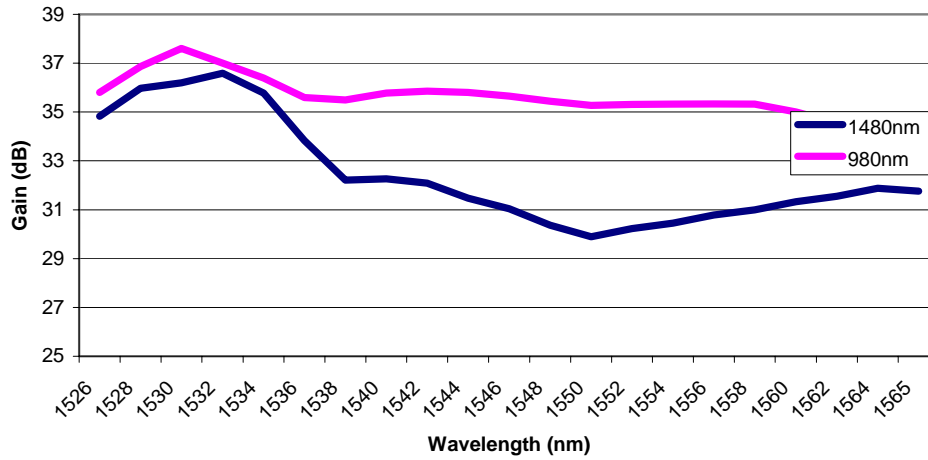**1480nm pump uv. 980nm pump (Simulation)**

Figure 44 EDFA gain variation with pumps at 980nm and 1480 nm.

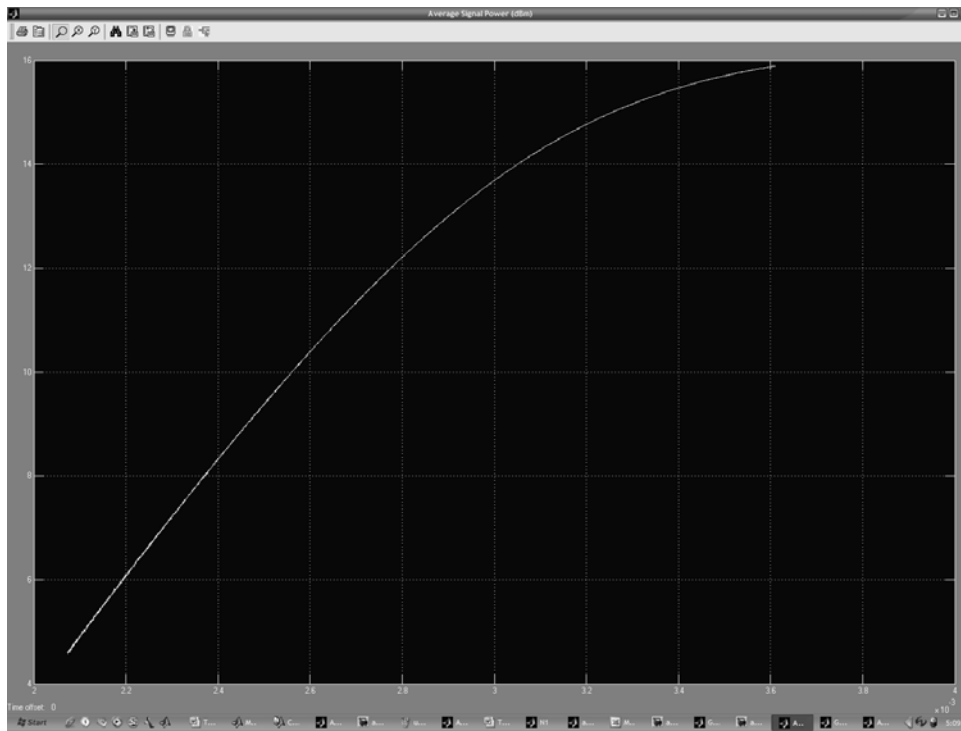### 8.1.4 Gain Pump Modulation Effect

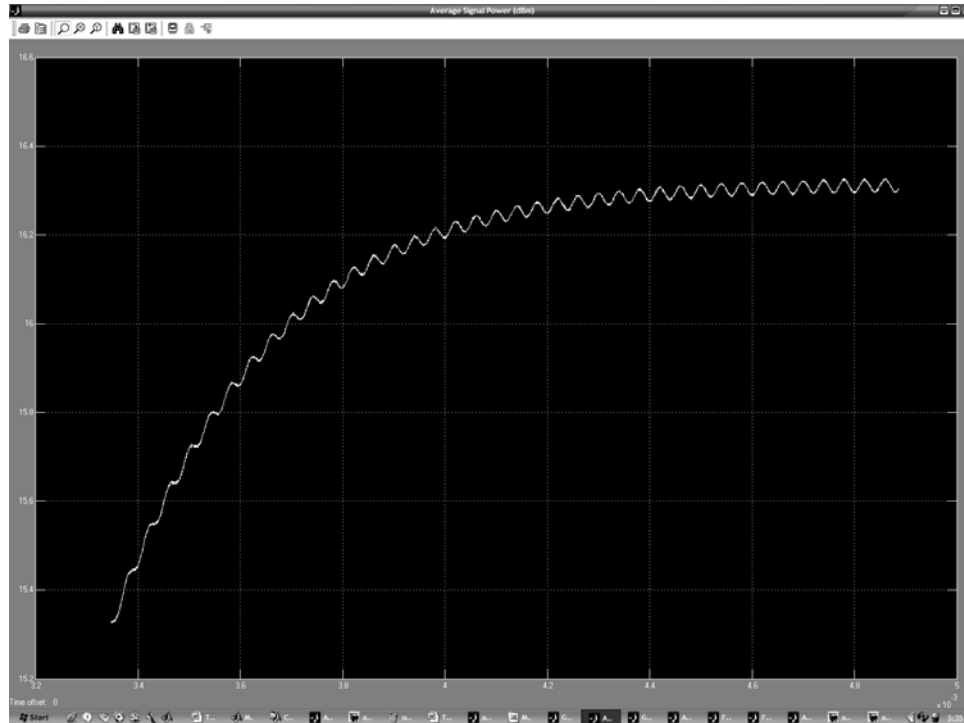*Figure 45 Output signal withoutpPump source modulation (Time dependent)*

Figure 46 Output signal with pump source modulation (Time dependent)

9   Samples of the SIMULINK simulator

This section shows the output scopes observed from the Simulink simulator. They can be decided into two sub sections: EDFA simulation scoping and EDFA module scoping. Here we demonstrate the operation of the Simulink EDFA simulator as an example incorporating simulatedl results. This provides the user with an example to follow when using the simulator. The example assumes the system parameters defined in the initialization file. Those parameters are loaded using the run command in the debug menu. This allows the loading in the MatLab platform the initialization of the simulation values.
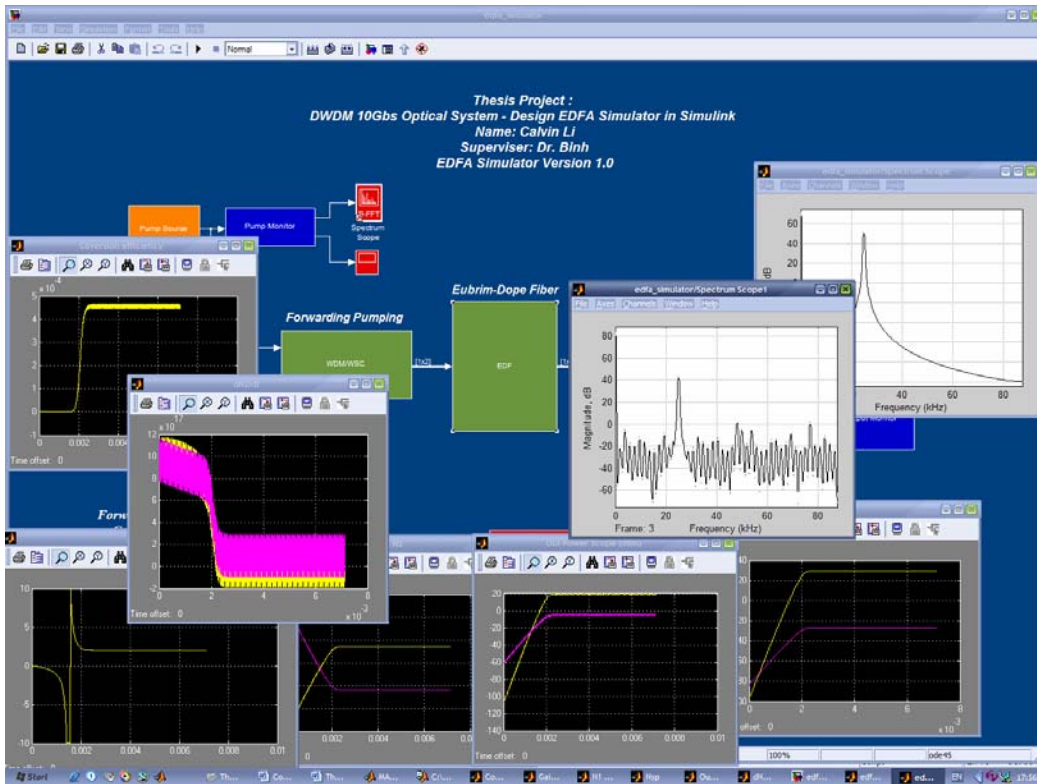
9.1 The EDFA Simulator

Figure 47 Sample screen shot on EDFA Simulator
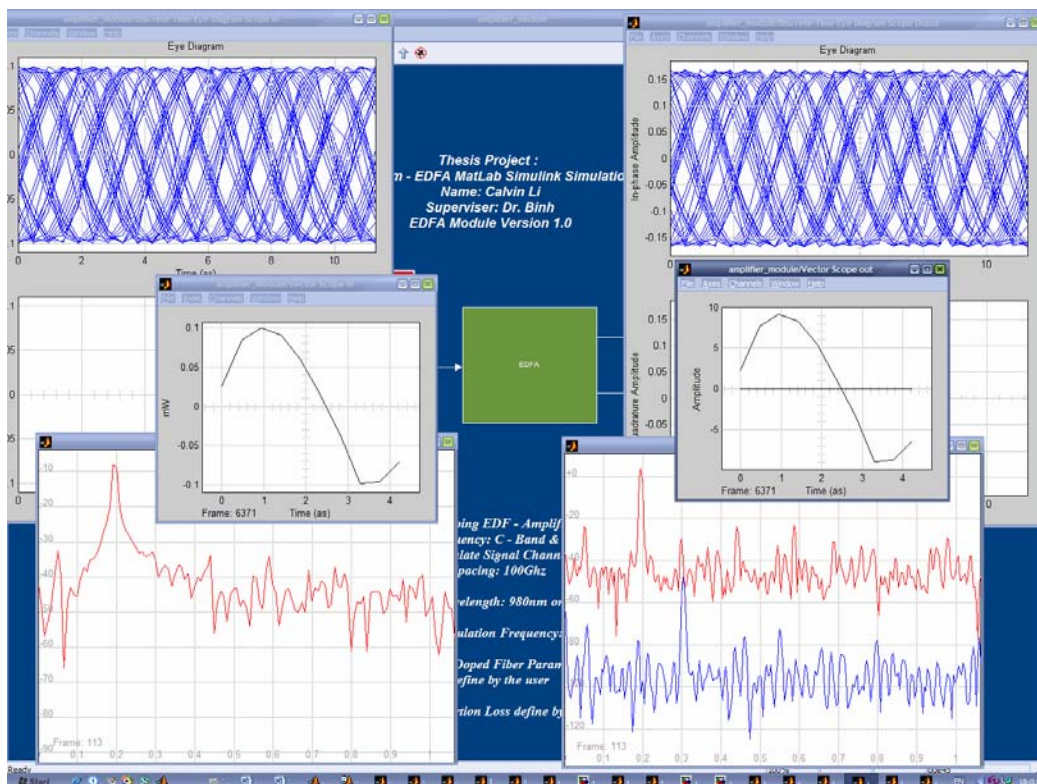
9.2 EDFA simulator Inspection Scopes

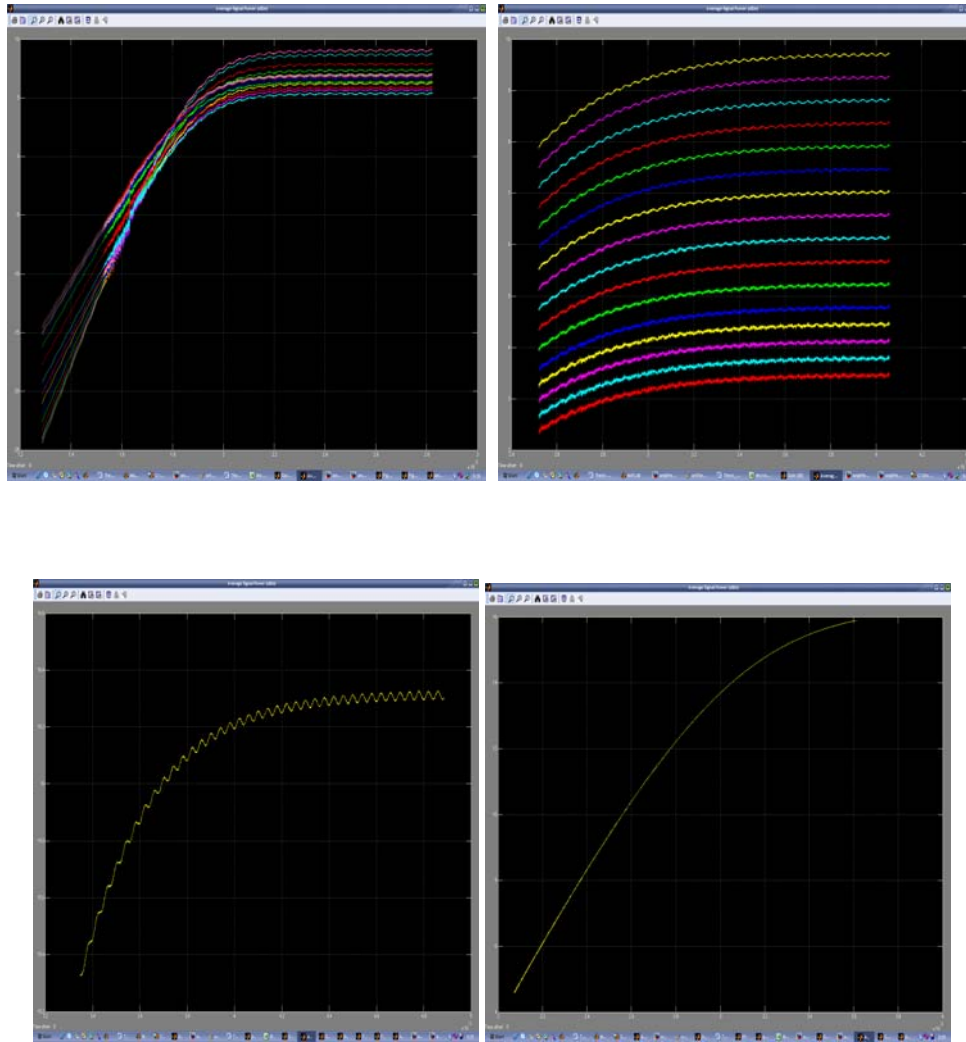*Figure 48: Sample screen shot on EDFA Simulator*

Figure 49

10   Concluding remarks

This report demonstrates the successful implementation of the modeling of the EDFA operating under the dynamic and steady states using MATLAB SIMULINK. The model has been used to investigate the characteristic of the Erbium-Doped fiber amplifiers over the C- and L-band spectral regions. Predicted results by varying the parameter settings are shown to be in good agreement with those obtained from experiments. The Matlab Simulink toolboxes for simulating the dynamic system offer significant advantages of being well known and its availability in worldwide teaching and research laboratories. Multiple wavelength signal propagation and ASE noise simulations have been taken into account in our EDFA SIMULATOR. Although we demonstrate only the Simulink [EDFA Module] using wavelength one for pump and one for signal, it is straightforward to modify the simulation to achieve the multiple-channel propagation as [EDFA Simulator]. The only limitation is the computer memory and the CPU runtime. Cascaded EDFAs system can also be connected

and the effects of propagation loss and noise in such systems can be modeled with ease. The gain modulation of the EDFA has not been discussed and will reported in a future article.

Primarily a powerful simulator of modern optical amplifiers module and their various components has been established. Future works will aim to incorporate a number of optimization components into the EDFA simulator, thence further enhancing the uses of the simulator. Multiple-channel propagation simulation in EDFA Module are also incorporated. The developed EDFA SIMULATOR and the EDFA Modules will provide the framework for near future development of the Raman amplifier simulation development using MATLAB Simulink.

11   References

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