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The 8-channel Dynamic Channel Equalizer and its adaptation as a "Smart Amplifier Solution"

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**The 8-channel Dynamic Channel Equalizer and its adaptation
as a
“Smart Amplifier Solution”**

By

Blerim Qela

A Thesis Submitted To
Faculty of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements
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To my parents, my wife, my children and the light of knowledge

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Abstract

In this thesis, design of the 8-channel DCE (Dynamic Channel Equalizer) for use in WDM (Wavelength Division Multiplexing) systems in general and in particular its adaptation as a “Smart Amplifier Solution” is presented. The innovative Optimized C-band Gain Flattened EDFA (Erbium Doped Fiber Amplifier) design without GFF (Gain Flattening Filter) and its integration with the DCE and embedded control electronics into a Smart Amplifier is proposed. Further improvement of the Smart Amplifier is suggested.

The systems design approach, where all subsystems are taken into account to optimize the WDM network was adopted. Hence, the Post and In-Line Amplifiers with APC (Automatic Power Control) are also considered and designed accordingly to achieve the optimized amplification and equalization results for the dynamic WDM networks. The experimental results and discussion for each design are presented and simulation data are provided for comparison and confirmation of the proposed Smart Amplifier design. In addition, simulation results with respect to feasibility of the Optimized C+L band EDFA and conditions under which it can be used as a broadband ASE source are discussed.

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List of Acronyms

ADC (A to D) – Analog to Digital Conversion

APC – Automatic Power Control

ASE – Amplified Spontaneous Emission

DAC (D to A) – Digital to Analog Conversion

DCE – Dynamic Channel Equalizer

DeMUX – Demultiplexer

DFB – Distributed Feedback

DWDM – Dense Wavelength Division Multiplexing

EDFA – Erbium Doped Fiber Amplifier

EVOA – Electronically Variable Optical Attenuator

FB – Fabry Perot

GFF – Gain Flattening Filter

GUI – Graphical User Interface

IL – Insertion Loss

ITU – International Telecommunication Union

MEMS – Micro Electromechanical Systems

MOVA – MEMS VOA

MUX – Multiplexer

NF – Noise Figure

OADM – Optical Add Drop Multiplexing

OSA – Optical Spectrum Analyzer

RAM – Random Access Memory

SMF – Single Mode Fiber

VOA – Variable Optical Attenuator

WDL – Wavelength Dependent Loss

WDM – Wavelength Division Multiplexing

Chapter 1

Introduction

1.1 Background

The difficulty in using EDFAs (Erbium Doped Fiber Amplifiers) for WDM (Wavelength Division Multiplexing) system designs is that the gain spectrum of a conventional EDFA is not constant over the bandwidth (refer to Fig.1.1 below). The non-uniform spectrum of gain in an EDFA does not have a significant impact on a single-channel transmission but manifests itself as a limitation with multiple channel transmission.

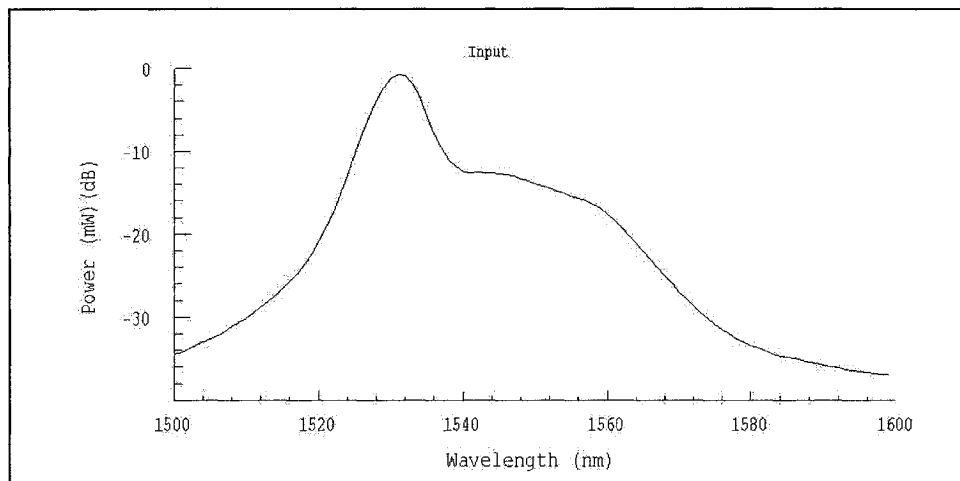


Figure 1.1 - EDFA gain profile

The Gain Flattening Filter (GFF) method, also known as a “static method of equalization”, might be useful in flattening the gain within the single or low channel system or subsystems where the tolerance and power fluctuations are not of concern.

However, when the WDM system is designed for higher number of channels (16, 32 or 64-channels), or where the gain flatness tolerance requirements are within ± 0.5 dB or lower and add/drop functionality is incorporated, the GFF as a static method would not suffice for equalizing the gain imbalances. Hence, the role of Dynamic Channel Equalization (DCE) schemes arises as a very useful solution.

The DCE uses attenuation to create an optical loss as a function of wavelength, which compensates for the wavelength dependence of the amplifier gain. The DCE are “smart attenuators” that use feedback control and channel-monitoring mechanisms to calculate how much attenuation is needed at a given wavelengths to produce uniform signal power throughout the network [1].

Using the gain profile of an EDFA, it is possible to create groups of wavelength within the C and/or L bands and provide necessary attenuation of the bands to equalize the entire wavelength spectrum in order to reduce the gain imbalances. The design and principles of operation are similar to the DCE design. The difference is that the equalized spectrum of wavelengths using this technique uses one EVOA (Electronically Variable Optical Attenuator) per band while DCE uses one EVOA per wavelength channel, hence its dynamic band equalization. Therefore, the design focusing only in the band equalization without careful consideration for the amplification design, including Post, In-Line and Pre Amplifiers, cannot provide a complete optimized solution. The impact of gain non-uniformities from one amplifier

stage to another, including the dynamics of the WDM network (wavelength add/drop, wavelength switching) would increase the gain non-uniformities (if optical amplifiers are not optimized with respect to gain flatness); hence the equalization of wavelength spectrum would not be optimized and the outcome would reflect a limited granularity of the model.

1.2 Thesis Outline

A review of WDM systems, Erbium Doped Fiber Amplifiers (EDFA) and Dynamic Channel Equalizers (DCE) is presented in chapter two (2).

In chapter three (3), design of the 8-channel DCE and its adaptation as a “Smart Amplifier Solution” is proposed; Design of the Optimized C-band Gain Flattened EDFA without GFF, Booster and In-Line EDFA, DCE algorithm, 8-channel DCE and its integration with the Optimized C-band EDFA design are presented and discussed.

In chapter four (4), experimental data for the Optimized C-band Gain Flattened EDFA without GFF, Optimized C-band Booster EDFA, Optimized Pre/Inline EDFA, 4-channel DCE, 4-channel DCE and Optimized C-band EDFA (C-band Smart Amplifier Solution) are presented and discussed.

In chapter five (5), simulation design models and results (using OptiAmplifier) for the Smart Amplifier Solution adapting 8-channel DCE and Optimized C+L band EDFA capable of amplifying and equalizing 64-channels within C and L band are discussed; Comparison of the Optimized C+L band EDFA with GFF and Smart Amplifier Solution (Optimized C+L band EDFA with 8-channel DCE) simulation results are

Chapter 1

discussed. In addition, feasibility of the Optimized C+L band EDFA to be used as a broadband ASE source is presented.

Conclusion, further improvements and recommendations for future research are presented in chapter six (6). Bibliography and Appendix A are made available for reference after chapter six (6).

Summary of Contributions

- Design of the Optimized C-band Gain Flattened EDFA without the GFF
(includes Control Electronics and Automatic Power Control)

- Design of the Optimized C-band Booster and In-Line EDFA with control electronics and Automatic Power Control to work well in conjunction with the Smart Amplifier Solution in order to provide the enhanced overall performance of the WDM system

- Design and integration of the DCE with the Optimized EDFA into a Smart Amplifier Solution to achieve a multi-channel dynamically gain controlled EDFA

- Conceptual design and simulation model for the future enhancement of the Smart Amplifier into a:
 - Optimized C+L band EDFA
 - Its adaptation and use as a Broadband ASE source

Chapter 2

Review of WDM systems, Erbium Doped Fiber Amplifiers (EDFA) and Dynamic Channel Equalizers (DCE)

2.1 Wavelength Division Multiplexing (WDM)

WDM is an optical technology that enables transmission of multiple channels each at different wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_n$) into one optical fiber. It offers high flexibility and bandwidth expansion in optical fiber transmission networks. It enables capacity upgrade of existing point to point optical transmission links, is bit-rate and protocol transparent - different wavelengths with different (independent) data formats can be transmitted simultaneously over the same fiber. A general WDM transmission system is shown in Figure 2 below, where multiple transmitted signals at different wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_n$) are multiplexed into one fiber, amplified and then demultiplexed at the receiver end.

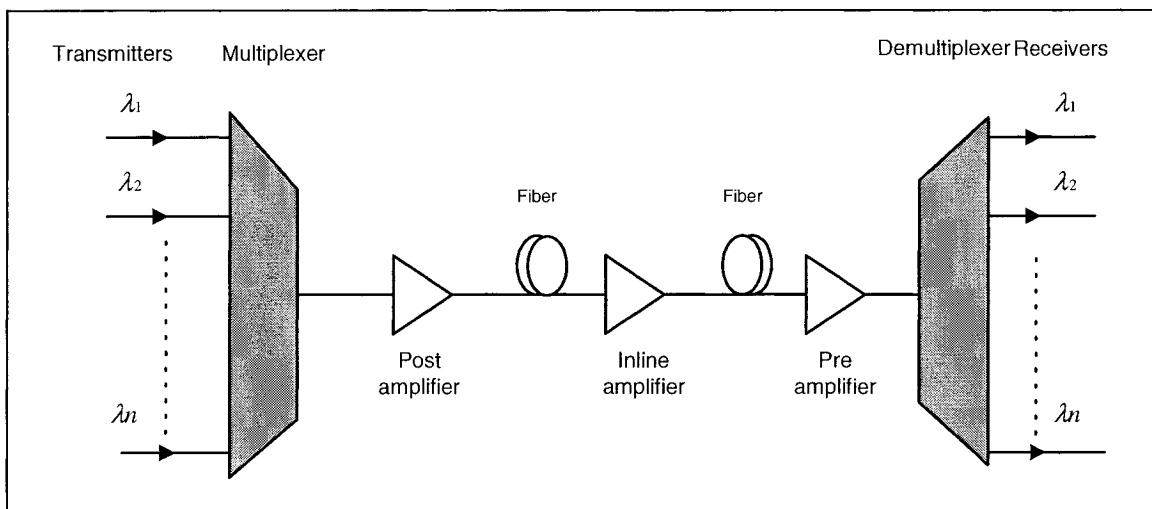


Figure 2 - A conceptual point to point WDM transmission system with amplifiers

The spectral domains used for transmission are in 1.3 μm and 1.55 μm window.

Between these two regions, there is a high fiber attenuation range at 1.39 μm due to the residual OH in silica fiber (absorption due to water peaks) imposing a limited use in 1.35 μm to 1.45 μm region. For medium and long-haul Dense WDM (DWDM) transmissions, covering C-band (1530 nm to 1565 nm) and L-band (1570 nm to 1610 nm) generally single mode (SM) fibers are used due to lower attenuation of fiber (~ 0.2 dB/km), availability of lasers and EDFAs offering amplification in C and L band.

The characteristics of sources (transmitters), optical amplifiers and fiber type used dictate the performance of WDM system. Fabry-Perot (FP) and distributed feedback lasers (DFB) are widely used in long-haul high bit-rate WDM systems. The DFB lasers offer higher output power and narrower spectral bandwidth in comparison to the FP lasers, are well suited for DWDM transmissions. The International Telecommunication Union (ITU) standard G.692 defines a laser grid for point-to-point DWDM transport systems based on 100GHz spacing (0.8 nm) with a center wavelength at 1552.52 nm (193.1 THz). The interchannel spacing in DWDM could be as close as 25GHz (0.2 nm). The necessity of EDFAs is essential for amplification of signals in long-haul WDM systems, where its gain flatness is an important element of the system performance. The single mode fiber (SMF) is widely used in C and L band DWDM applications.

2.2 Erbium Doped Fiber Amplifiers (EDFA)

Introduction

Due to the attenuation of signals in the fiber (~ 0.2 dB/km) the optical amplification of signals is necessary to compensate for the loss and hence increase the channel transmission distance in WDM systems.

EDFAs are bit rate transparent and provide optical amplification within optical networks, eliminating the need for complex and expensive Optical-Electrical-Optical (O-E-O) conversion. The O-E-O process involves photon-to-electron conversion, electrical amplification, retiming, pulse reshaping, and electron-to-photon conversion and can be very expensive and complex when dealing with high-speed multiwavelength optical systems [2]. Therefore, the EDFAs role as a solution for all optical amplification needs within the WDM systems is valuable. The use of Erbium is not limited just to amplifiers. It is also used in fiber laser design such as the tunable fiber ring lasers. The output power non-uniformity exists also in lasers based on erbium-doped fiber. With respect to the wideband tunable fiber lasers using erbium-doped fiber similarly to EDFAs, several techniques have been proposed to flatten the output power spectrum. A wideband tunable fiber ring laser with flattened output power spectrum was achieved by using a high-birefringence fiber loop mirror by utilizing a number of high-birefringence fiber sections and polarization controllers in order to get a reflection spectrum that compensates for the output power spectrum [3].

Amongst amplification and laser applications, it has been reported the use of the EDFA for temperature sensing measurements using temperature dependence of EDFA gain [4].

2.2.1 EDFA amplification in Three-Level System

In order to get a better understanding of how amplification in an EDFA occurs, it is necessary to observe the energy level structure of the erbium [5,6]. The Er^{3+} ions (erbium atoms that have lost 3 electrons in their outer shell) is the preferred ion for lasing and amplification in the 1.5 μm region due to the long transition time from the metastable state (level 2, refer to Fig. 2.1, pg. 23) to ground state (level 1, refer to Fig. 2.1, pg. 23) due to large energy gap between the upper and lowest level of the amplifying transition. As a result of a long metastable state within the Er^{3+} doped fiber, the erbium doped silica fiber amplification is possible [5].

The amplification (by stimulated emission) in EDFAs is achieved by exciting the erbium ions of Er^{3+} in erbium doped silica glass by the pump to a higher energy state (level 3, refer to Fig. 2.1, pg. 23), after a very short lifetime ($\sim 1 \mu\text{sec}$), these ions transit to the metastable state with longer lifetime ($\sim 10 \text{ msec}$). As a flux of signal photons with energy levels corresponding to the band-gap between the metastable and ground state pass through the EDFA, a small part of these photons will be absorbed by ions in the ground state (raising them to the metastable state); A major part of the signal photons will stimulate excited erbium ions to emit new photons of the same

wavelength and energy during transition to the ground state, hence amplification of light occurs.

Rate Equations for Three-Level system

The simplest observation of the EDFA is by considering a three level atomic system [7]. Three level-system model is used to obtain the main characteristics of the amplifier [7,8]. In the Figure 2.1 (refer to pg. 23) are shown three energy levels of the erbium, where level 1 corresponds to the ground state, level 3 which is the intermediate state into which the energy is pumped (also known as a pump level) and level 2 is the metastable state (characterized with longer lifetime τ in comparison to the lifetimes of the states that led to this state). State 1 is the lower level of the amplification transition and state 2 is the upper level, whereas the population of states 1, 2 and 3 are denoted as N_1 , N_2 and N_3 respectively; ϕ_p and ϕ_s are the pump and signal flux, while σ_p and σ_s are the pump and signal cross section; Γ_{32} (nonradiative transition) and Γ_{21} (radiative transition) are the spontaneous transition rates of the erbium ions.

In order to obtain amplification, inversion population between levels 1 and 2 is needed. The change in population for each level is mainly due to the spontaneous absorption of photons from the incident light field, spontaneous and stimulated emission. Typically, by pumping photons at 980 nm or 1480 nm, excitation of ions from the ground state (level 1) to the upper levels is accomplished.

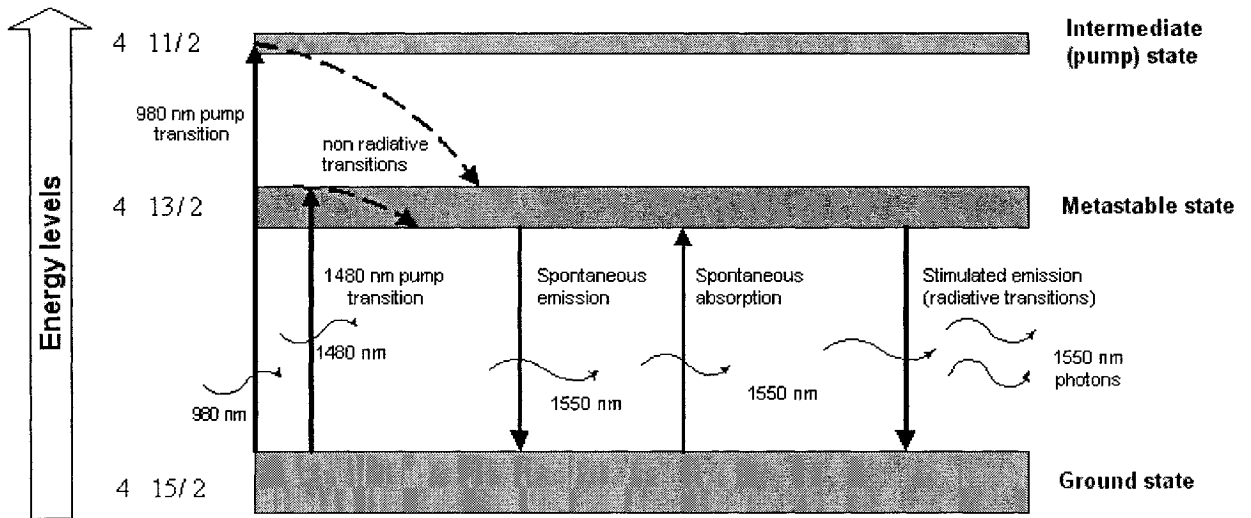


Figure 2.1 - Three-level system for amplifier model

A pump laser emitting photons at 980 nm excites the erbium ions from the ground state (level 1) to pump state (level 3) that decay quickly to metastable state (level 2) contributing to the inversion population. Similarly, a pump laser emitting photons at 1480nm excites the erbium ions from the level 1 to level 2.

The lifetime of a level is inversely proportional to the probability per unit time of the radiative (τ_r) and nonradiative (τ_{nr}) lifetimes and is expressed as follows:

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \quad (2.1)$$

The radiative lifetime (τ_r) of excited erbium ions is longer - around 10 msec compared to the fast decay - nonradiative (τ_{nr}) lifetime which is around 1 μ sec.

The rate equations corresponding to the populations of level 1, 2 and 3 can be written as:

$$\frac{dN_3}{dt} = -\Gamma_{32}N_3 + (N_1 - N_3)\varphi_p\sigma_p \quad (2.2)$$

$$\frac{dN_2}{dt} = -\Gamma_{21}N_2 + \Gamma_{32}N_3 - (N_2 - N_1)\varphi_s\sigma_s \quad (2.3)$$

$$\frac{dN_1}{dt} = \Gamma_{21}N_2 + (N_2 - N_1)\varphi_s\sigma_s - (N_1 - N_3)\varphi_p\sigma_p \quad (2.4)$$

In a steady state regime, where the population are time invariant we have:

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = 0 \quad (2.5)$$

Total population is given by:

$$N_T = N_1 + N_2 + N_3 \quad (2.6)$$

Under the steady state conditions, from equation 2.2 we can rewrite the population N_3 as follows:

$$N_3 = \frac{N_1 \cdot \varphi_p \cdot \sigma_p}{\Gamma_{32} + \varphi_p \cdot \sigma_p} = \frac{N_1}{1 + \frac{\Gamma_{32}}{\varphi_p \cdot \sigma_p}} \quad (2.7)$$

Due to the fast decay from the pump state to metastable state, the $\Gamma_{32} = 1/\tau_{nr}$ is very large in comparison to $\varphi_p\sigma_p$; hence N_3 is close to zero, which implies that the population is mainly in metastable and ground state. In order to derive the population N_2 we substitute the equation 2.7 into equation 2.3 and obtain the following:

$$N_2 = \frac{N_1 \cdot \left(\varphi_s \sigma_s + \frac{\varphi_p \sigma_p}{\Gamma_{32}} \right)}{\Gamma_{21} + \varphi_s \sigma_s} \quad (2.8)$$

Using equation 2.6 we solve for N_1 and N_2 and the difference $N_2 - N_1$ yields the following equation for the population inversion:

$$N_2 - N_1 = N_T \frac{\varphi_p \sigma_p - \Gamma_{21}}{\Gamma_{21} + 2\varphi_s \sigma_s + \varphi_p \sigma_p} \quad (2.9)$$

In case of the population inversion threshold when $N_2 - N_1 = 0$, from equation 2.9 we obtain the following equation for the pump flux (threshold):

$$\varphi_{pth} = \frac{\Gamma_{21}}{\sigma_p} \quad (2.10)$$

Substituting the for transition lifetime $\Gamma_{21} = 1/\tau_r$ where τ_r is the metastable lifetime, we obtain the following equation for the required pump flux:

$$\varphi_{pth} = \frac{1}{\sigma_p \tau_r} \quad (2.11)$$

In order to pass the threshold and obtain the gain on the transition from metastable to ground state, condition to be satisfied for the population inversion is $N_2 - N_1 \geq 0$

EDFA Power Conversion Efficiency (PCE)

Based on the terms of energy conservation, the input and output power of an EDFA can be expressed as follows [9,6]:

$$P_{Sout} \leq P_{Sin} + \frac{\lambda_p}{\lambda_s} \cdot P_{Pin} \quad (2-1)$$

where:

P_{Sout} is signal output power

P_{Sin} is signal input power

P_{Pin} is pump power

λ_p is pump wavelength and

λ_s is signal wavelength

The formula 2-1 shows that the output power depends on the input signal power, pump power and the ratio $\frac{\lambda_p}{\lambda_s}$ between pump and signal wavelengths. The maximum output

power depends on this ratio $\frac{\lambda_p}{\lambda_s}$.

The power conversion efficiency (PCE) is defined as:

$$PCE = \frac{P_{Sout} - P_{Sin}}{P_{Pin}} \quad (2-2)$$

Conditions such as the $\frac{\lambda_p}{\lambda_s} < 1$ and $P_{S_{in}} \ll P_{P_{in}}$ must be met for the pumping scheme to work and in order to have appropriate gains.

$$PCE \approx \frac{P_{S_{out}}}{P_{P_{in}}} \leq \frac{\lambda_p}{\lambda_s} \leq 1 \quad (2-3)$$

Another term which is used for reference purposes is Quantum Conversion Efficiency (QCE) and is defined by [9,6]:

$$QCE = \frac{\lambda_p}{\lambda_s} \cdot PCE \quad (2-4)$$

Theoretically if all the pump photons were converted to signal photons, QCE maximum value would be unity.

EDFA Gain and Noise Figure

The EDFA gain is expressed as the ratio between the input and output signal levels, neglecting the amplified spontaneous emission (ASE) noise and polarization dependent effects accompanying the signal at the output.

$$Gain(dB) = 10 \cdot \log_{10} \frac{P_{out}}{P_{in}} \quad (2-4)$$

While the optical Noise Figure (NF) of an EDFA is expressed as:

$$NF(dB) = 10 \cdot \log_{10} \left(\frac{P_{ase}}{h\nu B_0 G} + \frac{1}{G} \right) \quad (2-5)$$

where:

P_{ASE} is the ASE noise of the EDFA measured in the bandwidth B_0 ,

$B_0 = (c / \lambda) (\Delta\lambda / \lambda)$ (equal to spectral bandpass of the OSA at signal frequency)

$$P_{ASE} = 2n_{sp}(G-1)h\nu B_0$$

n_{sp} is the population inversion factor (spontaneous emission) and is defined as:

$$n_{sp} = n_2 / (n_1 - n_2)$$

n_1, n_2 are population of electrons in states 1 and 2

h is the Plank's constant ($h = 6.626 \times 10^{-34} \text{J}\cdot\text{s}$)

ν is the optical frequency (Hz) and

G is gain of the EDFA at signal frequency

EDFA Building Blocks

Basic building blocks of an EDFA are:

- Erbium Doped Fiber
- Pump Laser (980 nm and/or 1480 nm)
- WDM Coupler (980/1550 nm and/or 1480/1550 nm)
- Input and Output Isolators

At the input and output of an EDFA, optional components are tap couplers (with typical splitting ration of 99/1 to 95/5) useful for power monitoring of input and output signals.

Pump configurations

Typical pump configurations used in EDFA designs are:

- Forward pumping (usually 980 nm pump laser)
- Backward pumping (1480 nm pump laser)
- Combination of both (forward and backward pumping)

Forward pumping (refer to Fig. 2.2, pg. 30) with 980 nm pump laser is optimized to give a low noise figure since it maximizes the inversion population at the signal input in comparison to backward pumping (refer to Fig. 2.3, pg.30) with 1480 nm pump laser, which offers higher output power but also higher noise figure [10]

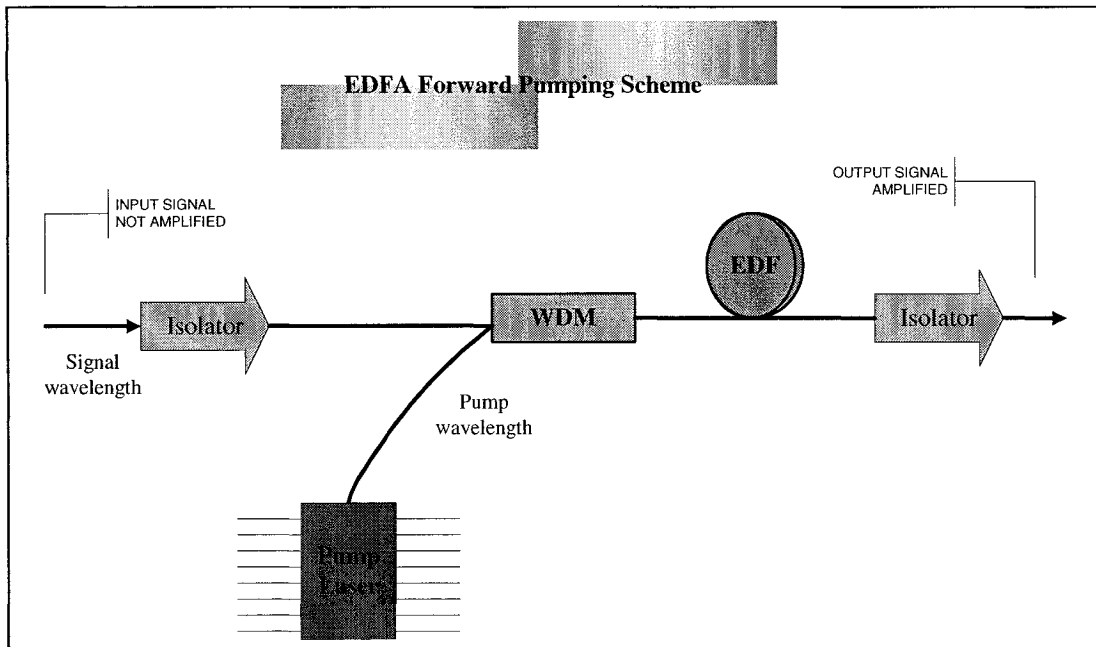


Figure 2.2 - EDFA Forward pumping

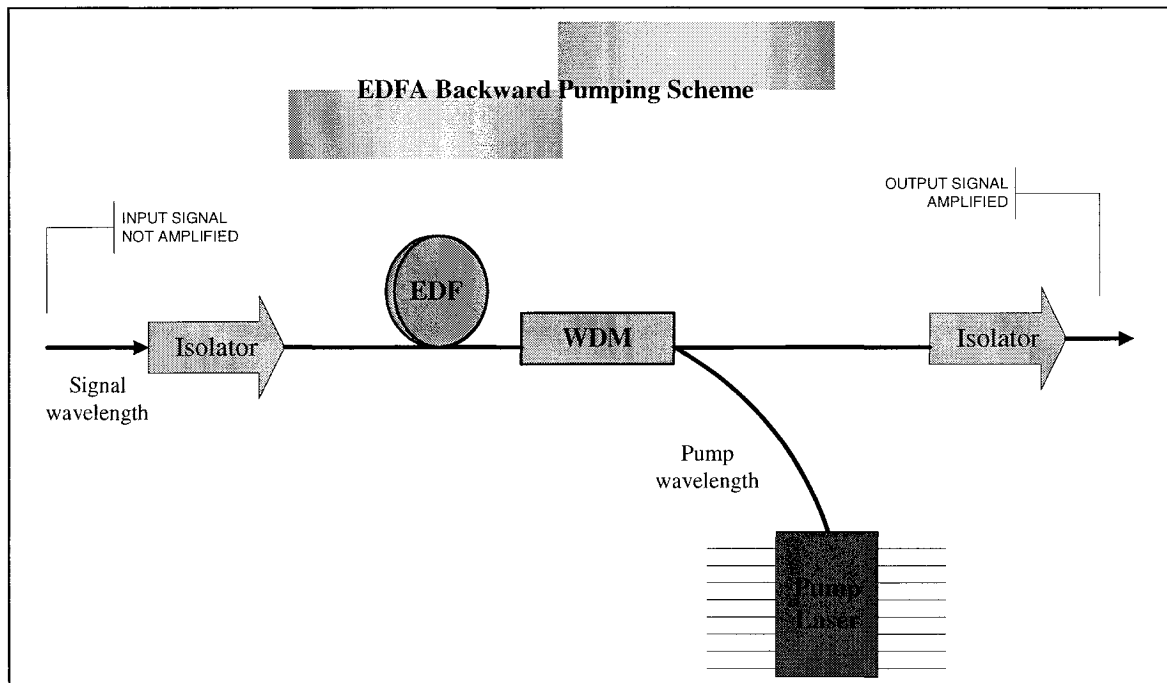


Figure 2.3 - EDFA Backward pumping

In cases when trade-off between high output power and low noise figure EDFA design exists, then combination of both schemes (dual pumping) can be used as per the Figure 2.4 below.

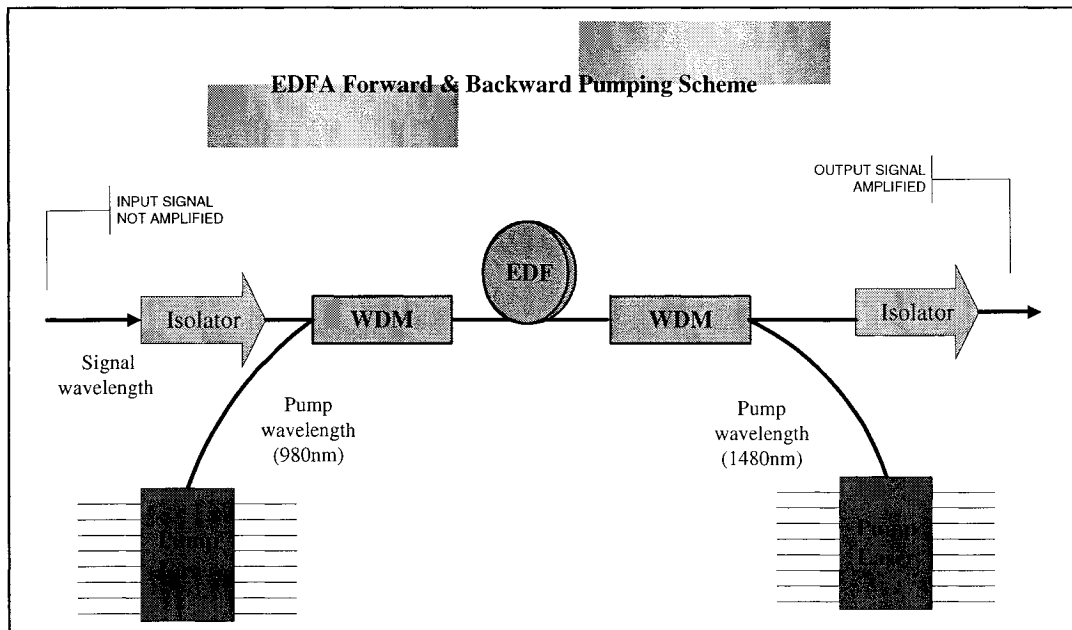


Figure 2.4 - EDFA Forward & Backward pumping scheme

EDFA Types

Based on where within an optical system amplifier is used there are three types of amplifiers:

- **Post (Booster) Amplifier** – input optical power ranges approximately from -10 dBm to $+3$ dBm and output power is an important parameter. It is placed immediately after the transmitter and its purpose is to boost the optical power, compensating for optical fiber loss and contributing to longer transmission links.

Using a booster amplifier in conjunction with a pre amplifier at the receive end of the optical link, repeaterless undersea transmission distances of 200 to 250 km can be reached [11].

- **Pre Amplifier** – input optical power ranges approximately from -33 dBm to -10 dBm and noise figure is an important parameter.

It is placed before the receivers and its purpose is to amplify the weak optical signals prior to reaching the receiver [11].

- **In-Line Amplifier** – input optical power ranges approximately from -26 dBm to -10 dBm and with respect to output power and noise figure represents a trade-off of both.

It is placed in mid-stage optical links and provides the amplification of the signals in long-haul networks compensating for optical fiber loss and increasing the transmission distance between the regenerative repeaters [11].

2.3 Dynamic Channel Equalizers

With the growth of WDM dynamic configurable networks where the power imbalances are present due to the EDFA gain non-uniformity and agile network systems with add/drop and/or wavelength switching capabilities, a need for gain control is critical [12] and a need for dynamic gain equalizers for WDM systems still remains actual. The fixed GFF method for flattening the EDFA gain spectra applies a fixed attenuation (a static method of equalization) is not flexible nor sophisticated enough to handle the power fluctuations in dynamic optical networks, which require components capable to respond and adjust optical power at amplifiers and node sites where add/drop functions are present. Figure 2.4 below, shows the EDFA gain spectrum before and after the GFF filter is introduced, equalizing the gain spectrum of EDFA.

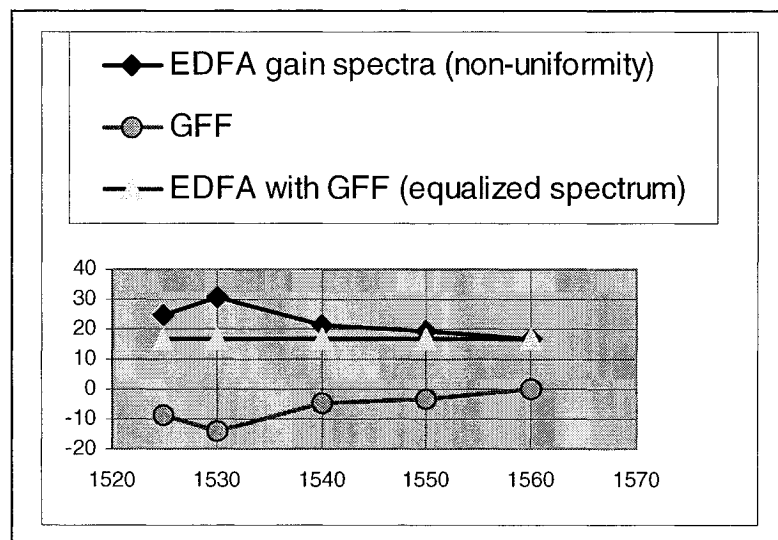


Figure 2.4 - EDFA equalization using GFF

As per the discussion above, GFF method works well only if optical power remains constant and is not capable of responding to dynamic network systems, where power fluctuations are frequent.

Thin film filters and long period grating have been successfully used for static gain equalization and are tailored to work well at the specific amplifier operating point. The acousto-optic tunable filters have also been utilized to dynamically control the gain of EDFAs [13,14]. The dynamic gain equalization (with ± 0.4 dB gain ripple), of the EDFAs within a narrow band 1542-1552 nm wavelength independent gain spectrum has also been achieved by using alumino-germanosilicate erbium doped fiber, attenuators and in conjunction with Mach-Zehnder filter within the wavelength operational range [15].

For the dynamic WDM networks, MEMS technologies (MEMS VOA) also have been employed to offer the dynamic flexibility for gain equalization [16,17,18]. Therefore, dynamic gain equalization techniques, which utilize micro-electro-mechanical systems (MEMS) or liquid-crystal attenuators to block and/or attenuate signals emerge, as a preferred solution for equalization needs in dynamic WDM networks.

The dynamic gain equalizers are smart attenuators which use feedback and channel monitoring mechanism in order to compare the power level of optical signals (monitoring of power imbalances) and use attenuation to adjust the power levels required for the power equalization.

The equalized spectrum of wavelengths using DCE technique uses one Variable Optical Attenuator (VOA) per wavelength channel. A slight variation of the DCE technique is its use for band equalization, which is accomplished by utilizing one VOA per band instead of one VOA per channel.

Figure 2.5 (refer to pg. 36) shows the principle of DCE operation. Dashed lines represent **pin diode feedbacks** (monitoring of input and output power levels) and **VOA control** lines (adjustment of attenuation level based on the pin diode readings). For simplicity only two channels are shown.

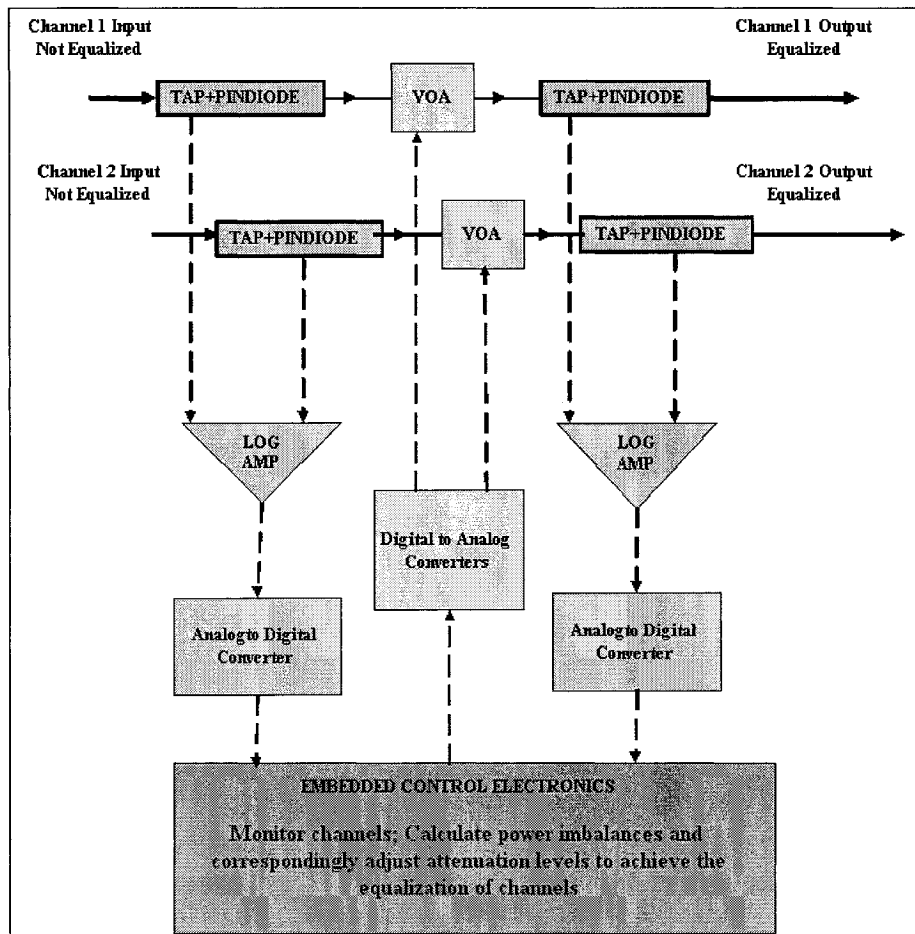


Figure 2.5 - DCE equalization principle

The DCE equalization is achieved by reading the input/output power levels via pin diodes prior to and after the VOA, then the difference between channels 1 and 2 (between input and output optical power levels) is calculated and attenuation to obtain equalized channels is applied accordingly. In this thesis, similar DCE functionality is achieved with only one pin diode placed after the VOA (refer to Fig. 3.4b, pg. 69).

Chapter 3

The 8-channel DCE and its adaptation as a “Smart Amplifier Solution”

3.1 Thesis Statement

With the growth of dynamically configurable - complex network systems, the need for efficient and low cost solutions such as the adaptation of the 8-channel DCE design as a “Smart Amplifier Solution” is necessary. The Smart Amplifier Solution is capable of offering **optimized amplification** for overall WDM system and **equalization** of the gain spectrum imbalances across all the channels in C (1530 to 1563 nm), L (1570 to 1600 nm) or C+L band, with comparable results to a 32-channel DCE.

3.2 Smart Amplifier Solution

The strategy is the development of an 8-channel Dynamic Channel Equalizer for use in DWDM systems in general and in particular its adaptation as a “Smart Amplifier Solution”. Smart Amplifier can amplify and equalize the gain spectrum imbalances, it also provides the output optical signals within acceptable output power tolerances in C, L or even both bands by designing an Optimized (Gain Flattened) EDFA with low delta of gains (throughout the spectrum) and integrating it with the 8-channel DCE. Block diagram of the Smart Amplifier Solution is presented in Figure 3.1 (pg. 38). The innovative Optimized C-band Gain Flattened EDFA design without the use of GFF is proposed as a part of the Smart Amplifier Solution. The Post and In-Line Amplifiers with Automatic Power Control are also considered and designed

accordingly, to achieve the optimum amplification and equalization results for the WDM network. Following the system level design approach, makes the Smart Amplifier Solution a powerful and very well 'synchronized' with the rest of the optical amplifiers within the system. The system level approach taken is not limited into solving one problem but finding the optimized solution for the overall system where all the components of the system, which in fact are subsystems within WDM, are considered and designed concurrently.

The use of a 32-channel DCE would be less attractive due to the high channel count, reflecting higher price per unit and the limited upgrade ability to the existing units.

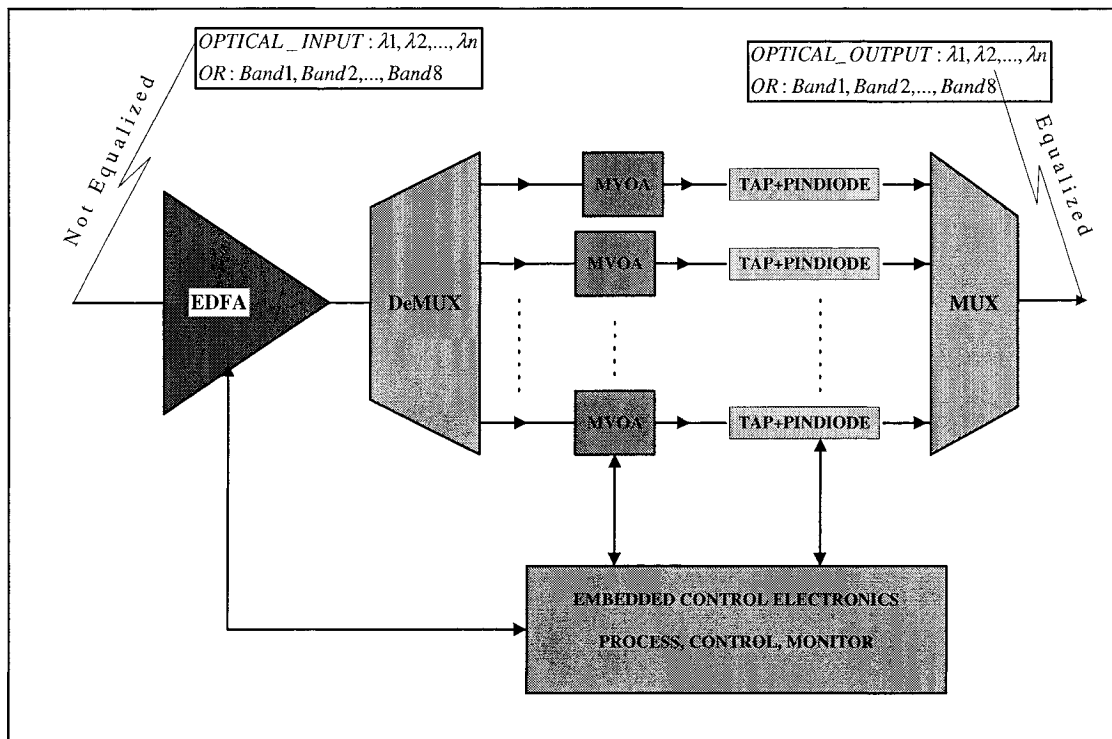


Figure 3.1 - Block diagram of the Smart Amplifier Solution

The Smart Amplifier is a complete optimized solution that will enable its use in long haul and metro applications as a dynamic amplifier with flattened output gain spectra. It will be able to adapt and respond to the changes in multiple channel WDM systems and provide optimized output comparable to the DCEs with respect to equalization. In addition to DCEs, Smart Amplifier will also provide optimized amplification.

Building blocks of the Smart Amplifier design

1. Optimized (Gain Flattened) EDFA
2. Demultiplexer and Multiplexer
3. Electronically Variable Optical Attenuators
4. Pin Diode Receivers
5. Embedded control electronics
6. Software for monitoring and control of the module

Additional building blocks of the design:

1. Booster and In-Line EDFA with control electronics and Automatic Power Control (APC)

Why adapt 8-channel equalization design?

The equalization across C and L band (~80 nm wavelength range) taking into consideration the non-uniformity of the EDFA gain spectrum, can not be optimized with the separation of only 4-bands. The use of 8-bands (C and L band equalization) is necessary in order to reach the efficiency and accuracy of the channel equalization technique.

In scenarios when the Smart Amplifier is used only for C or L band amplification and equalization, adaptation of the 4-channel DCE to equalize 4 bands within C or L window is appropriate when used with the optimized EDFA.

Why a Smart Amplifier Solution is an optimized design?

- It adapts to any network and offers comparable performance to DCE but will offer more functionality - including the optimized amplification
- It is an all-in-one solution (EDFA amplifier + DCE equalizer)
- It also offers suitable solution for additional WDM network amplification needs, Post and In-Line Amplification
 - Booster and In-Line EDFAs are designed and optimized to work well with the Smart Amplifier as a whole or as a stand-alone units
- It is less expensive and more flexible than DCE

- Optimized Gain Flattened EDFA without GFF
- Optimized Booster and Pre, In-Line EDFAs with short Erbium Doped Fiber (EDF) lengths
- Can cover the C-band, L-band or the entire C+L band with careful choice of optimized EDFA and 8-channel equalization technique compared to 32 or 64-channel DCE
- System designer needs to change or specify only the band filters to adapt the design to suit their network needs (no redesign or change of other components is necessary)
- It revolutionizes the use of Smart Amplifiers, reduces the complexity and consideration with regard to the EDFA gain non-uniformities in future designs

WDM system – gain ripple analysis

The block diagram in Figure 3.1a below, is a generic representation of a possible WDM system configuration with optical amplifiers (Post, Inline, Pre) and optical add/drop multiplexer (OADM). The optimized WDM system performance depends on how well the subsystems within it are ‘synchronized’ with the rest of the system. The interaction among different sub-stages of the system are important. The impact of power fluctuation (gain ripple) from one stage (post amplifier, OADM, Inline, Pre amplifier stage) to the other is analyzed using generalized expressions.

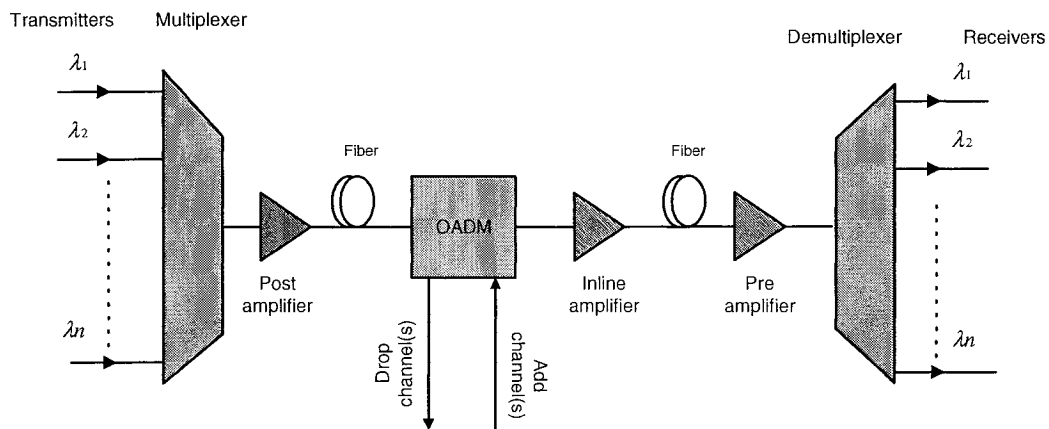


Figure 3.1a – WDM system with amplifiers and OADM

$$\Delta G = \max \{P_{\text{out}}(\lambda_a)\} - \min \{P_{\text{out}}(\lambda_b)\} \text{ [dB]}, \quad (3-1)$$

where ΔG is power fluctuations and P_{out} is the output optical power from any subsystem and λ_a, λ_b are the corresponding wavelengths of the maximum and minimum output power used to calculate the maximum gain ripple.

The delta of gain (gain ripple) for the post (booster) amplifier is expressed as follows:

$$\Delta G_{\text{post}} = \Delta G_{\text{post}}(\delta) \text{ [dB]}, \quad (3-2)$$

where δ is a function of transmitter and multiplexer performance.

$$\delta = f(\text{Transmitter performance}, \text{Multiplexer performance})$$

The delta of gain (gain ripple) for OADM is expressed as follows:

$$\Delta G_{\text{AD}} = \Delta G_{\text{AD}}(\alpha) \text{ [dB]}, \quad (3-3)$$

where α is a function of the amplifier performance and dynamics of the network.

$$\alpha = f(\text{Post amplifier performance}, \text{Dynamics of network})$$

ΔG_{inline} is the delta of gain for the inline amplifier, where β is a function of inline amplifier performance and dynamics of network:

$$\Delta G_{inline} = \Delta G_{inline} (\beta) \quad [\text{dB}], \quad (3-4)$$

$$\beta = f(\text{Inline amplifier performance, Dynamics of network})$$

ΔG_{pre} is the delta of gain for the pre amplifier and γ is a function of the preamplifier performance and dynamics of network

$$\Delta G_{pre} = \Delta G_{pre} (\gamma) \quad [\text{dB}], \quad (3-5)$$

$$\gamma = f(\text{Pre amplifier performance, Dynamics of network})$$

And finally, total gain ripple (delta of gain) of the system is denoted with ΔG_T and is function of all subsystems and is expressed as follows:

$$\Delta G_T = f(\Delta G_{post}, \Delta G_{A/D}, \Delta G_{inline}, \Delta G_{pre}) \quad [\text{dB}] \quad (3-6)$$

In the ideal case $\delta = \alpha = \beta = \gamma = 0$, hence $\Delta G_{post} = \Delta G_{A/D} = \Delta G_{inline} = \Delta G_{pre} = 0$ dB resulting in a perfectly flat response. But, $\delta, \alpha, \beta, \gamma$ parameters as shown in expressions above are not only function of the amplifier performance/design but also

network dynamics. Therefore, the goal is to reduce the effect of power imbalances in each sub-stage of the WDM system as close as possible to zero. The impact of poor design reflects on the power imbalances leading to less transmission distance or more amplifier and equalizer stages. By taking into account all the subsystems' overall effects one must decide to consider the amplification and equalization design/performance needs for the WDM network based on the system design approach. The optimized performance with respect to gain flatness in WDM might be accomplished by taking into consideration all the subsystems from transmitter to booster, inline, possible equalizer and preamplifier.

3.3 Design of the Optimized C-band Gain Flattened EDFA without GFF

The Optimized C-band Gain Flattened EDFA is accomplished using a new design technique that **does not require** gain flattening filters (GFF) to achieve gain flatness over the entire C-band (1530 nm to 1563 nm).

The Optimized C-band Gain Flattened EDFA offers typical gain flatness of +/- 0.625 dB or less over the entire C-band (refer to pg. 73 for experimental results), high gains and lower cost compared to the existing C-band Gain Flattening EDFAs. It can be used as a stand-alone solution (In-Line amplifier) or in conjunction with the DCE as a Smart Amplifier Solution.

How does it work?

Instead of using conventional C-band erbium doped fiber (EDF) for C-band EDFA amplification and GFF for flattening the gain spectrum of the EDFA, the specific EDF with slightly higher gains of approximately 20 to 25 dB/m was selected. The conventional C-band EDF usually offers lower gains per meter of EDF used.

By careful design of the EDFA, using forward (980nm) pump configuration, specific EDF length and pump power levels the shape of the EDFA gain spectrum is optimized and ASE spectra of the EDFA is shifted and fine tuned. The gain flatness with typical values of +/- 0.625 dB was achieved, covering wavelengths from 1530 nm to

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1563 nm, typical gain values of 20 to 25 dB, optimal input optical power of operation from -17 dBm to -3 dBm and typical noise figure of 4.5 to 5 dB. Figure 3.2 (refer to pg. 48) represents the block diagram of the Optimized C-band Gain Flattened EDFA with Control Electronics.

Block Diagram of the Optimized C-Band Gain Flattened EDFA Design with Control Electronics

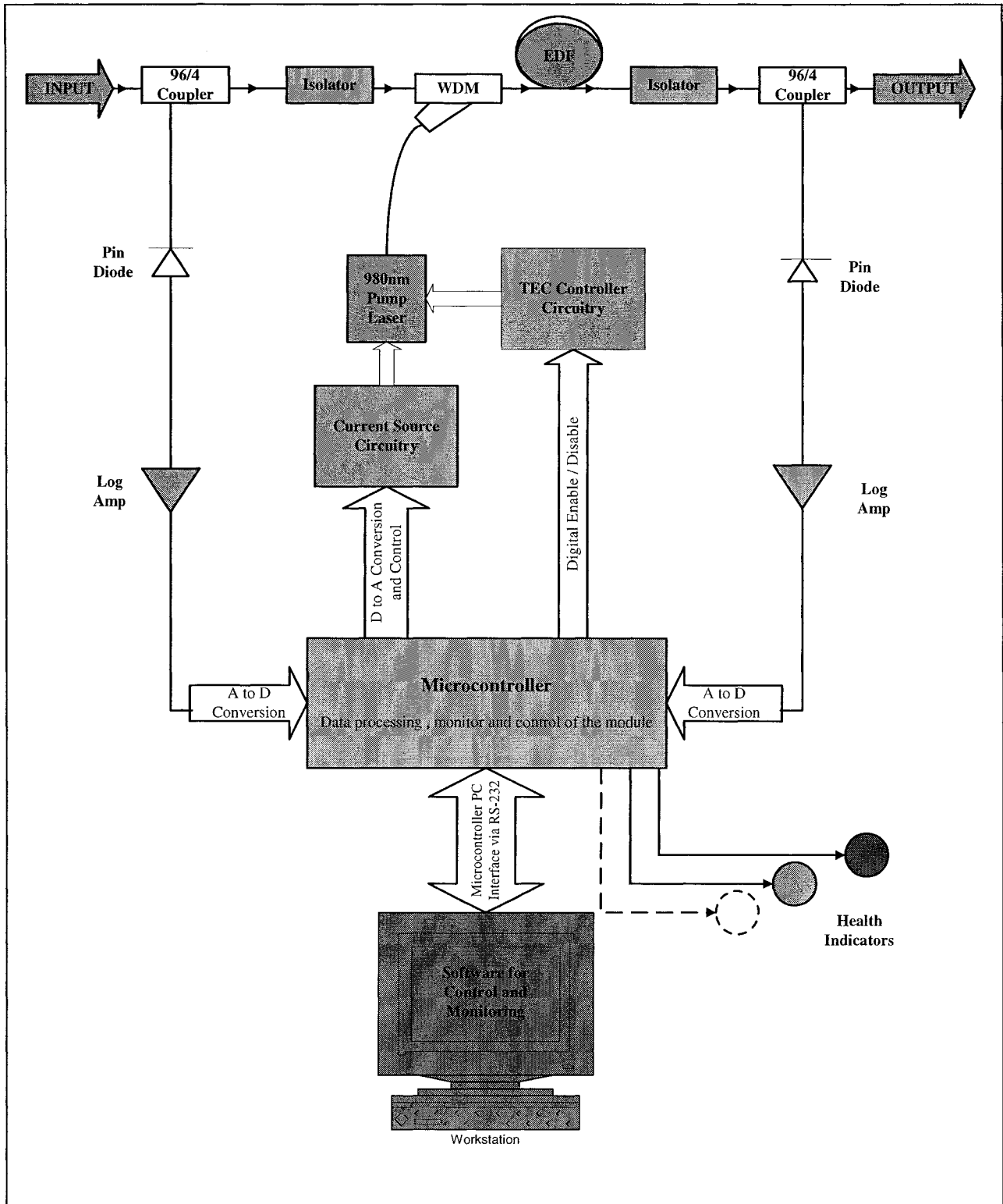


Figure 3.2 - Block Diagram of the Optimized Gain Flattened EDFA

The induced ASE has been used widely in L-band amplifiers to enhance the gain of the amplifier [19] or the PCE [20]. Another L-band Gain flattened EDFA method utilizing the forward ASE pumping of the C-band EDFA as the pump source for obtaining the gain shift for L-band EDFA implementation was proposed [21].

The optical (electro-optical) components of the design

- 96/4 tap (optical component)
96 percent of the optical power passes through the optical path (input to output) and 4 percent goes to the pin diode receiver, where the optical signal is converted to electrical for input optical power monitoring
- 1550 nm isolator (optical component)
Isolates the input optical path from back reflections
- 980/1550 nm WDM (optical component)
Combines the 980 nm pump laser signal with the 1550 nm (C-band) signal
- 980 nm pump laser (electro-optical component)
Provides the necessary optical power to the EDF to amplify the 1550 nm (C-band) optical signal

- Erbium doped fiber (optical component)
Fiber doped with high concentration of rare earth ions Er³⁺
- 1550 nm output isolator (optical component)
Isolates the output optical path from back reflections
- 96/4 tap (optical component)
96 percent of the optical power passes through the optical path (output) and
4 percent goes to the pin diode receiver, where the optical signal is converted
to electrical for output optical power monitoring

The control electronics components of the design

- Thermoelectric Cooler (TEC) controller
Maintains a stable temperature inside of the 980nm pump laser module at a
constant 25 °C
- Laser driver
A current source controlled by a microcontroller is used to drive the pump
laser at the desired power levels by setting the appropriate current value

- **Microcontroller**
Used for efficient data processing, decision-making, feedback, serial communication, EDFA performance monitoring, control of the module and for the output alarms (health indicators)
- **Digital to Analog Converters (DAC)**
Together with the microcontroller provides the means to accurately control the pump laser drive current
- **Logarithmic amplifiers**
Used to amplify the weak electrical signals received by the pin diodes (optical to electrical signal converters)
- **Temperature sensor**
Used to monitor the temperature within the module

The Automatic Power Control (APC)

The conventional APC control design uses one EVOA to control the output optical power. Taking into consideration that the EVOA cost ranges from \$350 to \$500 for small quantities, it is convenient to achieve the APC functionality (without the use of an EVOA) by dynamically controlling the pump laser drive current.

The APC control of the module (refer to Fig. 3.2a below) was designed using the input and output monitoring signals as a reference signals for the feedback. These signals are fed to the inputs of an Analog to Digital converter and then processed by the microcontroller.

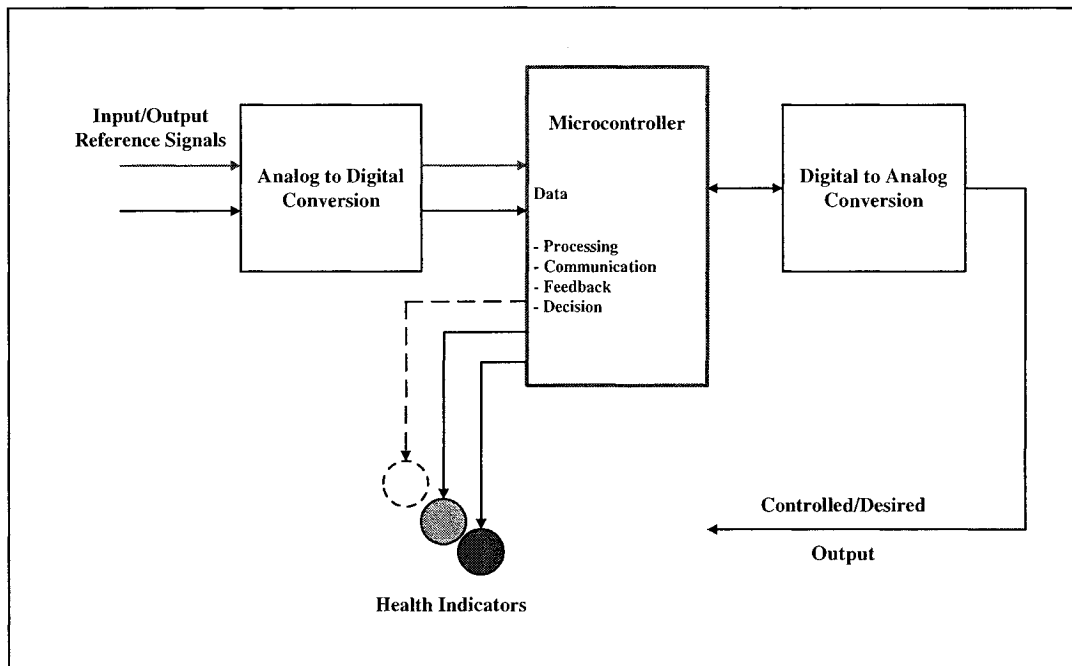


Figure 3.2a - The APC functional block diagram

After being processed the information is used to increase or decrease the drive current of the pump laser accordingly to maintain the desired/controlled output power level (using the Digital to Analog converters). In addition, implementations of the extra features such as the health indicators for the module are possible.

The software for monitoring and control of the EDFA

The EDFA software was developed to control and monitor the module using VBasic 6, by allowing the flexibility to experiment with the pump laser drive currents, monitor the input and output power levels, observe the EDFA Gain and choose appropriate drive currents to achieve the desired output power.

The Optimized EDFA module with control electronics and software offers all the above functionality within one GUI window (via RS-232 interface of the module and PC).

The drive current sent to the module is verified by the control circuitry - microcontroller and confirmation of the received data by the module is displayed on “Confirmation of sent ↔ received data” display.

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The input and output optical power, EDFA Gain and module temperature (refer to Fig. 3.2b, pg. 55) is displayed continuously. These data are calibrated to offer accurate readings of the input and output power. Clicking on the Save Data button (refer to Fig. 3.2b, pg. 55) will save the data automatically in an edfa.txt file in the following format:

```
*****  
Date and Time: 01/29/2005 4:25:59 PM  
Laser Drive current = 120 mA  
Optical Input Power = -15 dBm  
Optical Output Power = 10 dBm  
EDFA Gain = 25 dB  
Case Temperature = 25°C  
*****
```

Clicking on the GAINSET button (refer to Fig. 3.2b below) sets the EDFA module in APC mode of operation.

The windows based help file EDFA.HLP is associated with the software and it contains all the information about the EDFA Software functionality and features.

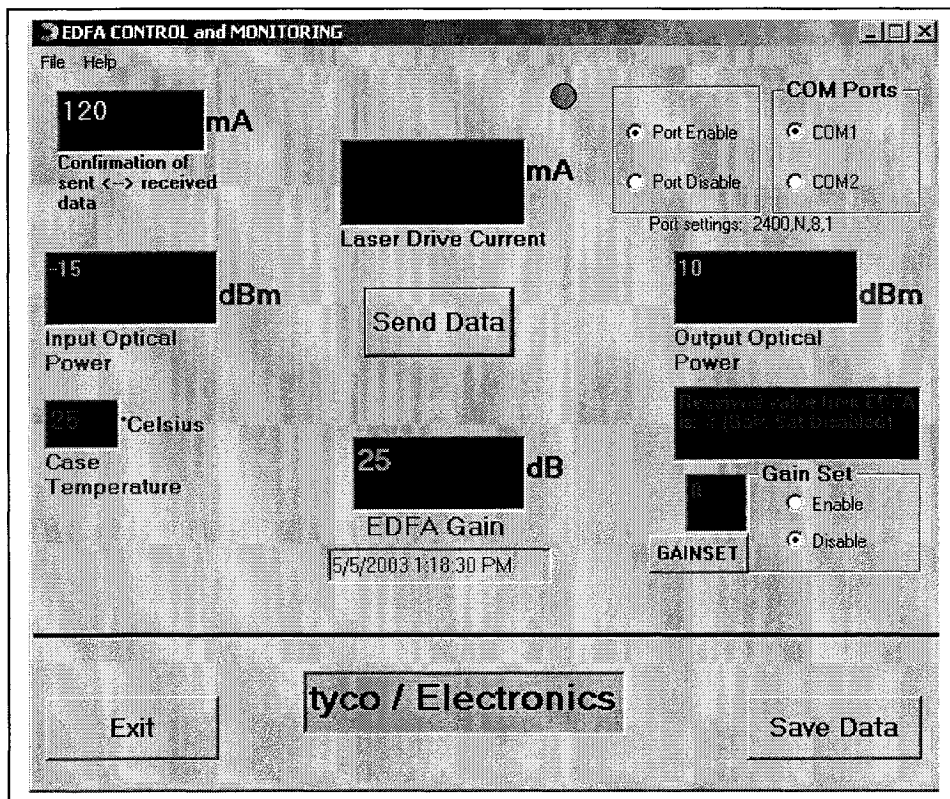


Figure 3.2b - The GUI for EDFA control and monitoring

How to communicate with the EDFA

The interface used to communicate with Tyco's EDFA is RS232 serial communication. The Serial Input (receive data pin) of the EDFA module is pin 16, whereas pin 29 is dedicated as a Serial Output (send data pin). Any PC Serial COM Port (COM1, COM2) can be used for the RS-232 communication between PC and EDFA Module.

Data is sent and received in asynchronous format using 8 data bits; no parity and one stop a bit (8N1). The settings for COM Port should be:

Bits per second:	2400
Data bits:	8
Parity:	None
Stop bits:	1
Flow Control:	None

Laser drive current:

To transmit the value of the laser drive current, send one-character string serially at a value that represents the ASCII character of the number 255 followed by one-character string value that represents the ASCII character of the number of desired drive current (**from 0 to 250 mA**).

Example - The RS232 communication of PC with EDFA module via Visual

Basic 6:

MSComm1.CommPort = 1

‘ Select COM1 port of the PC for communication

MSComm1.Settings = “2400,N, 8,1”

‘2400 baud, no parity, 8 data bits, 1 stop bit

MSComm1.PortOpen = True

‘Enable the port for communication

MSComm1.Output = Chr\$(255) & Chr\$(vout)

‘Where vout is the desired drive current value selected from 0 to 250

The EDFA module knows that when receiving the 255 character, next value is the desired laser drive current.

Gain set using software:

Send one-character string serially at a value that represents the ASCII character of the number **100** followed by one-character string value that represents the ASCII character of the number 0 or 1 for the **gainset (0 for disabled or 1 for enabled)**. The gainset feature is used for setting the gain of the EDFA module using software.

MSComm1.Output = Chr\$(100) & Chr\$(gainset)

‘Where gainset can be 1 for enable and 0 for disable

Gain set using hardware:

Hardware gain set is achieved by applying the TTL logic high (5 VDC) to the Set Gain (Pin 26).

The order and format of the sent data from the microcontroller to PC:

Sent the ASCII characters in 8-bit format in the following order: **laser drive current value, input pindiode1 reading, output pindiode 2 reading, temperature, gainset and 10.**

Example of the microcontroller code sending data to PC:

```
SEROUT S1, N2400, [vout_ret, diode1, diode2, temperature, gainset, 10]
```

Where S1 corresponds to Serial Out pin of the EDFA module

Microcontroller

The **PIC16F877** microcontroller unit (MCU) from **Microchip Technology PICmicro®** was selected for control and monitoring of the **EDFA module**. And the compiler used was PicBasic Pro (PBP) Compiler from MicroEngineering Labs. Some of the PBP features include direct access to all of the PICmicro MCU registers, real **If Then Else Endif** statements, hierarchal expression handling, I2C instructions to access more external devices including serial EEPROMs, (bit, byte and word) arrays, ability to perform math and logical functions with 16 bit precision and rich instruction set library.

The PBP compiler is capable of programming a variety of PICmicro MCUs from 8 to 84 pins, where the user/programmer has direct access to all of the PICmicro microcontroller registers.

PIC16F877 features

The PIC16F877 is a high performance RISC CPU, 8-bit microcontroller.

Some of the PIC16F877 features include operation speed of DC – 20MHz, 35 instructions, 33 I/O ports (A, B, C, D, E), multi-channel 10-bit Analog to Digital Converters, 8x1k Flash memory (code space), internal EEPROM data memory (256bytes), RAM (368 bytes), 2 Pulse Width Modulators (PWM) with 10 bit resolution, interrupt capabilities, timers, serial communication capabilities, 5V In-Circuit Serial Programming capability, wide supply operation range covering from 2 to 5.5V and low power consumption.

A snapshot of the initialization code and A to D readings for the EDFA is provided below:

```
*****
```

' EDFA control and monitoring using PIC16F877 (firmware)

```
*****
```

```
Include "Modedefs.Bas"
```

```
Define OSC      20
```

```
Symbol S0=PORTC.7      ' receive from PC
```

```
Symbol S1=PORTC.6      ' transmit to PC
```

```
Symbol TEC_disable= PORTC.0    ' TTL high disables the TEC
Symbol Amp_Off=PORTC.1         ' TTL low disables the amplifier
Symbol Loss_Pin=PORTD.0        ' Loss of input power alarm - TTL high
Symbol Loss_Pout=PORTD.1       ' Loss of output power alarm - TTL high
Symbol EDFA_Temp=PORTD.4       ' EDFA temperature alarm (TTL high when
' T>65°C)
Symbol Set_Gain=PORTD.5        ' TTL high - to set desired gain
Symbol Gain_Ack=PORTD.6        ' TTL high - acknowledgment of gain set
Symbol TEC_Amp_Off=PORTD.7     ' TTL high - to disable TEC+Amplifer
' Configure Port A for Analog to Digital Conversion
TRISA=255                       ' Set all PORTA pins to inputs
ADCON1 = 0                       ' PORTA is analog
Define ADC_BITS 10               ' set number of bits to 10 for A to D result
Define ADC_CLOCK 2               ' Set clock source to Fosc/32
Define ADC_SAMPLEUS 50           ' Set sampling rate of 50 microseconds
ADCON1.7=1                       ' Result right justified
...
ADCIN 0,diode1                   ' Read input pin diode and store the value in
' variable diode1
Pauseus 5                         ' wait for 5usec
ADCIN 1,diode2                   ' Read output pin diode and store the value in
' variable diode2
Pauseus 5                         ' wait for 5usec
```

ADCIN 2, temperature ' Read temperature of the module and store the
.... ' value in variable called temperature

EDFA Design Features

- High gain
- Wide bandwidth of operation ~40 nm
- Low noise figure
- Isolated optical input and output
- Input and output optical power monitoring
- Gain Flatness
- Automatic Power Control
- Low power consumption
- Single 5V operation
- Advanced microprocessor design
- Serial interface & communications
- PC control of the module through RS-232 and software
- TTL – compatible alarm outputs (health indicators)
 - Loss of input power alarm
 - Loss of output power alarm
 - EDFA module temperature alarm
 - Thermoelectric Cooler (TEC) enable/disable
 - Pump temperature alarm

For additional information about EDFA specifications please refer to **Appendix A**.

3.4 Design of the Optimized C-band Booster EDFA

The key features considered while designing the Booster C-band EDFA were the high output optical power (longer network reach without amplification), gain flatness with respect to the wavelengths selected (1530 nm to 1563 nm) in order to minimize the gain fluctuations in other amplification stages within the WDM system and the cost. As described in the Experimental Results for the Optimized C-band Booster EDFA section 4.2 (refer to pg. 77), the most suitable input power levels for the lowest gain fluctuations are determined accordingly. The design is optimized using only one high power pump and short EDF length.

The temperature dependence of the gain in EDF fibers when pumped at 1480 nm was shown to be around -0.07 dB / °C between -20 and 85°C , while for 980 nm pumping are negligible [22]. Therefore, the EDFA forward pumping scheme with 980 nm pump laser and highly doped EDF fiber was chosen.

The high power 980 nm pump laser and the erbium-doped fiber type were selected to accommodate the key features of this design, its high output power and gain flatness. Liekki EDF fiber with high erbium concentration selected was very suitable for 980 nm pumping and for shorter EDF length C-band Booster EDFA designs. For Liekki EDF specifications please refer to Appendix A.

Control electronics developed for the Optimized C-band Gain Flattened EDFA are also adopted in this design to provide automatic power control for maintaining the output power levels locked within limits (± 0.25 dB) of the desired set value.

3.5 Design of the Optimized C-band EDFA for Pre and In-line amplification

The primary design option for the In-line amplification scenario is the Optimized C-band Gain Flattened EDFA (refer to section 3.3, pg. 46). However, for the WDM system configurations where the multi-channels are de-multiplexed into narrow bands and/or single channels, amplified and multiplexed again (refer to Figure 3.3a below), using the EDFA in Automatic Power Control mode enables the gain flatness control of these narrow bands and/or single channels (if the gain tilt is not very large). Therefore, the secondary design option of the Optimized C-band EDFA for Pre and In-Line amplification is proposed, offering similar results to the Optimized C-band Gain Flattened EDFA with reduced cost due to shorter EDF lengths.

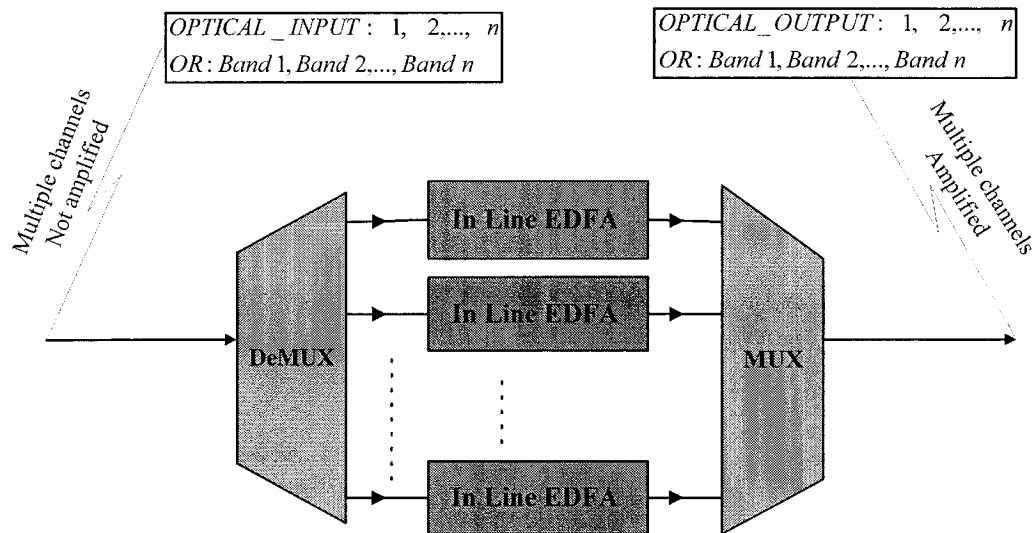


Figure 3.3a - Scenario for possible use of the Optimized C-band EDFA as a In-Line EDFA

Other possible scenarios for use of the optimized C-band EDFA is the option presented in Figure 3.3b below, where the EDFA is being utilized for pre-amplification due to its low NF with typical values of 4 dB. For the experimental results refer to section 4.3 (refer to pg.80).

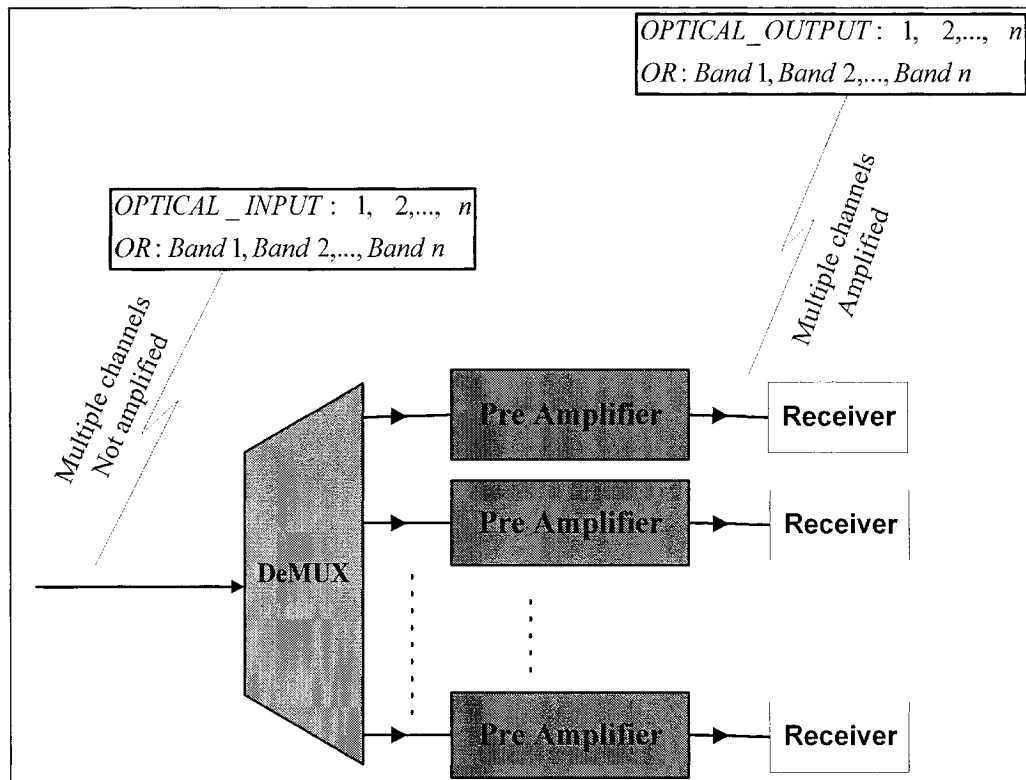


Figure 3.3b - Scenario for possible use of the Optimized C-band EDFA as a Pre-Amplifier

3.6 Design of the 8-channel DCE

The DCE uses attenuation to create an optical loss in order to compensate for the optical input signal imbalances. The DCE with embedded control electronics acts as a “smart attenuator” which uses feedback control and channel-monitoring in order to calculate how much attenuation is needed at a given wavelengths to produce uniform optical output signal.

The main parts of the DCE are:

- MEMS VOAs
 - Micro-electromechanical system VOA used for attenuation of input signals; Voltage controlled devices: 0 to 5 VDC corresponding to 0 to 30 dB of attenuation (refer to Appendix A for Santec MEMS VOA specification)
- Pin diodes
- Logarithmic Amplifiers
- Microcontroller
- A to D converters
- D to A converters
 - Used in conjunction with the microcontroller to control the VOAs

The DCE design and microcontroller code was written as per the DCE algorithm (refer to Fig. 3.4a, pg. 68 - DCE Algorithm) and the functional block diagram of the DCE is presented in Fig. 3.4b, pg. 69.

DCE Algorithm

The DCE algorithm below represents (captures) the general idea behind the microcontroller coding and DCE functionality.

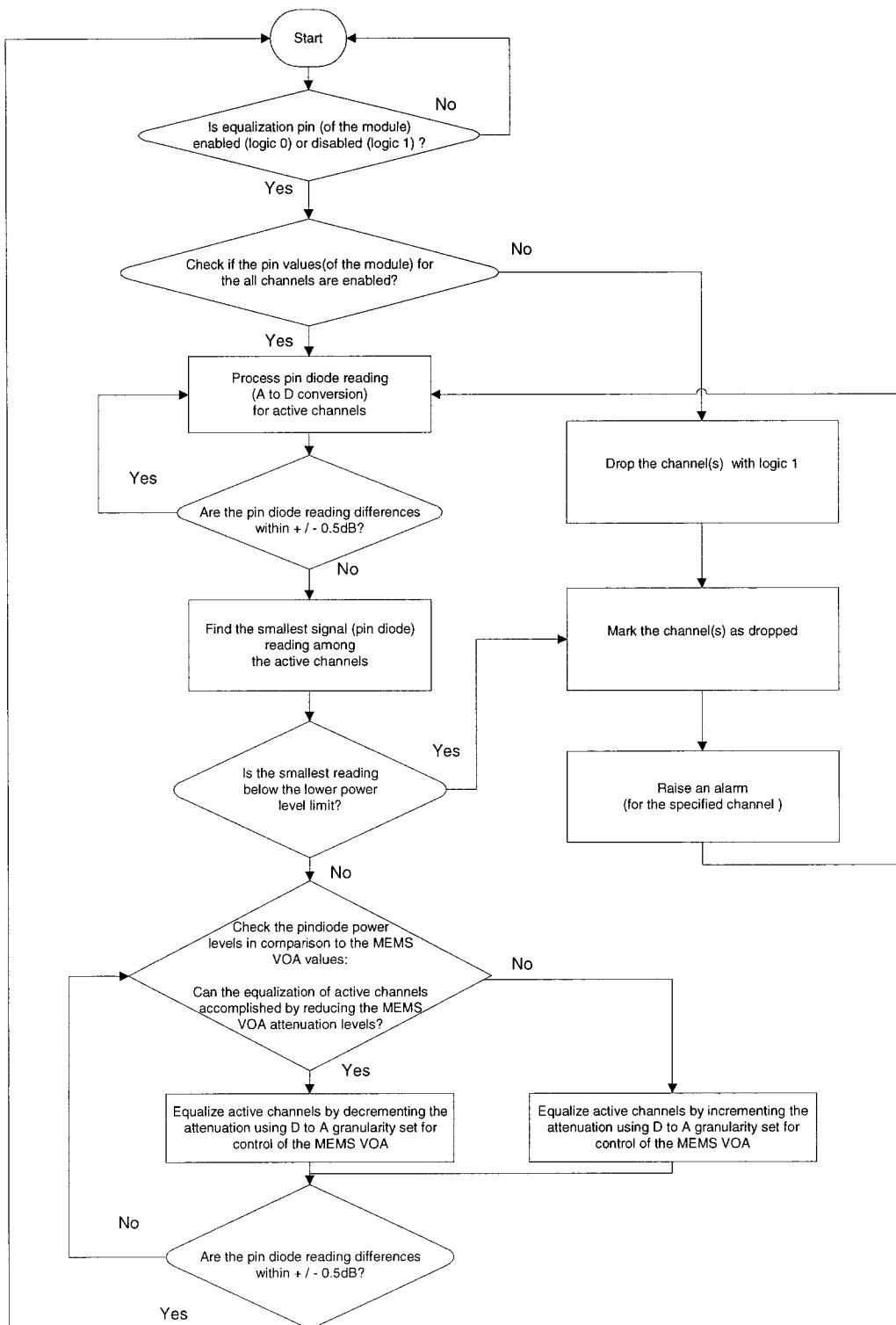


Figure 3.4a – DCE Algorithm

DCE Block Diagram

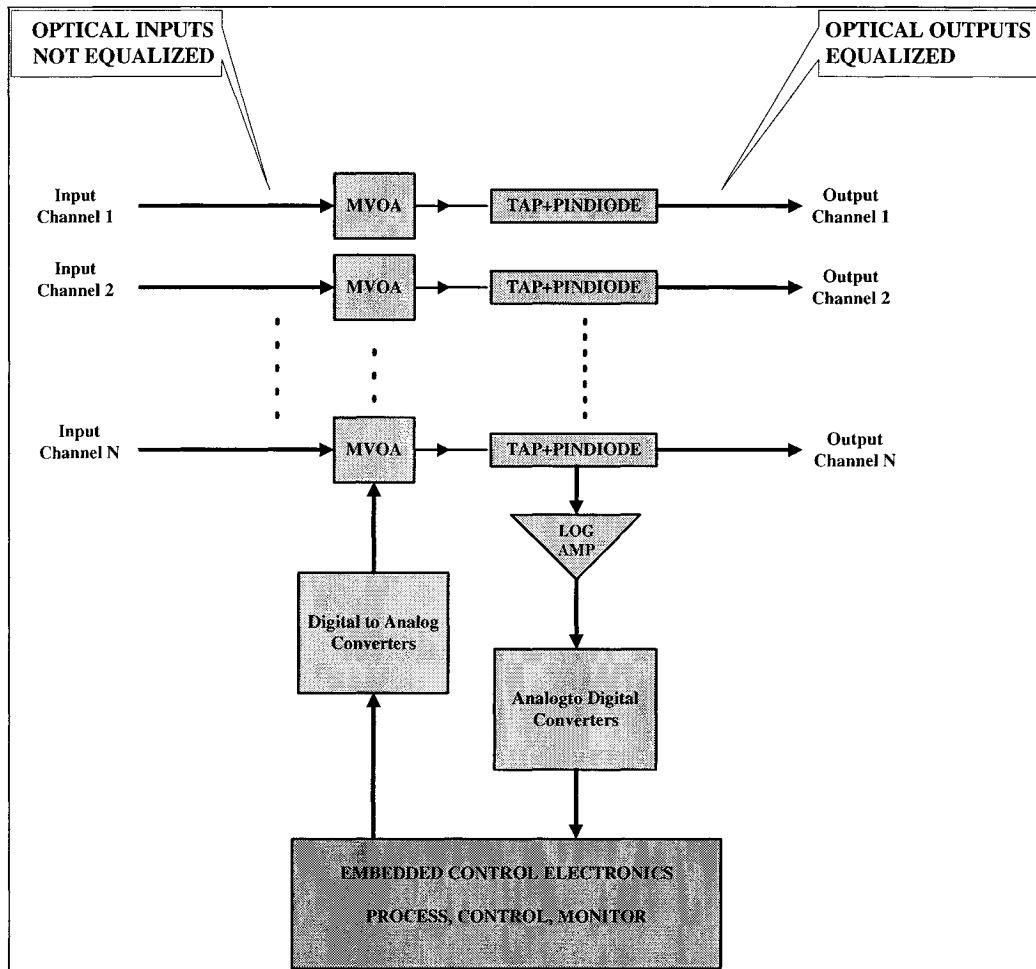


Figure 3.4b - DCE Block Diagram

The input power was calculated based on the VOA voltage applied, which corresponds to certain attenuation level. The Random Access Memory (RAM) of the microcontroller was used to store the final D to A value sent to MEMS VOA prior to last equalization, which is utilized for calculation of the optical input power (refer to Fig. 3.4b, input channels).

Chapter 3

The attenuation (dB) versus voltage curve for MEMS VOA was provided by Santec. Based on the attenuation values (voltage representation) of the MEMS VOA and the output power at the pin diode, the input power was processed and calculated within microcontroller. By using this design technique, input optical power level monitoring is possible without using any input pin diodes, utilizing only MEMS VOAs, output pin diodes and RAM within microcontroller (where the last D to A values of MEMS VOAs voltage reading are stored); the cost efficiency (reduction) in this case is equal to the price of 8 tap + pin diodes, 8 logarithmic amplifiers and 8 A to D converters.

3.7 Integration of the 8-channel DCE and Optimized C-band EDFA into a Smart Amplifier Solution

The high-level block diagram of the Smart Amplifier (refer to Fig. 3.5 below) consists of three main subsystems, which are the Optimized EDFA, 8-channel DCE and the embedded control electronics. Data processing, monitoring and control of the corresponding subsystems is achieved using microcontroller and its associated control circuitry. The Optimized EDFA has input and output pin diodes and is set to run on the APC mode. The 8-channel DCE consists of 8 VOAs (used to control the attenuation level of the incoming signals) and 8 tap + pin diodes (used to monitor the power level of signals).

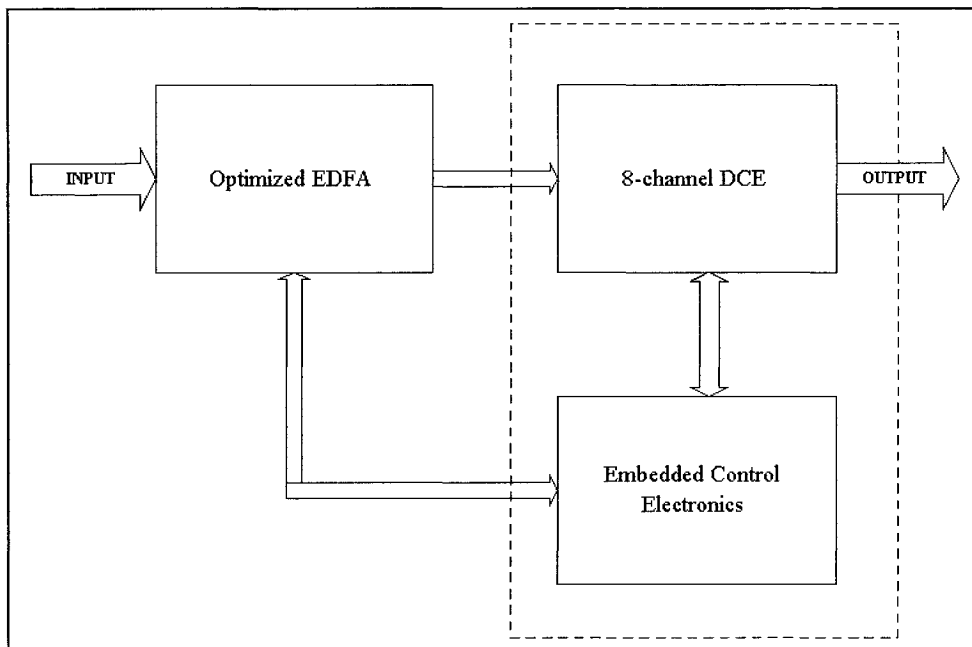


Figure 3.5 – High Level Block Diagram of the Smart Amplifier

The embedded control circuitry interacts with the DCE subsystem by monitoring the pin diodes (after amplification of weak signals with logarithmic amplifiers; processing amplified signals using A to D converters) and controlling the VOAs correspondingly as per the DCE algorithm (refer to Fig. 3.4a, pg. 68).

The amplification and equalization of the optical input signals is realized by the interaction of the Smart Amplifier subsystems. The optical input signals are first amplified by EDFA and then equalized by DCE. As a result, at the output of Smart Amplifier, optical power levels are amplified and equalized (refer to Fig. 3.6 below).

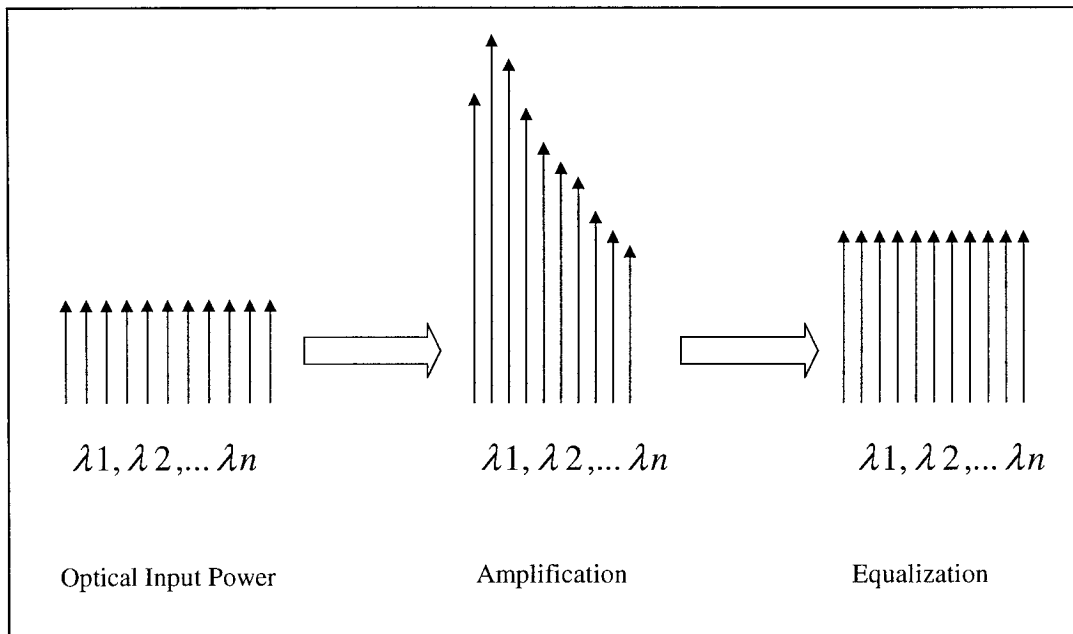


Figure 3.6 – Amplification and Equalization via Smart Amplifier

Chapter 4

The Experimental Results and Discussions

4.1 Experimental Results for the Optimized C-Band Gain Flattened EDFA without GFF

The typical gain flatness of the Optimized C-band Gain Flattened EDFA is less than 1.25 dB peak to peak (± 0.625 dB) for input optical powers of -15 dBm up to -8 dBm and maximum delta of gain of 1.62 dB (± 0.81 dB) for input optical power of -17 dBm. The Figure 4.1 below, shows the relationship between output and input optical power of the C-band Gain Flattened EDFA for different wavelengths of operation. The encircled area corresponds to the optimal gain flatness¹ results.

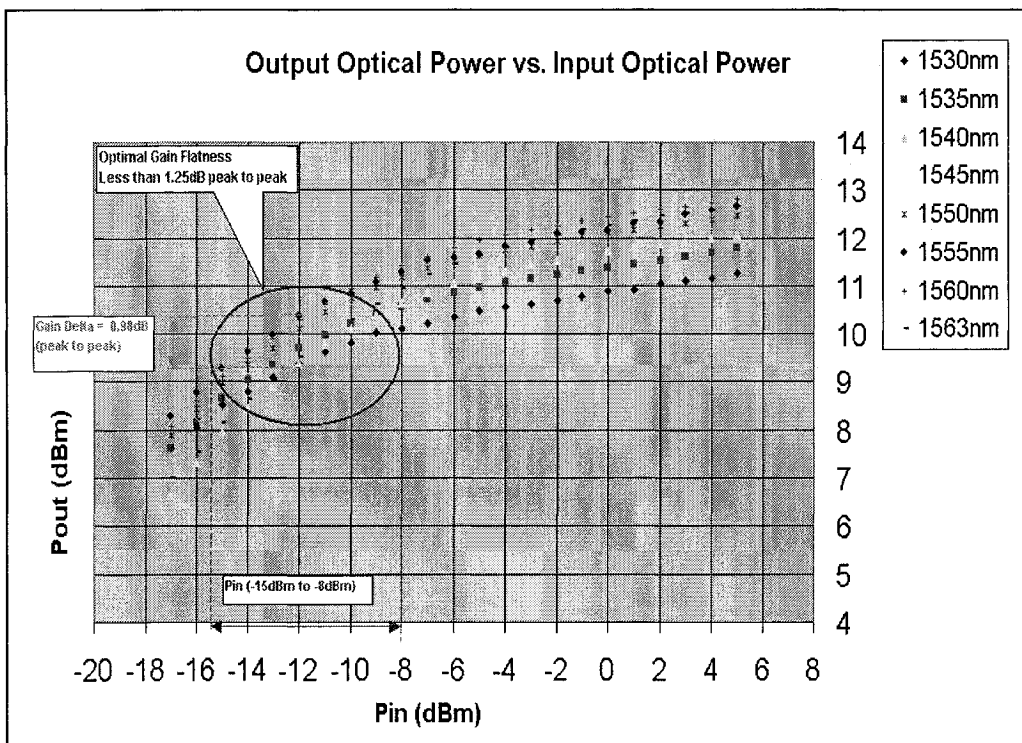


Figure 4.1 - Output Optical Power vs. Input Optical Power

¹ Gain flatness (delta of gain) is defined as the difference between the maximum output optical signal power at wavelength λ_x and the minimum output optical signal power at wavelength λ_y

The best gain flatness is achieved within the range of input power levels of -15 dBm to -8 dBm. Figure 4.2 below, shows the maximum delta of gain (gain flatness) for all wavelengths from 1530 nm to 1563 nm with respect to the input optical powers from -17 dBm to 0 dBm. The graph was built by checking the highest delta of change within the wavelengths covered for each particular input optical power.

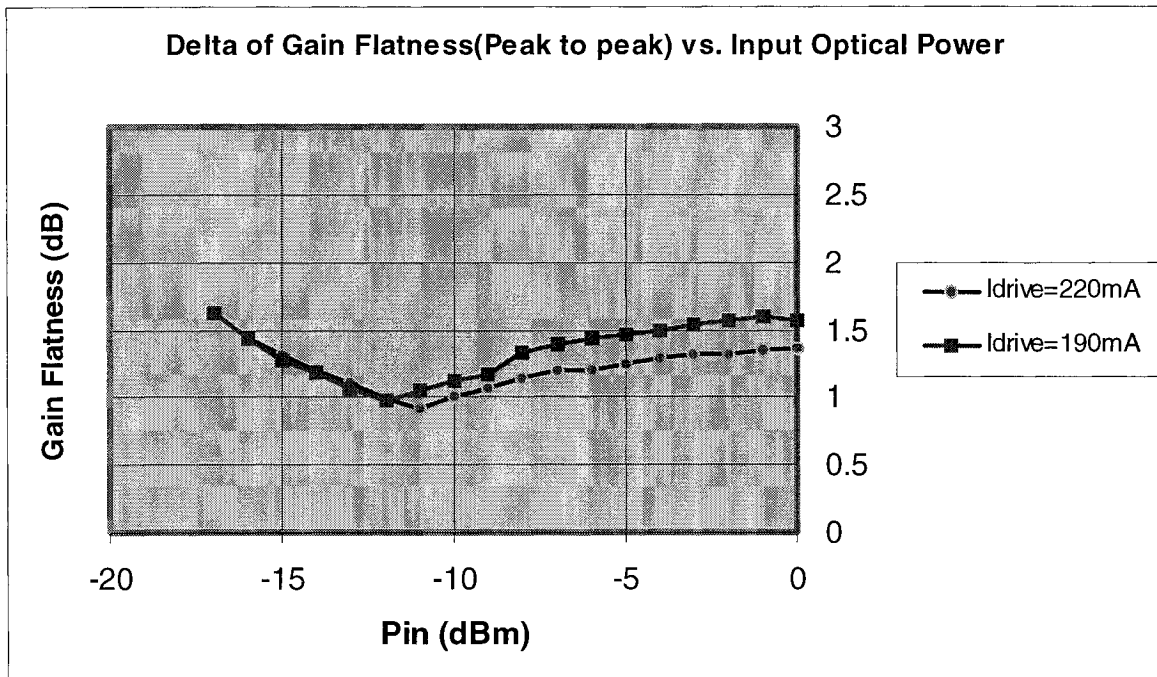


Figure 4.2 - Delta of Gain Flatness (peak-peak) vs. Input Optical Power

The test data for Gain vs. Wavelengths for pump laser drive currents = 220 mA is represented in the Figure 4.3 below. It shows the dependence of EDFA gain with respect to the wavelengths of operation (1530 nm to 1563 nm), which offers the performance of one optimized design and it is feasible for use within the Smart Amplifier Solution.

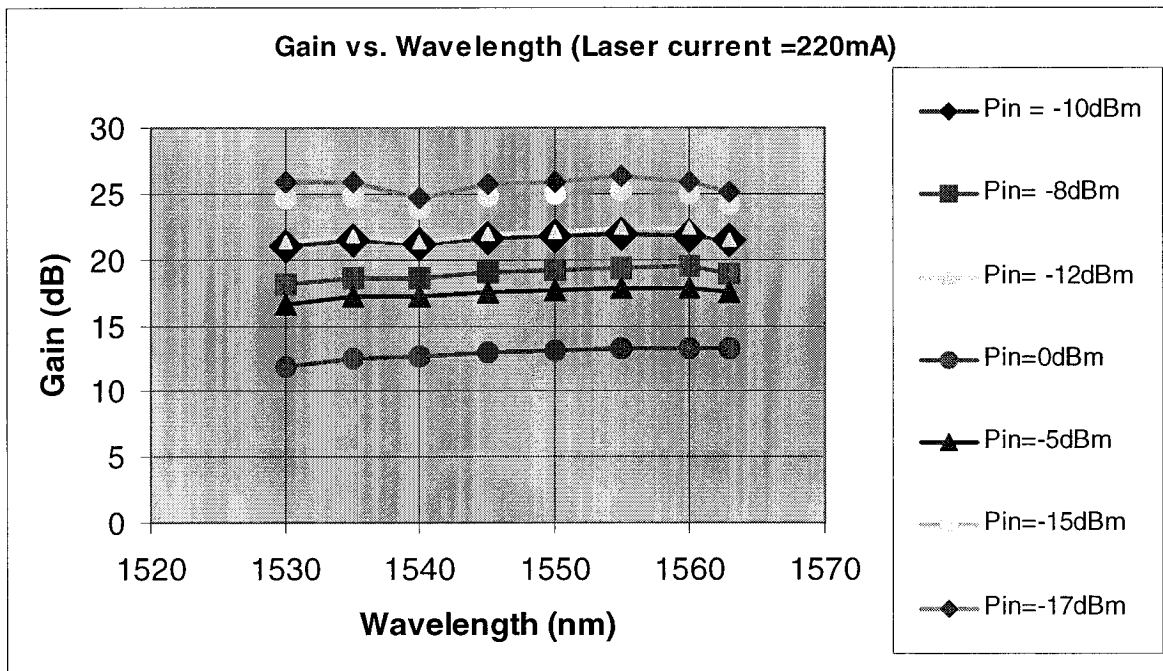


Figure 4.3 - Gain vs. Wavelength (Laser current = 220mA)

The Gain vs. Output Optical Power for different laser drive currents (corresponding to different 980 nm pump power levels) is shown in Figure 4.4 below. The amplifier gain increases as the laser drive current (I_{drive}) increases; therefore, the curve for $I_{drive} = 220$ mA corresponds to the highest gain levels and the curve for $I_{drive} = 150$ mA corresponds to the lower gain levels achieved with this particular design.

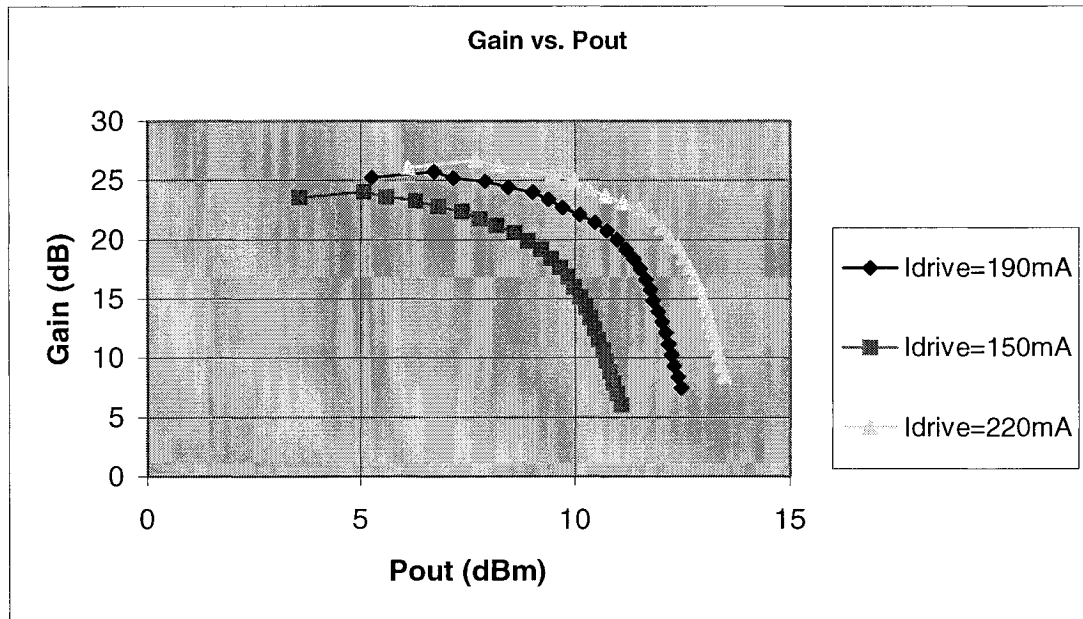


Figure 4.4 - Gain vs. Output Optical Power

4.2 Experimental Results for the Optimized C-Band Booster EDFA

The optimized solution was achieved using high power 300 mW (500 mA laser drive current) laser pump and Liekki Inc highly doped EDF with a length of 5 meters. The Optical Spectrum Analyzer resolution was set to 0.2 nm for better accuracy of the test data.

The encircled area (refer to Fig. 4.5 below) corresponds to the best suitable range for achieving the highest output powers and optimized gain flatness of the design with respect to wavelengths chosen for transmission within the C-band (1530 nm to 1563 nm).

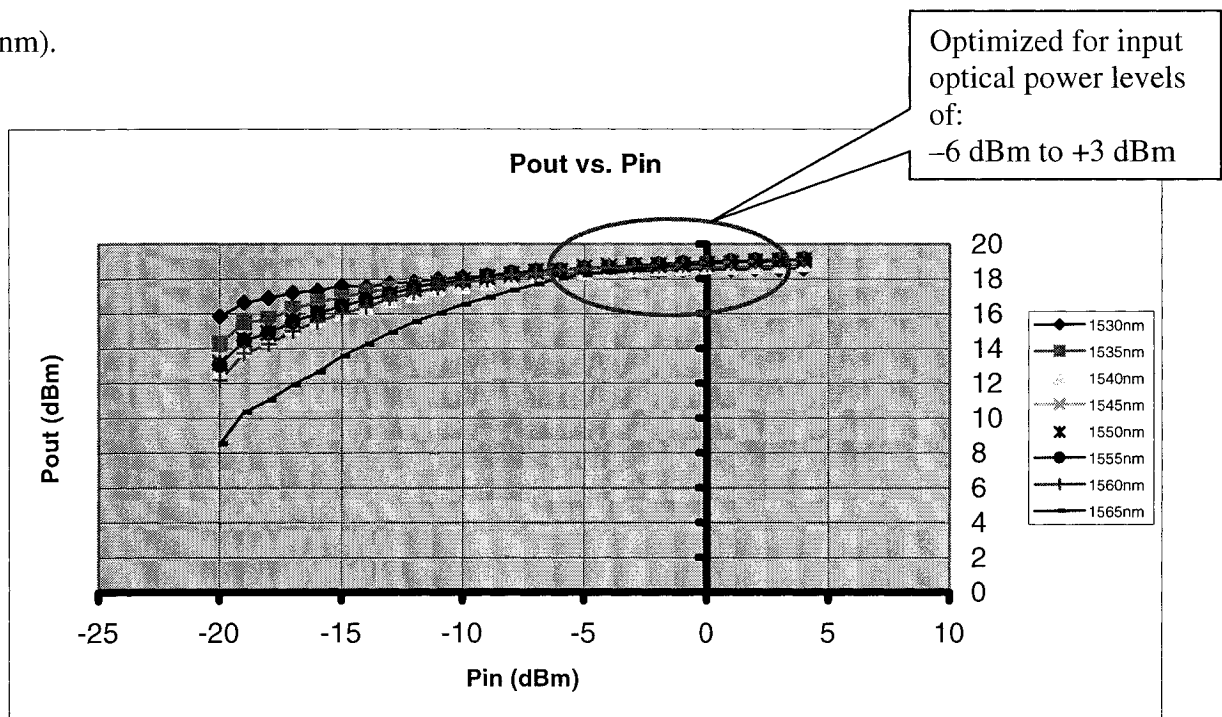


Figure 4.5 - Output Optical Power vs. Input Optical Power

The output power of the Optimized C-band Booster EDFA is approximately +18 dBm for optical input powers of +3 dBm to -6 dBm.

The maximum measured wavelength dependent loss (WDL) also known as a “gain tilt” for input optical powers of -6 dBm to +3 dBm is 0.54 dB within the C-band (refer to Fig. 4.5 pg. 77 and Fig. 4.6 below). The gain versus output optical power is shown in Figure 4.7 (refer to pg. 79), where typical gains of the amplifier range from ~ 25 dB to 33 dB for input powers of -20 dBm to +4 dBm measured at 1550 nm.

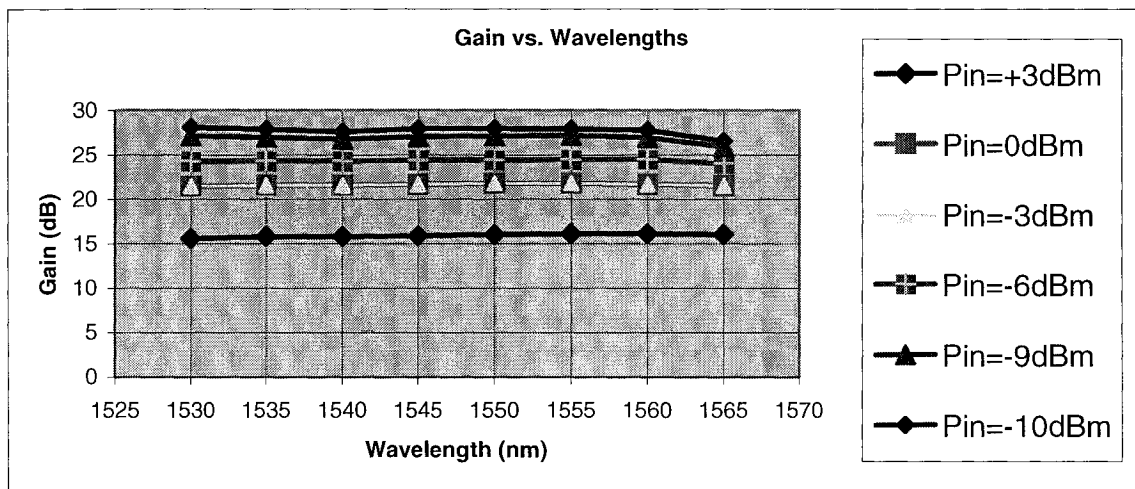


Figure 4.6 - Gain vs. Wavelength

For the input optical powers ranging from -7 dBm to -10 dBm the maximum measured gain tilt is 1.57 dB. Hence, the best suitable range of input optical powers to be used with this C-band Booster EDFA design is $+3$ dBm to -6 dBm.

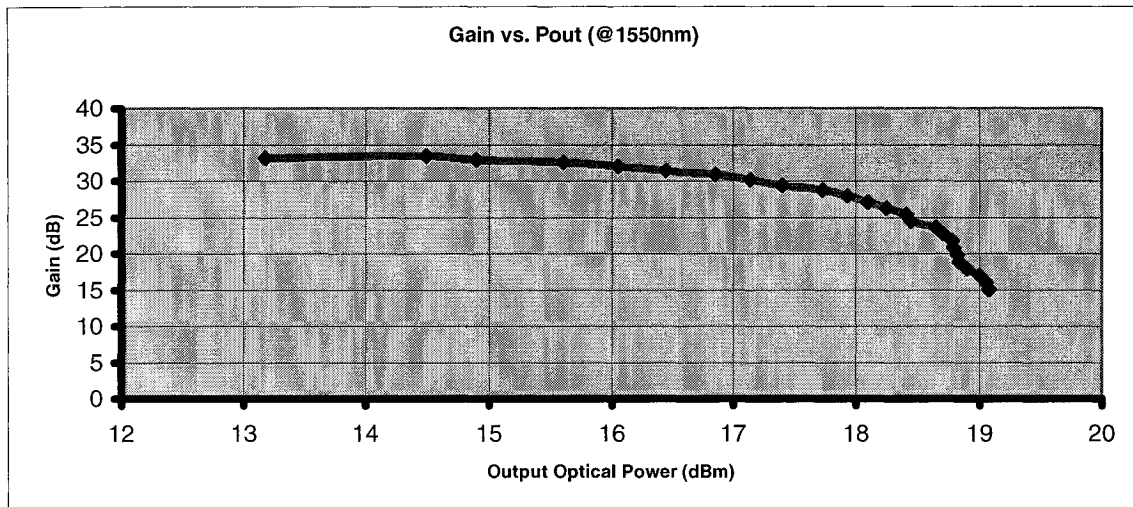


Figure 4.7 - Gain vs. Output Optical Power @1550nm ($P_{in} = -20$ to $+4$ dBm)

4.3 Experimental Results for the Optimized C-band In-Line EDFA

The optimized solution for the In-Line EDFA was chosen after performing numerous tests with different EDF fibers from different manufacturers, taking into account the gain vs. output optical power for input optical powers of -30 dBm to -10 dBm while observing the WDL (gain tilt) of the amplifier compared to the Optimized C-band Gain Flattened EDFA. The lengths of EDF in the EDFA affect the cost of the unit. Therefore, the performance of the unit is optimized for short lengths of EDF. The design options, using EDF from two different manufacturers were considered.

In-Line EDFA design using Liekki EDF

The Figure 4.8 below, shows the relationship of Gain versus Output Optical Power at 1550 nm wavelength for the In-Line EDFA design using 3 meters of Liekki EDF.

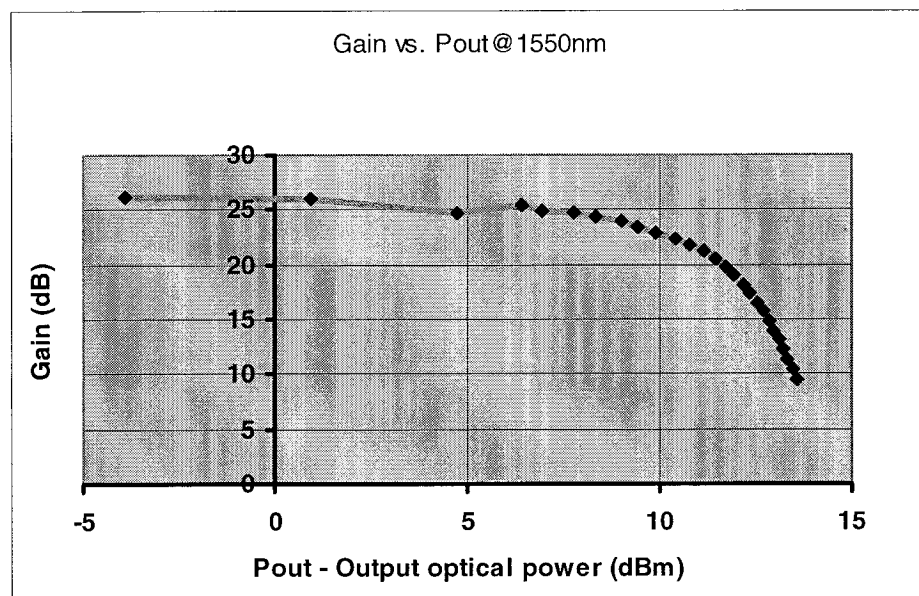


Figure 4.8 - Gain vs. Pout using Liekki EDF

The Figure 4.9 below, shows the relationship of Gain vs. Wavelengths for the Input Optical Power of -20 dBm, for the In-Line EDFA using 3 meters of Liekki EDF.

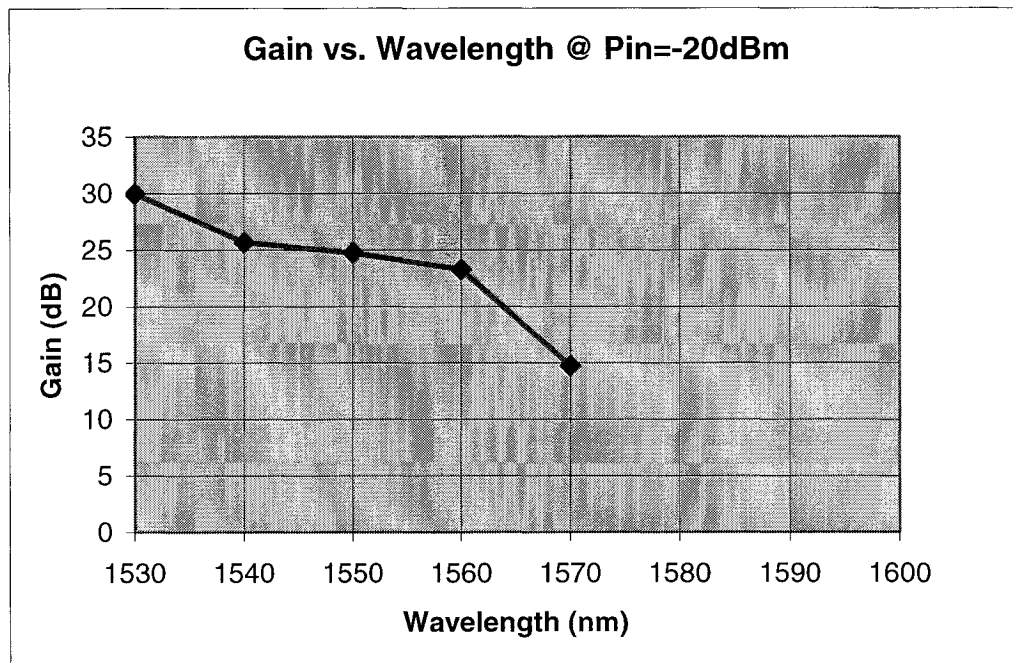


Figure 4.9 - Gain vs. wavelength using Liekki EDF

In-Line EDFA design using Manufacturer A EDF

The Figure 4.10 below, shows the relationship of Gain vs. Wavelength for the In-Line EDFA design using 3 meters of EDF from Manufacturer A.

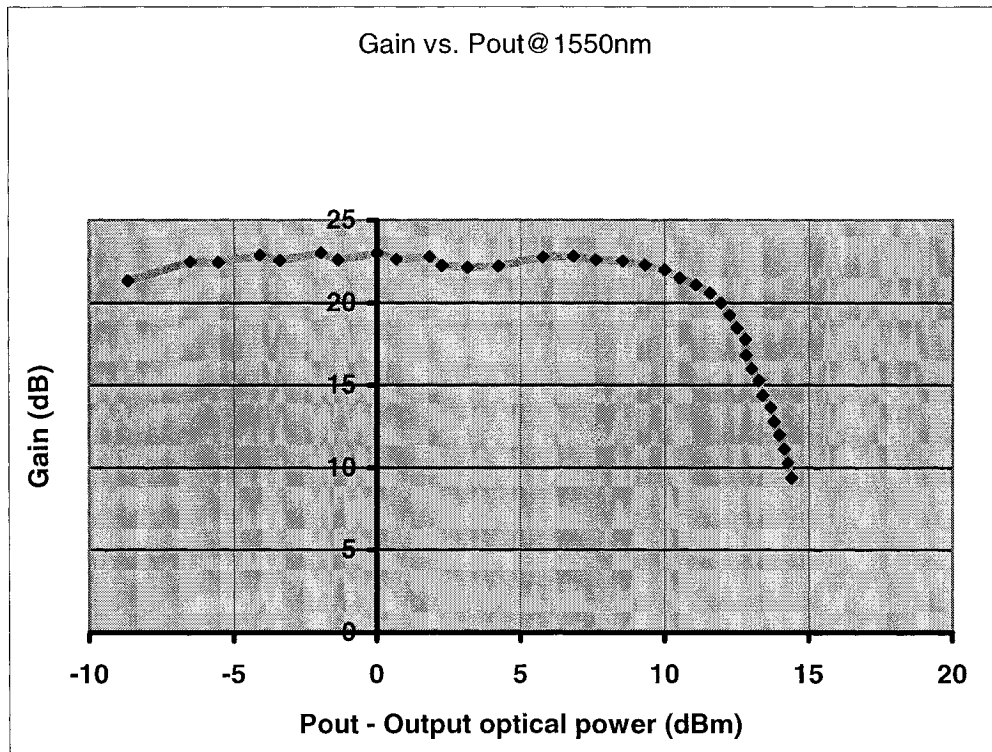


Figure 4.10 - Gain vs. Pout using EDF from Manufacturer A

The Figure 4.11 below, shows the relationship of Gain vs. Wavelengths for the Input Optical Power of -20 dBm, for the In-Line EDFA using 3 meters of Manufacturer A EDF.

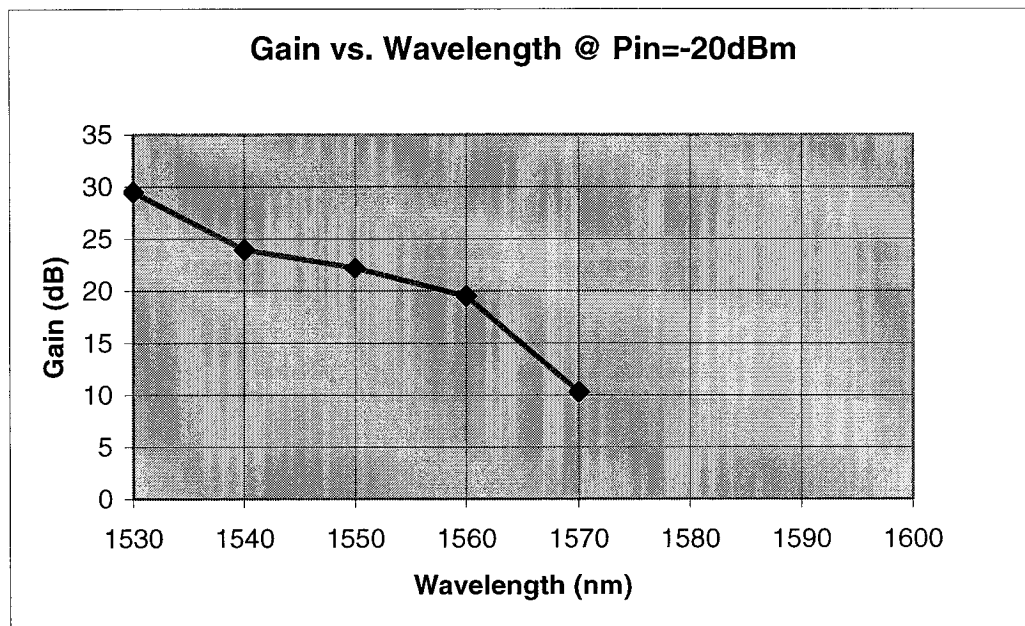


Figure 4.11 - Gain vs. wavelength using Manufacturer A EDF

After the comparison of the unit performance, the best performer chosen for this design was the In-Line EDFA using 3 meters of Liekki EDF. The name of other manufacturer was not mentioned but referenced as Manufacturer A.

The selection criterion was based on the performance of the unit per EDF length, considering the gain profile, WDL (gain tilt) and the price of unit per EDF length. All other parameters of the In-Line EDFA design were unchanged throughout the experimenting. For information about the C-band In-Line EDFA specifications please refer to Appendix A.

4.4 Experimental Results for the 4-channel DCE

Testing of the DCE prior to implementation of the Smart Amplifier Solution was done according to the DCE Block Diagram (refer to Fig. 3.4b, pg. 69). Four optical sources (optical input) and power meters (optical output readings) were used to perform the testing.

INPUT: NOT EQUALIZED

Test number	Input 1 (dBm)	Input 2 (dBm)	Input 3 (dBm)	Input 4 (dBm)	Max. Delta (dB)	Min. Delta (dB)
1	-8.45	-9.8	-5.4	-11.67	6.27	1.35
2	-15.5	-9.85	-12.71	-19.69	9.84	2.79

OUTPUT: EQUALIZED (USING DCE)

Test number	Output 1 (dBm)	Output 2 (dBm)	Output 3 (dBm)	Output 4 (dBm)	Max. Delta (dB)	Min. Delta (dB)
1	-11.41	-11.46	-11.26	-11.7	0.44	0.05
2	-20.13	-20.21	-19.34	-19.69	0.87	0.08

The results of both DCE tests indicate that the maximum delta of power difference at the input of DCE prior to equalization is 6.27 dB for test number 1 and 9.84 dB for test number 2. After the DCE is enabled and equalization takes place, the maximum

delta of power difference is 0.44 dB for test number 1 and 0.87 dB for test number 2 respectively.

Graphical Representation of DCE Test number 1 data

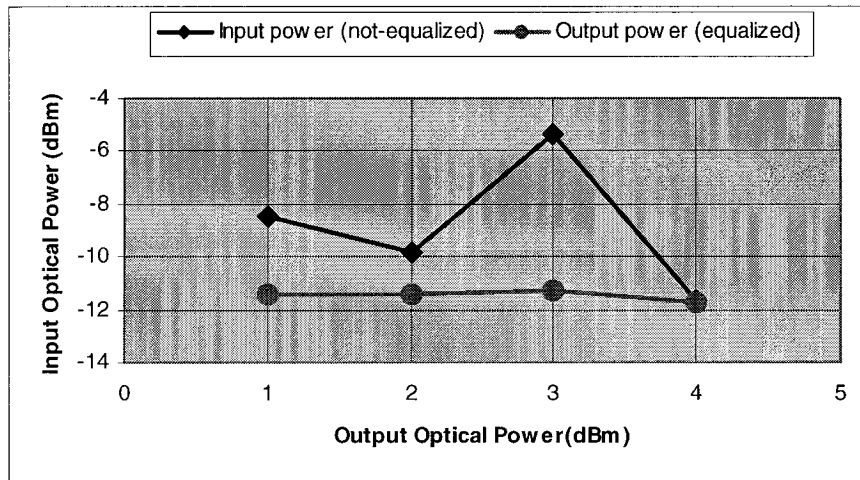


Figure 4.12 – DCE test nr.1

Graphical Representation of DCE Test number 2 data

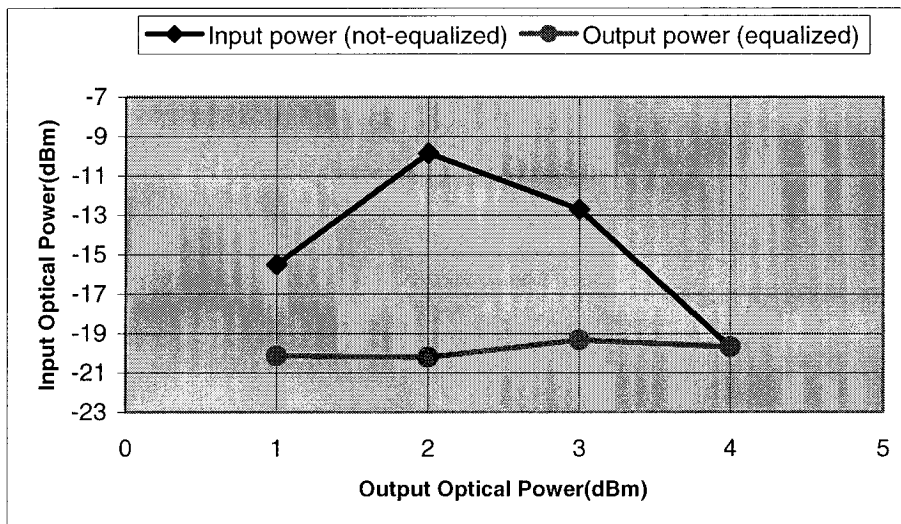


Figure 4.13 – DCE test nr.2

4.5 Experimental Results for the 4-channel DCE and Optimized C-band EDFA (C-band Smart Amplifier Solution)

Smart Amplifier Test Setup

The Smart Amplifier test setup was accomplished as per the block diagram of the Smart Amplifier design (refer to Fig. 3.1 pg. 38). Figure 4.14a below, is the test setup used to perform necessary measurements in order to validate the design.

Three C-band Tunable Laser Sources (TLS), one OSA, 4-band MUX/DeMUX (two multiplexers and one demultiplexer) with center wavelengths at 1530 nm, 1540 nm, 1550 nm and 1560 nm and bandwidth of approximately 6.6 nm were used to test the Smart Amplifier design consisting of one EDFA and 4-channel DGE module with control electronics.

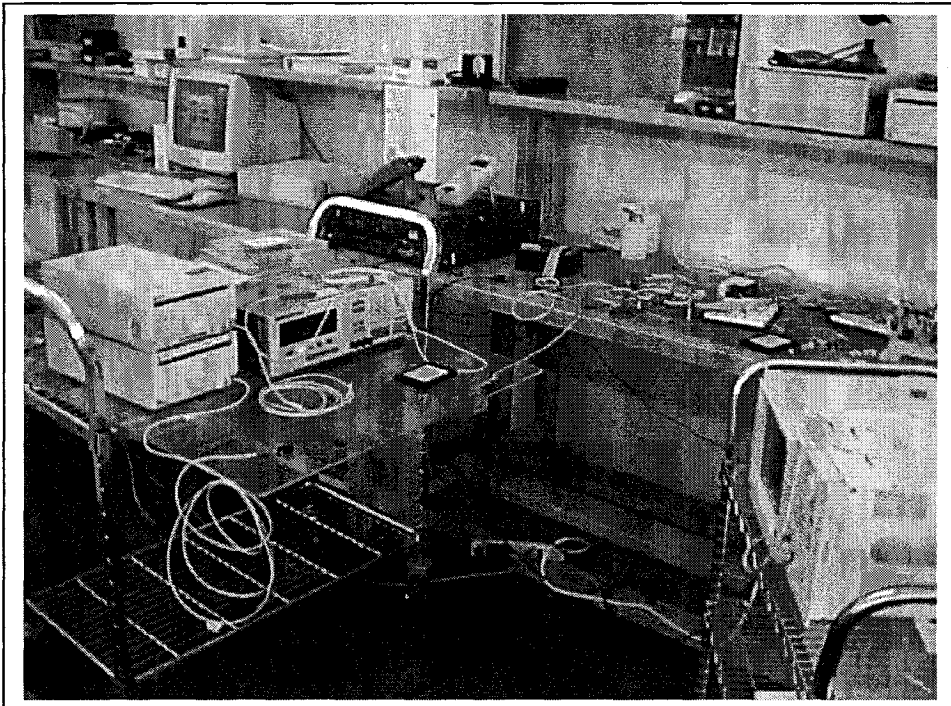


Figure 4.14a – Smart Amplifier test setup

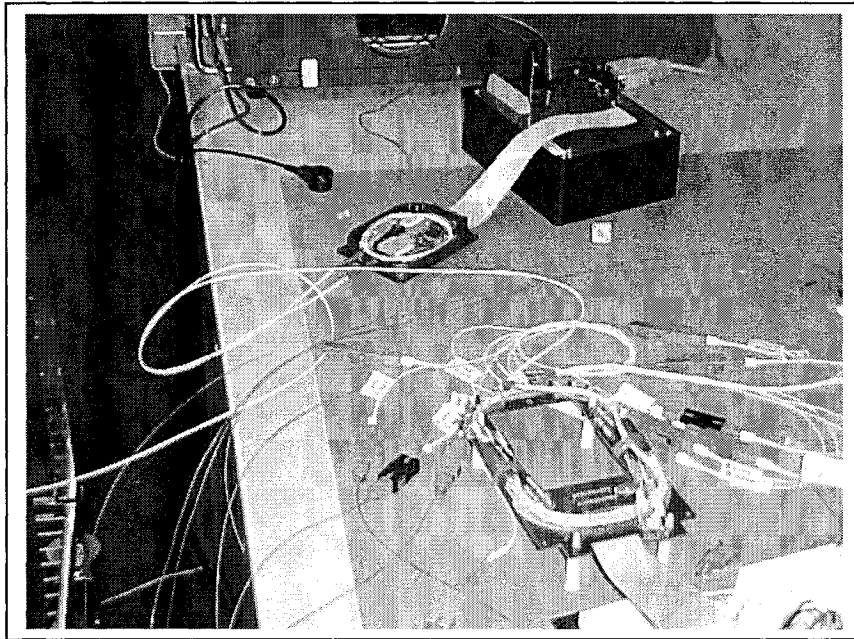


Figure 4.14b – Smart Amplifier test setup

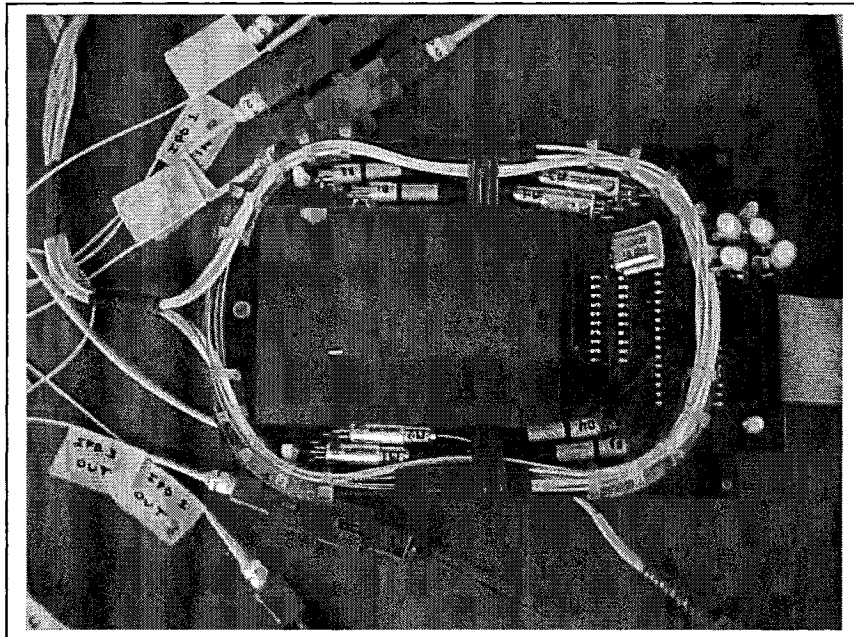


Figure 4.15a – DGE module (top)

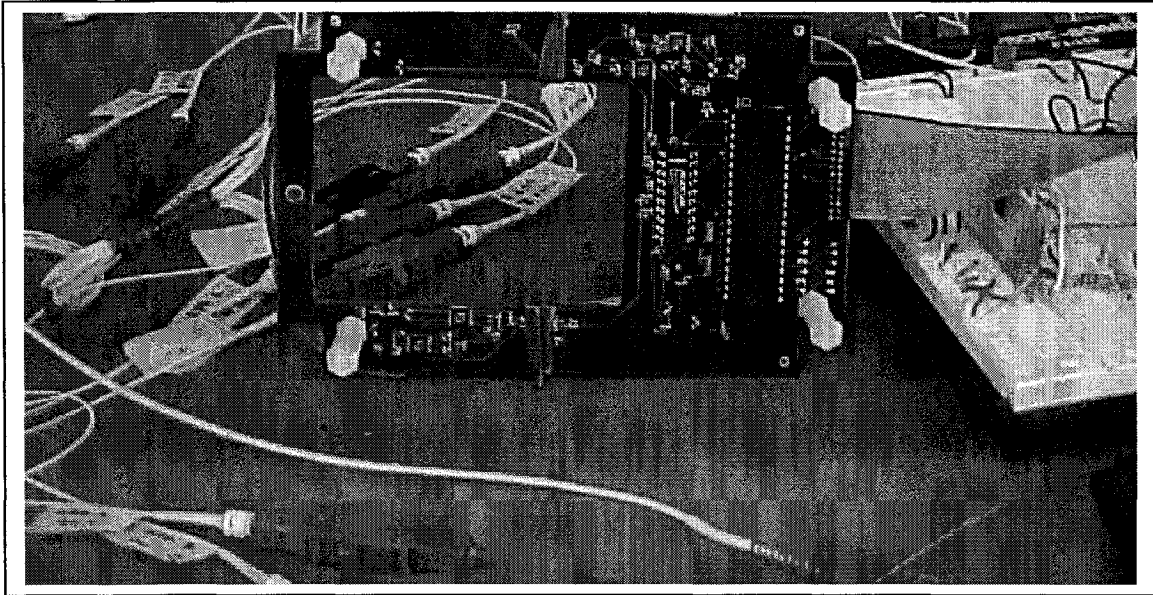


Figure 4.15b – DGE module (bottom)

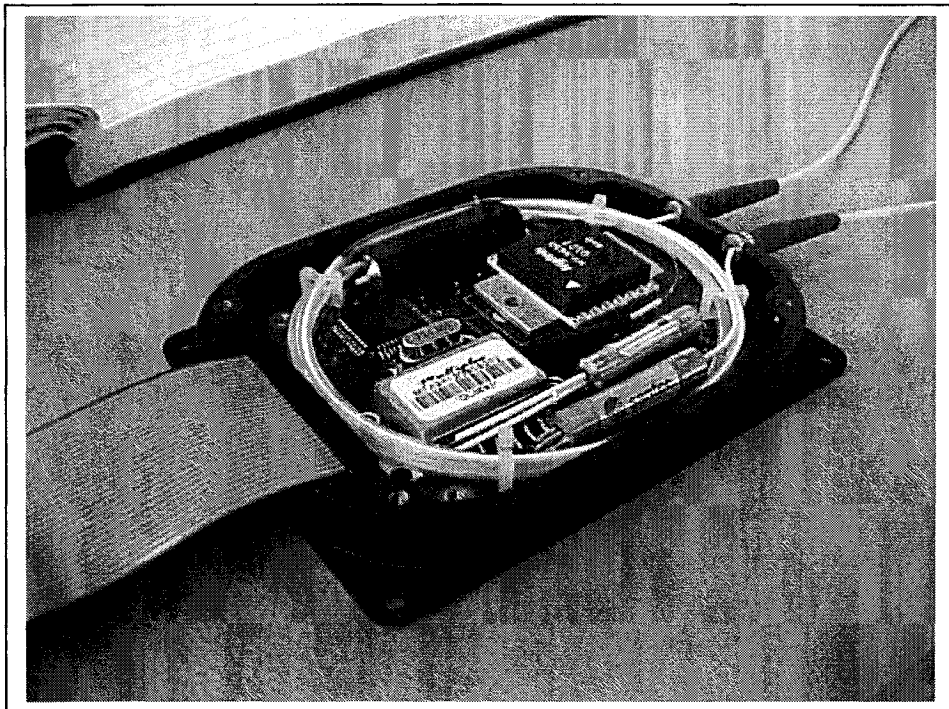


Figure 4.16 – EDFA module

The ASE of the EDFA was used as the source for the input to the multiplexer and the results of the C-band EDFA band pass profiles before and after the equalization are shown below, in Figure 4.17 and Figure 4.18 respectively.

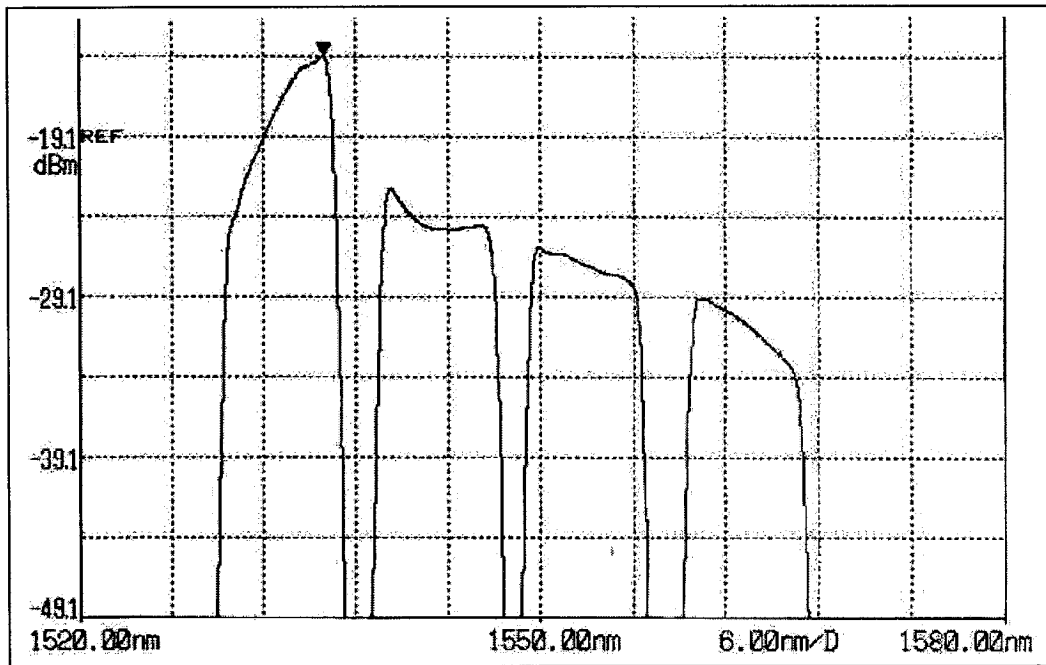


Figure 4.17 – EDFA band pass profiles not equalized

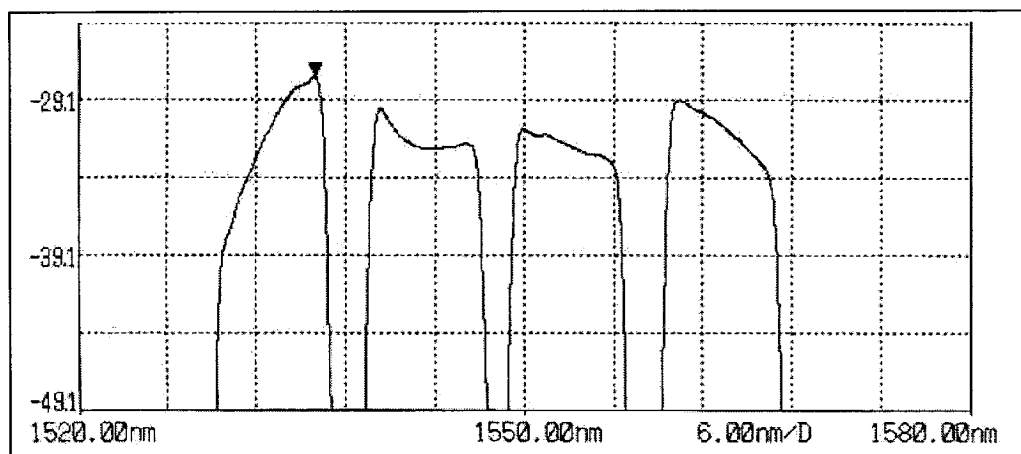


Figure 4.18 – EDFA band pass profiles equalized

The output optical power results in Figure 4.19a below and Figure 4.19b (refer to pg. 91), where acquired using three different input signals centered at wavelengths: 1530 nm, 1540 nm and 1560 nm with the DGE module disabled - resulting in not equalized output power levels, and after the DGE module is enabled, equalization of the output power levels is observed (refer to Fig. 4.19b, pg.91). The delta of gain after equalization was less than +/-0.75 dB.

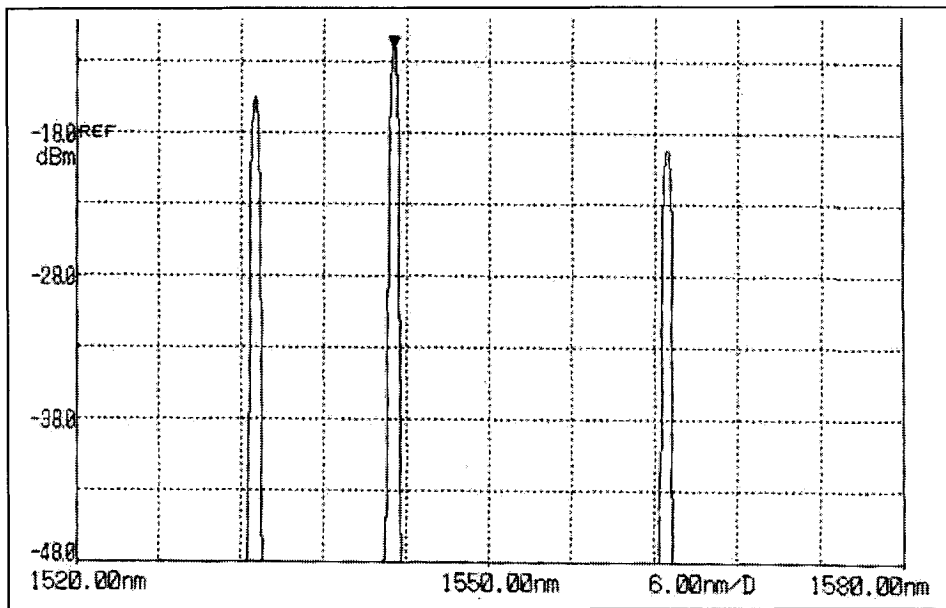


Figure 4.19a – Three C-band channels not equalized (DGE disabled)

The equalized channels are within +/-0.5 dB after being equalized by the DGE and the additional IL is due to the imbalanced insertion loss of the MUX 4-bands (1530 nm to 1560 nm) and connector losses. The probability to get a MUX/DeMUX with equal insertion loss between bands/channels is quasi impossible. Therefore, in order to further improve equalization tolerances of the Smart Amplifier design the effect of MUX IL and connector loss at the output of DGE must not be neglected in future designs.

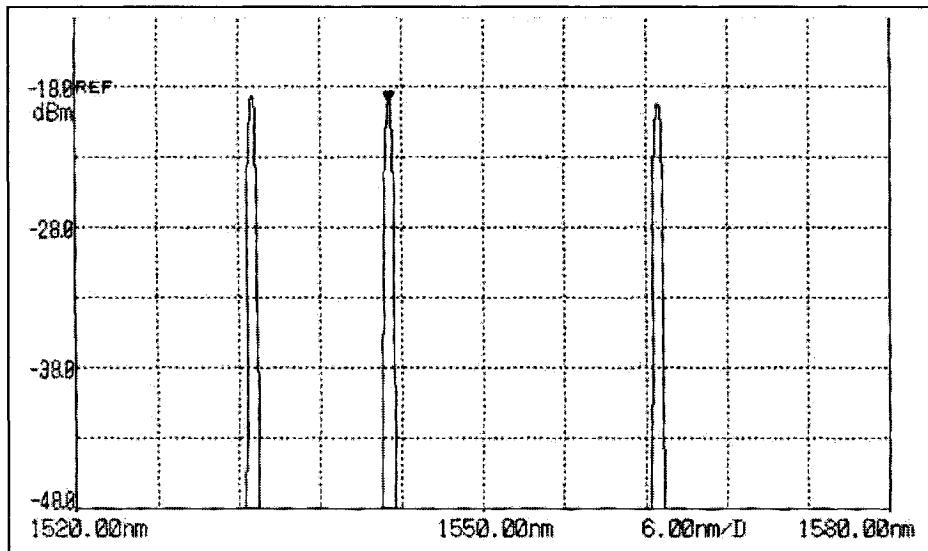


Figure 4.19b – Three C-band channels equalized (DGE enabled)

Chapter 5

Simulation Design Model and Results of the Smart Amplifier Adapting Optimized C+L band EDFA and DCE

5.1 OptiAmplifier Simulation Software

The modeling and simulation analysis of the optical subsystems and/or components is beneficial to be considered prior to prototype and design stages. The OptiAmplifier is an optical fiber amplifier and laser design simulation tool developed by Optiwave Inc.[23], which is a powerful simulation tool and can be used for this purpose.

OptiAmplifier is a powerful software tool, has a very friendly GUI (Graphical User Interface), with an extensive library of active and passive components (provided with realistic parameters). It is a very useful tool for simulation/design of optical fiber amplifiers, its performance optimization, significantly accelerating a design and development process [23].

Some of the specific OptiAmplifier applications are:

- Single and multi-stage EDFA design for CATV or WDM networks
- Reflective, split-band and bi-directional amplifiers
- Linear and ring fiber lasers
- ASE broadband sources
- Link budgets for optical service channels
- Gain-flattening filter calculations

5.2 Simulation Results for the Optimized C+L band EDFA using OptiAmplifier

The parallel configuration for the optimized C+L band EDFA was adopted using C-band in parallel with the L-band EDFA that is favorable but has a poor L-band EDFA efficiency [24]. To compensate for the inefficiency of L-band EDFA in the simulation design, a higher power pump was used. In practice though, it has been shown that tuning of the pump wavelength +/- 30 nm away from 980nm absorption peak provides 3-5 dB improvement in pump to signal conversion [25].

Simulation of the Optimized C+L band EDFA was done by using following major parameters for the pump lasers and EDF fibers:

Pump 1 (for C band) = 180 mW EDF1 = 6 meters

Pump 2 (for L band) = 300 mW EDF2 = 15 meters

This particular C+L band EDFA design is optimized as an inline amplifier of up to 64 channels with 100GHz spacing (32 in C-band, 32 in L-band). The GFF for C and L band were designed for optimized performance (best gain flatness) when the input power is set to -20 dBm.

The block diagram for the simulation is presented in Figure 5.1, pg. 94 (Optimized C+L band EDFA). The transmission filter at the input reflects the L band and transmits C-band

signals and the GFF filters were tailored to offer the lowest gain ripple within -20dBm input optical power.

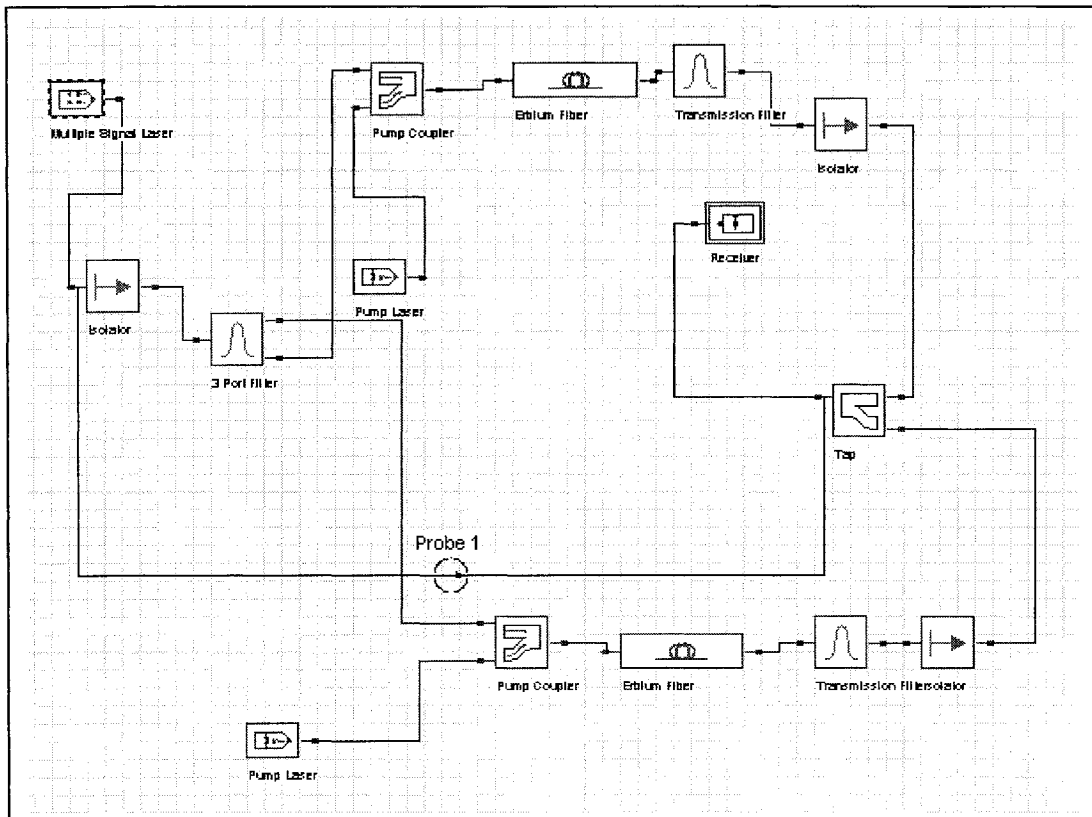


Figure 5.1 - Optimized C+L band EDFA

Optimized C+L band EDFA components necessary for the simulation are:

- Multiple signal laser (64-channels)
- Input and Output isolator
- Two 980 nm pump lasers (for C and L band) and pump couplers
- 3 port filter (pass C-band in one port and reflect L-band in the other port)

- Two GFF designed for C and L band
- 1x2 coupler (combines C and L band at the output)
- Receiver (pin diode)

The 32 C-band and 32 L-band channels with 100GHz spacing, selected from the DWDM ITU grid are:

From 1535.04 nm up to 1559.79 nm (C-band) and

From 1570.01 nm up to 1595.91 nm (L-band)

Typical gains of 15 to 20 dB are achieved with maximum NF = 4.5 dB. The **delta of gain** (difference between maximum and minimum output optical power) within all 64-channels is 0.23 dB at input power of -20 dBm. But, as the input optical power changes to lower or higher power levels, delta of gain also changes and gain non-uniformities are more apparent.

Figure 5.2 (refer to pg. 96) shows the optical output signal non-uniformities, gain imbalances of the C+L band EDFA without GFF for optical input power of -20 dBm. The simulation results presented, are prior to optimization of the EDFA design with respect to gain flatness.

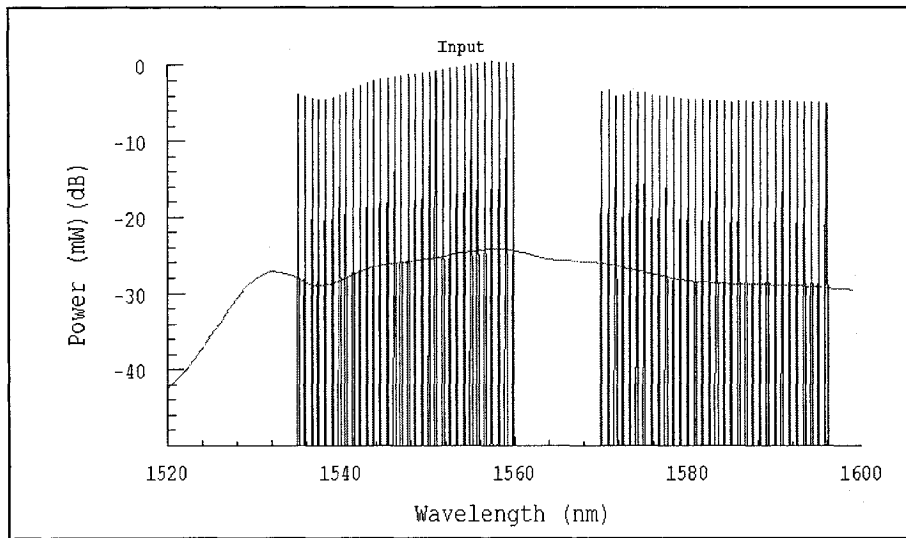


Figure 5.2 - Output power of the EDFA without GFF when $P_{in} = -20\text{dBm}$

Figure 5.3 below, shows the optical output signal response of the C+L band EDFA with GFF design (after the optimization) when optical input power is -20 dBm. The GFF is designed based on the gain profile presented above in order to reduce the gain imbalances within C+L band EDFA for a specific input optical power.

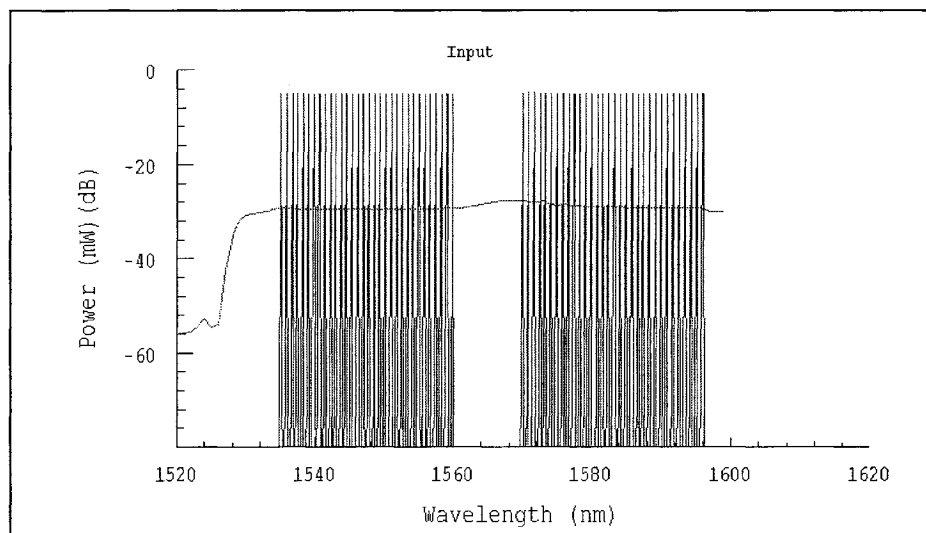


Figure 5.3 - Output optical power of the Optimized EDFA when $P_{in} = -20\text{dBm}$

When the input power is reduced to -23 dBm the delta of gain is 2.93 dB. Similarly, when the input power is increased to -17 dBm delta of gain is 2.257dB and increases further as the input power fluctuates further away from -20 dBm. This indicates that GFF as a static method of equalization would not offer satisfying performance for dynamic networks where power fluctuations are present due to the EDFA gain non-uniformities and dynamics of the system (add/drop functionality, transmitter power fluctuations).

Figure 5.3a below, shows the optical output signal response of the Optimized C+L band EDFA for optical input power of -23 dBm.

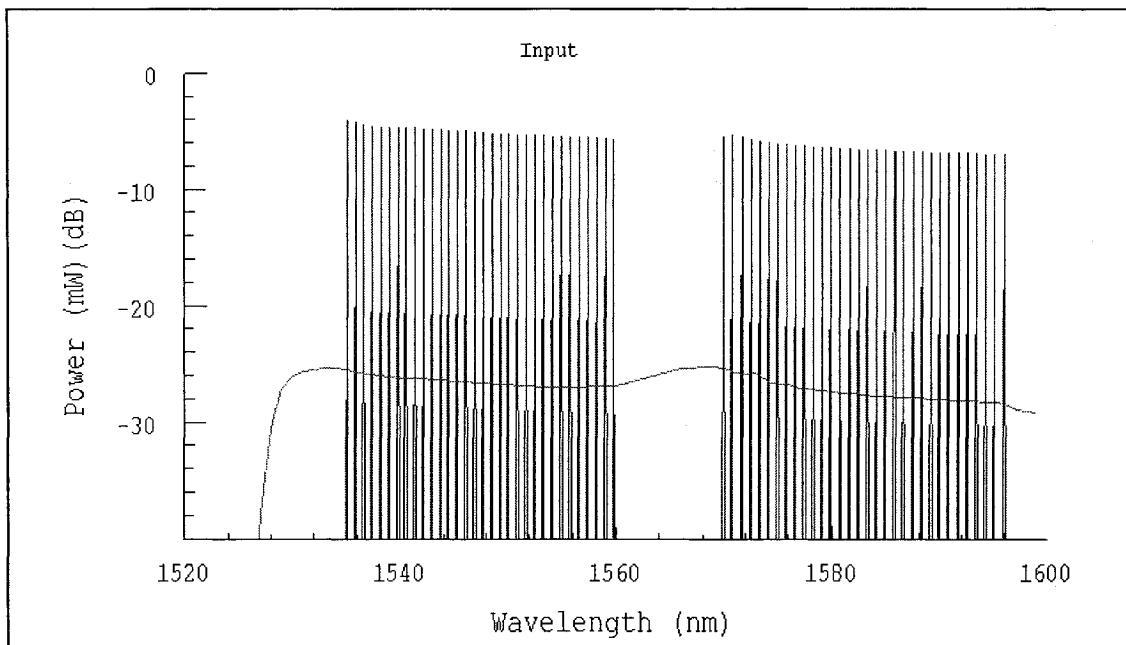


Figure 5.3a - Output optical power of the Optimized EDFA when $P_{in} = -23\text{dBm}$

5.3 Simulation Results for the Smart Amplifier Solution using OptiAmplifier 4.0

The Smart Amplifier Solution consists of the Optimized C+L band EDFA and the DCE. The DCE is additional feature of the optimized amplifier to improve the performance with respect to the gain flatness and offer dynamic gain flat response with respect to the input power changes.

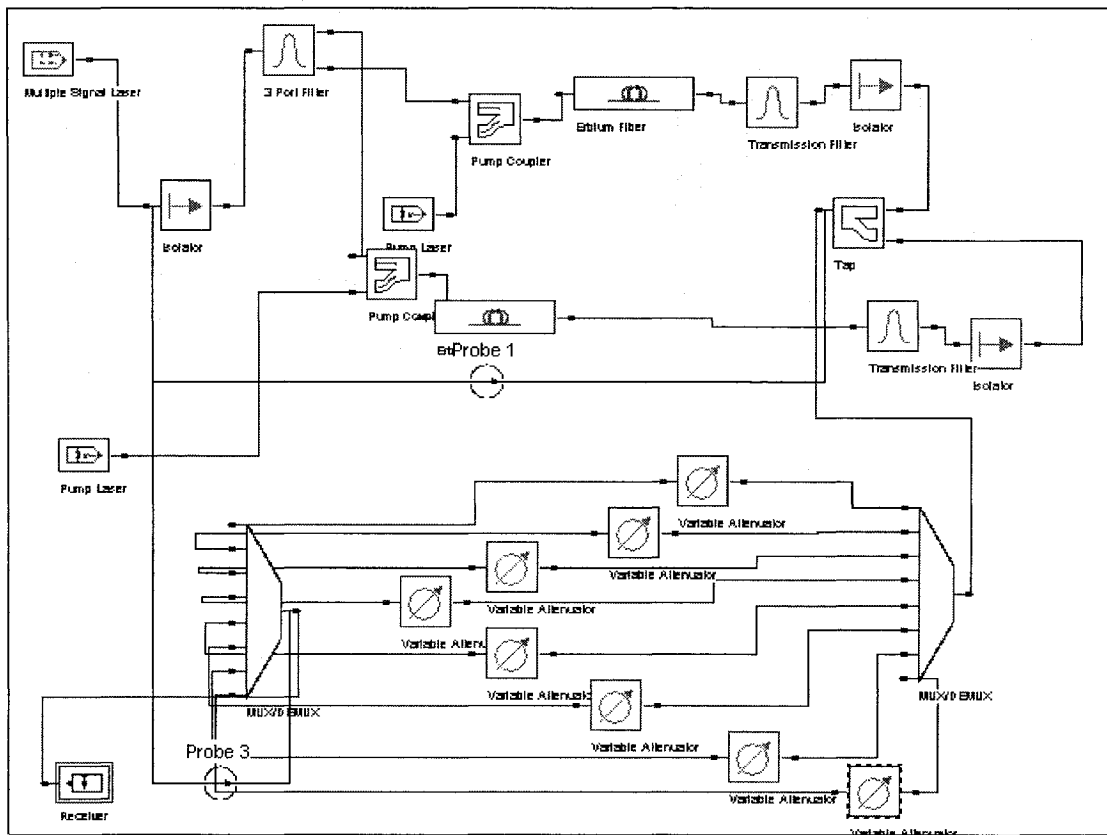


Figure 5.4 - Smart Amplifier Solution

Chapter 5

The scenarios when input power levels fluctuate and have different values which is not -20 dBm as per the discussion in previous section “Simulation of the Optimized C+L band EDFA” it was observed that GFF does not suffice nor offer the gain flatness across the C and L bands. The use of DCE is necessary to compensate and equalize the output power levels at the desired levels (e.g. within +/- 0.5 dB tolerance). Figure 5.4 (refer to pg. 98), represents a block diagram of the Smart Amplifier Solution.

The DCE components for the Smart Amplifier simulation (in addition to Optimized C+L band EDFA) are:

- One 8-band MUX and one 8-band DeMUX; each consisting of 8-bands with bandwidth of 10 nm, depth of 12 dB and center wavelengths at 1530 nm, 1540 nm, 1550 nm, 1560 nm, 1570 nm, 1580 nm, 1590 nm and 1600 nm)
- 8 VOAs to control the optical power level (attenuation) of bands for best equalization results

From the previous simulation data of the Optimized C+L band EDFA it was observed that the delta of gain (output optical power fluctuations) for the input power of -23 dBm was 2.93 dB. The same scenario is repeated for the Smart Amplifier after adjustment of the 8 VOAs at the levels below:

VOA 1 (for band centered at 1530 nm) = 0 dB

VOA 2 (for band centered at 1540 nm) = 3.4 dB

VOA 3 (for band centered at 1550 nm) = 2.8 dB

VOA 4 (for band centered at 1560 nm) = 2.2 dB

VOA 5 (for band centered at 1570 nm) = 2 dB

VOA 6 (for band centered at 1580 nm) = 1.3 dB

VOA 7 (for band centered at 1590 nm) = 1.2 dB

VOA 8 (for band centered at 1600 nm) = 0.5 dB

The delta of gain achieved was 0.88 dB compared to 2.93 dB without DCE block (refer to Fig. 5.4a below).

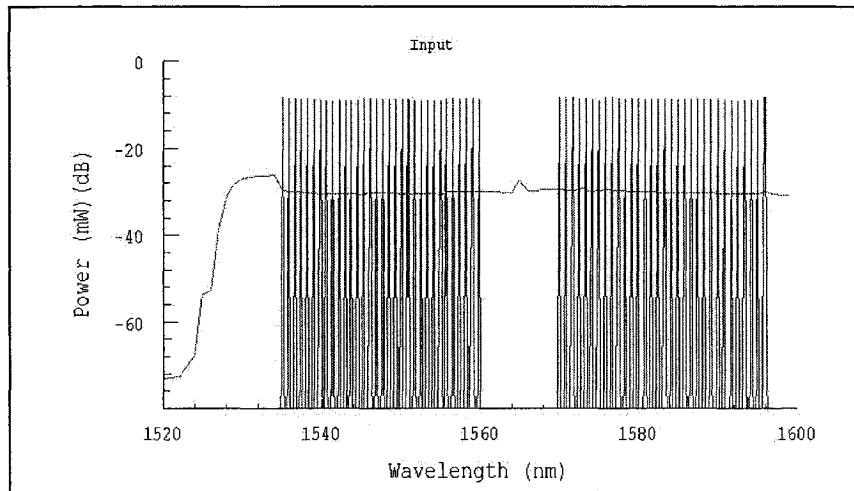


Figure 5.4a - Output optical power of the Smart amplifier when Pin = -23dBm

Compiled delta of gain comparison graph of the Optimized C+L band EDFA with Smart Amplifier for input power levels of -25 dBm up to -15 dBm versus the delta of gain is shown in Figure 5.5 below.

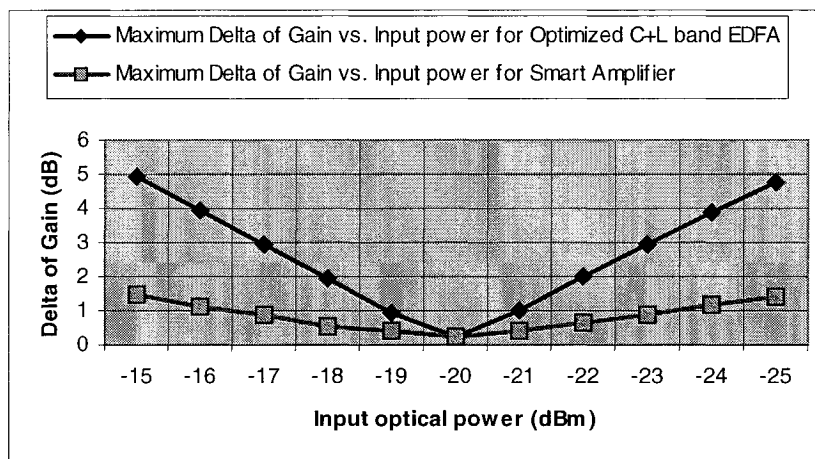


Figure 5.5 - Delta of Gain Comparison between Optimized EDFA and Smart Amplifier Solution

From the Figure 5.5 (refer to pg. 101), it can be observed that as the input optical power shifts from -20 dBm to lower or higher optical input power values, the delta of gain for the Optimized C+L band EDFA increases significantly. For the input powers of -15 dBm and -25 dBm, the delta of gain is 4.92 dB and 4.75 dB respectively. The high delta of gain values are due to the fact that the Optimized C+L band EDFA utilizes only GFF, which is a static method of equalization. While for the Smart Amplifier Solution, which utilizes GFF and the DCE², as the input optical power shifts from -20 dBm point to -15 dBm or -25 dBm, it can be observed that the delta of gain is much lower, 1.41 dB and 1.44 dB respectively.

²DCE is a dynamic method of equalization

5.4 Adaptation of the Optimized C+L band EDFA as a Broadband ASE Source

Conditions under which the Optimized C+L band EDFA can be used as a Broadband ASE Source:

The Optimized C+L band EDFA can be used as a broadband ASE source in a scenario when input power to the unit is turned off and the power level for C-band pump laser is set to 20 mW and for L-band pump laser is set to 190 mW respectively (other parameters such as EDF lengths for C and L band remain unchanged). This Broadband ASE covers wavelengths ranging from 1530 nm to 1600 nm with typical output power levels of -25 dBm to -27 dBm.

The results from the simulation using the above conditions are represented in the Figure 5.6 below.

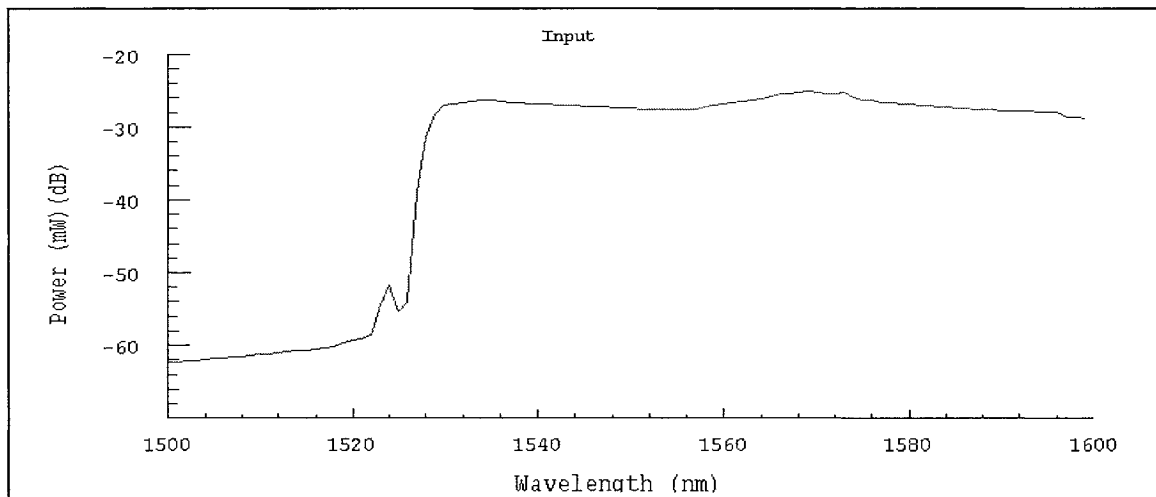


Figure 5.6 - Optimized C+L band EDFA adaptation as a Broadband ASE

By changing the attenuation level (at the output port of the unit using a VOA) or by adjusting the pump laser power levels (current control) one can reduce or increase the output optical power levels to lower or higher values.

Chapter 6

6.1 Further Improvement of the Smart Amplifier Solution

Further improvement of the Smart Amplifier Solution would be to take into account the IL of a MUX, which usually is not equal among wavelength channels/bands (IL non-uniformity of channels/bands) being multiplexed. The effect of a MUX IL non-uniformity among channels/bands reduces the DCE equalization granularity, since it is located after the pin diodes (refer to Fig. 3.1 pg. 38) and the DCE “can not see it” (can not account for the IL of a MUX). However, by adjusting the MEMS VOA initial default values of 0 dB (corresponding to each channel/band initial value) to the appropriate (adjusted) attenuation values, IL of a MUX after the DCE can be compensated. The MEMS VOA values levels in this way, can be fine-tuned (calibrated) to take into account the IL of a MUX which is located (at the output) after the DCE block (refer to Fig. 3.1 pg. 38).

As an example, if the IL of a 4-channel MUX for the channel 1 is 0.5 dB and for the channels 2, 3 and 4 is 1 dB, by adjusting the MEMS VOA corresponding to channel 1 to 0.5 dB value³ (when initialized) and the other MEMS VOAs corresponding to channels 2, 3 and 4 to their default 0 dB value (when initialized), the effect of a MUX IL non-uniformity will be accounted for in the equalization process of all channels.

³ normally when the IL of MUX is equal among channels: **default value of MEMS VOA = 0 [dB]**; however, when IL of the MUX differs among the channels then: **default value of MEMS VOA = 0 + adjusted value [dB]**

6.2 Conclusion

The innovative Optimized C-band Gain Flattened EDFA design without the use of GFF (for In-Line amplification) is demonstrated as a part of the Smart Amplifier Solution. Typical gains of 20 to 25 dB and gain flatness of +/-0.625 dB or less were demonstrated for input optical powers of -15 dBm to -8 dBm and maximum delta of gain of +/-0.81 dB for input optical power of -17 dBm. In order to achieve the optimized amplification and equalization results for WDM network, C-band Booster and In-Line Amplifiers with Automatic Power Control were also designed accordingly. For the Booster amplifier, high output optical powers of +18 dBm were achieved with typical gain flatness of 0.54 dB across the C-band (for input optical powers of -6 dBm to +3 dBm). A secondary design option for the In-Line amplifier (for single or narrow band amplification), with typical gains of 25 dB was demonstrated in addition to the Optimized C-band Gain Flattened EDFA.

Following the system level design approach, where all the optical amplifiers within WDM are considered, makes the Smart Amplifier Solution a powerful and very well 'synchronized' with the rest of the system.

Through experimental and simulation results it has been shown that the Smart Amplifier Solution is an **optimized solution** for overall WDM system amplification

and equalization needs. From the experimental results, it has been demonstrated that the delta of power difference for Smart amplifier is approximately +/- 0.5 dB depending on the insertion loss (IL) of the multiplexer (MUX) at the output of the DCE. If the IL is not equal among bands in order to improve further the delta of gain (equalization) the calibration of the MEMS VOA by adjusting the initial default values is proposed for future designs.

Simulation results for Optimized C+L band EDFA and Smart Amplifier Solution, were used to prove the concept and the Smart Amplifier capabilities of equalizing 32 or even 64-channels utilizing the Optimized C+L band EDFA with 8-channel DCE.

Simulation results and conditions under which the Optimized C+L band EDFA can be used as a Broadband ASE Source are demonstrated.

6.3 Recommendations for Future Research

Within the domain of WDM amplification needs, future research would be development of a Smart DWDM Amplifier capable of analyzing, equalizing, amplifying, monitoring and providing the dynamic optimized output response, for any present and future dynamic network configurations. The proposed Smart DWDM Amplifier would provide further improvement for the existing and future WDM networks.

The use of new innovative techniques to further enhance the performance and cost efficiency of the Smart Amplifier into a Network Adaptable Amplifier Solution (NAAS) will be investigated.

The NAAS performance in addition to analysis, amplification, monitoring and equalization of all the channels, will also offer the capabilities of adapting and learning through its operation. The learning/adaptability, as a new feature would improve the performance and provide an all-in-one solution for present and future dynamic WDM systems of high complexity, capable of offering optimized functionality.

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APPENDIX A

Tyco Electronics C-band Gain Flattened EDFA Product Specifications

Optical Parameters	Min	Typical	Max	Unit
Wavelength Range	1530		1563	nm
Input Power Range	-17		-3	dBm
Gain Range		20	25	dB
Output Power @ -3dBm input power			13	dBm
Gain Flatness		+/- 0.5		dB
Gain Flatness (Maximum) Peak to peak at Pin = -12dBm			0.98	dB
Polarization Dependent Gain			0.3	dB
Polarization Mode Dispersion			0.4	ps
Optical Stability		0.2		dB
Noise Figure		4.5 to 5		dB
Electrical Parameters	Min	Typical	Max	Unit
Pump Laser Diode Threshold Current			35	mA
Pump Laser Diode Forward Current		190	220	mA
Pump Laser Diode Reverse Voltage			2	V
Monitor Photodiode Forward Current	0.1		3	mA
Monitor Photodiode Reverse Voltage			20	V
Power Consumption			3.5	W
Environmental Parameters	Min	Typical	Max	Unit
Operating Temperature Range	-5		70	°C
Storage Temperature Range	-40		85	°C
Operating Humidity	5		95	%RH

Tyco Electronics C-band In-Line EDFA Product Specifications


Optical Parameters	Min	Typical	Max	Unit
Wavelength Range	1530		1570	nm
Input Power Range	-30		-10	dBm
Gain Range		25	35	dB
Output Power (@ -10dBm input power)			10	dBm
Output Power Stability		0.2		dB
Polarization Dependent Gain			0.3	dB
Polarization Mode Dispersion			0.4	ps
Noise Figure		4.5		dB
Electrical Parameters	Min	Typical	Max	Unit
Pump Laser Diode Threshold Current			35	mA
Pump Laser Diode Forward Current			250	mA
Pump Laser Diode Reverse Voltage			2	V
Monitor Photodiode Forward Current	0.1		3	mA
Monitor Photodiode Reverse Voltage			20	V
Power Consumption			3.5	W
Environmental Parameters	Min	Typical	Max	Unit
Operating Temperature Range	0		70	°C
Storage Temperature Range	-40		85	°C
Operating Humidity	5		95	%RH

U-CONN Technologies MUX/DeMUX

CWDM Component test report

P/N : FCWDM-4-10-M-02-10-SC/SC-1530
Description : 4 Channel - CWDM
S/N : 35100050001
Manufactured by : U-CONN
Tested by : 831

	Out 1	Out 2	Out 3	Out 4
Measured Wavelength (nm)	1530.04	1540.44	1550.02	1560.45
Insertion Loss (dB) (max) 2.5	1.38	1.23	1.28	1.47
BW1:@0.5 dB (nm) (min) 5	6.66	6.84	6.73	6.75
BW2:@25 dB (nm) (max) 15	9.09	9.62	9.16	9.54
Adjacent Isolation(dB)(± 7.5nm) > 25	44.98	48.49	47.94	47.23
Non-adjacent Isolation(dB)(± 17.5nm) > 35	48.03	47.99	47.26	46.37
PDL ITU (dB) (max) 0.1	0.02	0.01	0.03	0.04
RL(dB) (min) 45	46.80	47.70	48.50	48.80
Mask Type	Band Pass	Band Pass	Band Pass	Band Pass

QC by: 

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