SUDAN UNIVERSITY FOR SCIENCE & TECHNOLOGY

College of Graduate studies

Optimization of Gain Flatness for Raman Optical Amplifier Based on Pump Power and Frequencies

امثلة استواء الكسب لمكبر رامان الضوئى اعتماداً علي قدرة المضخة وتردداتها

A thesis submitted in partial fulfillment for the degree of MSC. in Telecommunication

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ (1) خَلَقَ الْإِنْسَانَ مِنْ عَلَقٍ (2) اقْرَأْ وَرَبُّكَ الْأَكْرَمُ (3) الَّذِي عَلَّمَ بِالْقَلَمِ (4) عَلَّمَ الْإِنْسَانَ مَا لَمْ يَعْلَمْ (5)

صدق الله العظيم

سورة القلم

Dedication

I dedicate this thesis to all certain people or groups who
have inspired the researches while doing the thesis
To all my Family, for there unlimited support.
To soul of my father and mother and all the beloved ones
may you rest in heaven.

Acknowledgement

I would first like to thank my thesis advisor **Dr. Ashraf Gasim Elsaid Abdalla** for his professional guidance as he taught me a great deal about both scientific researches through the process of researching and writing this thesis. The door to Dr. Ashraf office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this research to be my own work, and steered me in the right direction whenever he thought I needed it.

Finally, I must express my very profound gratitude to colleagues and friend in optical field for providing me with unfailing support and continuous encouragement throughout my research study and providing me with simulation software, also my gratitude extended to HUWEI vendor instructors for their support and guidance. This accomplishment would not have been possible without their ultimate support.

Thank you

Abstract

Raman optical fiber amplifier well suited for multiwavelength long-distance transmission systems. In such applications, optical amplifiers must provide equal gain and noise for each wavelength. The method is based on adjust the power and frequency of the four pump of Optical Raman Amplifier and use Multi Parameter Optimization (MPO) feature in Opti-system simulation software to get the desired flatness, the multi parameter feature adjust and tune the frequency and power of four pump to get the target gain and flatness through rounds of iterative optimization process, the gain for each channel can be observed through Dual spectrum analyzer, The improvement of gain flatness begore and after optimization can be observed through spectrum analyzer, a comparison of two scenarios of gain flatness is conducted, the first comparison is about compare flatness for 64 wavelengths before optimization **with** optimized at gain **6db** and the second comparison is about compare the 64 wavelengths before optimization with optimized at gain at **10db**., as conclusion it has been noticed the considerable improvement of gain unflattens from 4db to 1.4db. getting 2.6 gain flatness for optical Raman amplifier at **10db** gain will be resulted in possibility to transmit more wavelengths which mean higher capacity for long-distance with lower bit error rate and noise

المستخلص

يعتبر مكبر رامان للألياف البصرية حل مناسب تماما لأنظمة النقل ذات الطول الموجي لمسافات بعيدة . في مثل هذه التطبيقات، يجب أن توفر المكبرات البصرية مكاسب وضوضاء متساوية لكل طول موجة. تعتمد هذه الطريقة على ضبط قدرة وترددات مضخة رامان ذات الاربعة مخارج للحصول على الاستواء المطلوب للكسب من خلال عدة دورات لميزة تحسين المعامل المتعدد الموجوده علي نظام المحاكاة الضوئي للحصول على الكسب والتسطيح المستهدفين من خلال عدة جولات لعملية التحسين التكراري

وذلك بتحليل الكسب من خلال محلل الطيف المزدوج لتحليل الكسب لكل قناة ، كما وباستخدام محلل الطيف لمراقبة الكسب قبل وبعد التحسين ، تم وضع الكسب المستهدف كـ 6 ديسيبل و 10 ديسيبل بالتوالي ثم تمت مقارنة الكسب قبل وبعد التحسين من خلال محلل الطيف ، في النهاية تم التوصل إلى تحسين في الكسب غير المسطح لعدد 64 طول موجي من حوالي 4 ديسيبل إلى حوالي 1.5 ديسيبل ، كخلاصة ، من خلال تسوية مكسب رامان البصري بنجاح لعدد 64 طول موجي، أصبح بالامكان زيادة العدد الإجمالي لعدد الاطول الموجيه المرسلة بالالياف الضوئية وبالتالي زيادة السعة المرسلة مع قلة معدل الاخطاء والضوضاء

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Chapter 1

Introduction

Chapter 1: Introduction

1.1. Preface

Rapid developments of WDM transmission systems have contributed a lot to the capability of components in networks, such as intensity of channels and signal bandwidth. One of the enabling technologies for long-distance and high-capacity fiber optical transmission systems is Raman Fiber Amplifier which is considered a promising choice for extending the operational range of optical transmission systems to wavelength out of other optical amplifier operational bands such as EDFA, especially with the progress in pump laser sources, higher power and wider operational wavelength range make Raman Fiber Amplifiers (RFAs) more efficient and practical due to the benefits of Raman amplifier, RA used for long-haul Ultra-Wideband (UW)-WDM optical communications systems, Optimizing Raman performance by flattening the output power gain will participate to widen the bandwidth, Raman gain bandwidth can be extended by adding pump wavelengths, The broad bandwidth and low noise figure of a Raman amplifier (RA) makes it attractive for use in high-capacity and long-haul transmission systems, another advantage that the Raman optical amplifier can operate over all defined wavelength bands of an optical fiber

In some applications Raman amplifier combined together with EDFA to perform better performance and to expand the signal bandwidth which called hybrid DRA/EDFAs. The combination of two different types of optical amplifiers enables them to compensate for each other's gain profiles through adjustment of the Raman amplifiers pump wavelength allocation to reduce the accumulated gain deviation. Through Raman amplifier can successfully transmit 2.1-Tb/s 7221-km by using hybrid DRA/EDFAs

So Raman amplifier (RA) is one of the enabling technologies for high-capacity long-distance DWDM (dense wavelength division-multiplexed) transmission systems. RA provides wider amplification bandwidth, low-noise characteristics and simplicity. Multiwavelength pumping scheme is usually used to ensure gain bandwidth for high-capacity DWDM transmission. Raman gain bandwidth can be easily extended by adding pump wavelengths and flatenning Raman gain

1.2 Problem Statement

Different gain of the output power for the Raman Optical Amplifier will affect Signal to noise ratio and generate bit errors that will affect the service and limit the bandwidth growth,

1.3 Proposed Solution

The gain output power of Raman optical amplifier can be better enhanced by adding more than one pump power to Raman Optical Amplifier and use multi-parameter optimization (MPO) feature on Opti system simulation to adjust and tune the pump power and frequency to get the desired gain flatness and enable bandwidth growth

1.4 Objectives

The aim of this research is optimizing the pump power and frequencies of Raman amplifiers for gain flatness of Raman Optical Amplifier, which will reflect positively for broadband bandwidth growth.

1.5 Methodology

A 64 C- band WDM Channels are used with appropriate channel spacing simulated through Opti-system simulator, Optical multiplexer used to combine the 64 channels into a serial spectrum of closely spaced wavelength signals and couple them onto a single fiber in one single fiber, the average power for each channel specified, Average Power for Raman amplifier that used to simulate the amplifier are specified. This model allows a fast and accurate estimation of the amplifier gain, the fiber type precisely selected for better Raman Amplifier performance, the setup of upper and lower Pump power and frequency are selected to optimize the frequency and the power within the upper and lower limit, **Dual Port WDM Analyzer** is used to measures amplifier gain and gain flatness, the upper and lower frequency for **Dual Port WDM Analyzer is** set to cover the 64- channel frequencies.

Four CW pump signals with initial values are used for backward pumping. Initial wavelengths and powers of these pumps are also specified. Initial and optimized parameters are used later for comparison.
The Multi-parameter Optimization (MPO) setup is prepared to perform the gain optimization process; by add the pump powers and frequencies to the optimization table and set the maximum and minimum of Pump power and frequencies to the optimizer to adjust and tune the power and frequency within the given maximum and minimum values. In the **Results**, gain for all channels from dual port WDM analyzer added to the table. Two comparison scenarios implemented, the first one about Raman Amplifier without optimization compared with optimized Raman amplifier at gain 6 db. as target value and the second comparison about comparing Raman Amplifier without optimization compared with Optimized Raman Amplifier at gain 10 db. as target value. After run the simulator, the desired flatness of gain for Raman amplifier obtained, all the mentioned settings depicted in Abstract 6-16

1.6 Thesis Outline

In Chapter one, overview about the contribution of WDM in transmission high volume of capacity through optical fiber cables, and the problem is well stated and addressed and followed by proposed solution for the gain flatness issue which will reduce or eliminate the BER and enhance OSNR and contribute to increase the volume of capacity and the objective and methodology clarified, In Chapter two, technical background and related gain flatness studies well explained, in Chapter three, the design of Raman Optical Amplifier for gain flatness simulated through Opti-system software are implemented and the optimization process of gain flatness generated, and in Chapter four is about the results and discussion for gain flatness before and after optimization, in chapter five is about the thesis conclusion and recommendations for new researches and studies

Chapter 2

Theoretical background and related studies

2. Chapter 2: Theoretical Background and Related Studies

2.1 INTRODUCTION

The attenuation is inevitable when optical signals are transmitted along optical fibers. As a result, the transmitting distance is limited by attenuation. Hence we need to re-generate and boost an optical signal to transmit signal over longer distance. But, this method shows many disadvantages. First, a regenerator can work only under the circumstance of a certain signal bit rate and signal format, so different regenerators will have to be available for different bit rates and signal formats; second, each channel will need a regenerator, and this will cause higher network cost.

With the development of optical communications technologies, a method has been available for enhancing optical signals without using a regenerator, that is optical amplification technology.

As longer transmission lengths are required, optical amplifier can satisfy the requirements of optical communication networks. An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. A basic optical communication link contains a transmitter and receiver, with an optical fiber cable connecting them. Although signals transmitting in optical fiber suffer far less attenuation than in other mediums, such as copper, there is still a limitation about 100 km on the distance the signals can travel before becoming too noisy to be detected. Optical amplifiers are widely used in fiber optic data links, so the optical amplifiers can be used to strengthen the performance of optical data links. A booster amplifier is used to increase the optical output of an optical transmitter just before the signal enters an optical fiber. The optical signal is attenuated as it tra vels in the optical fiber, an inline amplifier is utilized to restore (regenerate) the optical signal to its original power level and optical pre-amplifier is operated at the end of the optical fiber link in order to increase the sensitivity of an optical receiver.

With Optical Amplifers possible to have longer fiber optical transmission link with big capacity and fast transmission rate can be achieved. The EDFA and Raman amplifiers are the two main options for optical signal amplification, so before implementing transmission link, it is important to define which one should be used for long fiber optical network and know what are the differences of the two optical amplifiers and which one would perform better to achieve the long fiber optical link and which one is more cost effective.

Raman amplifier (RA) is one of the enabling technologies for high-capacity long-distance DWDM (dense wavelength division-multiplexed) transmission systems. RA provides wider amplification bandwidth, low-noise characteristics and simplicity. Multiwavelength pumping scheme is usually used to ensure gain bandwidth for high-capacity DWDM transmission. Raman gain bandwidth can be easily extended by adding pump wavelengths.

Broadband RAs for wavelength division multiplexing (WDM) have to be able to provide a flat gain response over their operational bandwidth. A promising option for achieving gain flatness without increasing the complexity of the amplifier by adding a large number of pumping sources is to make those pumps spectrally broader through the effect of fiber nonlinearity

2.2 DWDM OPTICAL TRANSMISSION TECHNOLOGY

2.2.1 DWDM CONCEPTION

Optical communication system can be classified according to different modes. If it is classified according to signal multiplex mode, it can be classified into FDM (Frequency Division Multiplexing), TDM (TDM-Time Division Multiplexing), WDM (WDM- Wavelength Division Multiplexing) and SDM (SDM-Space Division Multiplexing). FDM, TDM, WDM and SDM refer to optical communication systems classified according to the frequency, time, wavelength and space. It can be said that frequency is closely connected with the wavelength. Frequency division is wave division. But in optical communication system, WDM system adopts optical spectral component that is different from filter adopted in the common communication. So, can be still classify them into two different systems.

WDM is a kind of transmission technology of fiber communication. Depending on the fact that a fiber can transmit several optical carriers of different wavelengths at the same time, it divides wavelength possibly used by fiber into several bands. As an independent channel, each band transmits a kind of optical signal with a preset wavelength. Optical and wavelength division multiplex is in fact the optical and frequency division multiplex on fiber (OFDM), but optical wave usually use wavelength instead of frequency, to describe, supervise and control. Along with the development of the electric-optical technology, the wavelength density in the same fiber will become very high. Compared with DWDM (DWDM-Dense Wavelength Division Multiplexing), there are still WDM with low densities that are called CWDM (CWDM-Coarse Wave Division Multiplexing).

A fiber can be regarded as a road with several driveways here. The traditional TDM system just uses one of driveways. To increase bit rate is to increase the driving speed in the driveway in order to increase the transportation burden in unit time. To use DWDM technology is similar to using the driveway not yet used, so as to obtain the large transportation capacity to be developed in fiber.

2.2.2 **DWDM PRINCIPLE**

Based on such features as bandwidth and low loss of the single mode optical fiber, the DWDM technology uses multiple wavelengths as carriers and allows the signals to be transmitted simultaneously over the carrier channels in the optical fiber as shown in figure 2.1. Compared with the general single channel system, the dense WDM (DWDM) not only drastically increases the communication capacity of the network system and fully uses the bandwidth of the optical fiber, but also has many advantages, such as simple expansion and reliable performance; especially it can directly access multiple services, so it enjoys bright prospects.

In analog carrier communication systems, the frequency division multiplexing (FDM) method is often adopted to make full use of the bandwidth resources of cables and enhance the transmission capacity of the system. That is, to transmit several signals of different frequencies simultaneously in the same cable and, at the receiver end; to utilize band-pass filters to filter the signal on each channel according to the frequency differences among the carriers.

In the same way, in optical fiber communication systems, optical frequency division multiplexing method can also be used to enhance the transmission capacity of the systems. In fact, this multiplexing method is very effective in optical communication systems. Unlike the frequency division multiplexing in analog carrier communication systems, optical fiber communication systems utilize optical wavelengths as signal carriers, divide the low attenuation window of optical fibers into several channels according to the frequency (or wavelength) difference of each wavelength channel and implement multiplexing transmission of multi-channel optical signals in a single fiber.

Since some optical components (such as narrow-bandwidth optical filters and coherence light source) are currently very immature, it is difficult to implement the ultra-dense optical frequency division multiplexing (coherence optical communication

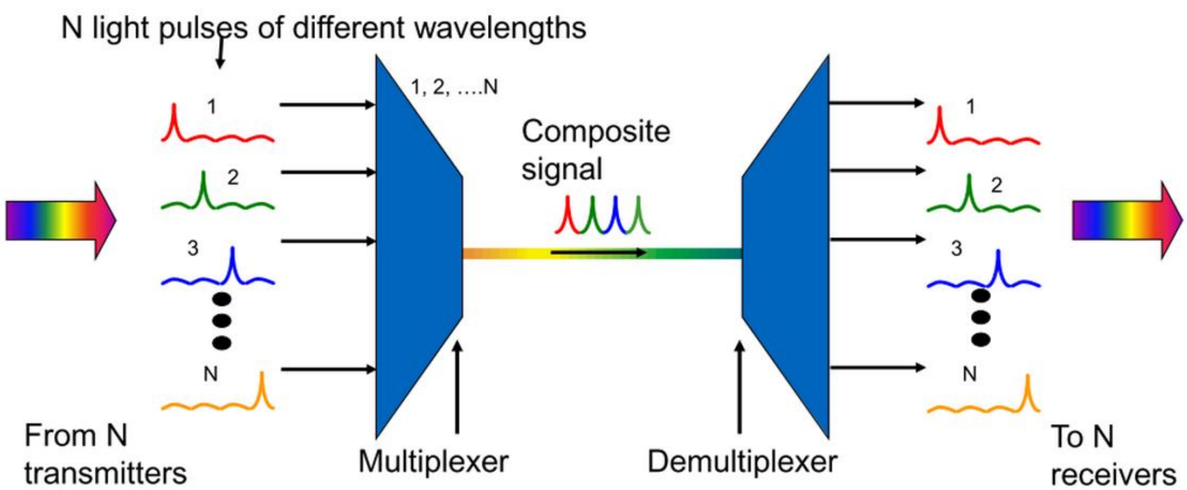


Figure 2-1 WDM fundamental {2}

At the transmitting end, the optical transmitter sends out the optical signals whose wavelengths are different but whose accuracy and stability satisfy certain requirements, such signals are multiplexed together through the optical wavelength multiplexer and sent to the Raman Fiber Amplifier or EDFA (the EDFA is used mainly to compensate for the optical power loss caused by the multiplexer and improve the transmitting power of the optical signal), then the amplified multi-channel optical signals will be sent to the optical fiber for transmission, when they get to the receiving end through or not through the optical line amplifier, where they will be amplified by the preamplifier (used to improve the receiving sensitivity to extend the transmission distance), then they will be sent to the optical wavelength demultiplexer to split the channels of optical signals

2.2.3 **ADVANTAGE OF WDM**

The capacity of optical fiber is huge. However, traditional optical fiber communication systems, with one optical signal transmitted in a single fiber, only exploited a little part of the abundant bandwidth of optical fiber. To fully use the huge bandwidth resources of optical fiber and increase its transmission capacity, a new generation optical fiber communication technology based on the dense WDM (DWDM) has emerged. The DWDM technology has the following features:

2.2.3.1 Super-large capacity

The transmittable bandwidth of the current widely used conventional fiber is very wide, but the utilization ratio is still low. By using DWDM technology, the transmission capacity of a single optical fiber is increased by several, tens of or even hundreds of times when compared to the transmission capacity of single wavelength systems.

2.2.3.2 Data transparency transmission

DWDM systems conduct multiplexing and de-multiplexing in terms of optical wavelength differences and are independent of signal rates and modulation modes, which is transparent to the data. A WDM system service can carry “service” signal of many formats, such as ATM, IP or signals that may appear in the future. WDM implements the transparent transmission. For signal at the “service” layer, each optical wavelength channel in the WDM system is like the “virtual” optical fiber.

2.2.3.3 Utmost protection during system upgrade

In expanding and developing the network, it is not necessary to make changes to the optical cable lines, instead, you can just change the optical transmitter and receiver, so this is an ideal expansion method and also a convenient way to introduce the broadband services (such as CATV, HDTV and B-ISDN etc). With an additional wavelength, you can add any new service or new capacity you want.

2.2.3.4 High networking flexibility, economy and reliability

When compared to the traditional networks using electrical TDM networks, new communication networks based on the WDM technology are greatly simplified in architecture and have clear network layers. Dispatching of various services can be implemented simply by adjusting the corresponding wavelengths of the optical signals. Because of the simple network architecture, clear layers and convenient service grooming, the flexibility, economy and reliability of networking are obvious.

2.2.3.5 Compatible with all optical switching

It is foreseeable that, in the all-optical networks realizable in the future, processing of telecommunication services adding/dropping and cross connections is implemented by changing and adjusting the optical signal wavelengths. So WDM technology is one of the key technologies to implement all optical networks. Moreover, WDM systems can be compatible with future all optical networks. It is possible to implement transparent and highly survivable all optical networks based on the existing WDM system.

2.3 WDM SYSTEM KEY TECHNOLOGY

There are four key elements that make the WDM technology appeared

2.3.1 OPTICAL AMPLIFIER

An optical fiber is needed to amplify optical signals directly without conversion into electrical signals, so the optical fiber amplifier is used in transmitting data in fiber optic communication systems. Amplifiers are inserted at specific places to boost optical signals in a system where the signals are weak. This boost allows the signals to be successfully transmitted through the remaining cable length. In large networks, a long series of optical fiber amplifiers are placed in a sequence along the entire network link referred to as booster amplifier, line amplifier and pre-amplifier

2.3.2 **MUX/DEMUX**

A multiplexer is needed to combine the optical output into a serial spectrum of closely spaced wavelength signals and couple them onto a single fiber. At the receiving end, a de-multiplexer is required to separate the optical singles into appropriate detection channels for signal processing, The two most commonly used MUX/DEMUX are Thin Film Filter and Arrayed Waveguide Grating as shows in figure 2-2 & figure 2-3.

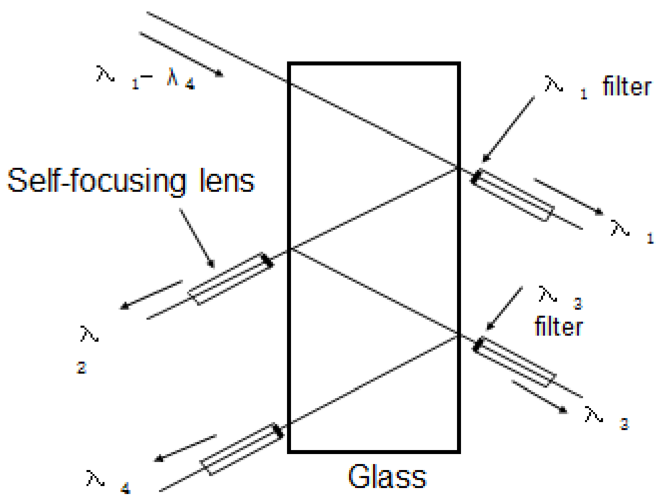


Figure 2-2 Thin Film Filter {2}

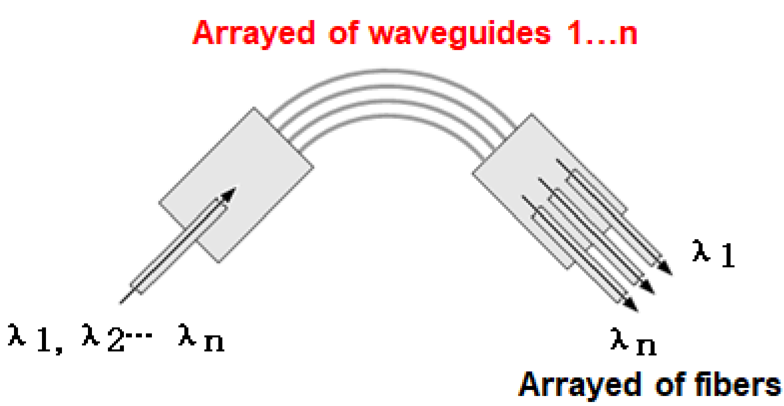


Figure 2-3 Arrayed Waveguide Grating {3}

2.3.3 **OPTICAL SOURCE**

The optical source is needed to converts an electrical signal into an optical signal, The two most commonly used optical sources are light-emitting diodes (LEDs) and laser diodes.

2.3.4 **OPTICAL SUPERVISORY CHANNEL**

The Optical Supervisory Channel (OSC) is an additional wavelength usually outside the amplification band (at 1510 nm, 1620 nm, 1310 nm or another proprietary wavelength). The OSC carries information about the multi-wavelength optical signal as well as remote conditions at the optical terminal EDFA/ Raman site. It is also normally used for remote software upgrades and user (i.e., network operator) Network Management information. ITU standards suggest that the OSC should utilize an OC-3 signal structure (though some vendors have opted to use 100 megabit Ethernet or another signal format). Unlike the 1550 nm band client signal carrying wavelengths, the OSC is always terminated at intermediate amplifier sites, where it receives local information before retransmission. The optical supervisory channel is used for maintenance purposes. The optical supervisory channel provides transport of Order Wire, two E1 and one Ethernet Data (user proprietary) NMS data; Figure 2-4 represent the OSC configuration

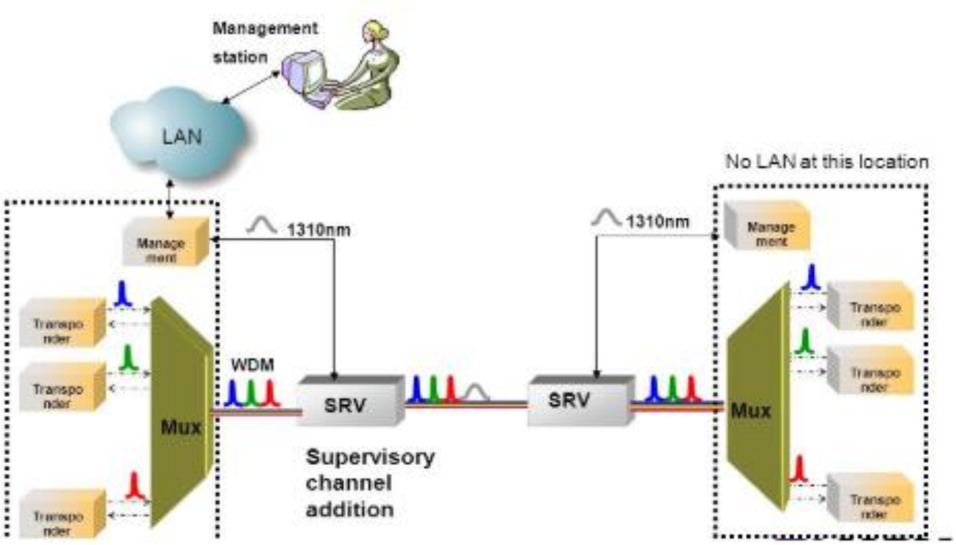


Figure 2-4 OSC configurations {3}

2.4 OPTICAL AMPLIFIER

2.4.1 CHARACTRISTIC OF OPTICAL AMPLIFIER

An optical amplifier is a device used to enhance optical signal intensity. Its principle is shown below figure 2-5

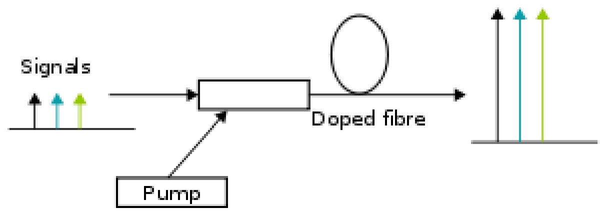


Figure 2-5 Optical Amplifier working principle {3}

Therefore, it will not be necessary for an optical amplifier to convert optical signals to electrical signals, and back to optical signals in its work. This feature leads to two great advantages of an optical amplifier over a regenerator. First, an optical amplifier supports any bit rate and signal formats, because it simply amplifies the received signals. This feature is usually described that an optical amplifier is transparent to any bit rate and signal formats; second, an optical amplifier not only supports amplification of a single signal wavelength (as a regenerator do), but also a certain region of wavelength. For example, an erbium-doped fiber amplifier (EDFA), is capable of amplifying all the wavelengths from about 1530nm to 1610nm. What is more, only an optical amplifier can support TDM (time division multiplexing) and WDM (wavelength division multiplexing) fiber-optic networks with a variety of bit rates, modulation formats, wavelength. As a matter of fact, only after the emergence of optical amplifiers, especially EDFA, has the wavelength division multiplexing technology been rapidly developed, and has wavelength division multiplexing become the mainstay of the large capacity fiber-optic communications systems. EDFA and Raman Amplifier is an optical amplifier in the widest use at present, and its emergence has greatly promoted the development of wavelength division multiplexing technology.

Practical fiber amplifiers include erbium-doped fiber amplifier (EDFA) and Raman fiber amplifier (RFA).

An optical amplifier is an analog device, so its characteristic parameters are all analog parameters.

2.4.1.1 Gain

Gain is the output optical power to input optical power ratio, that is:

Gain=POUT/PIN ………….. [3]

Where, POUT and PIN are output optical power and input optical power respectively, in watt. Usually, gain is expressed in decibel (dB), that is:

Gain (dB)=10log (POUT/PIN) ………. [3]

2.4.1.2 Noise Figure (NF)

Noise Figure (NF) of an optical amplifier is defined as Signal to Noise Ratio (SNR) of an optical amplifier input and output ports:

$$NF = \frac{SNR_{in}}{SNR_{out}} \qquad [3]$$

2.4.1.3 Gain Bandwidth

Gain bandwidth is the effective frequency (or wavelength) range of an optical amplifier; usually it is referred to as the corresponding wavelength range when the gain is dropped by 3dB from its maximum value. For example, in Figure 2-6 the range between λa and λb. The gain bandwidth comes in nm.

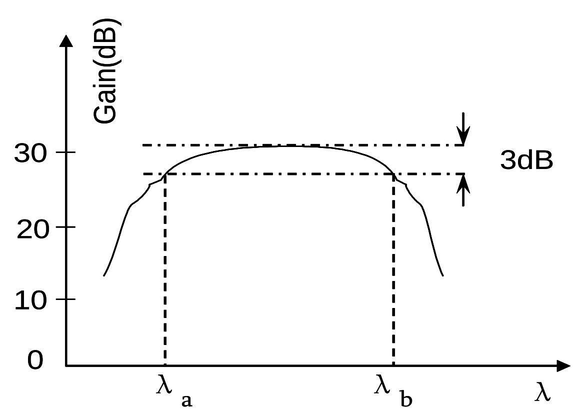


Figure 2-6 Relationship between gain and input signal wavelength {3}

2.4.2 **RAMAN FIBER AMPLIFIER**

2.4.2.1 Principles of Raman Fiber Amplifier

In a conventional fiber system, the optical power is not great, and the fiber shows a linear transmission characteristic. When the optical power in an input fiber non-linear optical medium is very high, pump light of high energy (with short wavelength) will scatter, transferring a small portion of the incident power to another light beam with shifted down frequency. The frequency down shift volume will depend on the medium jiggling mode. This process is called Raman effect. A photon, which is described as an incident optical wave in quantum mechanics, is scattered as another photon of low frequency by a molecule, and the molecule accomplishes inter-vibration-state jump. The incident photon is called pump light, and the low frequency photon is called stokes wave. Common Raman scattering needs a powerful laser power. But in fiber communications, a single-mode fiber, as a non-linear medium, has a very small core diameter (generally less than 10μm), so a single-mode fiber can limit the mutual effect between a strong laser field and a medium into a very small section, thus greatly enhancing the optical power density of an incident optical field. In a low attenuation fiber, the effect of optical field and media can be maintained to a long distance, allowing full energy coupling therein, so that it will be possible to make use of stimulated Raman scatter.

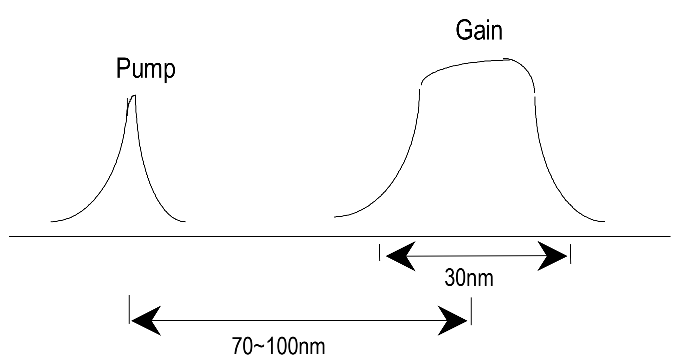


Figure 2-7 Raman fiber amplifier gain spectrum {3}

Experiment shows that quartz fiber has a very wide Stimulated Raman Scatter (SRS) gain spectrum, and there will be a wide gain peak when the pump light frequency shifts down to about 13THz. If a weak signal and a strong pump light wave are simultaneously transmitted in a fiber, and the weak signal wavelength is placed in the Raman gain bandwidth of the pump light, the weak signal light will be amplified. This optical amplifier based on the stimulated Raman scatter mechanism is called a Raman fiber amplifier. For stokes light, a description with a physical graph can be given: An incident photon disappears, a frequency down shift (about 13THz) photon (i.e., stokes wave) is created, the remaining energy will be absorbed by the medium in the form of molecule vibration, accomplishing inter-jiggling state jump. Figure 2-7 shows a schematic diagram of Raman fiber amplifier gain spectrum. A pump light of a certain wavelength (such as 1440nm) will create a wide gain spectrum when its frequency shifts down some 13THz (in 1550nm band, wavelength about 100nm), (in the conventional single mode fiber, a pump light with a power of 500mW will generate a 30nm gain bandwidth).

Raman amplifier gain is switch gain, that is, the difference between the output powers when the amplifier is switched on or switched off.

2.4.2.2 Characteristics of Raman Fiber Amplifier

Raman fiber amplifier has three prominent characteristics:

Its gain wavelength depends on pump light wavelength, so long as the pump source wavelength is appropriate, signal amplification of any wavelength can be realized theoretically, as shown in 0Figure 2-8, where the broken line indicates the gain spectrum generated by the three pump sources. Because of this characteristic, Raman fiber amplifier can amplify bands that EDFA cannot. If multiple pump sources are used, a gain bandwidth much greater than what EDFA can get will be realized (limited by the energy level leap mechanism, EDFA gain bandwidth is 80nm only). Therefore, for the development of the entire fiber low consumption area, 1270nm-1670nm are of importance that cannot be replaced.

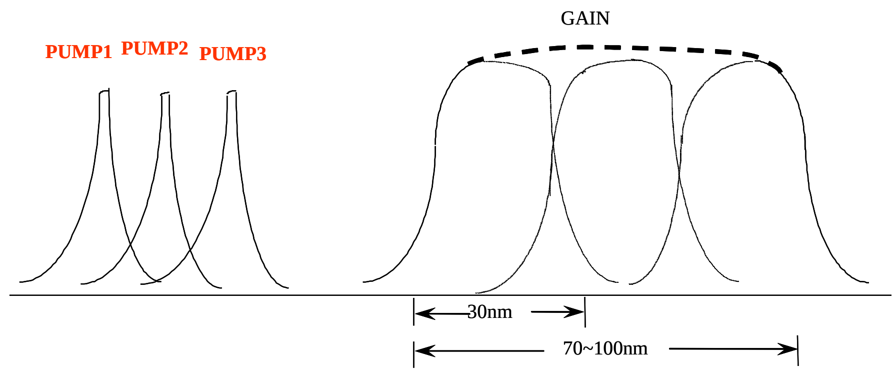


Figure 2-8 Raman gain spectrum in case of multiple pumps {3}

Its gain medium is the transmission fiber itself. This allows Raman fiber amplifier a function of online amplification of optical signals, forming distributed amplification, and realizing long-distance non-repeater transmission and remote pumping, especially applicable to submarine fibers, for which availability of repeaters is not convenient, as shown in Figure 2-9. In addition, the amplification is distributed along the fiber instead of concentrated, with a little signal optical power in various places of the fiber, so the interference of non-linear effect, especially Four-wave Mixing (FWM) effect, can be reduced.

Low noise figure, which makes it possible to greatly reduce the noise figure of the system when it is used together with conventional EDFA, as shown in Figure 2-6.

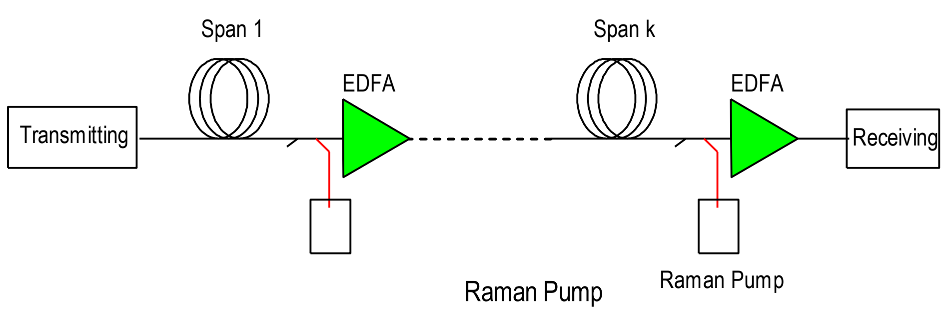


Figure 2-9 WDM system using distributed Raman auxiliary transmission {3}

2.4.2.3 Types of Raman Fiber Amplifiers

Raman fiber comes in two types: discrete Raman amplifier and distributed Raman amplifier (DRA). The fiber gain medium used by the former is relatively short, usually within 10km, and high pump power is required, usually several to more than a dozen watts. A high gain of 40dB and up can be generated, to be used, like EDFA, for centralized amplification, so it is mainly used for bands that cannot be amplified by the EDFA. In the European Optical Communications Conference held in 2000, researchers from Stanford University reported the results of their discrete Raman amplification experiment: it is educed from a comparison between ten different fibers as gain amplification media that the dispersion compensation fiber is the best choice for a high-quality discrete Raman fiber amplifier. It indicates that dispersion compensation can be performed simultaneously with amplification of signal high gain and low noise, without mutual affecting. The latter uses longer fibers, usually tens of km, and the pump source power can be reduced to hundreds of mw, mainly used to assist EDFA to enhance DWDM communications system performance, suppress non-linear effect and enhance signal to noise ratio. In the DWDM system, greater capacity, especially more multiplexed wavelengths make the optical power transmitted in the fiber greater and greater, causing stronger and stronger non-linear effects, hence channel crosstalk and signal distortion. The use of distributed Raman fiber amplification auxiliary transmission can greatly reduce signal incident power, and maintain an appropriate optical signal to noise ratio (OSNR). This distributed Raman amplification technology is widely used in long-distance systems due to the requirement of large capacity of system transmission.

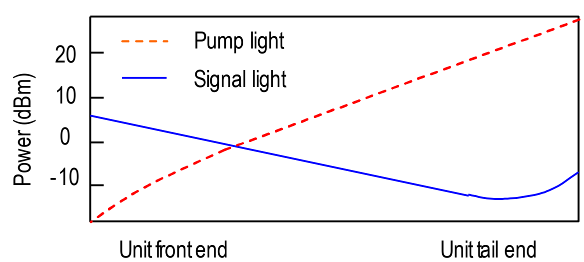


Figure 2-10 Curve of power changes of signal light and pump light along transmission unit {3}

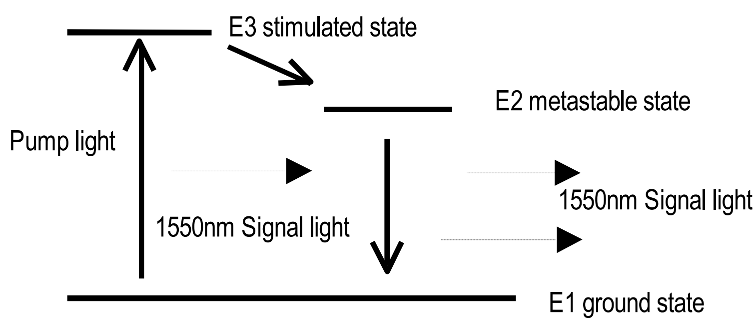
2.4.3 **Erbium-Doped Fiber Amplifier (EDFA)**

One class of fiber amplifier is rare earth ion doped fiber amplifier. A rare earth ion doped fiber amplifier uses a rare earth ion as its working medium and uses the ion stimulated emission of radiation to perform optical signal amplification. Usaually, rare earth ions used in an optical amplifier are Er, Nd, Pr and Tm. Among rare earth ion doped fiber amplifiers, the erbium-doped fiber amplifier is relatively mature.

2.4.3.1 The Principle of Erbium-Doped Fiber Amplifier

2.4.3.1.1 Stimulated Emission by Radiation and Self Emission by radiation of Er^{3+} Ion in Erbium-Doped Fiber

The erbium-doped fiber is the core of a fiber amplifier. It is a fiber with a certain density of Er3+ doped inside. To explain its amplifying principle, we will have to start from an erbium energy-level diagram. There is a three energy level structure around the peripheral electron of an erbium ion (E1, E2 and E3 in Figure 2-11), where E1 is the ground state energy level, E2, the metastable state energy level, and E3, the high energy level, as shown in Figure 2-11



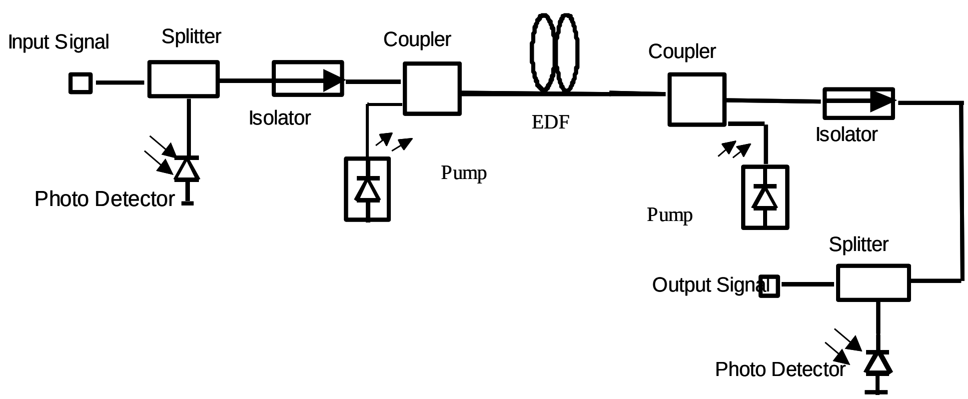
2-11 EDFA energy level diagram {3}

When a high energy pump laser is used to stimulate an erbium-doped fiber, a great quantity of shackled electrons of erbium ions can be stimulated from the ground state energy level to E3, the high energy level. However, as the high energy level is unstable, the erbium ions will soon fall to E2, the metastable state energy level after a radiationless leap (that is, no photon is relesed). Whereas E2 energy level is metastable, on which particles can live longer (about 10ms). Particles stimulated by pump light are continuously converged to the energy level in a non-radiational leap pattern, so that reverse distribution of particles is realized, that is, there are more ions on the metastable state energy level E2 than on the ground state E1. When optical signals with 1550nm wavelength pass through this erbium-doped fiber, the metastable state particles, stimulated by signal photons, will leap to the ground state in a pattern of stimulated emission by radiation, and will create photons completely the same with the input signal photons, so as to greatly increase the number of photons in the signal light, that is, the function that signal light is continuously amplified during the erbium-doped fiber transmission course is realized.

In an EDF, most of the stimulated Er ions are forced to return to ground state E1 due to being stimulated by radiation, but some of them fall to the ground state by temselves. When disintegrating, these stimulated ions spontaneously emit photons. The spontaneously emitted photons are in the same frequency (wavelength) range with the signal photons, but the former are random. Those spontaneously emitted photons in the same direction as the signal photons are also amplified in the EDF. These spontaneously emitted and amplified photons for amplified spntaneous emission (ASE). As they are random, they make no contribution to the signals, on the contrary, they generate noises within the signal spectrum range.

2.4.3.1.2 Optical Structure of Erbium-Doped Fiber Amplifier (EDFA)

In order to amplify optical power, some optical passive devices, pump source and erbium-doped fibers are combined with a special chemical structure, hence an EDFA optical amplifier. Figure 2-12 shows the optical structure of a typical dua-pump source erbium-doped fiber amplifier.



2-12 Typical diagram of internal optical paths in an EDFA {3}

As shown in Figure 2-12, the signal light and the pump light sent out by the pump laser are coupled in the WDM before entering the EDF, where the two pump lasers form a 2-level pumping. Under the excitation of the pump light, the EDF can perform the amplification function, thus realizing the function of amplifying optical signals.

I. *Erbium-doped fiber*

For the working principle of erbium-doped fiber mentioned above.

II. *Coupler*

An optical coupler has a function to couple the signal light and pump light, and send them together into the erbium-doped fiber. It is also called an optical multiplexer. Usually, a fiber fusion conical coupler is used.

III. *Isolator*

The two isolators in the optical channel have the following functions respectively: the input optical isolator can prevent the inverse ASE in the erbium-doped fiber from interfering the transmitter in the system, and prevent the inverse ASE from entering the erbium-doped fiber, after being reflected at the input end, to make greater noise; and the output optical isolator can prevent output amplified optical signals from entering the erbium-doped fiber, after being reflected at the output end, to consume the particles and hence affect the amplifying characteristic of the erbium-doped fiber.

IV. *Pump laser*

A pump laser is the energy source for an EDFA. Its function is to provide energy for amplification of optical signals. Usually, it is a kind of semiconductor laser, with wavelengths 980nm or 1480nm. When pump light passes through an erbium-doped fiber, erbium ions will be pumped from a low energy level to a higher energy level, so that there will be reversion of particle number, whereas when signal light passes, the energy will be converted to the optical signals, hence realizing optical amplification.

V. *Splitter*

The optical splitter in an EDFA is a one into two devices, with a function to split a small portion of the optical signals from the main channel and send them into the photodetector, so as to realize monitoring over the optical power in the main channel.

VI. *Photodetector*

A photodetector is a light intensity detector, with a function of converting optical power received into optical current via photoelectric conversion, so as to exercise monitor over the input and output optical power of the EDFA module.

2.4.4 **EDFA vs. RAMAN**

After knowing the basic information of EDFA and Raman optical amplifiers, it appeared that the Raman amplifier performs better for two main reasons. Firstly, it has a wide band, while the band of EDFA is only from 1525 nm to 1565 nm and 1570 nm to 1610 nm. Secondly, it enables distributed amplification within the transmission fiber. As the transmission fiber is used as gain medium in the Raman amplifier, it can increase the length of spans between the amplifiers and regeneration sites. Except for the two advantages mentioned above, Raman amplifier can be also used to extend EDFA.

although the Raman amplifier is a better option, but in some application there is still need choosing the EDFA amplifiers, compared with Raman amplifier, EDFA amplifier also features many advantages, such as, low cost, high pump power utilization, high energy conversion efficiency, good gain stability and high gain with little cross-talk.

So, when designing long-haul transmission link require consideration many factors and the of pros and cons of each amplifier to decide the selection between EDFA and Raman Amplifier or use both of them, Raman Amplifier or using both in the link design, some of these factors that should be considered are wavelength, required gain profile, distance, cost, ...etc.

2.5 Related Studies

2.5.1 Backward Pumped Fiber Raman Amplifiers Gain Enhancement

The rapid revolution of communications in the last few years has opened the field of research on optical communication and placed it on research objectives in communications engineering, and also the broad features of optical networks make it as back bone communication systems. One solution to renew the signal is to convert the optical signal to the electric field and then convert it back to a new optical signal. However, pure optical amplifiers are usually preferred. When the Raman pump wave has slight random power fluctuations in time, it is almost the case, individual bits, differential amplification, which can lead to capacitance fluctuations or jitter. If the rear pump is applied, the average voltages in amplitude will be calculated. Raman fiber amplifiers are now used all Raman or hybrid RAs/EDFAs at both long distances and very long wavelength wavelengths divided by multiplex optical communication systems. Optical amplifiers are essential elements of any fiber optic communication system. Although modern optical fibers have losses below 0.2 dB/km, the repeated amplification of the signal sent to its original power becomes necessary at sufficiently long distances. One solution to renew the signal is to convert the optical signal into the electric field and then convert it back to a new optical signal. However, it is recommended that the amplification on the optical field be considered as conversion time, noise resulting from the conversion process, cost and reliability. Therefore, the optical amplifiers have advanced rank. It can help design optical transmission system issues such as mid-distance visually amplify, and enhance bandwidth using Raman optical amplification (ROA) technology. ROA does not suffer from EDFA limitations in that it can be integrated with transmission fibers, and is pumped at any wavelength to provide wide gain bandwidth and gain flatness by using a combination of different wavelength pumping sources. Raman amplifier is based on Raman scattering motif phenomena is a nonlinear optical process in which the photon is absorbed and called the photon pump by the material while simultaneously emit a photon of different energy. The difference in photon energy is compensated by changing the vibrational state of the substance. There are two Raman speakers; a separate Raman amplifier and a distributed Raman amplifier (DRA). The distributed fiber optic type is used as an active medium. If the amplifier is included in the box at the end of the transmitter or receiver of the system, it will call a separate Raman amplifier. One of the most commonly used in contemporary submarines and long-distance terrestrial networks is the distributed Raman Amplifier (DRA), where Raman amplification can occur in any fiber at any signal wavelength by proper selection of the pump wavelength. The Raman gain process is very fast. In this study presented two optical amplifiers in cascaded form to enhancement the gain of the amplifier the first is forward pump amplifier and the second is backward pump amplifier, also we simulate and analyze the parameters affecting on Raman gain of fiber Raman amplifier for three different fiber types

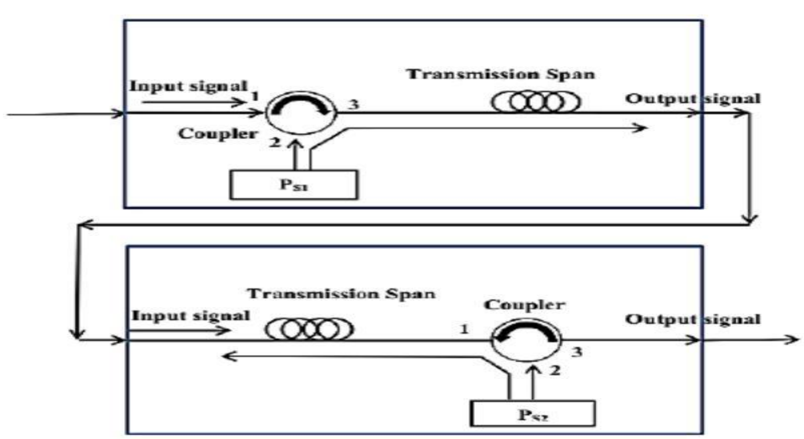


Figure 2-13 Design model of Raman amplifier system scheme. {5}

2.5.1.1 Model and Equations Analysis

The scheme of a typical DRA which uses two Raman fiber amplifiers the first forward pump Raman amplifier and the second is feedback pump Raman amplifier in cascaded form to enhancement the Raman gain of feedback Raman amplifier is shown on Figure 2-13. When the pump power propagates in the direction of the signal, it is called co- or forward pumping scheme, and when the pump travels in the opposite direction, it is called counter or backward pumping. The pump sources marked as PS1 and PS2 are placed at both ends of the transmission span and their power are switched in the medium of the silica fiber using optical couplers.

The fiber signal propagates in fiber media with the power signal according a couple of differential equation, this equation describes not only the signals attenuation due to propagation but also the power transfer from the power signal as follow:

$$\pm\frac{\partial P_p}{\partial Z} = -\frac{\omega_p}{\omega_s} G_R P_p P_s - \alpha_p P_p$$ (1) …………….. [5]

$$\frac{\partial P_s}{\partial Z} = G_R P_p P_s - \alpha_s P_s$$ (2) …………………….[5]

where G_R is the Raman gain coefficient related to the fiber type ($W^{-1}.m^{-1}$), α_s and α_p are the attenuation coefficient related to the optical signal and the pumping power in same order, ω_s and ω_p are the angular frequency related to the optical signal and the pumping power in same order.

Therefore, to calculate the pump power at point z it can be used:

$$P_p(Z) = SP_p(0).e^{-\alpha_p Z(1-s)} = P_p(0).e^{-\alpha_p(L-Z)}$$ (3) ……………………..[5]

If the values of P_P are substituted in differential eqn. (2), and it is integrated from 0 to L for the signal power in the forward and the backward pumping, it can be written as:

$$P_s(Z) = P_s(0).e^{\left(G_R P_0\left(\frac{(1-\exp(-\alpha_p Z))}{\alpha_p}\right)-\alpha_s Z\right)} = G_F.P_s(0)$$ (4)……..[5]

$$P_s(Z) = P_s(0).e^{(G_R P_0\left(\frac{\exp(-\alpha_p L)(1-\exp(-\alpha_p Z))}{\alpha_p}\right)-\alpha_s Z)} = G_B.P_s(0), \quad (5)........[5]$$

where G_F, G_B are the net gain in the forward and backward pumping respectively. With PO being the pump power at the input end, α_S and α_P are the linear attenuation coefficient of the signal and pump power in the optical fiber respectively, can be expressed as:

$$\alpha_{S,P} = \alpha / 4.343, \quad (6) ....[5]$$

where α is the attenuation coefficient in dB/km.

From equation. (4) and (5) can get the total gain of fiber Raman amplifier due to using forward pump Raman amplifier and feedback pump Raman amplifier in cascaded form to enhancement the Raman gain of feedback Raman amplifier can be expressed as:

$$G_T = G_F \times G_B \quad (7) ....[5]$$

Where, G_T the total gain of forward pump Raman amplifier and feedback pump Raman amplifier then,

$$G_T = exp\left[g_R P_0 \, x \frac{\exp(-\alpha_P L)(\exp(\alpha_P z)-1)}{\alpha_P} - \alpha_S Z\right] \times exp\left[g_R P_0 \, x \frac{1-\exp(-\alpha_P z)}{\alpha_P} - \alpha_S Z\right] \quad (8)....[5]$$

$$G_T = exp\left[g_R P_0 \, x \frac{\exp(-\alpha_P L)(\exp(\alpha_P z)-1)}{\alpha_P} + g_R P_0 \, x \frac{1-\exp(-\alpha_P z)}{\alpha_P} - 2\alpha_S Z\right] \quad (9)....[5]$$

$$G_T = exp\left[g_R P_0 \, x \frac{a-b-c}{\alpha_P} - 2\alpha_S Z\right] \quad (10) ....[5]$$

Where;

$$a = \exp(-\alpha_p L).\exp(\alpha_p z), \; b = \exp(-\alpha_p L) \text{ and } c = \exp(-\alpha P Z) \quad (11)........................[5]$$

The signal intensity at output of amplifier, fiber cable length L is determined by the following expression:

$$P_s(L) = P_s(0)\exp\left(\frac{g_0 P_0 L}{A_{eff}} - \alpha_s L\right)$$ (11) …………….[5]

The effective length, L_{eff} is the length over which the nonlinearities still holds or stimulated Raman Scattering (SRS) occurs in the fiber and is defined as:

$$L_{eff} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p}$$ (12) ……………[5]

Hence the amplification gain defined as the ratio of the power signal with and without Raman amplification, is given by the following expression:

$$G_A = \frac{P_S}{P_S(0)\exp(-\alpha_s L)}$$ (13) …………[5]

2.5.1.2 Result and discussion

As conclusion simulation results gives enhancement the gain of the amplifier, The Raman gain of an optical signal is observed to depend on the selection of pump power. The Raman Amplifier gain is obtained as a function of fiber length and pump power. According to the obtained results, gain is strongly dependent on the fiber length and pumping power.

Chapter 3

Methodology, Design and Implementation

Chapter 3: Methodology, Design and Implementation

3.1 Methodology

Opti-system simulator is selected as simulation tool to simulate the system bearing in mind the optimization features of the simulator, figure 3-1 show the configuration setup of the system, the optimization of the Pump power and Pump frequency will be resulted in gain flatness for 64- C WDM channels shown in figure 3.2, Opti-system simulation tools well thought-out suitable simulator for such case as provided all required parameters to design and implement our thesis requirement and to get the desired results, 64 C-band channels used to form the project, the 64 channels between 1512 and 1562.4 nm with 0.8 nm separations are multiplexed onto a single fiber through Optical Wavelength Multiplexer and amplified through Raman Optical Amplifier, four pump with initial power and wavelength added to the Opti-system simulation, Dual spectrum analyzer is used to analyze the gain for each channel, spectrum analyzer used before and after Raman amplifier, by performing the optimization for pump power and pump wavelength and with rounds of iterative optimization process the gain flatness obtained and be visualized through spectrum analyzer

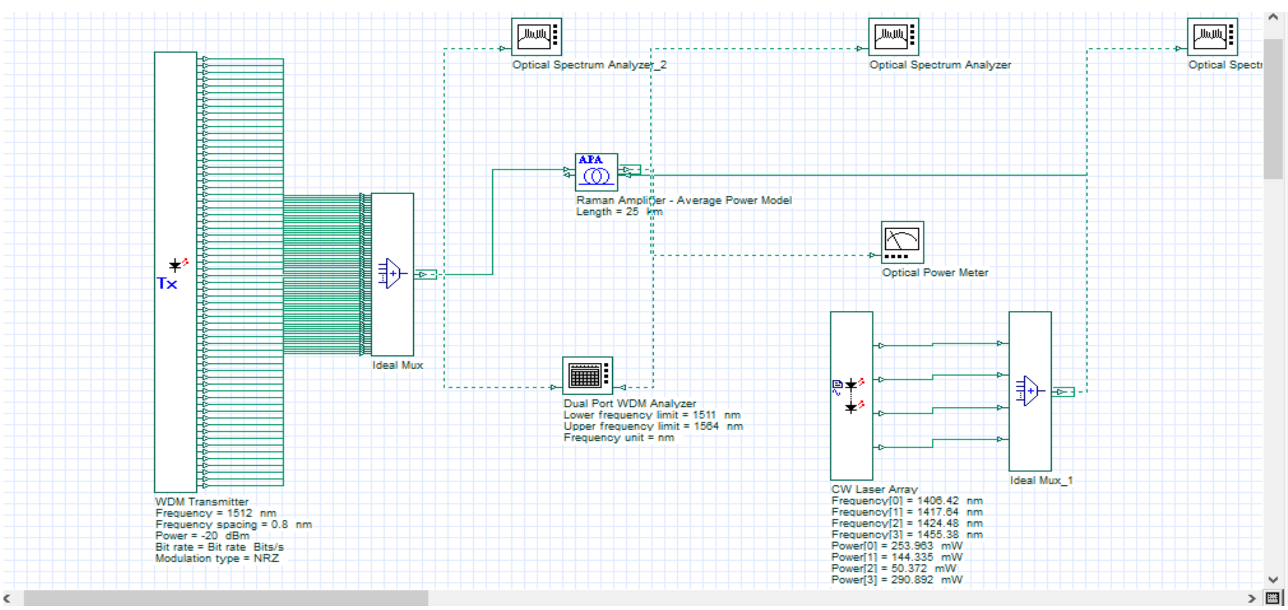


Figure 3-1: Simulation configuration setup

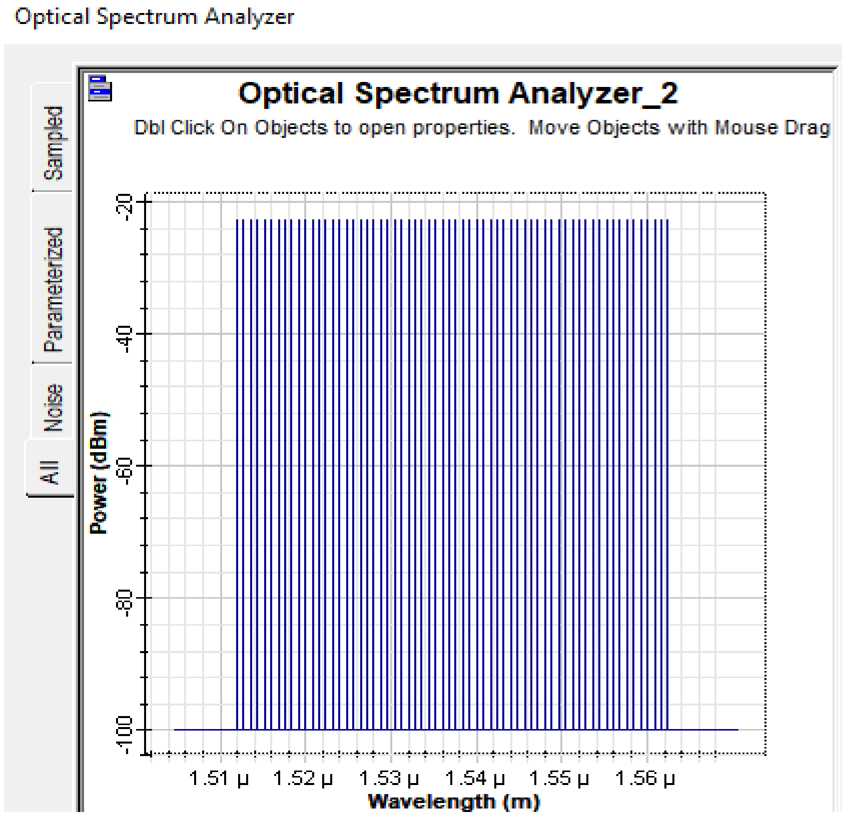


Figure 3-2 WDM channels before amplification

3.2 Design and Implementation

The requirements are to have multi-wavelength of Raman amplifiers with a flattened gain, determination of the amplifier specifications such as signal level, required gain profile, and number of allowed pump channels should be precisely specified before implementation, the optimization procedure can generate a combination of pump wavelengths and input powers that would result in the gain profile approximating the specified one as close as possible. Important notice that the optimization may require a huge number of iterations since interaction between channels and pumps are very complicated. Therefore, it is very important to give good estimated initial values, especially for pump wavelengths to the Opti-system to lower the required number of iterations, as our endeavor is **optimizing the pump power and frequencies for gain flatness,** so the values named as **Initial** with the initial pump configuration and **Optimized** with the optimized pump configuration and a Multi-Parameter Optimization (MPO) setup.

3.2.1 Characteristics of Multi-pump Raman Amplifier

The aim behind the optimization of multi-pump Raman amplifier is to get better gain flatness and reduce ripples instead of utilizing any gain flattening techniques. Gain bandwidth can be improved by Raman amplifier by efficient utilization of DWDM system adopting the MPO optimization using Opti-System simulation software. The optimized four pump powers are utilized to transfer energy from pumps to the signal to provide better gain flatness and reduce ripples. MPO tools are available in Opti-System software to optimize the pump powers and frequencies to achieve the target gain to keep the DWDM system with 0.8 nm channel spacing. This multi-pump optimization is based on nonlinear least square (LSQ) algorithm. For the initial stage the four types of pumps are randomly chosen with input power -20 dBm for 64 channels of DWDM system. The MPO is executed with several iterations for the goal attainment of gain flatness to achieve high gain. The signal power was at length L to amplify the continuous wave signal

$$P_s(L) = P_s(0)\exp\left(\frac{g_R}{a_P}P_0L_{eff} - \alpha_s L\right) \quad .....[5]$$

Where $L_{eff} = [1 - \exp(-\alpha_P L)]/\alpha_P$ represent the effective length of the Raman fiber amplifier, where g_R represents Raman gain coefficients, where a_P is the pump cross-sectional area, α_s is the fiber loss, P_0 is the input power, and $P_S(0)$ is the signal power a L = 0. The basic simulation setup in Figure 3-1 shows 64 channels where each channel is spaced with 0.8 nm

The design layout is as shown in Figure 3-1; total of 64 channels between 1512 and 1562.4 nm with 0.8 nm separations are multiplexed. The average power of each channel is -20 dBm. The Average Power Raman amplifier model to simulate the amplifier is selected. This model allows a fast and accurate estimation of the amplifier gain. The fiber used as gain medium is a 25 km fiber with 9.5e-014 m/W peak Raman gain coefficient. The effective area of the fiber is 55-micron square. The loss of the fiber is 0.2 dB/km

In the design the main focus and interest in the frequency domain response of the amplifier. Therefore, the simulation conducted with Parameterized signals. To do so, Parameterized option is selected from Signals tab of the Initial Parameters window. Regarding the setting of upper pump frequency is selected from Enhanced tab of the Raman Amplifier component and the Upper pump reference parameter is set to 1510 nm. in the design, a Dual Port WDM Analyzer measures amplifier gain and gain flatness. To limit the measurement window within signal spectrum, the lower and upper frequency limits from the Main tab of Dual Port WDM Analyzer set to values 1511 nm and 1564 nm, respectively.

Four pump signals with initial powers and frequency setting shown in Table 3-1 are used for backward pumping. These parameters are chosen for comparison. The Initial configuration is shown in the Layout named “Initial”. The initial power from optical spectrum analyzer depicted in figure 3-3 and the output power before optimization shown in figure 3-4 and Raman gain value before optimization shown in table 3-2

Pump Wavelength	**Pump Power**
1405.0	**110.0**
1415.0	**140.0**
1435.0	**170.0**
1460.0	**140.0**

Table 3-1 Initial pump parameters

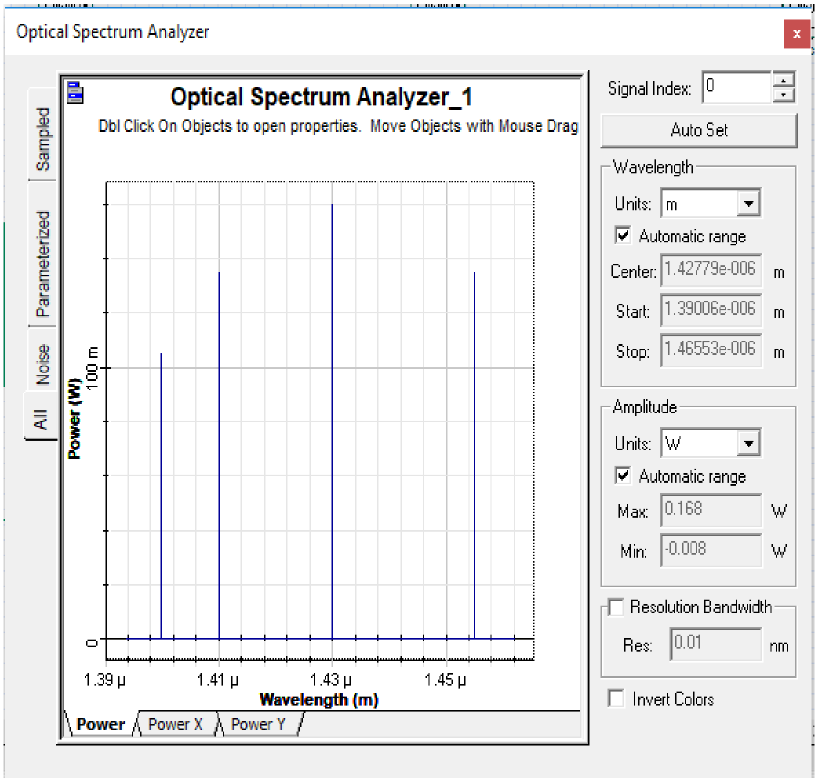


Figure 3.3 Initial pump power allocation

With this initial pump configuration, the output power spectrum observed in Figure 3-4. The obtained gain flatness is 3.7 dB, these values can be seen by double clicking on Dual Port WDM Analyzer by observe the highest output power of amplifier channels and compared with lowest output power of Raman Amplifier channel as it shown in table 3-2

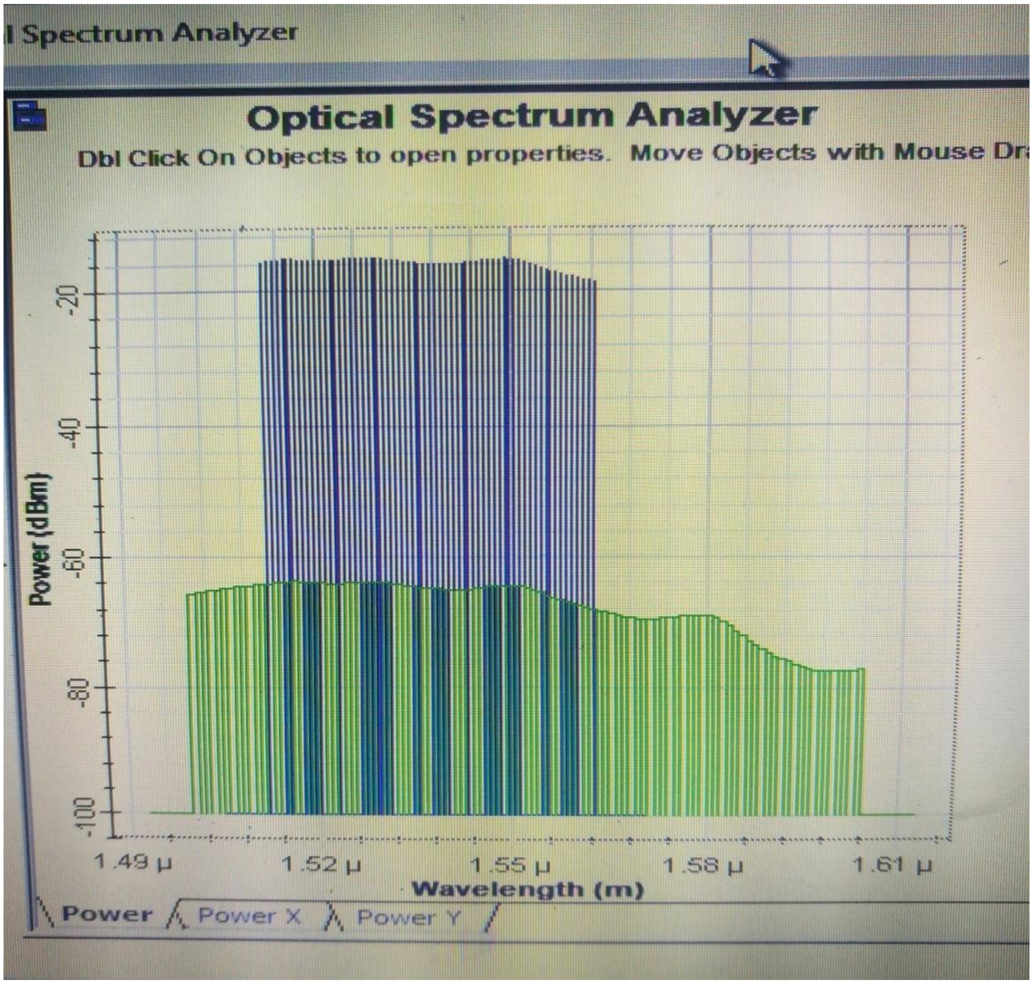


Figure 3.4 Output power spectrum before the optimization

Dual Port WDM Analyzer

Frequency (THz)	Gain (dB)	Noise Figure (dB)
191.879	3.2891523	8.50799
191.978	3.4669805	8.56047
192.076	3.6382485	8.61186
192.175	3.805317	8.4427
192.273	3.9736101	8.50027
192.372	4.1491365	8.56297
192.471	4.3382769	8.64675
192.57	4.5498129	8.75607
192.669	4.7957274	8.50803
192.768	5.0735699	8.59286
192.867	5.3669997	8.66986

Signal Index: 0

Frequency Units: THz

Power Units: dBm

Resolution Bandwidth Res: 0.10000 nm

Analysis | Details

Table 3-2 Raman gain values before optimization

The optimization configuration setup process through Opti-system shown from Appendix 6 to Appendix 16 for pump and wavelength with following optimization parameter setup, the **Gain Flattening** type of optimization has been selected; pump powers and frequencies are added to the table, the Minimum and maximum pump powers are selected to be 0 and 300 mW respectively. minimum and maximum pump wavelengths are selected to be 1400 nm and 1500 nm, respectively.

In the **Results** tab, the Gains for all channels from dual port WDM analyzer added to the table. Target gain are 6 db. in the first scenario and 10.0 db. for the second scenario inserted. Number of Goals to achieve exactly is same as the number of channels and automatically set.

Gain flatness is measured by the **Dual Port WDM Analyzer**. As a constraint, gain flatness less than 1.5 dB is required.

For specific designs, and for the given set of requirements, optimization procedure only needs to adjust the pump powers.

Chapter 4

Results and Discussion

Chapter 4: Results and Discussion

4.1 INTRODUCTION

The basic principle of optical communication system is that light can carry information over long distances. Optical fiber communication systems provides us with the large bandwidth but still bandwidth cannot be fully utilized because of requirement of too many sources for sending many signals and problem of multiplexing. The development of wavelength division multiplexed systems (WDM) has overcome this problem up to a certain extent by utilizing the bandwidth of optical communication systems. WDM is a potential technology in which multiple optical carriers with different wavelengths are modulated by electrical bit streams and are then transmitted over the fiber. In optical fiber communication systems, amplifiers are vital for regenerating, amplifying and retransmitting the optical signals. Amplifiers are needed to prevent the seriously attenuated optical signals. Raman amplifiers are generally used as compared to other amplifiers because of merits of high gain, better performance, low noise figure and amplifying the whole working band

As there is an increasing demand of transmission bandwidth for long haul wavelength division multiplexed optical fiber communication systems. Bandwidth can be well utilized by using wideband and gain flattened amplifiers. Wideband amplification can be done by combining several amplifiers having different gain bandwidths. Different gain flattening techniques are available for gain flattening purposes to reduce gain ripples

Because of practical issues, L-band EDFA has gained more interest in terms of gain flatness and enhancement. So as to utilize the transmission bandwidth, EDFA can be cascaded with Raman amplifier having different gain bandwidths so as to obtain wideband amplification.

4.2 Technique of Gain Flattening

The gain of optical fiber amplifiers is wavelength dependent due to which imbalance of power occurs in the transmitted channels. Therefore, there e is a need for gain flattening techniques to be applied to overcome this problem as wideband and gain flattened optical amplifiers are crucial for long haul optical communication systems, fig. 4.1 show the flattening concept

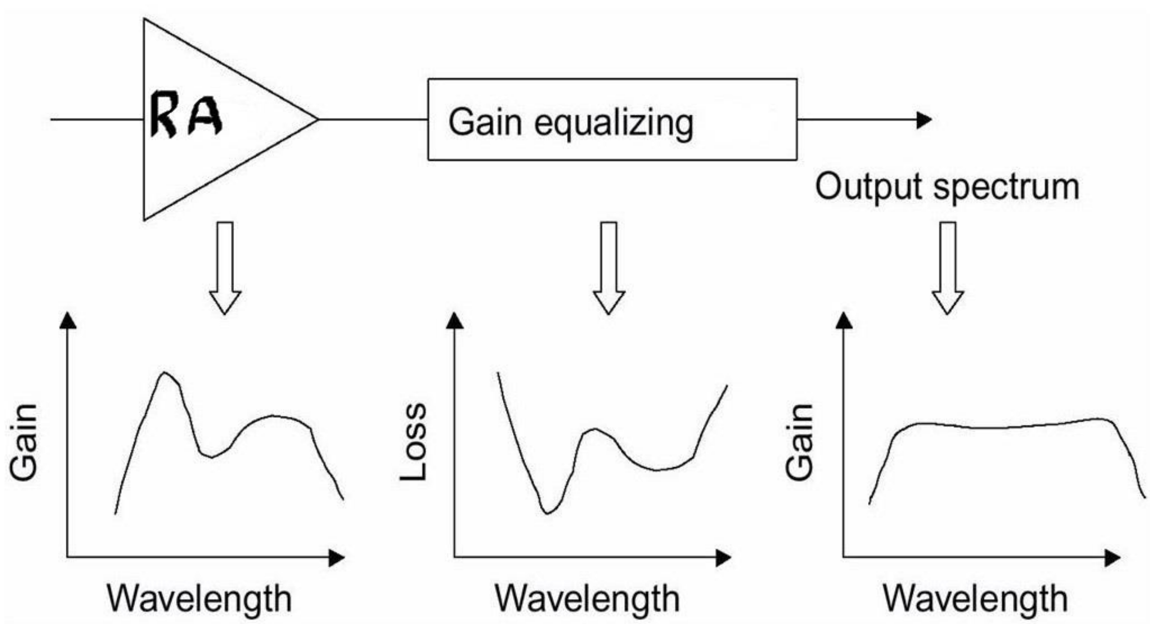


Figure 4.1 Gain flattening concept

Flattening of the gain contour in wideband Raman amplifiers is one of the most important tasks for the designers of Raman amplifiers. Currently, different pump techniques are being used for Raman gain flattening. In our "WDM pumping," is used which employs a set of several 14XX-nm diode laser pumps with optimized wavelengths and/or output power. Our target gain flatness of Raman amplification in the C- plus L-band. The deploying of pumping schemes for fiber Raman amplifiers has disadvantage related to relatively high of Pump.

4.3 Results and Discussions

Total of 64 channels from C- Band as descripted in figure 4-1 to has been used to perform the gain flattening through opti-system simulation

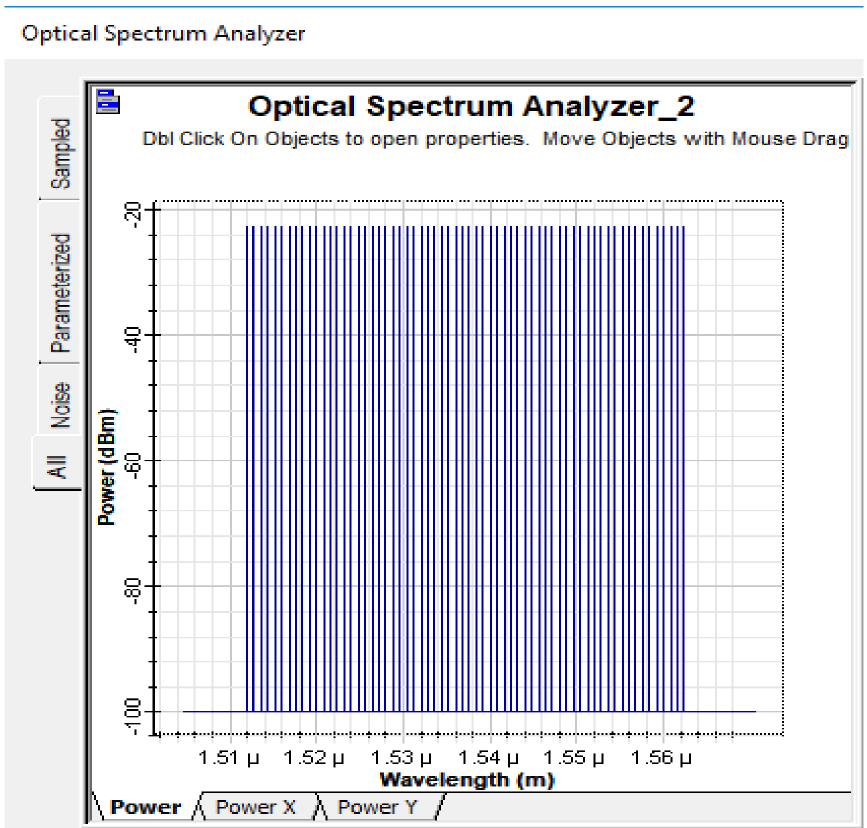


Figure 4-2 64 C-band channels

The 64 channels multiplexed through WDM multiplexer onto one single fiber and amplified with Raman optical amplifier and the gain of Raman amplifier has been optimized through MPO process with rounds of optimization iteration for pump power and pump wavelength, the initial pump power and wavelength shown in Figure 4-3 and table 4-1, the desired output of the whole design is to get out put power flatness of the Raman amplifier

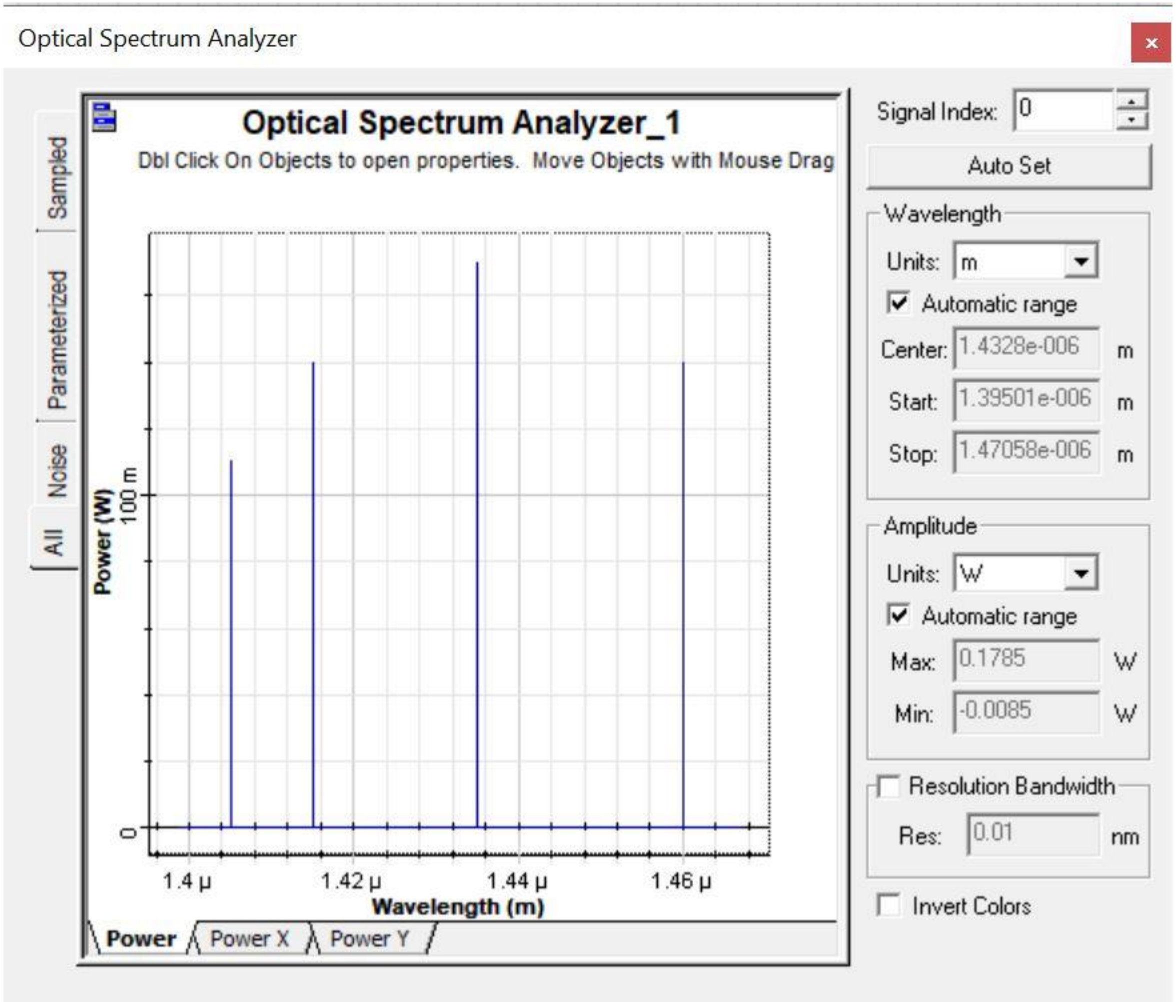


Figure 4.3 Initial pump power allocation

Pump Wavelength	Pump Power
1405.0	110.0
1415.0	140.0
1435.0	170.0
1460.0	140.0

Table 4-1 Initial Pump power and wavelength

4.3.1 Scenario one

compare Raman Amplifier gain flatness **before optimization** to Raman amplifier gain flatness **after optimization at 6 db. gain** as target value

Before Optimization

The initial parameters values of pump power and wavelength as shown on table 4-1 will be changed to meet the flatness requirement through Multi-Parameter Optimization (MPO), more details about MPO setting in Opti-system shown in appendix 5-15

The gain ripples before optimization obtained from optical spectrum analyzer shown in figure 4-4 and from dual spectrum analyzer in table 4-2, from the table the gain flatness is about **3.7 db.** obtained from the difference between highest power gain with lowest power gain

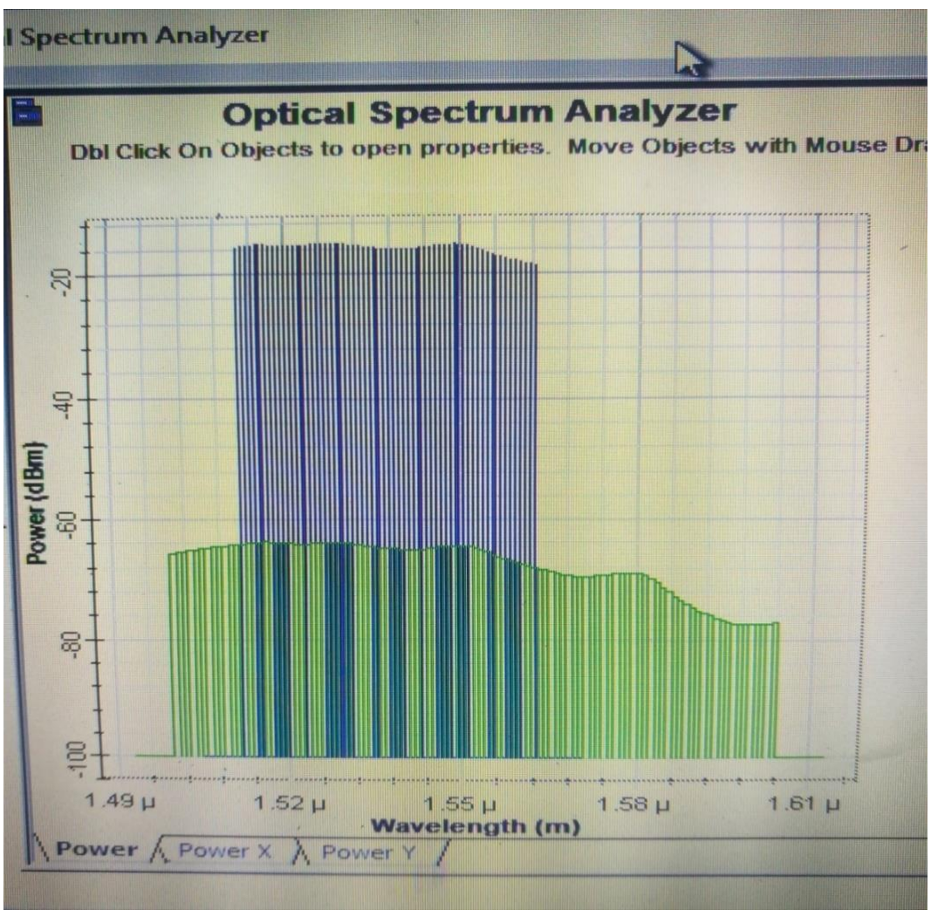


Figure 4-4 Raman gain before Optimization

Frequency (THz)	Gain (dB)	Noise Figure (dB)
191.879	3.2891523	8.50799
191.978	3.4669805	8.56047
192.076	3.6382485	8.61186
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192.471	4.3382769	8.64675
192.57	4.5498129	8.75607
192.669	4.7957274	8.50803
192.768	5.0735699	8.59286
192.867	5.3669997	8.66986
192.966	5.6598742	8.73259
193.066	5.936248	8.75485
193.165	6.1794289	8.50951
193.265	6.369251	8.53658
193.365	6.4953883	8.53172
193.464	6.5675674	8.51467
193.564	6.5945149	8.47709
193.664	6.581522	8.48791
193.765	6.5339159	8.47801
193.865	6.459788	8.46102
193.965	6.3672698	8.43833
194.066	6.2595987	8.54383
194.166	6.1432153	8.53232
194.267	6.0301912	8.52768
194.368	5.9333812	8.54029
194.468	5.8631269	8.57284
194.569	5.8265093	8.60728
194.67	5.8245424	8.62954
194.772	5.8522449	8.65889
194.873	5.8999945	8.69293
194.974	5.9569171	8.72458

Dual Port WDM Analyzer

194.974	5.9569171	8.72458
195.076	6.014925	8.66439
195.177	6.0708326	8.68912
195.279	6.1250698	8.71766
195.381	6.1827961	8.75146
195.483	6.2514251	8.80622
195.585	6.3393637	8.71609
195.687	6.4498035	8.75948
195.789	6.5731668	8.80185
195.892	6.6977158	8.83655
195.994	6.8099279	8.84795
196.097	6.8959998	8.75967
196.199	6.9428061	8.77627
196.302	6.9415409	8.77035
196.405	6.8988369	8.74932
196.508	6.8253252	8.73434
196.611	6.7349608	8.82249
196.714	6.6427178	8.81957
196.818	6.5618044	8.83135
196.921	6.5044707	8.86312
197.024	6.4789617	8.91817
197.128	6.4904615	8.90446
197.232	6.5339031	8.93541
197.336	6.5974371	8.97653
197.44	6.6696998	9.00691
197.544	6.7384936	9.01801
197.648	6.7874253	8.96685
197.752	6.8009982	8.97715
197.857	6.7757306	8.97541
197.961	6.7174979	8.9578
198.066	6.6330443	8.9386
198.171	6.5296364	9.03977
198.275	6.4169052	9.0367

Analysis | Details

Signal Index: 0

Frequency Units: THz

Power Units: dBm

Resolution Bandwidth Res: 0.10000 nm

Table 4-2 Raman gain before optimization

After Optimization at 6 db gain as target value

The aim is to reduce the gain ripples from **3.7 db.** to lower value, after run multi-parameter optimization on opti-system and through round of optimization iteration, noticeable improvement is gained as shown in figure 3-6 from optical spectrum analyzer, and the numerical value of gain obtained from dual spectrum analyzer in table 4-3 and the gain flatness ripples improved from **3.7 db.** to **1.8 db.**

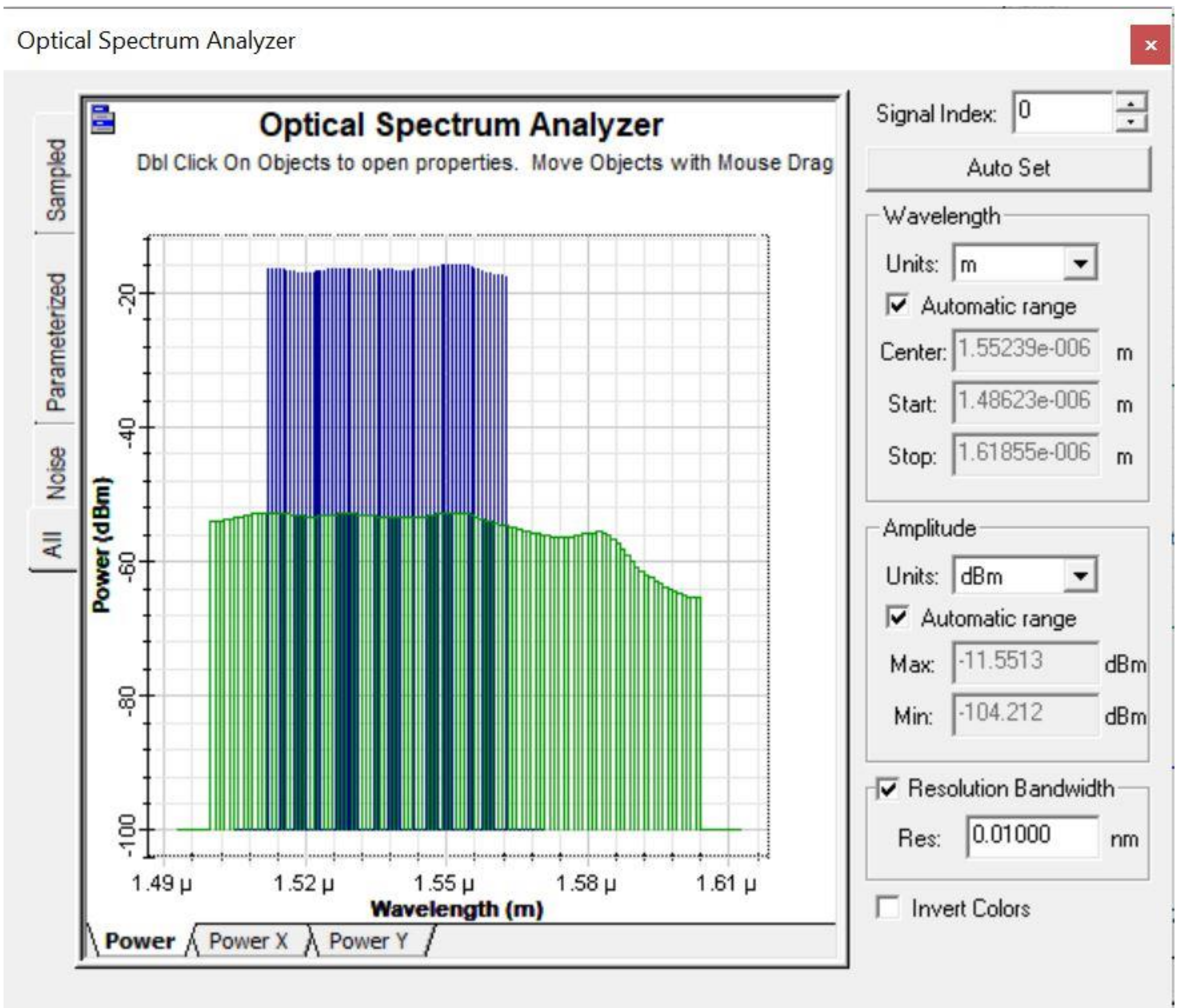

Figure 4-5 Raman gain after Optimization at gain 6 db

Dual Port WDM Analyzer

Frequency (THz)	Gain (dB)	Noise Figure (dB)	Input S
191.879	5.0170586	8.49297	-22.59
191.978	5.1310119	8.53852	-22.59
192.076	5.2508067	8.59356	-22.65
192.175	5.380852	8.46138	-22.59
192.273	5.5256599	8.51536	-22.59
192.372	5.6897268	8.57729	-22.65
192.471	5.8725446	8.64302	-22.59
192.57	6.0641517	8.6943	-22.59
192.669	6.2539833	8.50231	-22.59
192.768	6.4315545	8.5446	-22.59
192.867	6.5860282	8.56417	-22.59
192.966	6.7066665	8.56209	-22.65
193.066	6.7854869	8.53863	-22.59
193.165	6.8263002	8.49564	-22.65
193.265	6.8332188	8.49979	-22.59
193.365	6.8100831	8.48647	-22.59
193.464	6.7607696	8.46975	-22.65
193.564	6.6891915	8.44205	-22.59
193.664	6.5990945	8.52997	-22.65
193.765	6.4932998	8.51817	-22.65
193.865	6.3788447	8.50824	-22.65
193.965	6.2639582	8.50752	-22.65
194.066	6.1568324	8.61247	-22.65
194.166	6.0658783	8.61253	-22.59
194.267	5.9993834	8.62768	-22.59
194.368	5.961334	8.65476	-22.59
194.468	5.9469461	8.68369	-22.65
194.569	5.9493089	8.67915	-22.59
194.67	5.9614499	8.70172	-22.59
194.772	5.9763977	8.71791	-22.59
194.873	5.9870815	8.7304	-22.59
194.974	5.9890394	8.74444	-22.59
195.076	5.9854823	8.74581	-22.59
195.177	5.9815364	8.7605	-22.65
195.279	5.9823882	8.78271	-22.59
195.381	5.9932708	8.81195	-22.59

Signal Index: 0

Frequency

Units: THz

Power

Units: dBm

Resolution Bandwidth

Res: 0.10000 nm

Analysis / Details

195.381	5.9932708	8.81195	-22.59
195.483	6.0194109	8.85821	-22.65
195.585	6.0638779	8.81155	-22.59
195.687	6.1197732	8.84248	-22.59
195.789	6.1784425	8.86834	-22.65
195.892	6.2311705	8.88646	-22.65
195.994	6.2692419	8.88643	-22.59
196.097	6.2839042	8.86956	-22.65
196.199	6.2680896	8.87842	-22.65
196.302	6.2258529	8.877	-22.65
196.405	6.1638525	8.86847	-22.65
196.508	6.0885285	8.86623	-22.65
196.611	6.0062901	8.94626	-22.59
196.714	5.9236988	8.94648	-22.59
196.818	5.8467455	8.95397	-22.65
196.921	5.7785663	8.96954	-22.65
197.024	5.7230386	8.99712	-22.65
197.128	5.6842012	9.03375	-22.65
197.232	5.6661817	9.05401	-22.59
197.336	5.6730869	9.095	-22.59
197.44	5.7089172	9.14572	-22.65
197.544	5.771002	9.20008	-22.65
197.648	5.8488655	9.12	-22.65
197.752	5.9318191	9.15772	-22.59
197.857	6.0090093	9.19223	-22.59
197.961	6.0694457	9.20381	-22.65
198.066	6.1023169	9.19818	-22.65
198.171	6.1033132	9.19496	-22.59
198.275	6.0750524	9.20716	-22.65

Table 4-3 Raman gain after optimization at 6 db gain

4.3.2 <u>Scenario two</u>

compare Raman amplifier gain flatness **before optimization** to Raman amplifier gain flatness **after optimization at 10 db**. gain as target value

Before Optimization

The initial parameters values of pump power and wavelength as shown on table 4-1 will be changed to meet the required flatness requirement through Multi-Parameter Optimization (MPO),

The gain flatness ripples before optimization obtained from optical spectrum analyzer shown in figure 4-4 and from dual spectrum analyzer in table 4-2, from the table the gain flatness is **3.7 db.** obtained from the difference between highest power gain with lowest power gain

After Optimization

The aim is to reduce the gain ripples from **3.7 db.** to lower value, after round of iteration on multi-parameter optimization of opti-system simulator noticeable improvement is gained as shown in figure 3-7, and the numerical values obtained from Dual spectrum analyzer and shown in table 4-4, from the table the gain ripples of Raman amplifier improved from **3.7 db.** to around **1.5 db.**

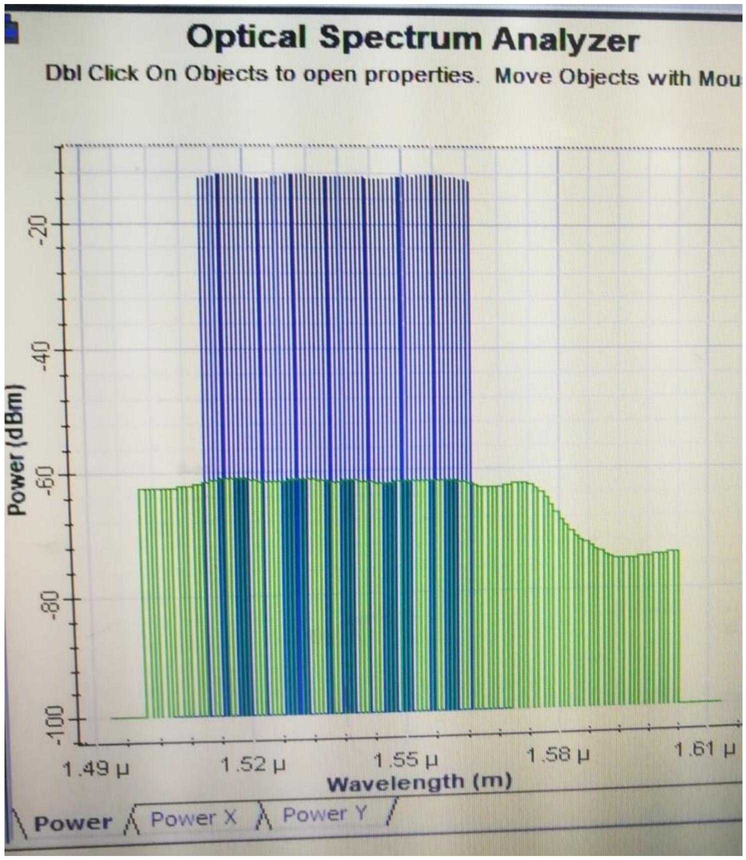

Figure 4-6 Raman gain after Optimization at **10 db**. gain

Dual Port WDM Analyzer

Frequency (THz)	Gain (dB)	Noise Figure (dB)
191.879	9.7046141	8.23903
191.978	9.7893135	8.2675
192.076	9.8706282	8.28734
192.175	9.9432983	8.21247
192.273	10.002515	8.2331
192.372	10.043488	8.23893
192.471	10.062442	8.23919
192.57	10.059824	8.23049
192.669	10.038576	8.24953
192.768	10.008896	8.25983
192.867	9.9842855	8.27998
192.966	9.9784605	8.32982
193.066	10.004539	8.39702
193.165	10.067055	8.3323
193.265	10.164473	8.38475
193.365	10.290186	8.43393
193.464	10.426097	8.46994
193.564	10.550704	8.463
193.664	10.642279	8.3692
193.765	10.683788	8.36995
193.865	10.6667	8.33717
193.965	10.586255	8.28075
194.066	10.450342	8.41445
194.166	10.274712	8.39393
194.267	10.075503	8.36845
194.368	9.8708787	8.35497
194.468	9.6797362	8.36492
194.569	9.518429	8.52401
194.67	9.3931886	8.52719
194.772	9.3015204	8.5416
194.873	9.2408183	8.57138

Signal Index: 0

Frequency
Units: THz

Power
Units: dBm

Resolution Bandwidth
Res: 0.10000 nm

Analysis | Details

194.974	9.2058415	8.6044
195.076	9.1852477	8.62277
195.177	9.1678561	8.63882
195.279	9.1519843	8.66035
195.381	9.1417716	8.68632
195.483	9.1418606	8.73003
195.585	9.1581758	8.71148
195.687	9.2016598	8.75147
195.789	9.2826495	8.80655
195.892	9.3932545	8.86767
195.994	9.5190996	8.92006
196.097	9.6465142	8.79041
196.199	9.7606343	8.83299
196.302	9.8428778	8.85044
196.405	9.8750492	8.83783
196.508	9.8581417	8.81715
196.611	9.8015973	8.87145
196.714	9.7134748	8.87008
196.818	9.6028991	8.86658
196.921	9.4848843	8.8743
197.024	9.3766164	8.90302
197.128	9.2905075	8.98688
197.232	9.2370266	9.00909
197.336	9.2273111	9.06438
197.44	9.2704731	9.13842
197.544	9.3604642	9.222
197.648	9.4836384	9.09656
197.752	9.6219311	9.14929
197.857	9.7536702	9.19292
197.961	9.8571947	9.19938
198.066	9.9132275	9.18146
198.171	9.9202115	9.17221
198.275	9.8852693	9.18405

Table 4-4 Raman gain after optimization at **10 db.** gain

The outcome of Raman gain optimization shown on above two scenarios is resulted in flattening the gain of Raman optical fiber amplifier which will be enabler for more channel to be transmitted and more bandwidth growth with higher OSNR and eliminate or reduce the BER.

from the two scenarios comparison, better improvement of gain flatness obtained at setting the target gain of Raman amplifier at **10 db**. which is reflected in better flatness value **1.5 db.** compared to **1.8 db.** at the target value set at **6 db.**

Besides bandwidth growth advantage that will be obtained from gain flatness, another advantage is wavelength power stability which reflected in service stability and better performance, on the other hand adding more pump with high power will generate hazard and risk for injury for human or equipment

Chapter 5

Conclusion and Recommendation

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

Optimization simulation results shows improvement of Raman Optical Amplifier gain, two scenarios conducted to prove the improvement, the first scenario set the target value on optimization parameter to Raman amplifier at **6 db.** and as results the gain ripples enhanced from **3.7db.** to **1.8 db.** on the second scenario the target gain of Raman amplifier on optimization parameter set at **10 db.** and the gain of Raman amplifier enhanced from **3.7 db.** to **1.5 db**. simple comparison between two scenario results, concluded that the best setting of Raman amplifier target gain value is **10 db.** to get best possible ripple flatness value which is **1.5 db.**

5.2 Recommendation

As gain flatness of optical Raman Amplifier can be better optimized, this will be enabler for more than 64 WDM channels to be transmitted as by the gain flatness mechanism and enhance the OSNR can be obtained and the BER eliminated or reduced to minimum, for example 128 or 256 WDM channels with 10,40 or 100G capacity can be transmitted with proper pump power selection to increase broadband capacity requirement, as it proven the possibility of flatten the gain of Raman Optical Amplifier and then enable the capacity growth, the challenge will be in better selection proper pump power and wavelength for Raman Amplifier for better results

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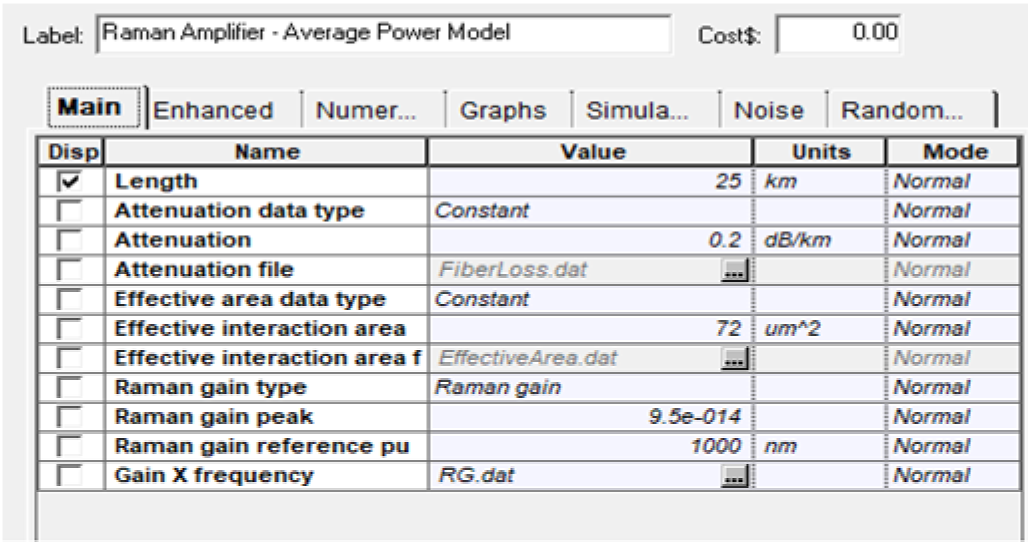
List of Abbreviation

Acronym	Description
ASE	Amplified Spontaneous Emission
ATM	Asynchronous Transfer Mode
CATV	Cable Access Television
DEMUX	De-multiplexer
DRA	Distributed Raman Amplifier
DWDM	Dense Wavelength Division Multiplexing
EFFA	Erbium-doped fiber Amplifier
FDM	Frequency Division Multiplexing
FWM	Four Wave Mixing
ISDN	Integrated Services Digital Network
MPO	Multi-Parameter Optimization
MUX	Multiplexer
NF	Noise Figure
NMS	Network Monitoring System
OFDM	Orthogonal Frequency Division Multiplexing
OSC	Optical Supervisory Channel
OSNR	Optical Signal to Noise Ratio
RA	Raman Amplifier
SDM	Space Division Multiplexing
TDM	Time Division Multiplexing
WDM	Wavelength Division Multiplexing
(UW)-WDM	Ultra-Wideband - Wavelength Dense Division Multiplexing

Appendix A

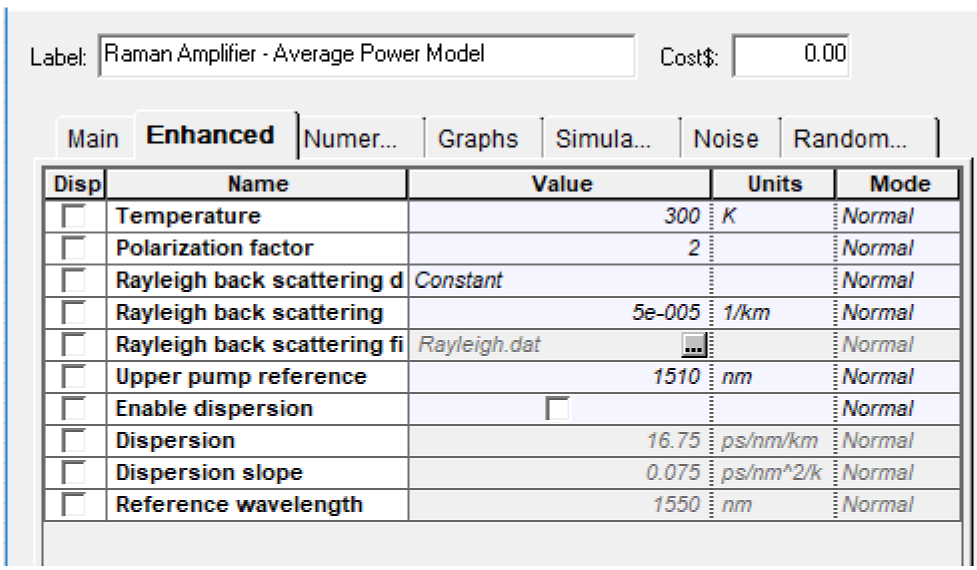


Label: Raman Amplifier - Average Power Model   Cost$: 0.00

Main | Enhanced | Numer... | Graphs | Simula... | Noise | Random...

Disp	Name	Value	Units	Mode
☑	Length	25	km	Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation file	FiberLoss.dat		Normal
☐	Effective area data type	Constant		Normal
☐	Effective interaction area	72	um^2	Normal
☐	Effective interaction area f	EffectiveArea.dat		Normal
☐	Raman gain type	Raman gain		Normal
☐	Raman gain peak	9.5e-014		Normal
☐	Raman gain reference pu	1000	nm	Normal
☐	Gain X frequency	RG.dat		Normal

Appendix 1: Raman Amplifier setting 1

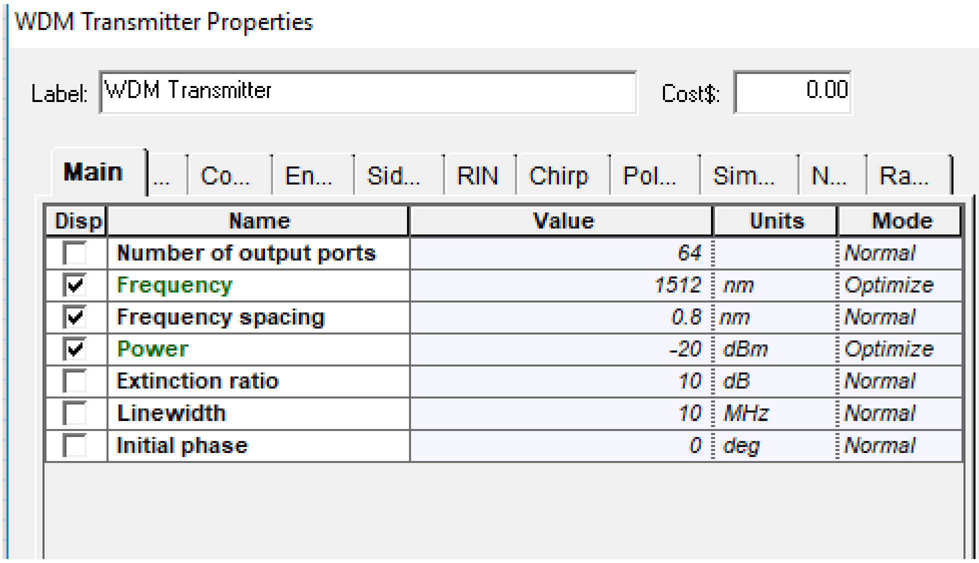


Label: Raman Amplifier - Average Power Model   Cost$: 0.00

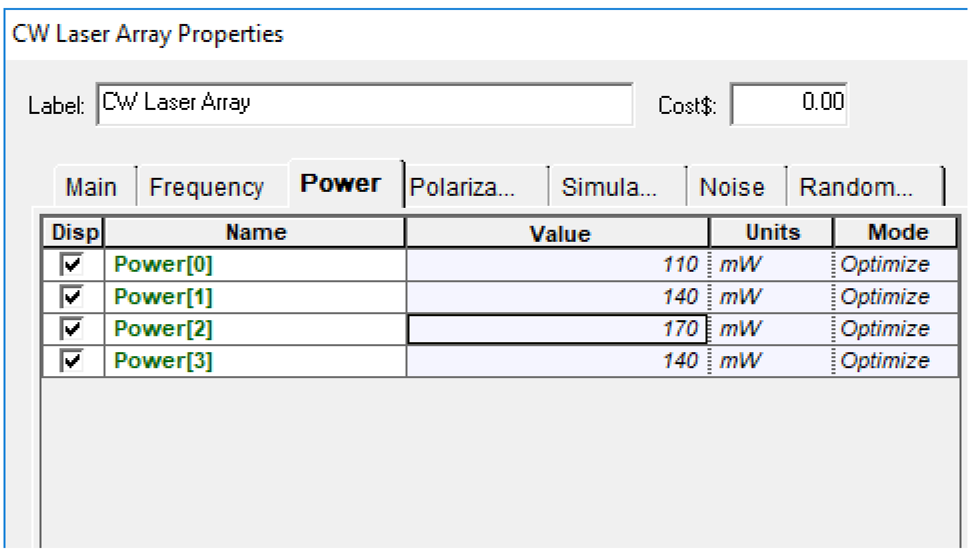
Main | Enhanced | Numer... | Graphs | Simula... | Noise | Random...

Disp	Name	Value	Units	Mode
☐	Temperature	300	K	Normal
☐	Polarization factor	2		Normal
☐	Rayleigh back scattering d	Constant		Normal
☐	Rayleigh back scattering	5e-005	1/km	Normal
☐	Rayleigh back scattering fi	Rayleigh.dat		Normal
☐	Upper pump reference	1510	nm	Normal
☐	Enable dispersion	☐		Normal
☐	Dispersion	16.75	ps/nm/km	Normal
☐	Dispersion slope	0.075	ps/nm^2/k	Normal
☐	Reference wavelength	1550	nm	Normal

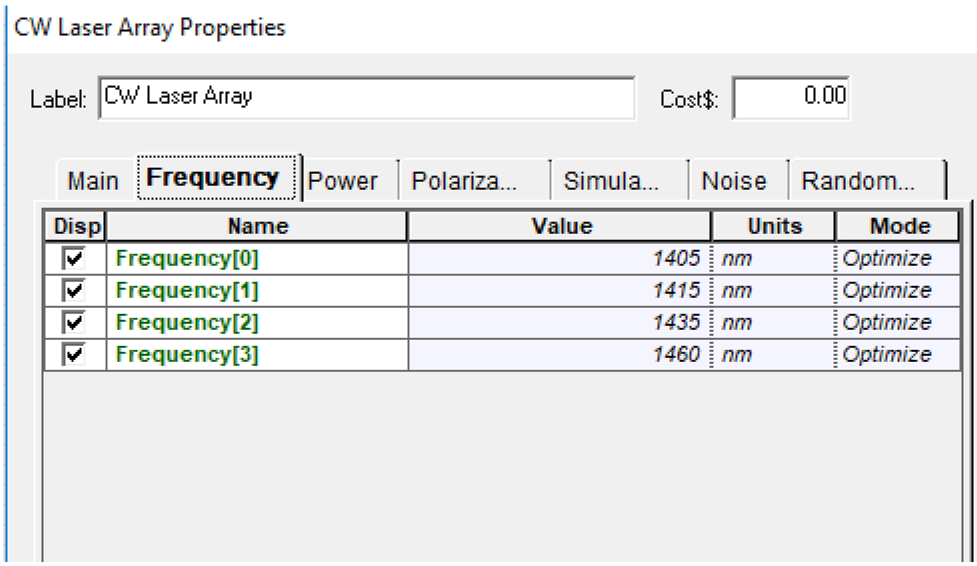
Appendix 2: Raman Amplifier setting 2



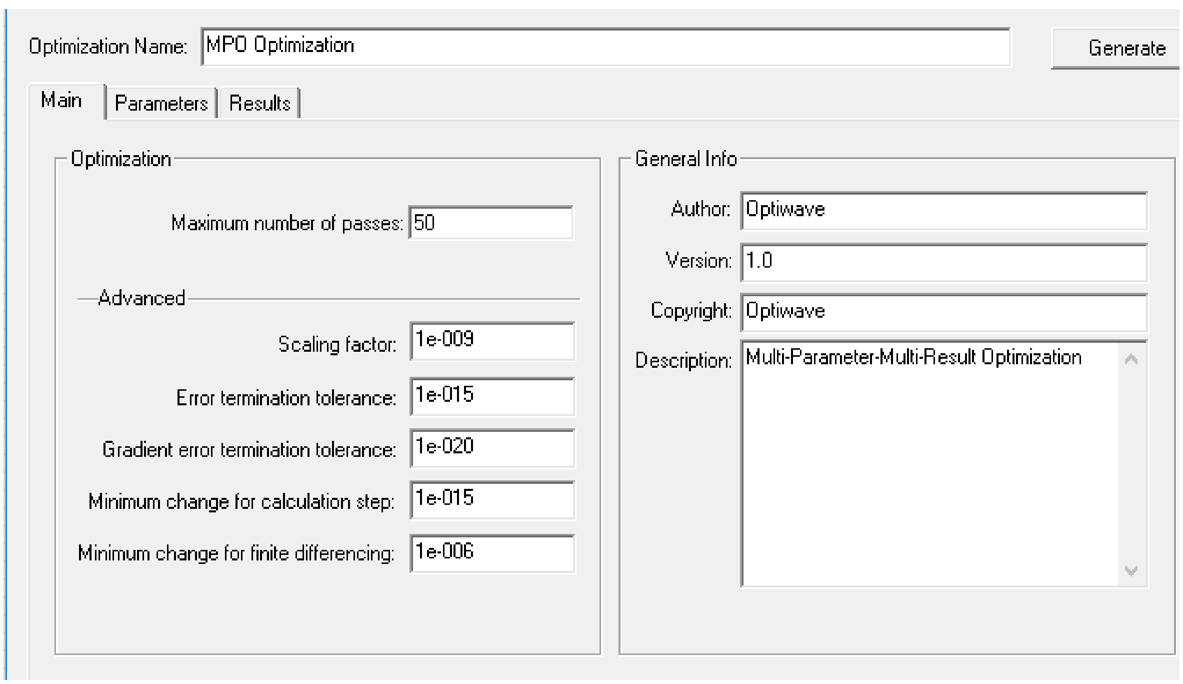
Appendix 3: WDM transmitter Configuration



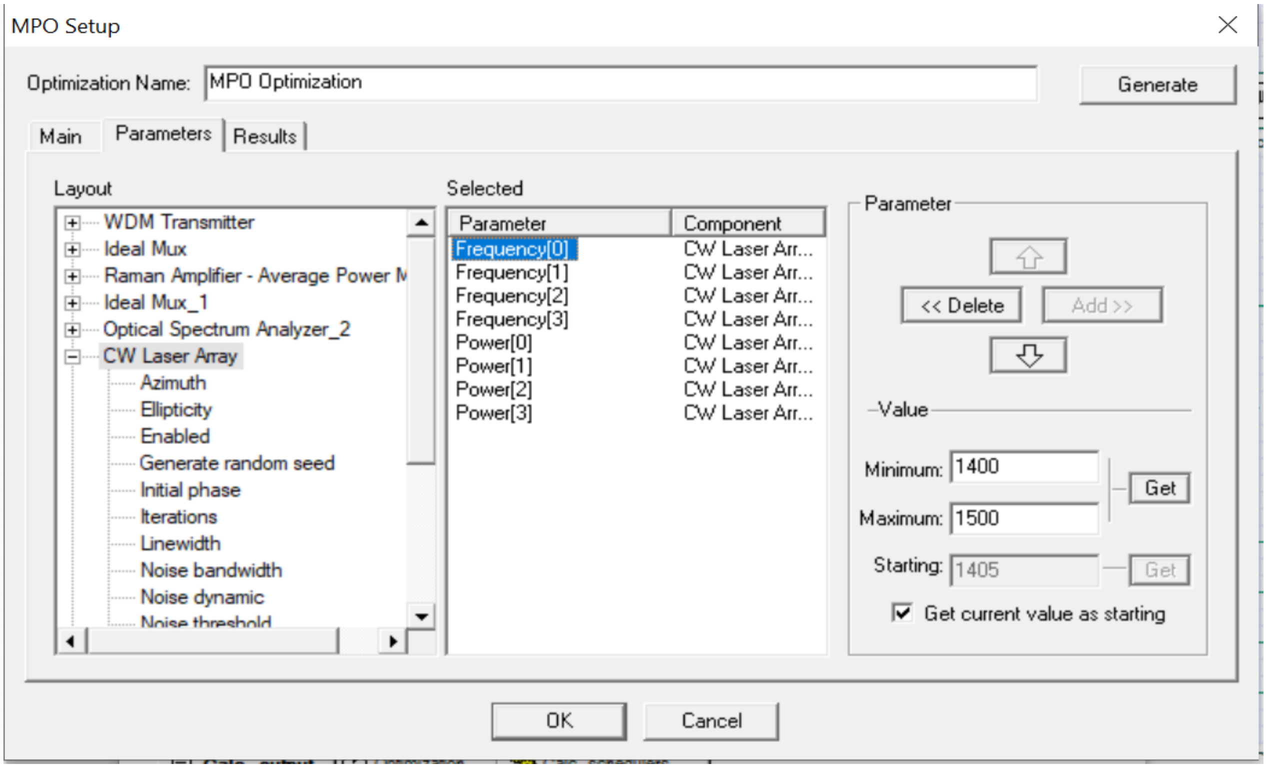
Appendix 4: Pump power settings



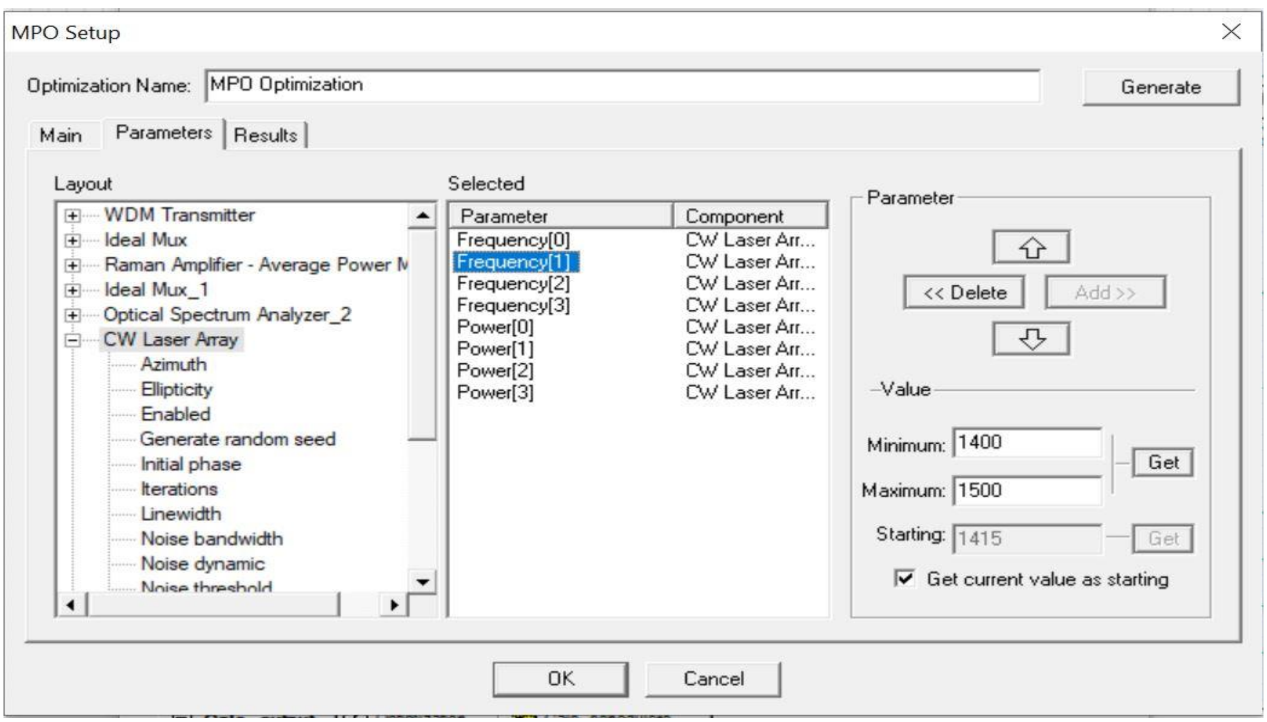
Appendix 5: Pump wavelength settings



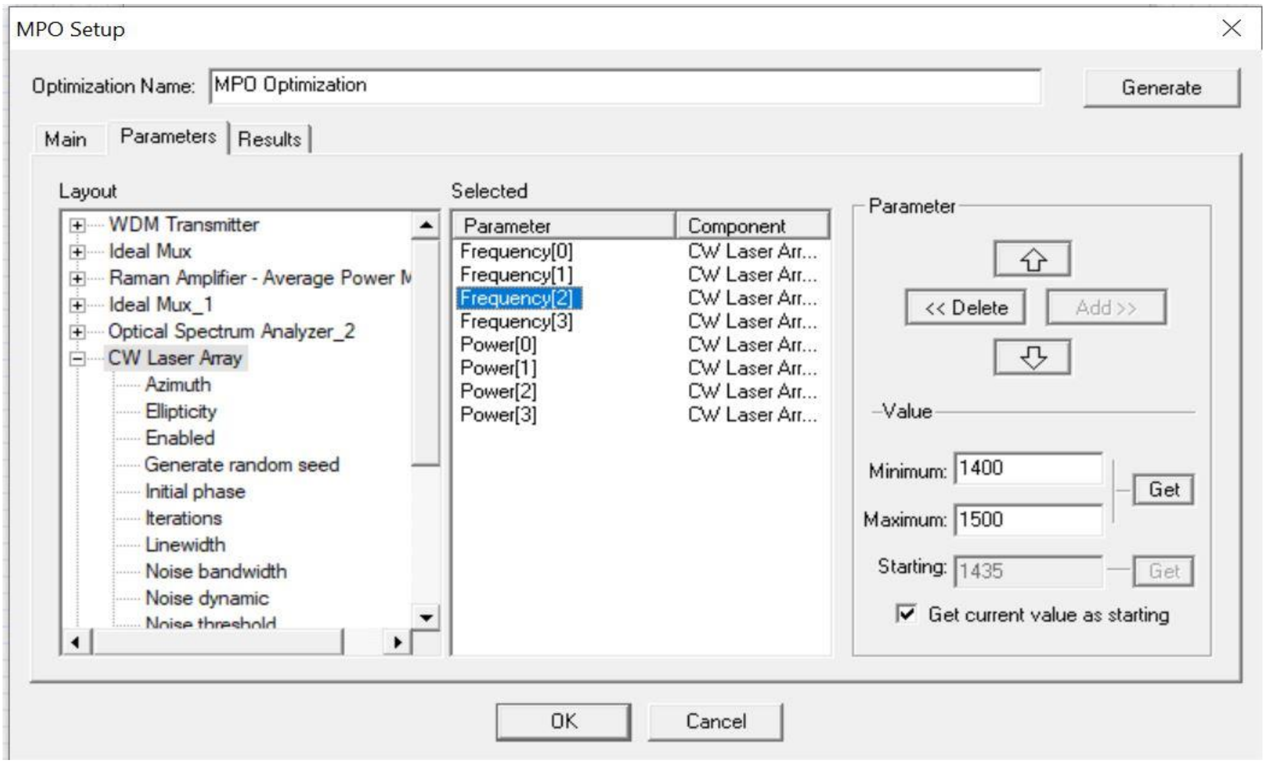
Appendix 6: Main tab of MPO



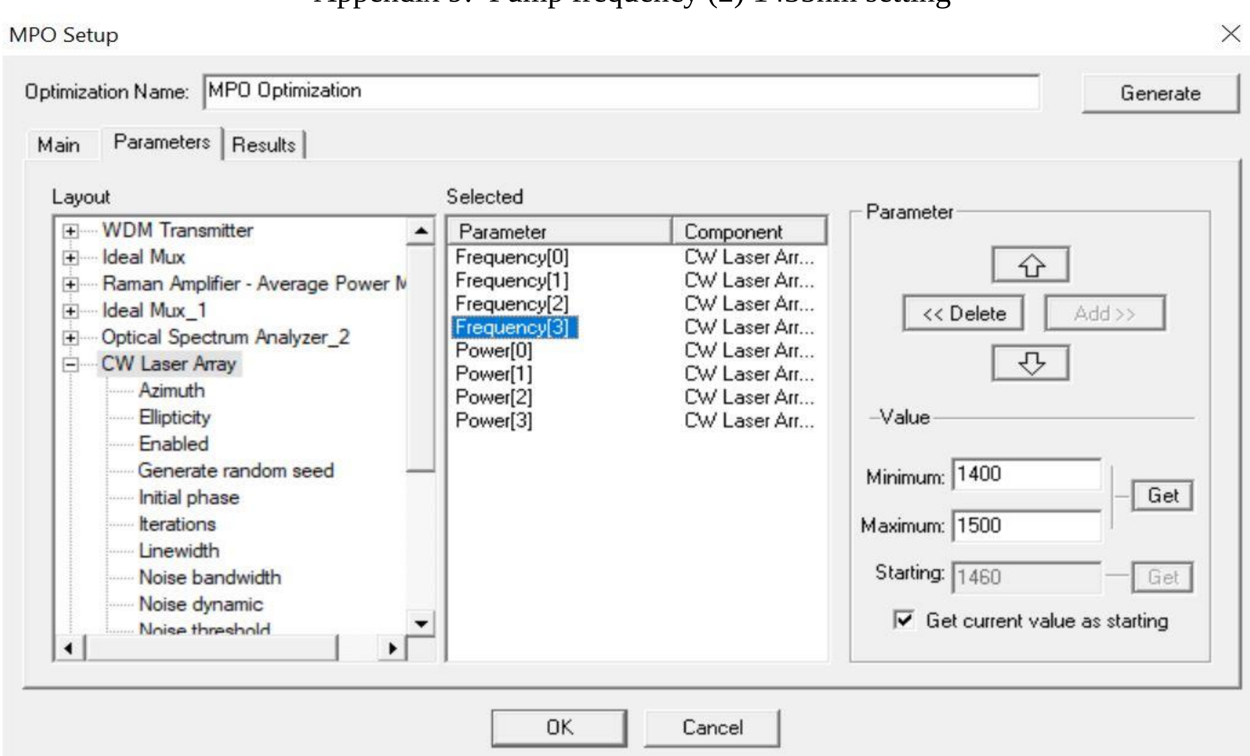
Appendix 7: Pump frequency (0) 1405nm setting



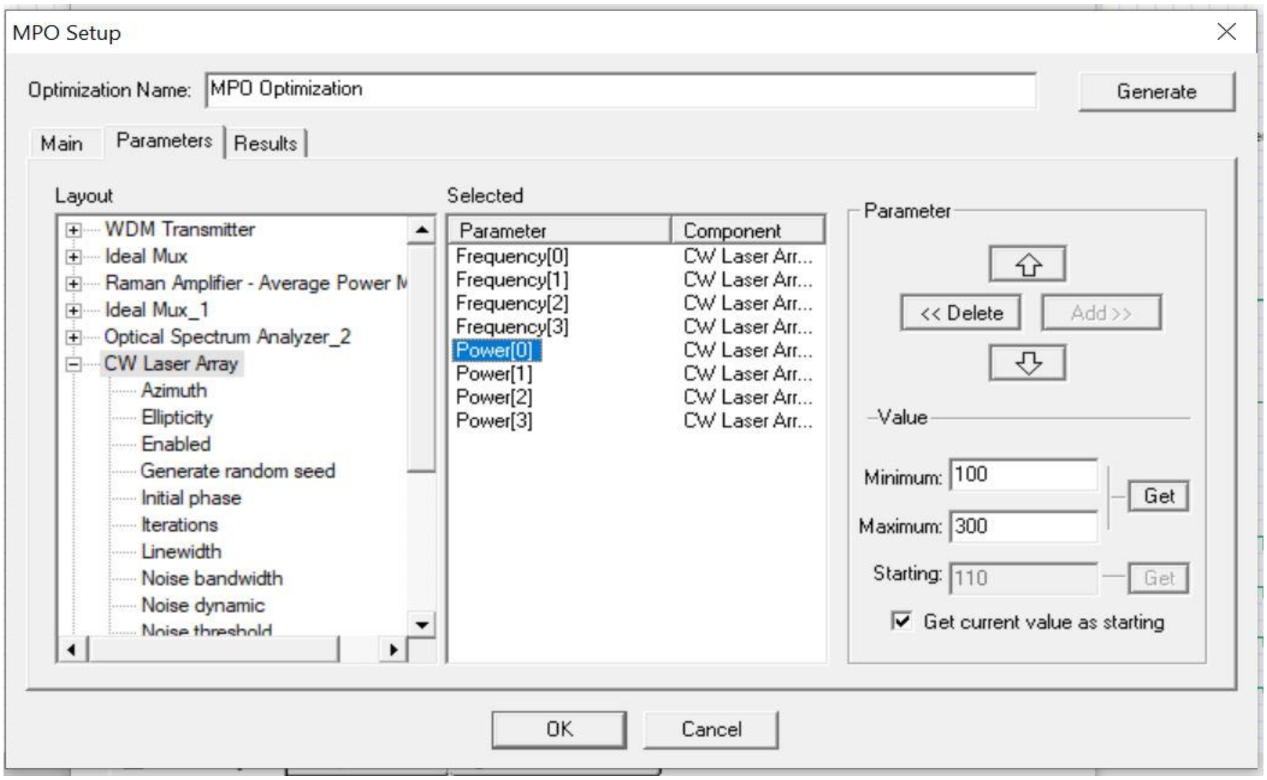
Appendix 8: Pump frequency (1) 1415nm setting



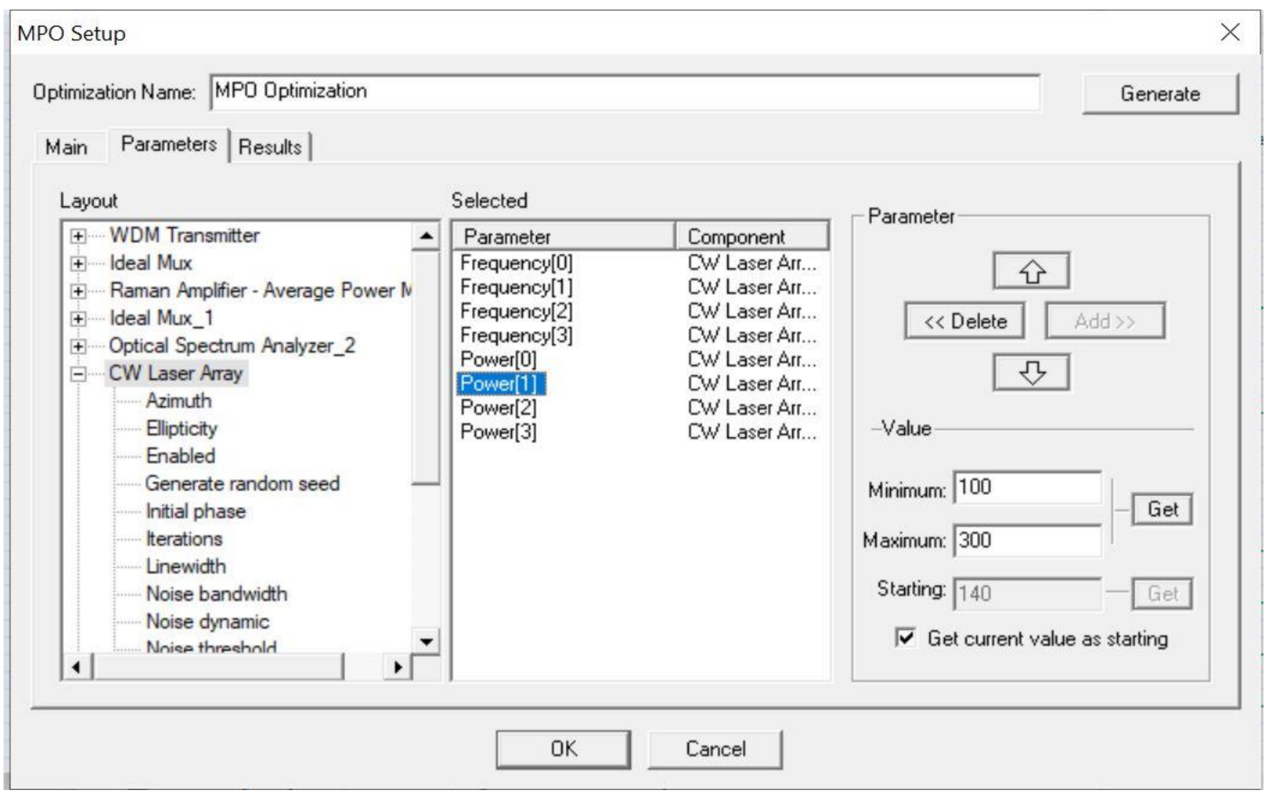
Appendix 9: Pump frequency (2) 1435nm setting



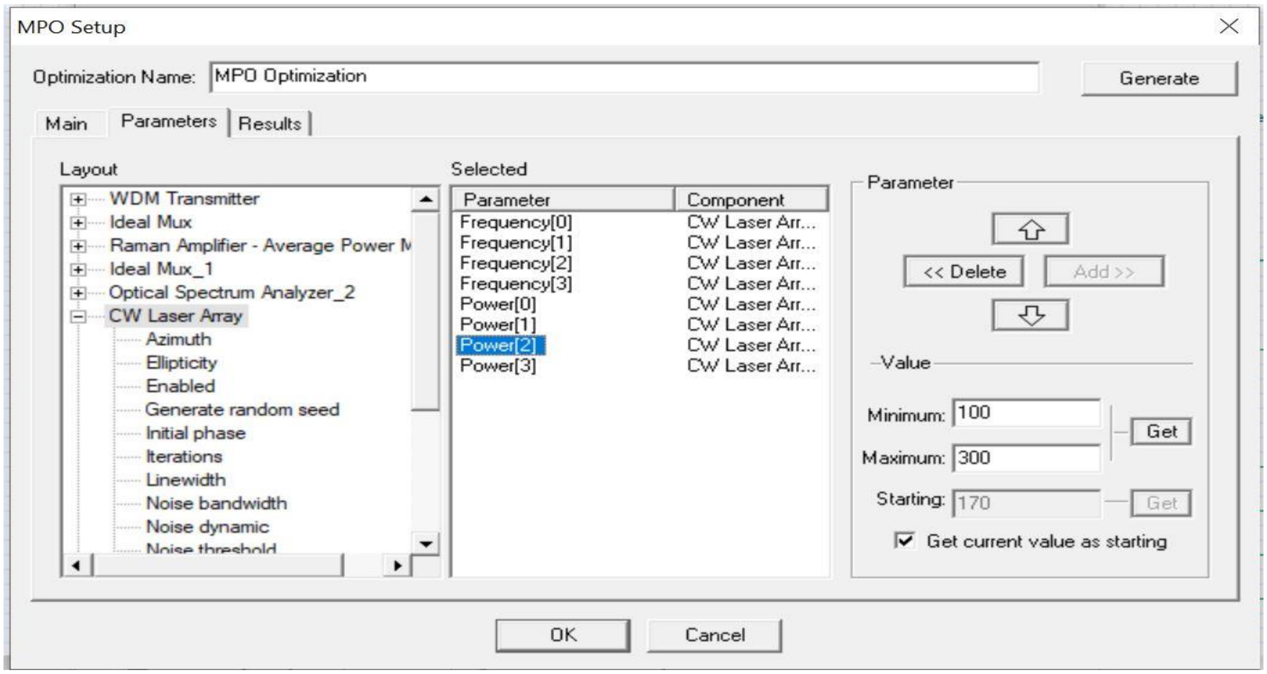
Appendix 10: Pump frequency (3) 1460 nm setting



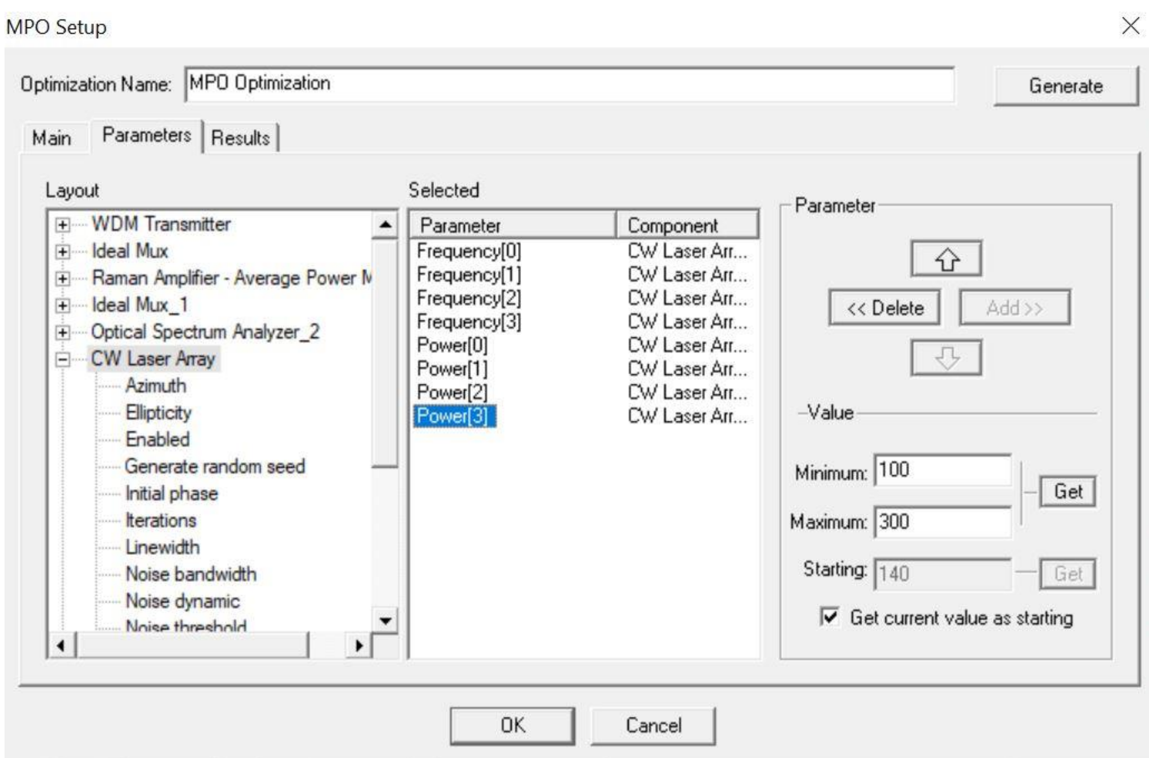
Appendix 11: Pump Power (0) setting starting from 110 dbm as staring value



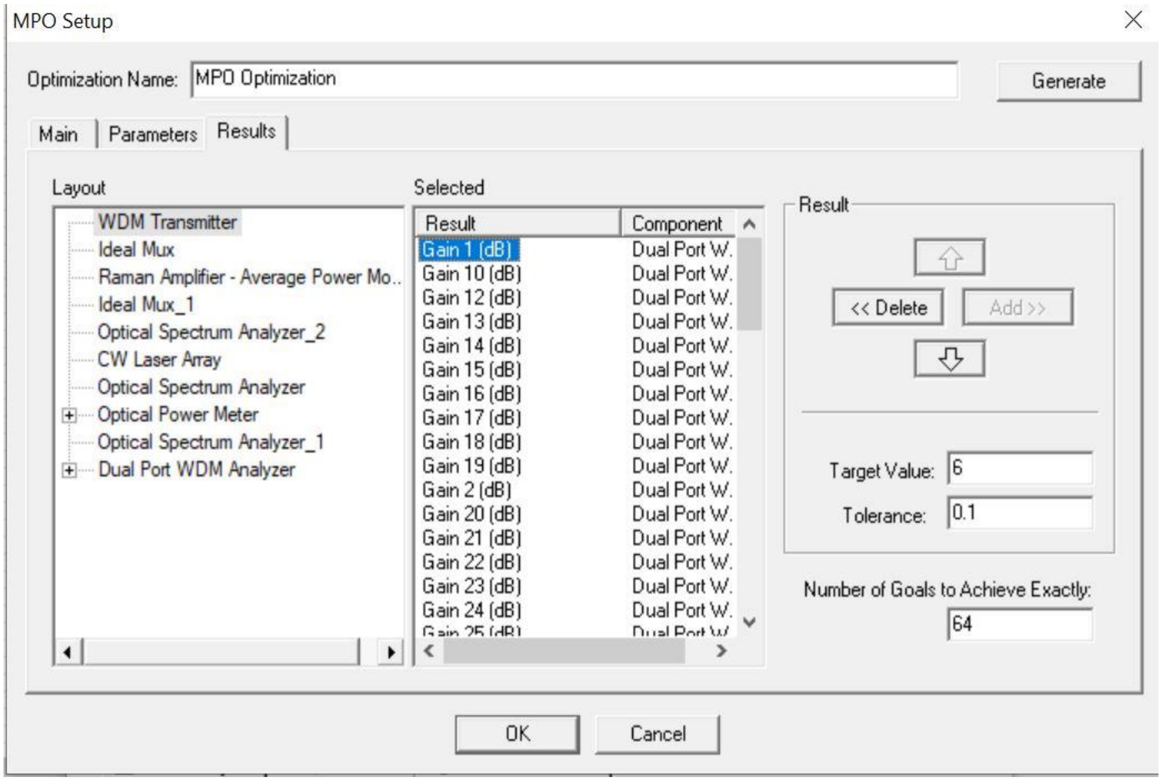
Appendix 12: Pump Power (1) setting starting from 110 dbm as staring value



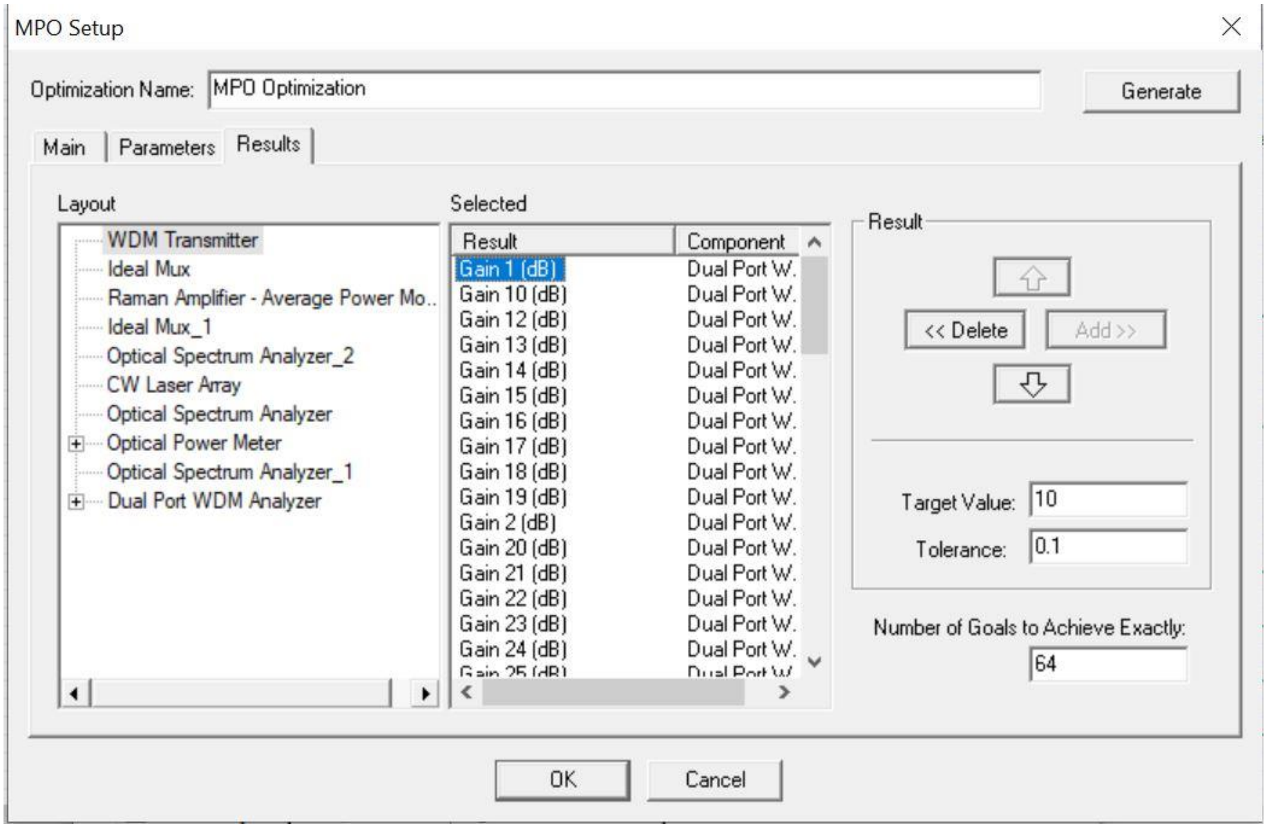
Appendix 13 Pump Power (2) setting starting from 170 dbm as starting value



Appendix 14: Pump Power (3) setting starting from 140 dbm as starting value



Appendix 15 Raman gain setting at 6 db



Appendix 16 Raman gain setting at 10 db.