

**Performance Optimization of Hybrid Optical
Amplifiers for Dense Wavelength Division
Multiplexed System**

A Thesis

Submitted in fulfillment of the requirement for the award of degree
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DOCTOR OF PHILOSOPHY

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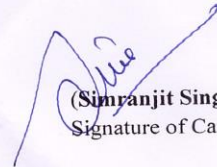
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Certificate

I, **Simranjit Singh** hereby certify that the work which is being presented in this thesis entitled "**Performance Optimization of Hybrid Optical Amplifiers for Dense Wavelength Division Multiplexed System**" in partial fulfillment of requirements for the award of degree of the Doctor of Philosophy in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried under the supervision of **Dr. R. S. Kaler**.

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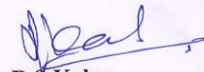
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Abstract

The optical fiber is the enabling and promising technology used in almost all the trunk lines of existing networks. It is also capable of allowing the transmission of many signals over long distances because of its huge transmission bandwidth (in THz) and low losses. For multichannel transmission and to efficiently utilize the fiber bandwidth the dense wavelength division multiplexing (DWDM) is a promising technique, in which a single fiber can independently carry several optical channels with different wavelengths. In optical fiber communication, the attenuation is the major limiting factor imposed by optical components or by fiber itself which degrades the system performance and limits the reach of the signals. To compensate these effects opto-electronic regenerators are used to reshape, retune or retransmit the signal, but simultaneously it increases the cost of the system. On the other hand, optical amplifiers boost the signals without going through the costly conversions from optical to electrical signal and vice versa. But due to the various non-linear effects and phase noise present in the optical amplifier, its use is restricted to limited applications in optical communications. So, there is demand of optical amplifiers which provide better performance (in terms of transient performance, power crosstalk, gain flatness, larger gain bandwidth etc.) for DWDM systems.

In order to achieve these objectives it is utmost important to design, characterize and investigate an appropriate optical amplifier for high capacity DWDM systems. As such, new ways to extend the bandwidth, improve the noise and dynamic properties of present-day amplifiers are constantly pursued. This thesis facilitates this process by tracking several system level challenges while acknowledging the limitations of existing devices.

The hybrid optical amplifier is an enabling and promising technique for future DWDM multi-terabit systems to minimize the impairments due to fiber nonlinearities and to enhance the gain bandwidth and/or gain flatness. This thesis mainly designs, characterizes and optimizes the new hybrid optical amplifiers for DWDM system and further various important aspects have been addressed, such as gain flatness; gain bandwidth product; transient phenomena; crosstalk etc.

Initially, the various combinations of optical amplifiers are proposed for a DWDM system and the impact of reduced channel spacing has been investigated in terms of output power, eye closure, bit error rate and quality factor. It is reported that the Raman-EDFA HOA provides better results with a maximum covered single span distance (220 km). Then we have further characterized this Raman-EDFA scheme in denser or

scaled up version and addressed methods to achieve better flat gain characteristics without using any other costly components like a gain equalizer, multiple pumping scheme etc. It is observed that, with an input signal power of 3 mW, a flat gain of >10 dB is obtained across the frequency range from 187 to 190.975 THz with a gain variation of <4.5 dB without using any gain-flattening technique. Further, a novel net gain analytical model of Raman-EDFA HOA is derived by taking the actual conditions and the various parameters are optimized using genetic algorithm. This optimized Raman-EDFA HOA shows the improved results in the term of gain which is >17.5 dB with a gain variation of less than 1.48 dB. The obtained noise figure is also lowest (< 4 dB/ channel) ever reported for a Raman-EDFA HOA at reduced channel spacing.

In order to check the performance of proposed Raman-EDFA HOA in various applications, the different high speed DWDM system and up-scaled LAN/ MAN have been considered. Initially, the hybrid Raman and EDFA is investigated for a high speed 16×40 Gbps differential phase-shift keying modulated system at different channel spacings. Then as a means of efficient utilization of bandwidth, a new optical data format based on simultaneous non-return-to-zero and polarization-shift-keying modulations has been proposed and investigated for Raman-EDFA for high speed DWDM system. In addition to further increase the speed with large spectral efficiency, the hybrid OTDM-DWDM technique is also investigated on the proposed HOA. The improved performance in the terms of gain ripple, cost, crosstalk, speed, etc. has been reported after comparing it with current state-of-the-art schemes. In respect to long haul communication system, it is found that, 70 km is the optimum span distance at which the proposed HOA achieves a 2450 km transmission distance with acceptable performance. Further, we introduce optimal and heuristic solutions for the scaled-up and denser version of sample LAN/MAN. The solution is based on placing hybrid optical amplifiers for high capacity DWDM links and by placing conventional optical amplifiers over local links with the goal of minimizing the total number of optical amplifiers needed in the network, hence reducing its cost.

As far as the cost and size of the components are concerned, the integrated optics technology can achieved it by the placing the several optical component into a single substrate. Our one next step to further improve this technology is to develop optical amplifiers that can be integrated with these devices. Such amplifiers can serve to compensate for the losses in splitters or other components, and can also serve as preamplifiers for active devices such as detectors. In this work, we proposed the various

configurations of these low cost waveguide amplifiers. In first configuration, a novel flat-gain optical amplifier is proposed using a hybrid configuration with an Er-Yb co-doped waveguide amplifier and a semiconductor optical amplifier for 100×10 Gbps DWDM system. On the other hand, in second configuration a new split-band hybrid waveguide amplifier (HWA) is proposed using parallel configuration of Er-doped waveguide amplifier and Er-Yb co-doped waveguide amplifier for C+L-band DWDM system. This HWA plays a role to boost the DWDM signals and giving a larger gain while keeping the little power/gain variations over effective gain bandwidth product.

Inter-channel crosstalk in optical amplifiers and the resulting output transients is a serious issue, particularly in high-speed and reconfigurable networks. Output power transients can lead to burst errors during detection and in the worst case cause damage to vital system components. A new all-optical hybrid control method for mitigating transients on the channel level is presented. Also, the proposed HOAs and HWAs are recommended for high capacity ultra-DWDM after checking the acceptable level of crosstalk at reduced wavelength spacing. The impact of word length of a pseudo-random bit sequence and the input laser power on nonlinear crosstalk induced by the different HOAs has also been examined.

This study establishes the design, characterization and optimization of hybrid optical amplifiers in the fiber optic communication system.

List of Publications

The thesis includes following research papers:

- [1] Simranjit Singh and R. S. Kaler, “Novel Optical Flat Gain Hybrid Amplifier for Dense Wavelength Division Multiplexed System”, **IEEE Photonics Technology Letters**, vol. 26, no. 2, pp. 173-176, Jan 2014.
- [2] Simranjit Singh and R. S. Kaler, “Flat Gain L-band Raman-EDFA Hybrid Optical Amplifier for Dense Wavelength Division Multiplexed System”, **IEEE Photonics Technology Letters**, vol. 25, no. 3, pp. 250-252, Feb. 2013.
- [3] Simranjit Singh and R. S. Kaler, ‘Influence of the Word Length and Input Power on Nonlinear Crosstalk Induced by Hybrid Optical Amplifiers’, **Elsevier: Optical Fiber Technology**, vol. 19, no. 5, pp 428-431, Oct. 2013.
- [4] Simranjit Singh and R. S. Kaler, “Optimizing the Net Gain of a Raman-EDFA Hybrid Optical Amplifier using a Genetic Algorithm”, **OSA: Journal of Optical Society of Korea**, vol. 18, no. 5, pp. 442-448, Oct. 2014.
- [5] Simranjit Singh and R. S. Kaler, “Performance Evaluation of Hybrid Optical Amplifier for High Speed DPSK Modulated Optical Signals”, **SPIE: Journal of Optical Engineering**, vol. 52, no. 9, pp. 096102 (1-6), Sep. 2013.
- [6] Simranjit Singh and R. S. Kaler, “Performance Investigation of Raman-EDFA Hybrid Optical Amplifier in the Scenario of High Speed Orthogonal Modulated Signals”, **SPIE: Journal of Optical Engineering**, vol. 53, no. 3, pp. 036102 (1-4), March 2014.
- [7] Simranjit Singh and R. S. Kaler, “Investigation of Hybrid Optical Amplifiers for Dense Wavelength Division Multiplexed System with Reduced Spacing at Higher Bit Rates”, **Taylor and Francis: Fiber and Integrated Optics**, vol. 31, no. 3, pp. 208-220, June 2012.

- [8] Simranjit Singh and R. S. Kaler, "Performance Evaluation of Hybrid Optical Amplifiers for DWDM system at ultra-narrow channel spacing", **Springer: Journal of Russian Laser Research**, vol. 35, no. 2, pp. 111-118, 2014.
- [9] Simranjit Singh and R. S. Kaler, "Placements of Hybrid/Conventional Optical Amplifiers in a Multi-wavelength Dense Metropolitan Area Network", **Optoelectronics and Advanced Material-Rapid Communication**, vol. 8, no. 7-8, pp. 762-769, August 2014.
- [10] Simranjit Singh and R. S. Kaler, "Power Transient and its Control in Raman-EDFA Hybrid Optical Amplifier Subject to Multi-Channel Bursty Traffic", **OSA: Journal of Optical Technology**, vol. 81, no. 10, pp. 590-593, 2014.
- [11] Simranjit Singh and R. S. Kaler, "Flat-gain characteristics of C+L slit-band hybrid waveguide amplifier for dense wavelength division multiplexed system at reduced channel spacing", **Optoelectronics and Advanced Materials-Rapid Communications**, vol. 8, no. 9-10, Sep-Oct 2014.

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List of Acronyms

HA	Hybrid Amplifier
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RFA	Raman Fiber Amplifier
HFA	Hybrid Fiber Amplifier
DCF	Dispersion Compensating Fiber
NF	Noise Figure
Tx	Transmitter
Rx	Receiver
SOA	Semiconductor Optical Amplifier
EDFA	Erbium Doped Fiber Amplifier
OA	Optical Amplifier
DRB	Double Rayleigh Backscattering
DWDM	Dense Wavelength Division Multiplexing
WDM	Wavelength Division Multiplexing
HOA	Hybrid Optical Amplifier
RIN	Relative Intensity Noise
DRA	Distributed Raman Amplifier
SRS	Stimulated Raman Scattering
EDWA	Erbium Doped Waveguide Amplifier
EYDWA	Er Yb Co-doped Waveguide Amplifier
SWB	Seamless Wideband
NB	Narrow Band
CMB	Combiner
DIV	Divider
O-E-O	Optical-Electrical-Optical
SNR	Signal to Noise Ratio
FOPA	Fiber Optic Parametric Amplifier
RA	Raman Amplifier
WRON	Wavelength Routed Optical Network
CCC	Constant Channel Compensation
MCC	Minimum Channel Compensation
GF	Gain Flatness
OGC	Optical Gain Clamped
OSNR	Optical Signal to Noise Ratio

QoS	Quality of Service
HWA	Hybrid Waveguide Amplifier
Q	Quality
DPSK	Differential Phase Shift Keying
BER	Bit Error Rate
R-E	Raman-EDFA
R-E-R	Raman-EDFA-Raman
E-R-E	EDFA-Raman-EDFA
GA	Genetic Algorithm
NRZ	Non Return to Zero
RZ	Return to Zero
ASK	Amplitude Shift Keying
PolSK	Polarization Shift Keying
MILP	Mixed Integer Linear Program
FBG	Fiber Bragg Grating
PDCF	Pumped Dispersion Compensating Fiber
MZM	Mach-Zehnder Modulator
Ch	Channel
OTDV	Optical Time Domain Visualizer
WL	World Length
PRBS	Pseudo- Random Bit Sequence
FWM	Four Wave Mixing
E-S-E	EDFA-SOA-EDFA
FTTH	Fiber To The Home
OXC	Optical Cross Connect
ASE	Amplified spontaneous emission
XGM	Cross gain modulation
XPM	Cross Phase modulation
TDM	Time Division Multiplexing
MAN	Metropolitan Area Network
LAN	Local Area Network
WAN	Wide Area Network
CW	Continuous Wave
SMF	Single Mode Fiber
ITU	International telecommunication union

Chapter 1

Introduction

1.1 Introduction and Motivation

Information uprising indicates that the multimedia and high capacity wavelength division multiplexed (WDM) networks need high bandwidth. The optical fiber is the only medium that offers such a huge bandwidth (in THz) by means of better performance [1]. Since 1980s, the optical fiber communication is one of the better alternative for the fast growing industries. It can also be used to full fill the demands of broadband applications. In the early days, the optical fiber could not be used for commercial applications because it had a very high attenuation up to 1000 dB/km. But currently various optical fibers are available with low losses (0.2 dB/km) which can be efficiently utilized in various multi-terabit and bandwidth efficient applications [2].

For efficient utilization of bandwidth, the dense wavelength division multiplexing (DWDM) is a technique which allows parallel transmission of various optical channels at different frequencies on a single fiber [3]. Early WDM systems were initiated in the late 1980s using the two broadly spaced channels which belong to two different bands i.e. 1310 nm and 1550 nm [4]. In early 1990s, the second generation of WDM was presented, in which more than six optical channels were processed. This is also called a narrow-band WDM system since the channels are located over the wavelength grid with reduced channel spacing (i.e. 400 GHz). In those days, the optical communication system with reduced channel spacing was the hot research topic on the way to efficiently utilize the bandwidth for cost effective solutions. In the beginning of 1990s, DWDM systems were developed with 20 to 50 channels with 100 GHz to 200 GHz of interval. By the late 1990s, the great evolution of DWDM systems had been observed with the transmission capability of 60 to 160 parallel channels, densely packed at 50 GHz [5], [6].

In the optical fiber communication, the degradation in signal along with the transmission distance is present due to the various non-linearities and other dominating errors [7]. The number of users can be improved by increasing the power budget, or reducing the losses in the network by using opto-electronic regenerators. But such regenerators become quite complex, time consuming and costly for DWDM systems because of the various processing levels i.e. de-multiplexing, optical-electrical-optical (O-E-O) conversion and

multiplexing. This reduces the reliability of the system or network as regenerator is an active device. Therefore, upgradation of the multichannel WDM network will require optical amplifiers which directly amplifies the transmitter optical signals without going O-E-O conversion [8]. The optical amplifiers are mostly used in WDM applications as all the channels with different wavelengths can be amplified simultaneously [5]. Optical amplifier increases the light signal power as pre-amplifier (by placing it just after the transmitter) and as post- amplifier (by placing it just before the receiver). As the need of higher capacity and long haul unrepeated transmission distance increases, the advent transmission methods have to be investigated to full-fill the demand of current technology. There are so many nonlinear effects (such as self-phase modulation (SPM), cross phase modulation (XPM), gain saturation, four wave mixing (FWM) etc.) and phase noises present in the optical amplifiers which restrict it to be used for various applications in optical communication systems. So, there is demand of optical amplifiers which provide better performance (in term of nonlinearities, transient performance, power crosstalk, gain flatness, larger gain bandwidth etc.) for DWDM systems. In order to achieve these objectives it is utmost important to design, characterize and optimize an appropriate optical amplifier for high capacity DWDM systems. As such, new ways to extend the gain bandwidth, improve the noise and dynamic properties of present-day amplifiers are constantly pursued.

At present, the hybrid amplifiers are promising and widely used technology for today's high speed broadband applications to enhance the system performance without using costly techniques [9]. Like most technologies, HOAs also come with some drawbacks that should be taken into account. These includes transience response, induced crosstalk, as well as other sources of noise that are particular to fiber Raman amplifiers (FRAs), such as double Rayleigh backscattering, pump-mediated relative intensity noise (RIN) transfer and problems with nonlinearities, due to high path-average power in the fibers. The aim behind proposing the HOA is to: (i) increase the gain bandwidth of WDM system with least gain variation over the effective bandwidth, (ii) reduce the losses due to induced nonlinearities, (iii) avoid the constraint of high cost gain flattening filters and multi-pumps for large gain flatness.

In reconfigurable metro networks the transience phenomena is present due to sudden change in overall power during add-drop operation. Because of this add-drop process, a robust deviation is present in the amplifier gain, which possibly reduces the Quality and BER performance. In this case, the erbium doped waveguide amplifier (EDWA) is the

best alternative among other conventional optical amplifiers because: it reduces maximum overshoot during transients; it offers fast transient recovery time due to short photon cavity lifetime; and it leads to a low cost dense footprint optical waveguide amplifier [10]. So it can be beneficial to propose and investigate the new architectures of waveguide amplifiers which provide high gain with less variation of power or gain.

1.2 Optical Amplifiers

1.2.1 The Role of Optical Amplifiers

As compared to regenerators, the optical amplifiers can efficiently amplify all the optical signals simultaneously without going to any complex, time consuming and expensive O-E-O conversions [4]. The large gain bandwidth of optical amplifiers has enabled the high capacity WDM technology, which is used to enhance the fiber capacity by propagating many parallel channels situated side-by-side on a wavelength grid. Furthermore, the low noise figure of these amplifiers has omitted the need for costly periodic electro-optic regeneration. Also, a single state-of-the-art erbium doped fiber amplifier (EDFA) can simultaneously amplify close to a hundred 10 Gbps WDM channels, corresponding to 1Tbps worth of traffic, without electro-optic conversion or any use of high-speed electronics.

However, as a result of the large bandwidth of modern single-mode silica fibers (SMF), the capacity of today's optical communication systems is restricted by the bandwidth of used amplifiers [11]. Similarly, the reach of currently used optical systems is also limited by the various non-linear effects and noises induced by the optical amplifiers [12]. Furthermore, the tendency to make increasing use of meshed and reconfigurable networks impose new stringent requirements on the dynamic performance of modern amplifiers to sufficiently reduce inter-channel crosstalk and prevent the appearance of output power transients. As such, new ways to extend the bandwidth, improve the noise and dynamic properties of present-day amplifiers are constantly pursued. The other convincing reasons to use optical amplifiers are:

Reliability

The optical amplifiers are the devices which just amplifies the WDM signals all optically, means no O-E-O conversion required, which makes the system reliable. On the other hand, when a repeater is used, the optical signal must be converted to electrical domain

and after amplification it is converted to optical form again which directly degrades the reliability.

Flexibility

The optical amplifiers are transparent to speed or code formats, it just amplifies whatever it gets. To increase and/or change the speed or code format on an existing amplified link, then just change in transmitter or receiver characteristics is required. On the other hand, a repeater is specialized to a particular signal characteristics and it is mandatory to replace them according to the currently used system parameters-something which is a little inconvenient in some environments, as in undersea cables.

Wavelength Division Multiplexing

In a WDM system many optical signals with different wavelengths are transmitted on the single fiber. In the case of repeaters it is required to de-multiplex the optical signals and then repeat every individual signal after O-E-O conversion. On the other hand, the optical amplifiers just amplify all the signals simultaneously. It is the development of the optical amplifier that has enabled and enhanced the practical WDM systems with better performance.

1.2.2 Principle of Optical Amplifier

The absorption and emission of light produce atoms, which exists in certain discrete energy state, to create a move from one distinct energy level to other or vice-versa. The energy of the emitted light is related to difference between the higher energy state (E2) and the lower energy state (E1) as shown in Figure 1.1. When photon with energy E is incident on an atom at lower energy state (E1), it may get excited to higher energy state (E2) through absorption of photon called absorption process as shown in Figure 1.1(a). As atom in energy state E2 does not remain stable, the atom yield to lower energy state in arbitrary manner by generating output photon as shown in Figure 1.1(b). This process is called spontaneous emission.

Optical amplification uses the principle of stimulated emission, similar to the approach used in a laser [13]. The stimulated emission occurs, when incident photon having energy $E = hc/\lambda$ interacts with electron in upper energy state, causing it to return back into lower state with creation of second photon as shown in Figure 1.1(c), where h is Plank constant,

c is velocity of light and λ is the wavelength of light [14]. The light amplification occurs, when incident and emitted photons are in phase and discharge two or more photons.

To achieve better optical amplification, the population of upper level has to be greater than that of lower level i.e. $N_1 < N_2$, where N_1 and N_2 are population densities of lower and upper state, respectively. This condition is known as population inversion. It can be achieved by using external source (called pump) which is responsible to excite the electron into higher energy level.

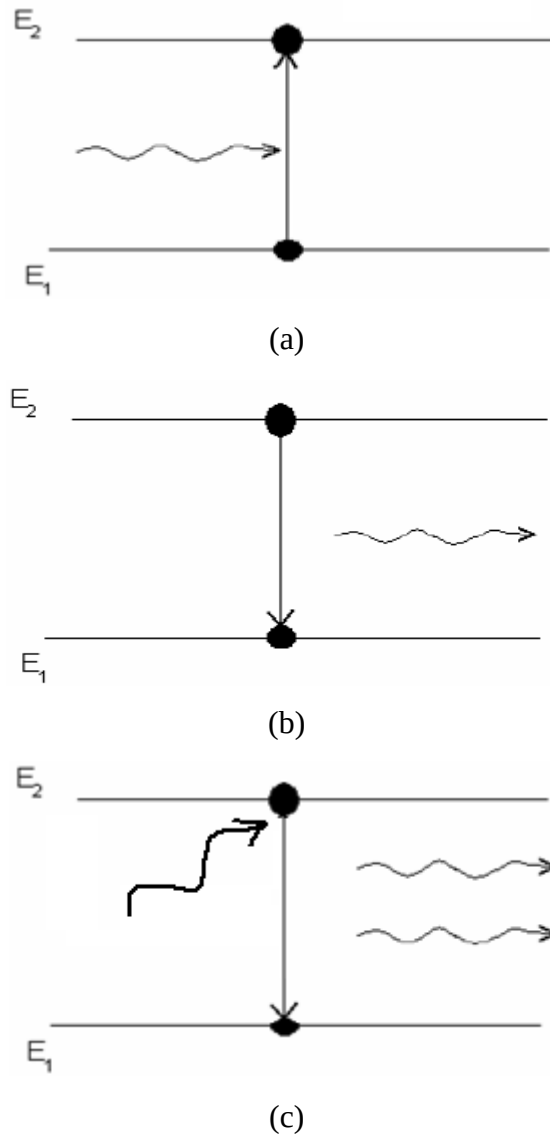


Figure 1.1: Optical amplification processes; (a) Absorption, (b) Spontaneous emission and (c) Stimulated emission.

1.2.3 Types of Optical Amplifiers

Optical amplifiers are categorized on the basis of construction, that is whether it is semiconductor based (such as Semiconductor optical amplifiers) or fiber based (such as

Rare earth doped fiber amplifiers, Raman and Brillouin amplifiers). The optical amplifiers are also classified as conventional (EDFA, SOA, TDFA etc.), doped waveguide amplifiers (EDWA, EYDWA etc.) and HOAs (different configurations of conventional optical or waveguide amplifiers).

1.2.3.1 Conventional Optical Amplifiers

A. Semiconductor Optical Amplifier

A semiconductor optical amplifier (SOA) is a modified version of semiconductor laser, as shown in Figure 1.2, which typically has different facet reflectivity and device length [15]. SOA is very similar to a laser except that it has no reflecting facets. A weak signal is guided through the active region of the SOA, which results in a stronger signal emitted via stimulated emission.

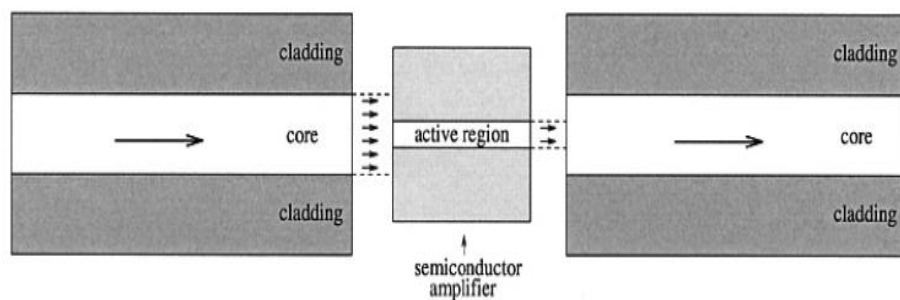


Figure1.2: Schematic of SOA [1].

The SOA is essentially a PN-junction and the depletion layer that is formed at the junction acts as the active region. The two ends of SOAs are given an antireflection coating which is responsible to eliminate the gain ripples. On the other hand, the surfaces can also be angled a little to diminish the reflection. In the case of a semiconductor laser, there would be no antireflection coating. The SOAs differ from other doped fiber amplifier in the manner in which population inversion is achieved. The populations are not those of ions in various energy states but of carriers (i.e. electrons or holes) in a semiconductor material.

B. Erbium Doped Fiber Amplifier

Rare-earth elements like erbium, ytterbium and thallium can be doped into optical fibers to make fiber amplifiers operate in different wavelengths from 0.5 μm to 3.5 μm .

Amplifier operating wavelength, gain bandwidth and other relative characteristics can be determined by the dopants instead of fiber material. An EDFA is, by far, the most widely used fiber amplifier, because EDFA is capable of amplifying all the wavelengths ranging from 1500 nm to 1600 nm [16], [17], [18].

The pump laser, length of EDF and wavelength selective coupler are three basic components of EDFA, as shown in Figure 1.3. The used optimal fiber length can be influenced by the quantity of erbium doping ions, pump wavelength, pump power and input signal power [1].

The numerous features that have made the EDFA as the choice in today's fiber optic applications are such as: (i) great coupling efficiency, (ii) polarization independent and (iii) convenience of compact high-power pump lasers.

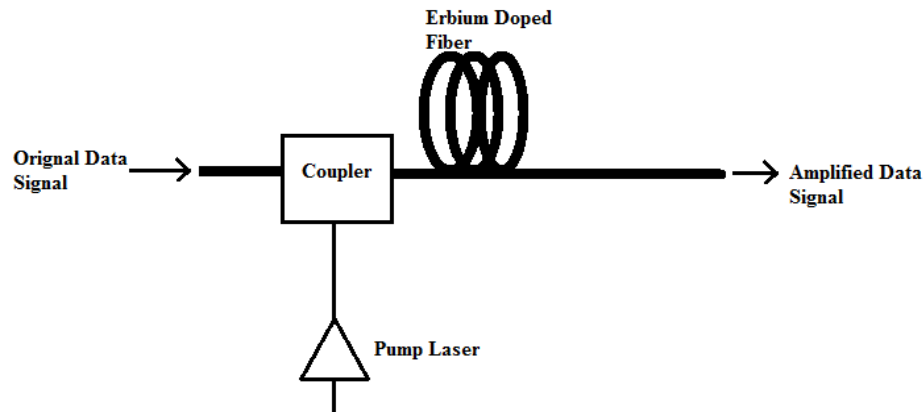


Figure 1.3: Erbium Doped Fiber Amplifier.

C. RAMAN Amplifier

For the cost effective solution, the optical fiber itself can be used as a gain medium, called Raman amplifier, for optical amplification under high pump power phenomena without using expensive doped ions [19]. The amplification is based on Raman scattering which is a nonlinear effect. This effect can be understood by in view of a simple spring. If a small load is attached to a spring, the extension of the spring is linear to the load and becomes non-linear as the load is relatively increased. Likewise the response of a dielectric medium, such as an optical fiber, to an intense amount of light is nonlinear, and Raman scattering is the result of such a nonlinear process. The same concept is shown in Figure 1.4. The pump photon (ν_p) is absorbed by a material and the energized molecules are excited to a non-resonant state (also called as virtual level) while after quick decay of

molecules to lower energy state, a photon of a different energy is released (ν_s). The molecular vibrational levels of the host material determine the shape of the Raman gain curve and frequency shift. During Raman scattering, light incident on a medium is converted to a lower frequency [20].

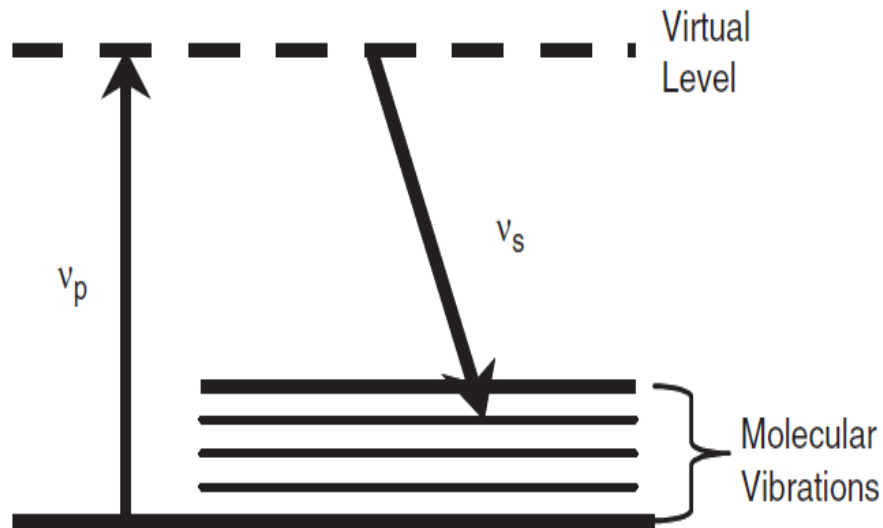


Figure 1.4: Quantum mechanical process of Raman scattering [15].

Stimulated Raman scattering (SRS), which is a gain mechanism in Raman amplifier, occurs in optical fibers when a pump wave is scattered by the silica molecules. A schematic of Raman fiber amplifier as optical communication system is shown in Figure 1.5. The signal from the optical transmitter propagates through the optical fiber and detected at the receiver side using photodiode. For a distributed Raman amplifier (DRA), power is provided by pumping the fiber; where the pump wavelength is shorter than the signal wavelength to be amplified by an amount that corresponds to an optical frequency difference of about 13.2 THz [21]. The signal then experiences gain due to SRS. In this process, pump and signal light are coherently coupled by the Raman process and is converted into a second signal photon that is an exact replica of the first one, and the remaining energy produces an optical phonon which yields the amplification [22]. Four important points which makes the Raman amplifier attractive and cost effective are (i) Raman scattering can occur in any type of fiber; (ii) its gain is non-resonant, which is available over the entire transparency region of the fiber Raman by proper choice of the pump wavelength; (iii) its gain is reasonably flat over a wide wavelength range and (iv) it has fast process of amplification because the upper state is a short lived virtual state.

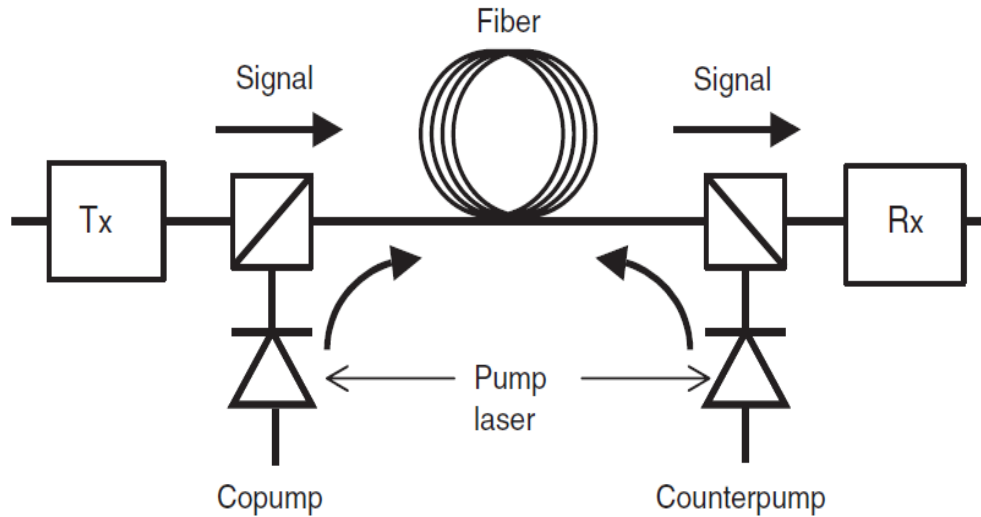


Figure 1.5: Schematic of a Raman fiber amplifier in optical communication system [16].

1.2.3.2 Doped Waveguide Amplifier

The introduction of EDFAs has greatly benefited the implementation of fiber optic links operating at $1.5\ \mu\text{m}$ wavelength, by reducing the need for electronic regeneration [23]. Even greater benefits could be realized from amplifiers in planar form, where they could be integrated with other functions [24]. These waveguide amplifiers can be used to compensate the losses induced by other integrated components; such as splitters, couplers, splicers, fiber etc.; and can also serve as pre-or post-amplifier for active devices such as detectors and transmitter, respectively. For these waveguide amplifiers, silicon is frequently used as a substrate, so that opto-electronic integration with other active or passive devices (light sources, detectors, modulators, splicer, coupler etc.) may become possible on same Silicon substrate.

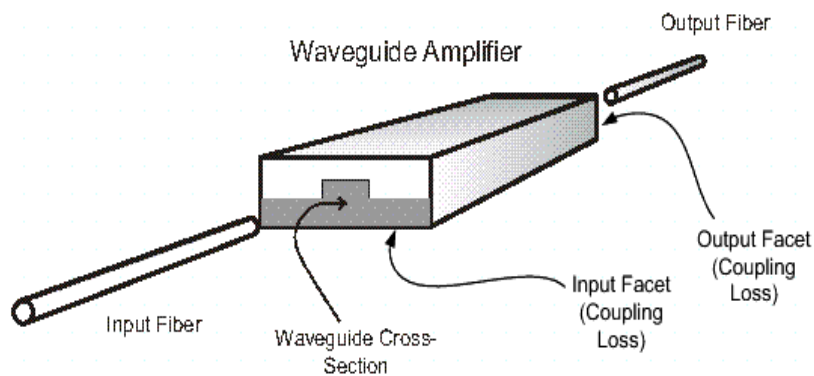


Figure 1.6: Simple schematic diagram of a waveguide amplifier [18].

In general, as compared to other amplifiers, the integrated planar waveguide amplifier is a scale down version of long fiber length amplifier (typically > 5 m). In this case, the doping ion concentration has to be increased to achieve the same amount of optical gain over that much compact dimensions. Figure 1.6 shows a simple schematic diagram of a waveguide amplifier in a common configuration, in which the amplifier is coupled to a pair of optical fibers. It can be seen that the light is injected into the amplifier from one end, and the amplified light is emitted from the other end. Therefore it is convenient to think of the two fibers as being input and output fibers respectively, and to think of the waveguide as having an input facet and an output facet. However, the amplifier and the fibers are bidirectional components, and so in general light can propagate in both directions in spite of these conventional definitions [25]. Also, the EDWA technology is commonly employed in optical communication system or network to mitigate the signal losses [26], [27]. The Er Yb co-doped waveguide amplifier (EYDWA) also received considerable attention because of their potential applications in integrated optics [10].

1.2.3.3 Hybrid Optical Amplifier

The increasing demand for bandwidth in today's backbone networks makes it increasingly necessary to extend the effective transmission bandwidth of the deployed fibers beyond the widely used C-band (1530 nm to 1565 nm) [11]. As the transmission bandwidth is mainly limited by today's amplifier-of choice, the EDFA, new ways of extending the amplifier bandwidth must be pursued. EDFAs designed to amplify in the L-band (1565 nm to 1625 nm) are commercially available and has been demonstrated with high gain and relatively low noise figure [28]. Such an amplifier can be combined with a C-band EDFA, to obtain composite C+L band EDFAs. However the several issues which make the system expensive are such as: (i) the fiber transmission length used for L-band amplifiers are usually many times longer than that of C-band EDFAs, (ii) the signal band must be split prior to amplification, (iii) separate amplifiers for each band of amplification are therefore required, and (iv) after amplification, a combiner is needed to combine the wavelength bands again. The splitter and combiner will contribute loss to the signals and hence increase the noise figure of the amplifier. Furthermore, a "seam" of useless bandwidth will be created between the bands, due to low gain and high noise figure in this region [29]. While the bandwidth of single EDFAs are limited and their power efficiency is high compared to Raman amplifiers. From an efficiency point of view, it is

therefore attractive to make as much use of the EDFA gain as possible and use other means of amplification beyond the EDFA bandwidth. As an example, hybrid combinations of EDFA and Raman amplifier have been used to extend the seamless bandwidth of discrete amplifiers up to 80 nm [30], 100 nm [31] and so on.

In general, the combination of more than one optical amplifier in any configuration is called hybrid optical amplifier (HOA). Mohammed N. Islam described that the net gain of the Raman-EDFA HOA (G_{Hybrid}) is the sum of the two individual gain of Raman and EDFA, respectively [21]. Gain partitioning in hybrid amplifier is as shown in Figure 1.7. Therefore, in the case of Raman-EDFA HOA the net gain is:

$$G_{\text{Hybrid}} = G_{\text{EDFA}} + G_{\text{Raman}}$$

The HOAs are an enabling and capable technology for high capacity DWDM systems, as also described in [31], [9], [32].

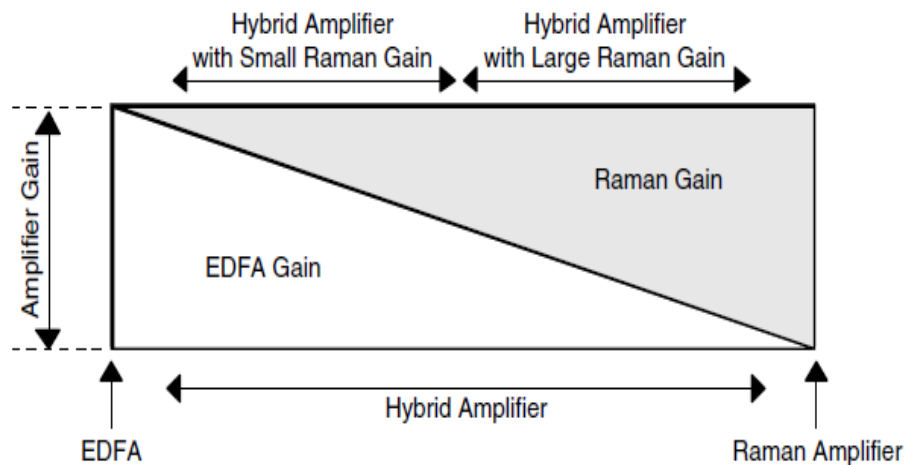


Figure 1.7: Gain partitioning in hybrid amplifier [21].

From Figure 1.7, it can be seen that, some part of the wavelength band is efficiently amplified by EDFA with high gain and the other is amplified by Raman, means over the whole wavelength grid single amplifier shows large variation. But if the Raman amplifier is combined with EDFA in any configuration (cascaded or parallel) then the large gain flatness can be achieved even with highest possible gain.

Mohammed N. Islam [21] compares the gain bands of numerous types of optical and HOA as shown in Figure 1.8. It can be observed that the hybrid configurations of

conventional optical amplifiers provide large gain bandwidth (i.e. > 80 nm) with better gain flatness.

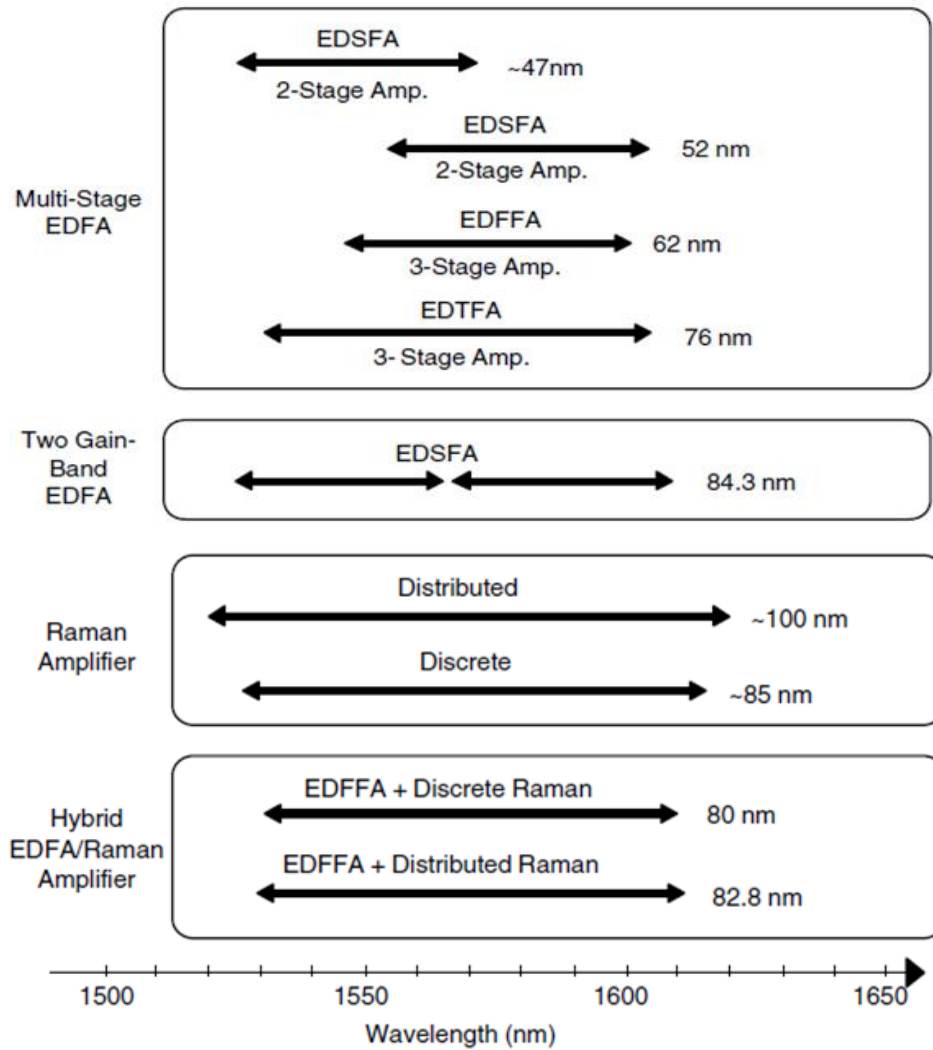


Figure 1.8: Gain bands of broadband fiber amplifiers [21].

1.2.4 Comparison Between Optical Amplifiers

The basic principle of all the optical amplifiers are almost same but its existence in particular application is depend on their features and constraints, as described in Table 1.1. As an on-chip switches, wavelength converters or logic gates; the SOAs are the best alternatives because of their compact size and less power compensation requirement as compared to Raman and EDFA. Besides the single Raman and SOA, the HOAs and EDFAs are the best alternatives for the high gain application. The EDFA, Raman and HOAs make the system costly as it requires high pump power to operate, while the SOAs need only an electrical bias supply at levels of around 50 mA. Also the non-linear crosstalk and inter-modulation distortion in DWDM systems are negligibly small in fiber amplifiers as compared to SOAs. After comparing the various features of optical

amplifier, described in Table 1.1, the HOA can be recommended for high capacity DWDM system where the high gain and/ or gain bandwidth with less variation is required. On the other hand, for limited users and for short haul DWDM communication system the EDFA and Raman can be used with appropriate pump wavelength and pump power, respectively.

Table 1.1: Comparison between optical amplifiers.

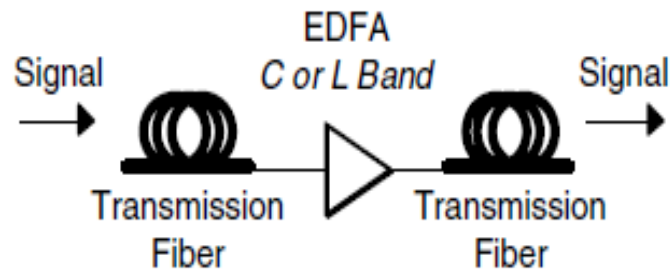
Feature	EDFA	SOA	Raman	Hybrid Optical Amplifier
Wavelength of Operation	1525 nm-1565 nm	Any (but limited to < 50 nm bandwidth)	Any, depend on pump wavelength and power	Any with high gain*
Gain Bandwidth	10 nm-40 nm	20 nm-50 nm	20 nm-50nm	>80 nm with the large gain flatness*
Noise	Low	Low	Very low	Low
Directions	Unidirectional and bidirectional	Unidirectional and bidirectional	Unidirectional and bidirectional	Unidirectional and bidirectional
Polarization sensitivity	0 dB	>few mW	0 dB	vary*
Optical Pump Wavelength	980nm, 1400 nm-1500 nm	NA	Stoke shift below signal	Same as COAs, but residual pump wavelength can be from 1400 nm-1500 nm
Optical Pump Power	20 mW-50 mW	NA	100mW-500mW	Same as COAs, but residual pump it can be from 100mW-600mW
*Depends which amplifiers are used in hybrid configuration.				

1.2.5 Basic Arrangements of an Inline Optical and Hybrid Optical Amplifiers

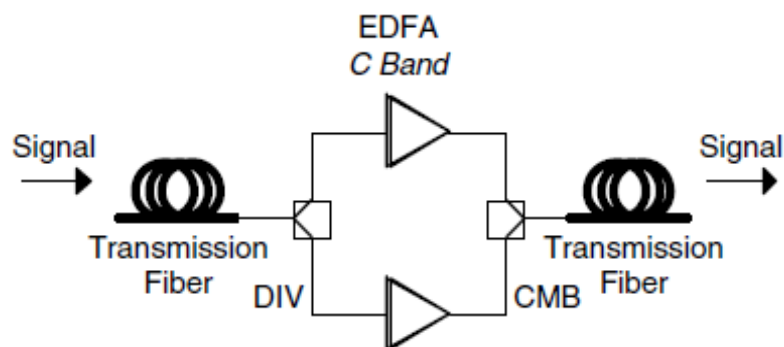
In 2000, Masuda [33] reported the four types of hybrid configurations and further it was extended by Lee *et al.* [9] in 2005 and presented various configurations of low cost HOA using single pump. Figure 1.9 shows some basic architectures of an inline amplifier.

An EDFA is used between two connected transmission input and output fibers, and amplifies the input optical channels (see Figure 1.9(a)). The EDFA offers C-(typically ranging from 1530 nm to 1560 nm) or L-(typically ranging from 1570 nm to 1600 nm) gain band coverage. Figure 1.9(b) shows the two EDFAs in parallel configuration to strengthen the C-and L-band, respectively, after band splitter. The combiner and splitter connected to the EDFAs to combine and split the WDM channels according to their

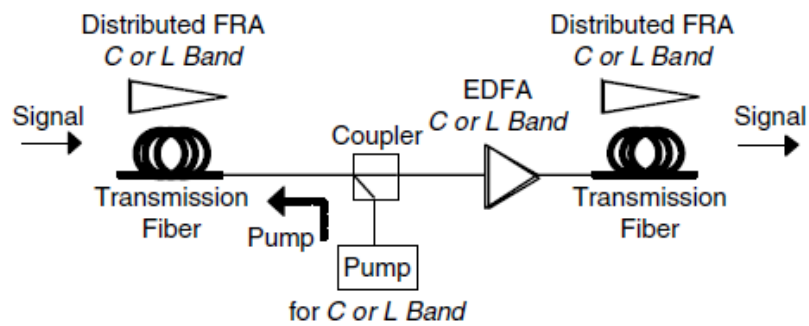
associated wavelengths. For C-or L- band coverage each EDFA has different optimized parameters which make the system expensive.



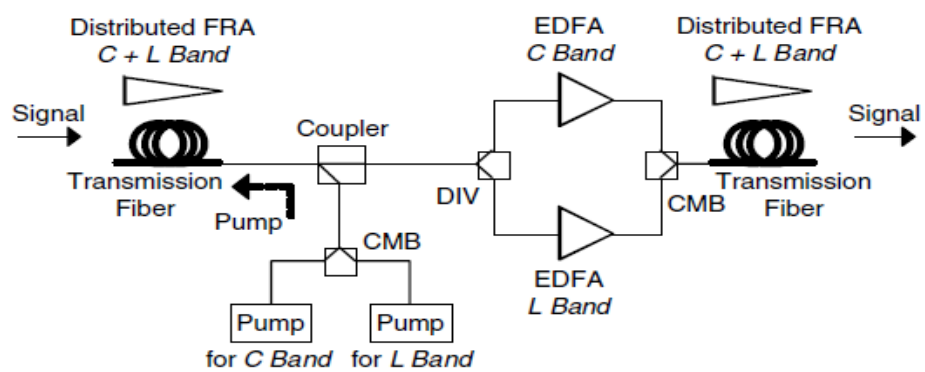
(a)



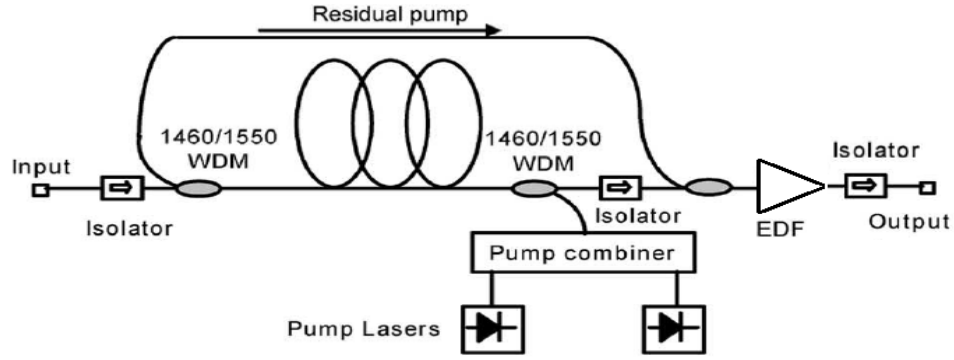
(b)



(c)



(d)



(e)

Figure 1.9: Architectures of inline optical and hybrid optical amplifiers: (a) a EDFA; (b) dual C-or L-band EDFAs in parallel configuration; (c) C+L band Raman-EDFA HOA in cascaded configuration; and (d) Raman-EDFA HOA, where the EDFAs are used in parallel configuration (CMB: combiner, DIV: divider) [21]; (e) cost effective Raman-EDFA HOA with residual pump [9].

Figure 1.9(d) shows a C-and L-band HOA. It contains two-wavelength pumped Raman amplifiers and a dual band EDFA. Finally, the Figure 1.9(e) shows a cascaded Raman and EDFA with recycling residual pumping for cost effective solution. It is cost effective HOA as both the amplifiers operate with single side pump only.

1.3 Summary

The optical fiber communication system and the optical amplifiers are introduced with the basic principles such as absorption, spontaneous emission, stimulated emission, SRS etc. From the system perspective, the various configurations of conventional optical and hybrid optical amplifiers have been discussed and its gain bands in wavelength domain are compared. As compared to the electro-optic regenerators, the optical amplifiers are more reliable, flexible, and can be used to amplify all the DWDM signals simultaneously with cost effective solution. We believe that the hybrid optical amplifier should be regarded as the best contender for future high-capacity DWDM system which can amplify broad gain bandwidth and can efficiently utilize the all fiber bandwidth.

Chapter 2

Literature Review and Outline

2.1 Introduction

Optical amplifiers are essential elements in advanced fiber-based telecommunications networks. They provide the means to counteract the losses caused by the fiber, inline optical components and the power division at optical splitters [12]. Amplifiers therefore facilitate the high global capacities, long transmission spans and multipoint-to-multipoint connectivity required for operation with growing data volumes. In their absence, fiber networks would need many more O-E-O converters for the electronic repeating, retiming and reshaping of attenuated and noisy bit streams. The consequences would be transmission at significantly lower data rates, requiring numerous fibers in each cable; more node buildings, often in expensive city center locations; larger equipment cabinets, occupying valuable floor space; increased total power consumption, with its associated environmental impact and, very importantly, higher operating costs to be passed on to the customer [34]. For these reasons optical amplifier technologies have been key enablers route to ubiquitous information availability.

Fiber amplifiers offer numerous advantages over electronic regenerator including (i) the system data rate can be changed as per the requirement (ii) it can be possible to transmit multiple channel rates (iii) there is no need to modify the inline transmission links or components to achieve above said advantages. This latter feature contributed to the realization of DWDM systems, in which terabit/sec data rates have been demonstrated [35]. Aside from rare-earth-doped glass fibers, which provide gain through stimulated emission, there has been renewed interest in FRA, in which gain at the signal wavelength occurs as a result of glass-mediated coupling to a shorter-wavelength optical pump. As the load on the network is increasing continuously, then the hybrid amplifiers are a promising and widely used technology to amplify those closely spaced large number of channels with better performance. The aim behind proposing the HOA is to further enhance the gain bandwidth of WDM system; to diminish the losses due to induced nonlinearities and to avoid high cost gain flattening filters or multi-pumps for better gain flatness. But still several issues are present in the HOAs (such as gain flatness, gain bandwidth product, transience response, crosstalk etc.) which have to be resolved before implementing it into the system or network. On the basis of above said issues the

comprehensive literature review and gaps in present study are described in following Sections.

2.2 Literature Survey

2.2.1 Gain Flatness and Gain Bandwidth Issues in Hybrid Optical Amplifiers

Improving the gain-bandwidth product of optical amplifiers is the most effective way to efficiently utilize the fiber bandwidth which yields to enhance the number of WDM channels. The gain-bandwidth can be improved by (i) using novel fiber host materials for EDFA, (ii) using gain-equalizing optical filters [36] (iii) employing parallel architecture of two gain-bands EDFAs [37] (iv) using Raman amplifier with multi-pump wavelengths [38] and (v) combining Raman with EDFA [39].

In 1997, Masuda *et al.* [40] proposed the broadband HOA which provides large gain over 65nm (1549 nm-1614 nm) of bandwidth. To obtain that much large gain bandwidth product, various external schemes and optical components are used, i.e. a new pumping scheme, gain equalizer, and backward pumped Raman amplification. After optimizing the two stage EDFAs, they achieved a broad gain bandwidth of 49 nm ranging from 1556 nm to 1605nm. The proposed system becomes unstable due to low Raman gain compression and high pump power. Thus if Raman amplifier is combined with EDFA then bit error rate (BER) and optical signal to noise ratio (OSNR) performance can be improved while still keeping the gain and output power at its higher value.

Delavaux *et al.* [37] demonstrated the two efficient hybrid EDFA structures as power booster. The two simulations pumps (tuned at 980 nm and 1480 nm) are used to pump the proposed amplifier. The offered amplifier provides large gain over broad spectrum (> 35 nm) with better gain flatness (i.e. 1 dB) and output power (17 dBm). They carried out a new hybrid pumping scheme to avoid inter-channel crosstalk effect for pumps of the same wavelength with different pumping power.

Kawai *et al.* [41] successfully transmitted the 14×2.5 Gbps WDM signals over 900 km using highly gain flattened hybrid amplifier. In this investigation, the proposed hybrid amplifier provides better results as compared to single or discrete EDFA.

Thomas *et al.* [42] proposed a hybrid Thulium dope fluoride amplifier (TDFA) and DRA for short wavelength amplification. Using the offered hybrid amplifier, the gain of greater than 20 dB over broad bandwidth (that is 75 nm ranging from 1445 nm to 1520 nm) was achieved with the noise figures of between 7 dB to 8 dB. Also, due to the similar gain

profile of these amplifiers, the expensive gain flattening techniques are exempted to achieve large gain flatness.

In Raman amplifier, it is better to use single pump wavelength instead of multiple pumps because: (i) it is easy to design with minimum cost and (ii) the profile of the Raman gain spectrum is independent to channel loading. Among these two, the second point is very important because the gain shape of saturated Raman amplifier with multiple pumps can be complex function of the present channels. Bolshtyansky et al. [43] demonstrated the hybrid flat or tilt free amplifier in a new wavelength range (i.e. L+ band ranging from 1610 nm to 1640 nm) using a single pump tuned at 1536 nm. It was suggested that, to reduce the micro-bend losses, the Raman gain media should be improved by optimizing the parameters.

Zimmerman et al. [44] studied several gain flattening approaches through numerical simulation. These methods included the hybrid Al-codoped with Al/P- codoped EDFAs, Raman-EDFA HOA and gain equalizer optical filters. After comparison it was reported that the gain equalizer filter was the most appropriate method to increase the gain bandwidth product of the EDFAs with large gain flatness. On the other hand, Raman-EDFA HOA provided the maximum reachable bandwidth without using any high cost or power inefficient optical filters.

Guimardes et al. [45] built the setup in which EDFAs are used as a booster and as inline amplifier. The hybrid EDFA and fiber optic parametric amplifier (FOPA) was used as a pre-amplifier. It was reported that, for inline amplification, the FOPAs shows better results as good as EDFAs. After comparison it was observed that the hybrid EDFA and FOPA delivers improved performance as compared to EDFAs. The performance has been improved in the term of gain, gain bandwidth, noise figure etc. As compared to back to back values, the proposed hybrid optical pre-amplifier also improved the system power penalty by 3.2 dB.

Seo et al. [31] demonstrated the novel broad band HOA covering 105 nm of gain bandwidth. For this investigation silica fiber has been used as transmission channel. By numerical calculations and simulations it was observed that the S, C, and L bands could be amplified simultaneously with the proposed mediums. The first medium was an in-line HOA constructed by an Er-doped cladding and a Ge-doped core. The second medium was a combination of EDF and DCF. In case of the first medium, it is simple to construct the amplifier since the splicer was not used between the mediums. Also the whole optical signals in the entire band are amplified at the same time along the fiber. The noise figure

can be easily controlled if the inline isolator is used between mediums. The hybrid Raman-EDFA using the second medium was reported as more realistic approach.

In recent years, the Raman amplifiers based on dispersion compensating fiber (DCF) have involved enormous research attention for their potential application in the future long-haul communication systems. The pumped DCF as Raman amplifier has two main advantages, i.e. the amplification band can be extended within the transparency window of the optical fiber by simply changing the pump wavelengths. Also, both the losses and the dispersion compensation in transmission fiber can be obtained at the same time. Lee et al. [9] demonstrated the new HOA in which the pumped DCF as Raman amplifier was used with the EDFA in cascaded way and further characterized in the term of gain and noise figure.

Martini et al. [46] demonstrated the Raman-EDFA HOA in the scenario of cost effective recycling residual pumps by choosing the optimized pump wavelength and power. This allows the structure of amplifiers with large gain bandwidth product, gain flatness and with high power conversion efficiency. It was observed that the proposed Raman-EDFA HOA provides best results when it was pumped with two pump lasers (which were tuned at 1425 nm and 1468.4 nm, respectively) with the pump powers of 296.3 mW and 61.3 mW, respectively.

Tiwari et al. [47] characterized the hybrid Raman and EDFA in the terms of gain variation and noise figure measurement. In this work, three types of HOAs are proposed for multichannel WDM system and it was observed that the multi-channel gain spectrum of the HOAs are quite different from the case of single-channel. It was concluded that the hybrid Raman-EDFA configuration using residual pumping scheme provided the best results in the term of gain and pump efficiency. But the better BER performance had been shown by hybrid I configuration, which is a combination of Raman and EDFA pumped by the residual Raman pump in a co-propagating geometry.

Rocha et al. [48] proposed a cost effective optical amplification over the S+C bands using a hybrid fiber amplifier (HFA). The cost factor has also been reduced by using single pump wavelength to pump the proposed HFA. The HFA configuration based on an EDFA which provides gain over C-band and a distributed Raman fiber amplifier (RFA) to attain gain over S-band. The HFA was numerically characterized and its optimal configuration was calculated using the optimization procedures based on genetic algorithms. They found an optimum EDF length, which allows a HFA configuration to

operate for several transmission distances. This configuration can operate up to 100 km, achieving a higher gain with an average NF of 5dB over the analyzed wideband.

Hsu et al. [49] proposed and demonstrated a 100 km dual band HFA in the bridge-type scheme. The proposed HFA consists of C-band EDFA and an L-band RFA using double-pass dispersion compensators in a loop-back scheme. Power equalization was realized by adjusting the pump ratio and optimizing the FBG reflectivity for the corresponding channels. On the other hand, the chromatic dispersion for all C+L band channels was optimally compensated to achieve flat power spectrum. After comparing simulation and experimental results, it was recommended that the proposed hybrid EDFA and RFA may find vast applications in WDM long-haul systems and in optical networks where power equalization, power budget and dispersion management are crucial issues.

Yuan et al. [50] introduced a configuration of the hybrid Raman-EDFA. They also made some restriction conditions to yield the optimum design. The influence of various Raman amplifier noises (such as amplified spontaneous emission and Rayleigh) on the SNR of the receiver had also been determined in the depth. In this work various important conclusions have been made, such as, with the same span length and with different large nonlinear weight, the value of Q-factor is larger. On the other hand, the Quality degrades, if the same nonlinear weight has been chosen with different span distance. The Quality factor degrades with respect to the increment in the span length which yields the amplified spontaneous emission (ASE) and Rayleigh noise.

For better clarity the progress of HOAs in the term of gain flatness, gain bandwidth and transmission distance has been briefly described in Table 2.1.

2.2.2 Transience and Crosstalk Impairments in Optical Amplifiers

In saturated amplifiers, transient crosstalk is generated between adjacent channels. This is due to the abrupt changes in average power of optical amplifier due to sudden fiber cut, add drop operation, re-configurability etc. This type of crosstalk can be a serious problem in today's reconfigurable networks where reconfigurable optical add/drop multiplexers (ROADMs) and optical cross connects (OXC's) are used for dynamic routing and switching of individual channels. In general, transients are always unwanted in a system, as they impair the receiver sensitivity, can cause potential damage to system components and increase the effect from system nonlinearities during transmission.

On the other hand, the optical networks are also moving towards the switching systems (such as packet or burst switching). Due to the switching techniques, the power per

channel varies and this variation will cause the transients on other channels propagating over the same amplifier. To suppress this undesired effect, many control methods have been proposed in literature.

Li et al. [51] investigated the performance of return-to-zero-differential phase shift keying (NRZ-DPSK) modulated DWDM system when a saturated SOA is used as booster. By introducing time interleaving, they suppressed the crosstalk induced by SOA nonlinearities and WDM component. It was reported that by providing proper time delay between the even and odd channels, the induced linear crosstalk can be mitigated. To reduce the self-phase modulation (SPM) and cross phase modulation (XPM), the time interleaving strategy is used in which the intensity summed over all the channels would remain constant. Shah *et al.* [52] investigated and mitigated the inter-channel crosstalk, especially cross gain modulation (XGM) and four wave mixing (FWM). The suppression of these undesired effects has been done by properly time-interleaved channels. The simulation and experiment of 2×20 Gbps WDM system has been conducted and further the acceptable and comparable results have been described.

Taniguchi et al. [53] presented a new way to multiplex the huge number of channels in ultra-dense DWDM phenomena (called super-DWDM) at reduced channel spacing. Further, the performance degradation has been observed due the induced undesired crosstalk between those compact channels. In this paper, they analyzed and estimated the performance of the proposed technique by different steps. In the first step, the analytical calculation has been done to find the relation between filter bandwidth and the sweep range per channel, which resembles to the channel spacing. Then in the second step, they assessed that the achievable number of channels yield the multichannel WDM signals. In this investigation, the optical filters were used with a bandwidth of about 10 GHz.

In the DWDM system, several impairments are present including gain excursion caused by XGM and induced nonlinear crosstalk which degrades the system performance. Awaji et al. [54] investigated the amplification of optical packets using EDFAs in various distinct cases in a WDM system. In this paper, the new class of EDFA is proposed adopting the EDF with the enhanced active area of erbium. Further using this amplifier they can be able to mitigate the gain excursion for the application of optical packet switched networks. Further, they extended their own work in 2008 by investigating the properties of the transient response of cascaded EDFAs with optical packets over WDM application. Moreover, the performance in several situations has also been analyzed that

is with different wavelength and timing allocations of packets, de-correlated WDM packet stream and dropping or adding of other channels.

Tong et al. [55] proposed a novel algorithm to analyze the power transient effect in backward pumped Raman amplifiers. The various dynamic responses have been checked after varying the input spectrums in single or in multichannel situations. From this investigation few beneficial recommendations are described using which the power transient can be mitigated up to the extent.

Chang et al. [32] presented the transient effect in Raman-EDFA HOA during channel add- drop process to observe the combined dynamics of Raman and EDFA. Further, using the gain control technique in the Raman-EDFA HOA, the transient response is successfully suppressed. It was reported that, if the optical switching speed is carefully chosen then the transient effect can be suppressed to that level on which the proposed Raman-EDFA HOA is proven to be enough for the WDM networks including reconfigurable OADM and transparent OXC.

Lin et al. [56] proposed a new cost effective technique to suppress the transience all optically without using any opto-electronic devices. This technique is called a power shaping. The power shaping is defined as adjusting and maintaining the temporal behavior of the power by adding the head and tail to the data of a channel or connection. The head and tail just increase or decrease the power level gradually when the abrupt change in power is present. They proposed the power shaping in all type of switching networks (Packet, Circuit and burst switched networks) and successfully suppressed the transience effect in all cases.

Puvvada et al. [57] presented the gain dynamics caused by cascaded EDFAs in wavelength-routed optical networks (WRONs). They have taken two phases, such as transient phase and steady state phase to characterize the EDFA gain dynamics. It was observed that the hybrid control method including channel power shaping and compensation techniques can efficiently suppress the gain transience of the cascaded EDFAs. After comparing two proposed methods, i.e. constant and minimum channel compensation, it was observed that the constant channel compensation shows better results.

Kaler [58] investigated the technique to control the transient's during channel adding/dropping process in the scenario of cascaded EDFAs. It was observed that as the number of cascaded EDFAs increases over the optical link, the transients are expressively suppressed. Further, a comparison between the transient response of compact EDFA and

transient EDFA was presented. It was observed that the suppression of the transients is better in case of the compact EDFAs as compared to transient EDFAs.

Singh et al. [59] evaluated the performance of HOA in the scenario of polarization and modified polarization interleaved systems. The results have been presented in the term of noise power, OSNR, signal power and optical eye-diagram. In this system reverse dispersion fiber is used instead of DCF. Unfortunately, in this setup pump power efficiency is very low to pump the DCF. It was recommended that the Raman-EDFA HOA can be used for better control of nonlinear effects even in the case of high capacity DWDM multi-terabit systems.

2.2.3 Optical Waveguide Amplifiers for WDM Systems

Due to the erbium doped ions, the gain curve of EDFA displayed the non-flatness and input-dependent behaviors in the effective gain range. Therefore, gain-flattened and gain-clamped EDFAs play a key role in the WDM optical communications where dynamic channels adding-dropping or abrupt breakdown of the other signal channels can occur. The EDWA is the best alternative to achieve gain clamping than other optical amplifiers, as also reported by Yeh et al. in [18].

Qian et al. [60] investigated the effects of designed geometries and nonlinear losses on the gain in crystalline silicon waveguides with erbium-doped regions. In this paper, effects of non-linear losses, power confinement and erbium concentration on gain are discussed in detail. They analyzed the nonlinear losses that mitigate the optical gain including excited-state absorption and up-conversion in erbium-doped Al_2O_3 as well as free-carrier absorption in silicon. It was observed that the distributing erbium ions over multi-trench areas improved the gain-to-nonlinear-loss ratio.

Ennser et al. [10] realized an optical gain clamped–erbium doped waveguide amplifier (OGC-EDWA) and further they compared the performance of OGC-EDWA with EDFA. The EDWA presented the better performance over EDFA in order of reducing maximum overshoot during transients. As the EDFA needed higher extra pump power for long haul optical communication, the OGC-EDWA require lower extra power and therefore, the cost will be strongly reduced. As compared to other conventional doped fiber amplifier, EDWAs has an easy mass production potentiality at low cost and smaller footprint that should further enhance its suitability for metro applications.

Ennser et al. [25] further extended their own work in 2009. They investigated a transparent bidirectional WDM ring network design using OGC-EDWA which is immune

to induced power transients. Due to bidirectional operation, this architecture allows cost effective, flexible, traffic re-routing type network operation, even in the case of node failure or fiber cut.

Yeh et al. [61] proposed two erbium fiber amplifier modules to retrieve gain-flattened and gain-clamped functions simultaneously. Firstly, they characterized the proposed gain-flattened erbium fiber amplifier module using two-stage EDWA and EDFA in serial and further confirmed it into system level. They proposed two models for gain flatness and gain clamping. In first scheme only gain flatness has been investigated and achieved the maximum gain variation of 2.5 dB. It was observed that, over the effective range of wavelength starting from 1528 nm to 1562 nm, the entire gains are above 35 dB. In the second scheme, by optical feedback method in the proposed fiber amplifier, they achieved GF and GC efficiencies simultaneously. Thus, the maximum gain variations of ± 0.8 and ± 1.8 dB can be obtained in the operating range from 1530 to 1564 nm, when input powers are fixed to -16 and -40 dBm, respectively.

Zhao et al. [62] discussed the bent waveguide structures. They designed the U-shape and F-shape bent waveguide architectures based on UV-sensitive $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped germinate glass substrates. This proposed model can be used to achieve high-gain C-band amplification which will provide useful support in the development of gain-flattened amplifiers. It was reported that F-bend waveguide is demonstrated the well-organized shape with an internal gain of 22.55 dB at 1533.8nm wavelength, which is higher than any of the designed shapes in literature.

Jiang et al. [63] solved the rate and evolution equations which are based on the combined model of EDWA with enhance erbium ion concentration. The dependence of the gain on EDWA parameters (such as pumping power, erbium ion concentration, and waveguide length) has also been checked. For better performance the optimization has been done and it was reported that with the optimized parameters (such as pump wavelength: 980 nm laser, pumping power: 150 mW, and waveguide length: 15 cm, and erbium doping concentration: $6 \times 10^{26} \text{ m}^{-3}$) the gain may reach 35 dB.

Wang et al. [64] derived the formulas from the rate and the propagation equations under the steady-state conditions in order to analyze the power conversion efficiency and the gain characteristics of the phosphate glass EYDWA. It was concluded that, for a definite planar waveguide length, gain is dependent on the total pump power of co- and counter propagating pumps wavelength, and are independent of the distribution proportion of the pump power.

Table 2.1: Progress of Hybrid Optical Amplifiers.

Author/ Year	Types	Gain B.W.	Channels	Gain Flatness	Length
Delavauz et al. [1992] [37]	Hybrid EDFAs	35 nm	14	1 dB	300 km
Masuda et al. [1998] [40]	Raman+EDFA+ equalizer	65 nm	17	6 dB	----
Kawai et al. [1999] [41]	Raman+EDFFA+ equalizer	67 nm	14	1.5 dB	900 km
Carena et al. [2001] [65]	Raman+two EDFAs+DCF	---	---	----	>200 km
Yeh et al. [2004] [18]	EDFA+SOA+ EDFA	60 nm	30	>3 dB	---
Sakamoto et al. [2006] [66]	TDFA+EDFA	80 nm	9	2 dB	----
Ummy et al [2009] [67]	Tendom and Unison	60 nm	---	5 dB	550 m of HNFL
Huri et al. [2011] [68]	EDFA+isolator+ SOA	30 nm	10	<4 dB	3 m of each EDFA
Hasan et al. [2013] [69]	Raman+EDFA	17 nm	40	<1.5 dB	80 km
Rocha et al. [2014] [48]	Raman+EDFA	60 nm	40	>5dB	100 km
Hsu et al. [2014] [49]	Raman+EDFA+ FBGs	70 nm	15	± 0.2 dB	100 km

2.2.4 Hybrid Optical Amplifiers in High Capacity and Long Distance Communication Applications

In comparison with conventional optical amplifiers, HOAs provides better results in high capacity optical communication system. The HOAs are designed in demand, to minimize the impairments due to fiber nonlinearities, to enhance the transmission distance, and to increase the ability of optical communication system in the term of channels and bandwidth. The references [69] and [32] are evident to the same.

Hasan et al. [69] proposed the HOA for broadband amplification which is capable of improving the system performance of a real time WDM network. For evaluating the

performance of offered HOA, the 40×40 Gbps DWDM network has been considered with 50 GHz of channel spacing. They proposed two schemes of HOAs and further compared its performance with Raman only in the term of gain, noise figure and cost. After analysis it was concluded that the EDFA-Raman HOA provides the better results with low cost. At an input power of 5 dBm, EDFA-Raman is able to cover a 200 km of transmission distance with an acceptable BER of 10^{-10} .

Chang et al. [32] compared the two generations of optical amplifiers i.e. conventional optical amplifier (EDFA) and Raman-EDFA HOA. After reporting the low noise figure, better quality factor, good OSNR and high output power, it was recommended that the HOA can be a better substitute to increase the performance of inline amplifier in its place of cascaded EDFAs. The HOA also shows the better results as compared to single EDFA even in the case of circulating loop experiment.

Chung et al. [7] demonstrated a long-haul communication of 16×10 Gbit/s over 1040 km of SMF using the hybrid amplifiers. The hybrid amplifier consists of the cascaded Raman and linear optical amplifiers. It was observed that the proposed HOA can achieve the transmission distance of more than thousand kilometer even with the large span distance (i.e. 80 km), where the span losses varies from 28 dB to 34 dB due extra impairments induced by optical components. After 1040 km, the acceptable Quality factor was measured (i.e. 12.7 dB to 14.5 dB) which is higher than the error-free threshold of the standard forward-error correction.

Peng et al. [70] demonstrated the feasibility of a novel fiber Bragg grating (FBG) sensor system using a fiber ring laser with a hybrid amplifier. The hybrid amplifier configuration contains an EDWA and a SOA. The experimental results demonstrated that the hybrid amplifier has a higher gain spectrum and ASE power. The multi-wavelength fiber laser produced steady and strong peak power. In conclusion it was suggested that the proposed fiber sensor system with hybrid amplifier might be recycled for long-distance or large-capacity smart structures. For better clarity the progress of HOAs in the term of gain flatness, gain bandwidth and transmission distance has been briefly described in Table 2.1.

2.3 Gaps in Present Study

The pervasive usage of Internet and multimedia streaming has dramatically increased the volume of data traffic, which has overtaken that of traditional traffic. Future network infrastructure should be able to accommodate increasing amount of data traffic, possibly

with different Quality of Service requirements. The difficulty in forecasting the behavior of broadband amplification type forces to propose the optimized optical amplifier which can efficiently amplify the broad bandwidth. Last, but not least, the gain flatness; large span distances with less transient effect and/ or induced crosstalk are the major issues for the next-generation optical communication or network. Today's amplifiers must be designed and kept in operation by maximizing the exploitation of available resources. According to the above requirements, HOA is an enabling and promising technology for future high capacity multi-terabit optical systems in order to minimize the impairments due to fiber nonlinearities and to enhance the gain bandwidth and/or gain flatness. But still the various undesired effects dominate the system performance.

In order to achieve these objectives, it is of utmost importance to propose and optimize a new hybrid optical amplifier and then address the various relative issues and effects, such as gain flatness, gain bandwidth product, transient phenomena, crosstalk etc. Based on the above discussion the gaps in present study are summarized as following:

1. Potential of hybrid optical amplifiers to provide broadband amplification and better gain flatness is an open area of research.
2. DWDM technology has been introduced to increase the single fiber capacity by adding many parallel channels. Further there is need to investigate the HOAs for DWDM systems at reduced channel spacing (25 GHz).
3. The performance evaluation and characterization of HOAs for ultra-DWDM is not yet done.
4. There is a scope of improvement in gain flattened and gain clamped amplifiers for larger bandwidth DWDM system.
5. There is a wide scope to avail better performance of hybrid optical amplifier by optimizing various parameters. An effective and easily implementable genetic algorithm can be used for multi parameter optimization of RFA.
6. The presence of hybrid waveguide amplifiers (HWAs) in optical communication system is readily available.
7. Moreover, the performance of doped waveguide amplifiers are investigated using WDM system at large channel spacing.

2.4 Objectives

Based on the initial studies, literature survey (as reported) and the understanding established the following objectives are proposed:

1. To design, characterize and optimize hybrid optical amplifiers to extend the gain bandwidth product and gain flatness for dense wavelength division multiplexed system.
2. To design new architectures of hybrid waveguide amplifiers for dense wavelength division multiplexed system and investigate the impact of various parameters (such as pump power, waveguide length, Er & Yb concentration etc.) on these amplifiers.
3. To investigate the control methods for hybrid optical amplifiers in order to suppress transient phenomena.
4. To investigate crosstalk for the designed hybrid optical/waveguide amplifiers in dense wavelength division multiplexed system with reduced wavelength spacing.

2.5 Basic Contribution of Thesis

The proposed HOAs and HWAs for DWDM system extend the gain bandwidth product which is efficiently utilized with ultra-narrow channel spacing over large gain flatness, while the previous works based on expensive optical amplifiers were restricted to narrow band with large channel spacing. Another innovative results presented in this thesis is the introduction of new bandwidth efficient hybrid modulation technique, using which the two different users can transmit the different data on single channel only. Furthermore, an analysis of the impact of proposed hybrid modulation on the performance of HOA is performed.

In fact, all the calculation of net gain presented in literature disregards the actual condition of the HOA gain, which was reported as multiplication or addition of individual optical amplifier gain used in hybrid configuration. But in original the gain of second cascaded amplifier (net gain) is dependent on the first amplifier gain. In this thesis, a simple analytical model is derived to calculate the net gain of HOA in consideration of actual condition. Finally, the transient and crosstalk phenomena of proposed HOA have been investigated. Also, the new hybrid technique, which is combination of link control channel and power shaping, is presented and shows improvement over the previous reported results.

In general terms, this thesis investigates the use of HOAs from an application perspective. The objective is to identify new areas where HOAs may find use, identify how these

amplifiers can be exploited to their maximum limits and determine when it is advantageous to use this amplifier in place of another type.

Specifically, the research on HOAs performed in this thesis can be summarized as:

- The use of various optimized HOAs and HWAs in high capacity DWDM applications.
- The analysis of transient effect and inter-channel crosstalk and how to remedy these unwanted effects.
- Placement of proposed HOAs in up-scaled and denser version of local and metropolitan area networks.

2.6 Organization of Thesis

The thesis has been organized into eight chapters. The content of each chapter is briefly described as below.

Chapter 1 introduces the overview of optical amplifiers and fundamental concept of the operating principle of SOA, EDFA and Raman amplifiers. The various configurations of these amplifiers are also presented to extend the gain bandwidth with large gain flatness.

Chapter 2 contains a comprehensive literature review of the concerned field. It also demonstrates the gaps in the literature survey and the objectives of research.

Chapter 3 deals with the first objective which is to design, characterize and optimize the HOA for DWDM system. Various configurations of HOAs are proposed and characterized in the term of gain, gain flatness, Quality factor, BER etc. In this Chapter, the net gain modal of proposed Raman-EDFA HOA is also derived and further the multi-parameter optimization has been done using genetic algorithm.

Chapter 4 is based on the application part of proposed HOAs. Firstly, the hybrid Raman and EDFA is investigated for a 16×40 Gbps DPSK modulation system at different channel spacings. A new optical data format based on simultaneously modulating NRZ and polarization-shift-keying has also been presented for high-speed applications by means of efficient utilization of bandwidth. Further, the very current issues, i.e. placement of optical amplifiers in LAN/ MAN, has been solved by introducing optimal and heuristic solutions which is based on placing HOAs in high capacity back bone DWDM links and by placing conventional optical amplifiers over local links.

Chapter 5 deals with the second objective of this thesis which is to design new architectures of hybrid waveguide amplifier (HWA) for DWDM system. A novel flat-gain optical amplifier is presented using a hybrid configuration with an EYDWA and a

SOA for 100×10-Gbps DWDM at 0.2 nm interval. Further, the split-band HWA is proposed using parallel configuration of EDWA and EYDWA for C+L-band DWDM system and the performance have been evaluated in the term of gain, gain flatness, optical power, Q-factor and OSNR etc.

Chapter 6 deals with the third objective of this thesis which is to investigate the control methods for HOAs in order to suppress transient phenomena. In this chapter, various control methods are addressed and implemented on proposed HOA. The control methods include the power shaping, link control channels, hybrid control module, optimized Raman-EDFA parameters etc.

Chapter 7 pertains the study and evaluation of crosstalk induced by proposed optical amplifiers at reduced wavelength spacing which is related to the fourth objective of this thesis. The influences of the word length of a pseudo-random bit sequence and the input laser power on nonlinear crosstalk induced by the different HOAs have been presented. The discussion of distortion in pulse shapes and crosstalk between the symbol which is due to the gain dynamics induced by HWAs and HOAs is also covered.

Finally, Chapter 8 covers the conclusions and recommendations on the basis of results obtained in the Chapters three to seven.

Chapter 3

Design, Characterization and Optimization of Hybrid Optical Amplifiers

3.1 Introduction

In this chapter, the first research objective, i.e. to design, characterize and optimize HOAs to extend the gain bandwidth product and gain flatness for DWDM system, has been investigated. In this work, various configurations of HOAs have been proposed to achieve better performance over the previously proposed amplifiers, as described in Table 2.1. These amplifiers incorporate the different configurations of Raman, EDFA and SOA for improving performance in the term of gain flatness and gain bandwidth product with better Quality factor, BER etc. Further, the new net gain model of Raman-EDFA HOA is calculated. On the basis of the proposed net gain model the multi-parameter optimization has been done using the popular global optimization technique called genetic algorithm (GA). Then using optimal parameters the flat gain characteristics has been presented with lowest obtained noise figure ever observed for a Raman-EDFA HOA at narrow channel spacing

3.2 Design and Characterization of Hybrid Optical Amplifiers

3.2.1 Design of Hybrid Optical Amplifiers for DWDM System

Two decades ago, the invention of EDFAs temporarily supplanted ongoing research on HOAs. On the other hand, SOAs and EDFAs emerged as attractive amplifiers for WDM systems because of their capability to offer an extremely high gain and also a longer transmission distance [71], [72], [73]. The broad-band EDFA can amplify multi-bands as it distinctly amplifies optical signals of each band, which yield increase in system cost. In recent years, the Raman amplifiers also concerned huge attention as it is promising technology for high capacity and long-haul optical communication system. Raman amplifiers can amplify any wavelength within the bandwidth of the fiber, by simple adjustment of the pump wavelength. However, as the gain spectrum for Raman amplifier is not uniform over the bandwidth, hence the high cost multiple pumps with gain equalizers and various expensive opto-electronics devices are normally used [74]. On the other hand, according to the current requirement of multi-terabit DWDM system, the hybrid amplifiers are the capable and widely used technology [9]. The HOAs are designed in order to minimize impairments resulting from the nonlinearities present in the fiber, to enhance the transmission distance,

and to increase the ability of optical communication system in the term of channels and/ or bandwidth. In literature, various combinations of optical amplifiers are proposed to achieve large gain bandwidth and gain flatness, as also mentioned in Table 2.1. Unfortunately, these proposed amplifiers are investigated for WDM system only (at large channel spacing). Moreover, these architectures cannot be used to design broadband HOAs due to the variation of gain, and the reported results are limited to gain and noise figure only. In this work, the HOAs are exploited for DWDM system at reduced channel spacing (< 12.5 GHz). The original contribution of this work is to provide broad band amplification with bandwidth efficient DWDM system unlike any other reported work in literature [68], [75], [76] .

In this section, several configurations of optical amplifiers have been proposed for a DWDM system and explores the influence of high bit rate at reduced channel spacing by observing various terms i.e. output power, BER, Q factor etc.

3.2.2 Different Configurations of Hybrid Optical Amplifiers

Figure 3.1 shows the studied system setup. Figures 3.2 (a) – 3.2 (d) correspond to four different schemes of a Raman, EDFA, and SOA. This investigation has been done using a commercially accessible Raman pump tuned to 1453 nm, offering an output power of 500 mW.

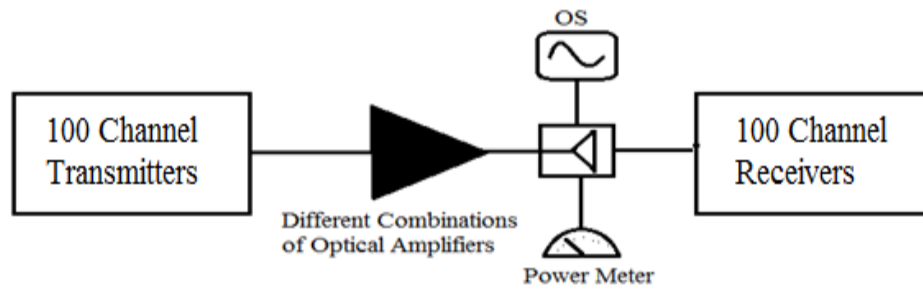


Figure 3.1: Simulation setup of 100 channel DWDM system for different HOAs;
OS: optical spectrum.

In the Hybrid I structure, the signal first boost by Raman amplifier before undergoing further amplification in the followed EDFA. In Hybrid 2, amplification arises first in the EDFA followed by a hybrid Raman and EDFA. In Hybrid 3, the SOA is used as an intermediate between the EDFAs, which was also proposed in [77]. In Hybrid 4, three times amplification occurs by the Raman followed by a hybrid EDFA and Raman. In all

these hybrid amplifier structures, the counter pumped Raman amplifier has been considered because it leads to a lesser pump noise coupling with signal [78].

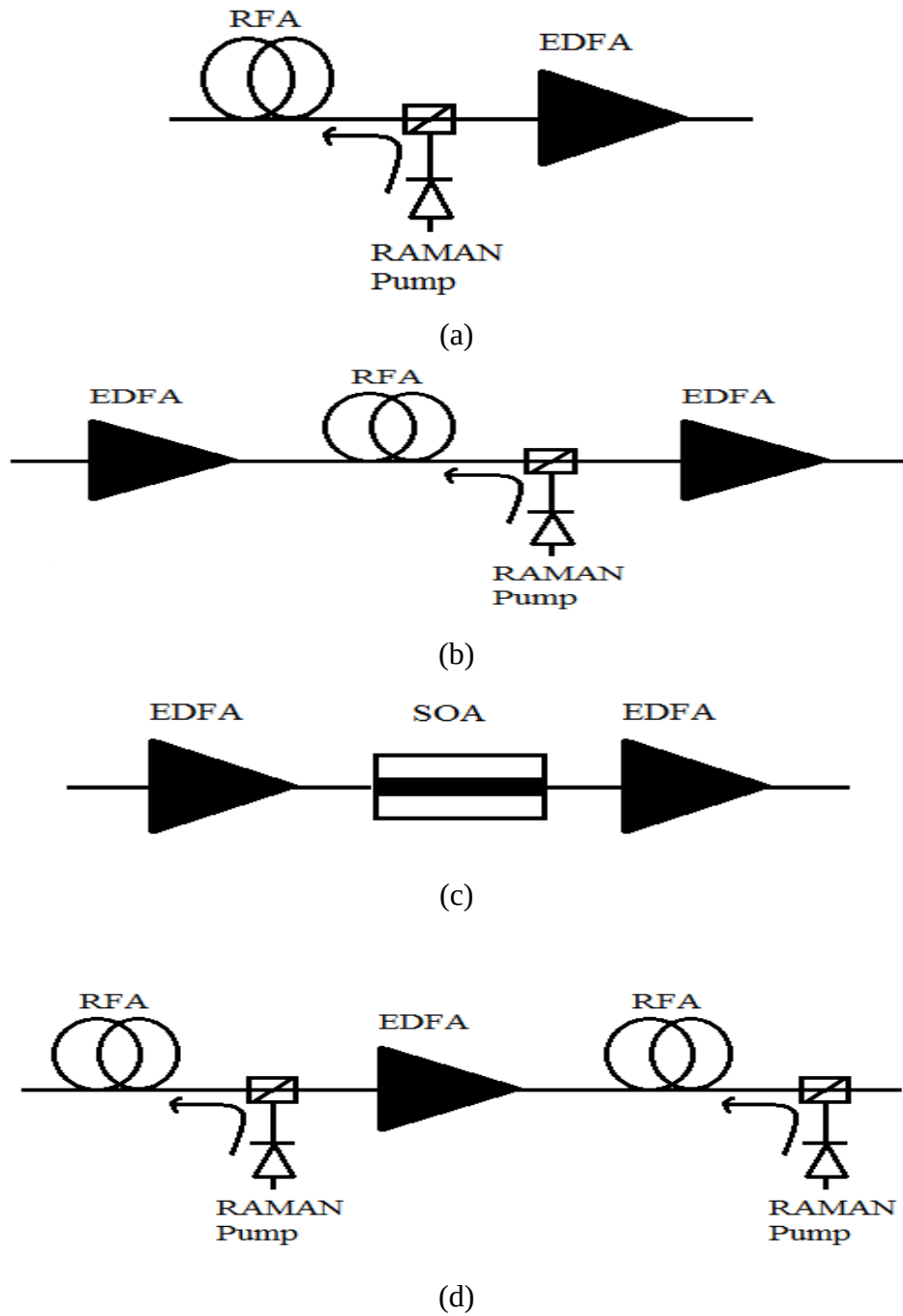


Figure 3.2: Various configurations of HOAs (a) Hybrid I, (b) Hybrid II, (c) Hybrid III and (d) Hybrid IV; RFA: Raman fiber amplifier.

These investigations were carried out using 100-laser sources operating at 1546.725–1551.575 nm, 1543.45–1553.15 nm, 1536.9–1556.3 nm, 1523.8–1562.6 nm, and 1497–1575.2 nm for the channel spacing of 6.25, 12.5, 25, 50, and 100 GHz,

respectively. Each laser source has a light beam with 1 mW of power. These laser beams are modulated by a $\sin^2$ amplitude modulator with an excess loss of 4 dB. The data rate is simulated at SONET/SDH rate (i.e. 2.488 Gbps) with a pseudorandom binary sequence. To analyze the eye diagram, it is necessary to convert optical signal into electrical, so a PIN photo-detector is used. The used parameters of PIN diode are: responsivity is 0.875 A/W, and the dark current is 0.1 nA. Tables 3.1–3.3 describes the various parameters of SOA, Raman, and EDFA.

Table 3.1: Raman Parameters for DWDM system.

Parameters	Value
Raman fiber length	12 Km
Raman loss	0.2 dB/Km
Pump wavelength	1453 nm
Pump power	500 mW
Pump attenuation	0.2 dB/km
Dispersion at reference frequency	2.15 ps/nm/km
Reference frequency for dispersion	1550 nm
Operating Temperature	300 K

Table 3.2: EDFA Parameters for DWDM system.

Parameters	Value
Output power	32 mW
Gain shape	Flat
Maximum small signal gain	35.6
Noise figure	4.5 dB

Table 3.3: SOA Parameters for DWDM system.

Parameters	Value
Bias current	100 mA
Amplifier length (10^{-6} m)	300
Active large width (10^{-6} m)	1.5
Active large thickness (10^{-6} m)	0.15
Confinement factor	0.35
Carrier lifetime	0.3 ns
Input/output insertion loss	3 dB

3.2.3 Result and Discussion

As the HOAs are placed in the system in the scenario of reduced channel spacing, the different quality of signal, output power, and eye closure penalty is obtained for each

channel. To illustrate the performance of HOAs, these performance parameters are observed at the first channel of proposed DWDM system.

Figures 3.3 and 3.4 shows the optical signal quality and output power after each HOA in the system. The DWDM system is observed for different channel spacing. It can be observed that with the decrease in channel spacing, there is a decrease in the quality of signal and an increase in output power. The variation in quality factor from different HOAs is 19.05 to 37.82 dB for the Raman–EDFA, 17.18 to 25.72 dB for the Raman–EDFA–Raman, 17.43 to 25.87 dB for the EDFA–Raman–EDFA, and 31.23 to 43.11 dB for the EDFA–SOA–EDFA, as shown in Figure 3.3.

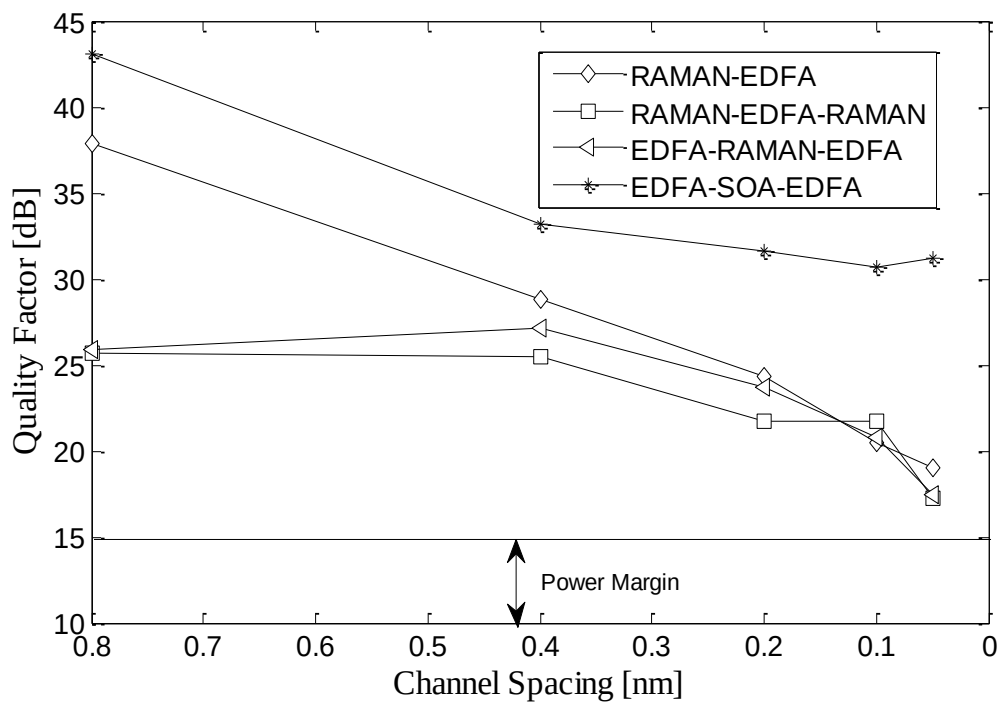


Figure 3.3: Quality factor versus channel spacing for 100 channel DWDM system.

On the other hand, the variation in output power from different HOAs is 5.71 to -5.96 dBm for the Raman–EDFA, 11.4 to 3.42 dBm for the Raman–EDFA–Raman, 5.75 to -2.6 dBm for the EDFA–Raman–EDFA, and 4.66 to -8.73 dBm for the EDFA–SOA–EDFA, as shown in Figure 3.4.

For comparison, a transmission investigation is also conducted, over 80 to 240 km, when the proposed HOAs are used as a pre-amplifier (before receiver) at 6.25-GHz channel spacing. In this setup, the dispersion-shifted-anomalous fiber is used as a transmission fiber and no DCF is used. An increase in transmission distance (80 to 240 km), the degradation in BER, Q-factor and eye closure occur, as shown in Figure 3.5-3.7. This

degradation occurs because of the continuous increase in the ASE with respect to an increment in span distance, which was as described in [79].

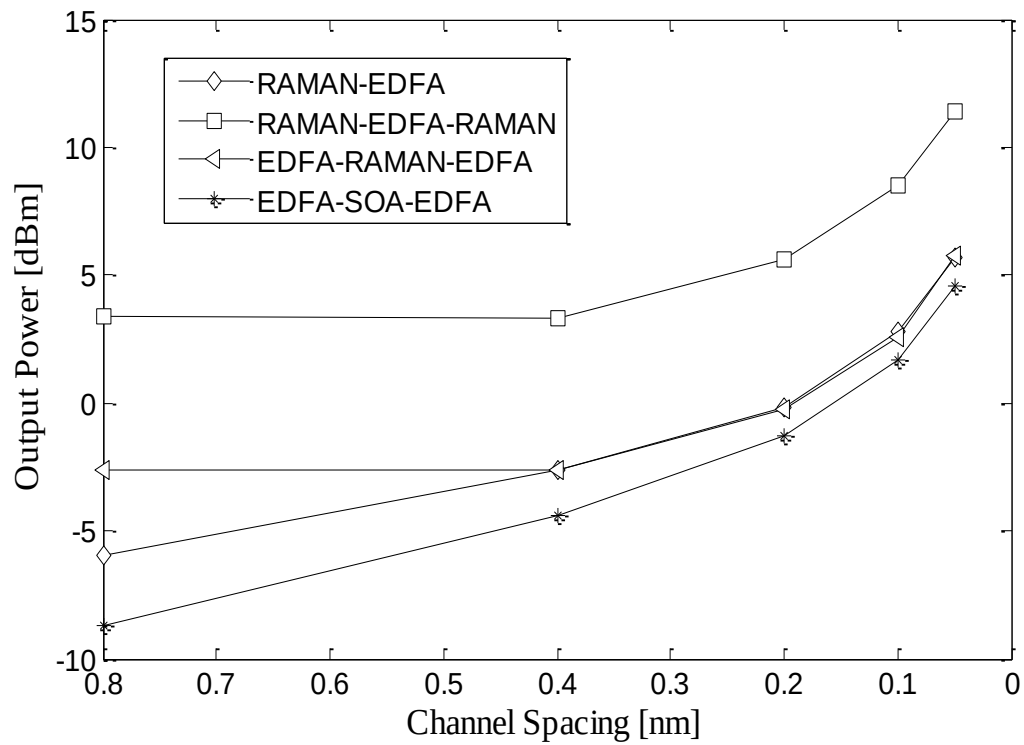


Figure 3.4: Output Power vs channel spacing for 100 channel DWDM system

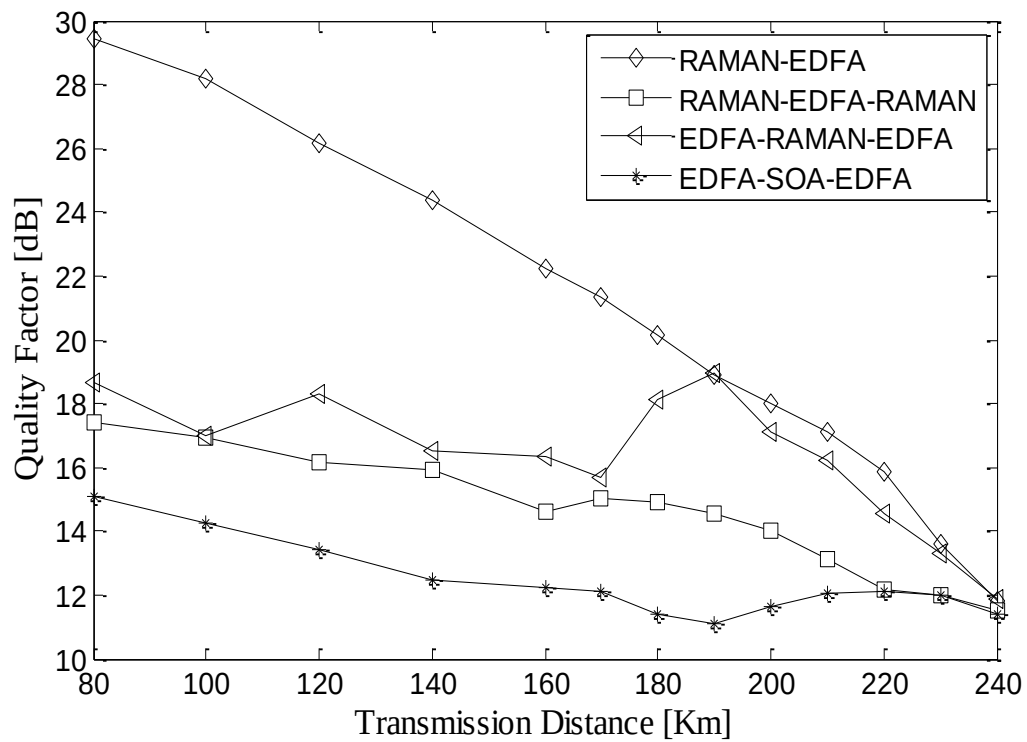


Figure 3.5: Quality of the signal vs transmission distance at 6.25 GHz channel spacing.

The variation in quality factor from different optical amplifiers for a given transmission distance at channel spacing of 6.25 GHz is 29.43 to 11.8 dB for the Raman–EDFA, 17.42 to 9.9 dB for the Raman–EDFA–Raman, 18.68 to 11.87 dB for the EDFA–Raman–EDFA, and 15.09 to 12.12 dB for the EDFA–SOA–EDFA as shown in Figure 3.5. Also, as compared to other proposed HOAs, least BER is shown by Raman-EDFA HOA, as shown in Figure 3.6.

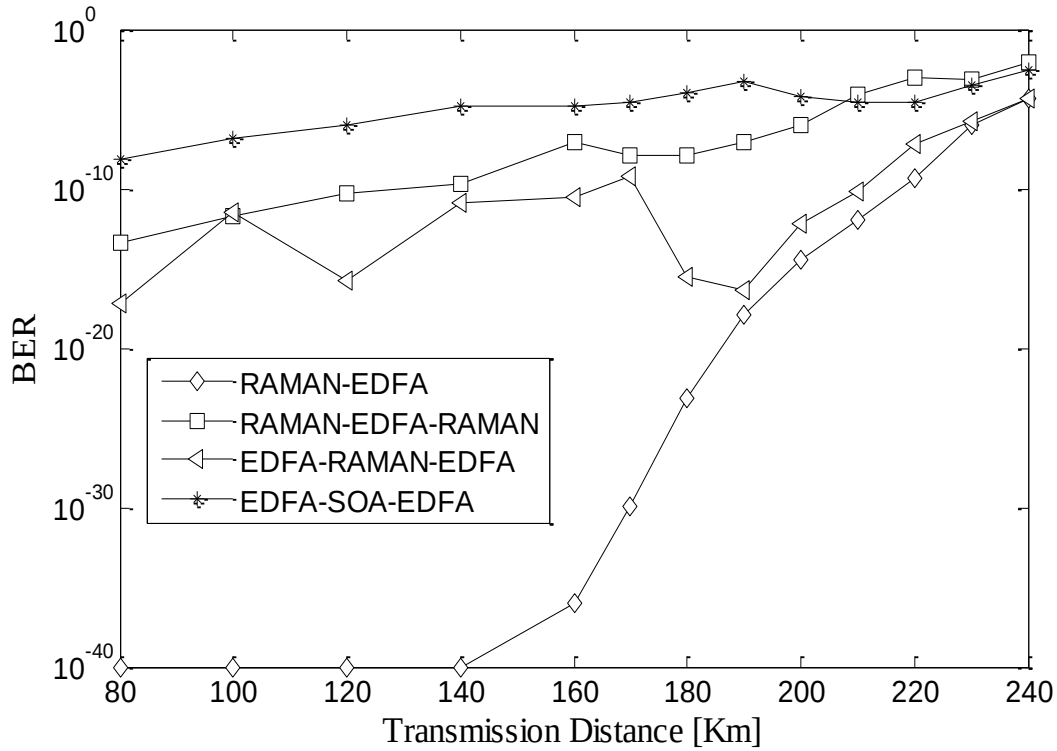


Figure 3.6: Bit error rate variation as function of fiber length at 6.25 GHz channels spacing.

Before a 220-km of transmission distance, the hybrid Raman–EDFA provides acceptable BER ($<4 \times 10^{-10}$). Hence, the Raman–EDFA covers the maximum single span distance as compared to EDFA–Raman–EDFA, Raman–EDFA–Raman, and EDFA–SOA–EDFA, which cover 210 km, 140 km, and 80 km, respectively, with an acceptable performance. The eye closure versus transmission distance is presented in Figure 3.7. Lesser eye closure leads to lesser BER and better communication. It can be observed that induced dispersion and nonlinear effects dominates the eye closure performance with the increase in transmission distance from 80 to 240 km. Raman–EDFA HOA again provides better results i.e. least eye closure (2.23 dB), even at the maximum transmission distance.

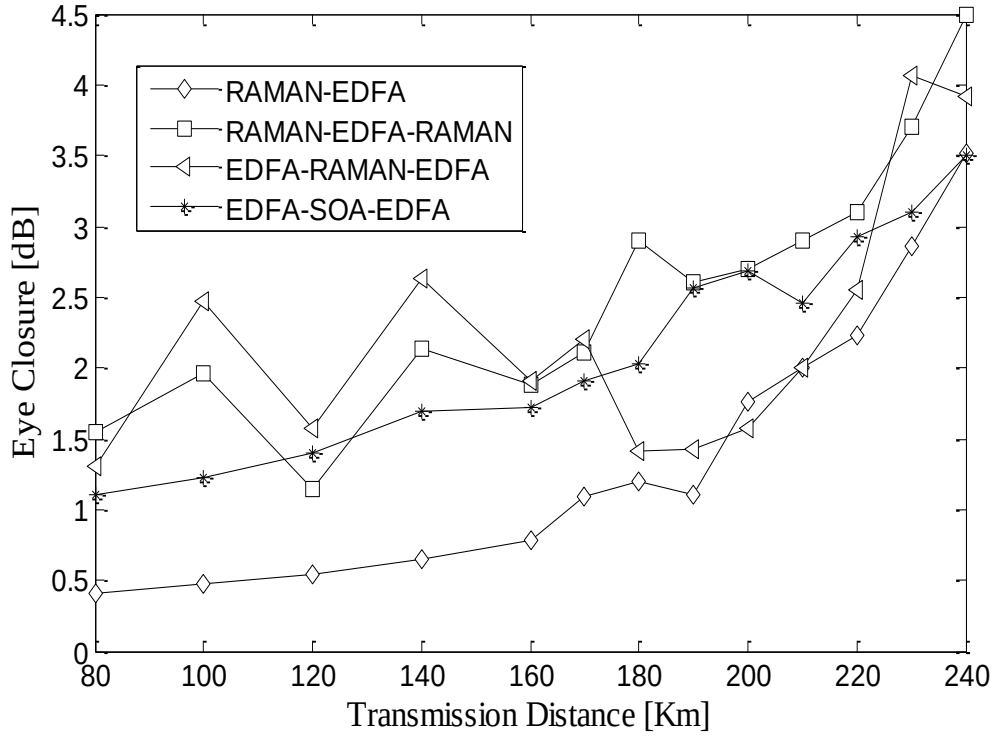


Figure 3.7: Eye closure penalty after different transmission distance at 6.25 GHz channel spacing.

From the previous results, the Raman-EDFA HOA can be recommended for high capacity DWDM system even at reduced channel spacing instead of other alternatives. Hybrid Raman-EDFA provided the maximum distance (220 km) using single span, even at such reduced channel spacing (6.25-GHz) without using any dispersion compensation techniques. At 220 km, it provides an acceptable BER (4×10^{-10}), quality factor (15.8 dB), and eye closure (2.23 dB); after that the degraded performance can be observed due to the induced ASE noise.

Table 3.4: List of maximum bit rate with acceptable BER and Quality factor for all configurations.

Configuration	Acceptable bit rate	Acceptable BER	Acceptable Q-factor
Raman-EDFA	< 20 Gbps	1.14×10^{-9}	15.01 dB
Raman-EDFA-Raman	< 16 Gbps	1.39×10^{-9}	16.28 dB
EDFA-Raman-EDFA	< 19 Gbps	1.28×10^{-9}	15.08 dB
EDFA-SOA-EDFA	< 20 Gbps	1.21×10^{-14}	15.86 dB

The previously reported results are limited to bit rate (i.e. 2.488 Gbps) because the performance of HOAs were investigated with 6.25-GHz channel spacing. Furthermore, to check the performance of HOAs with respect to different bit rates the same system has been considered with 12.5 GHz of channel spacing. The quality factor variation (recorded at first channel) with respect to the bit rate is shown in Figure 3.8. As expected the hybrid Raman-EDFA provides a better quality factor (33.95 dB) for every bit rate. Figure 3.9 shows the deviation in BER with respect to different bit rate. Table 3.4 describes the acceptable BER and quality factor for the maximum acceptable bit rate per channel. Figure 3.10 presented the eye diagrams response from first channel of proposed DWDM system utilizing the Raman-EDFA HOA at different bit rates (i.e. 4, 10, 20, and 30 Gbps).

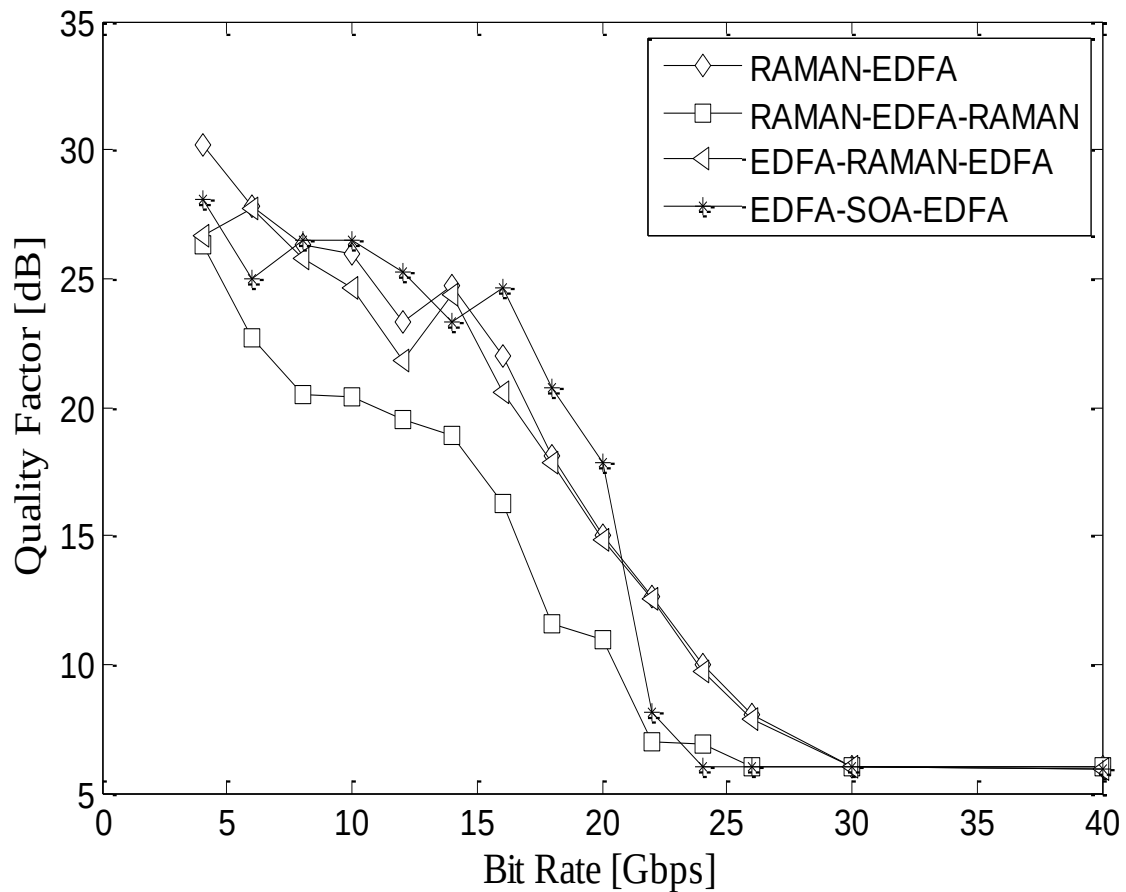


Figure 3.8: Quality factor versus Bit rate at 12.5 GHz channel spacing.

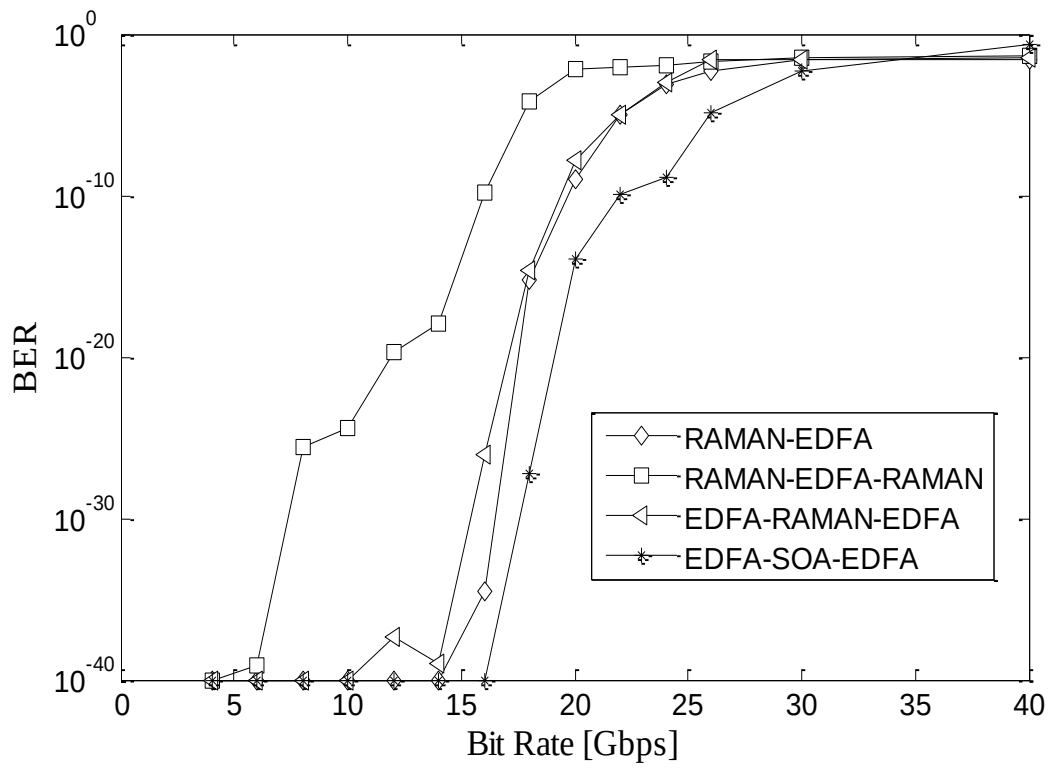
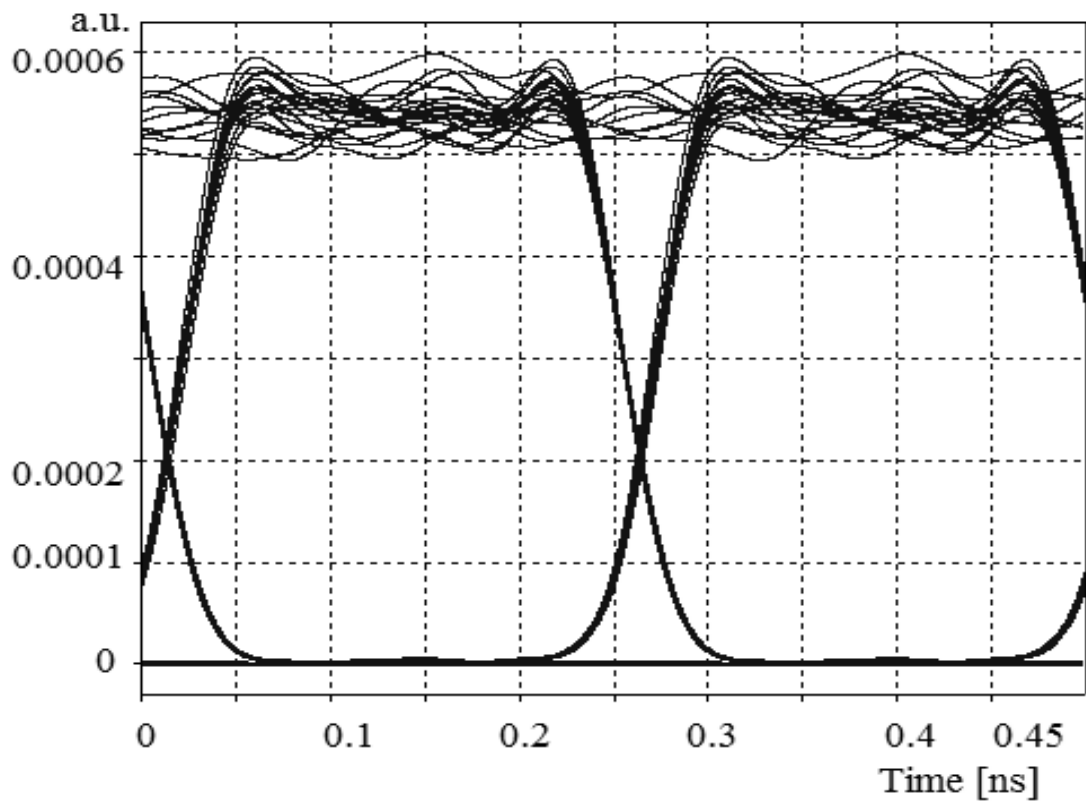
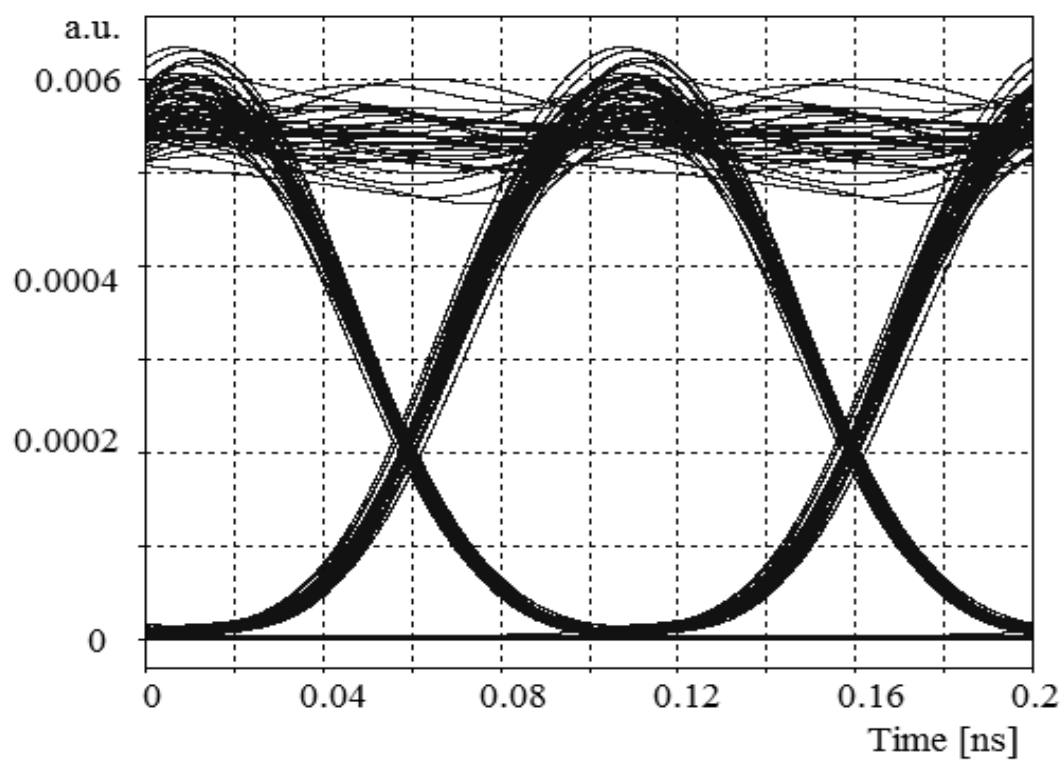


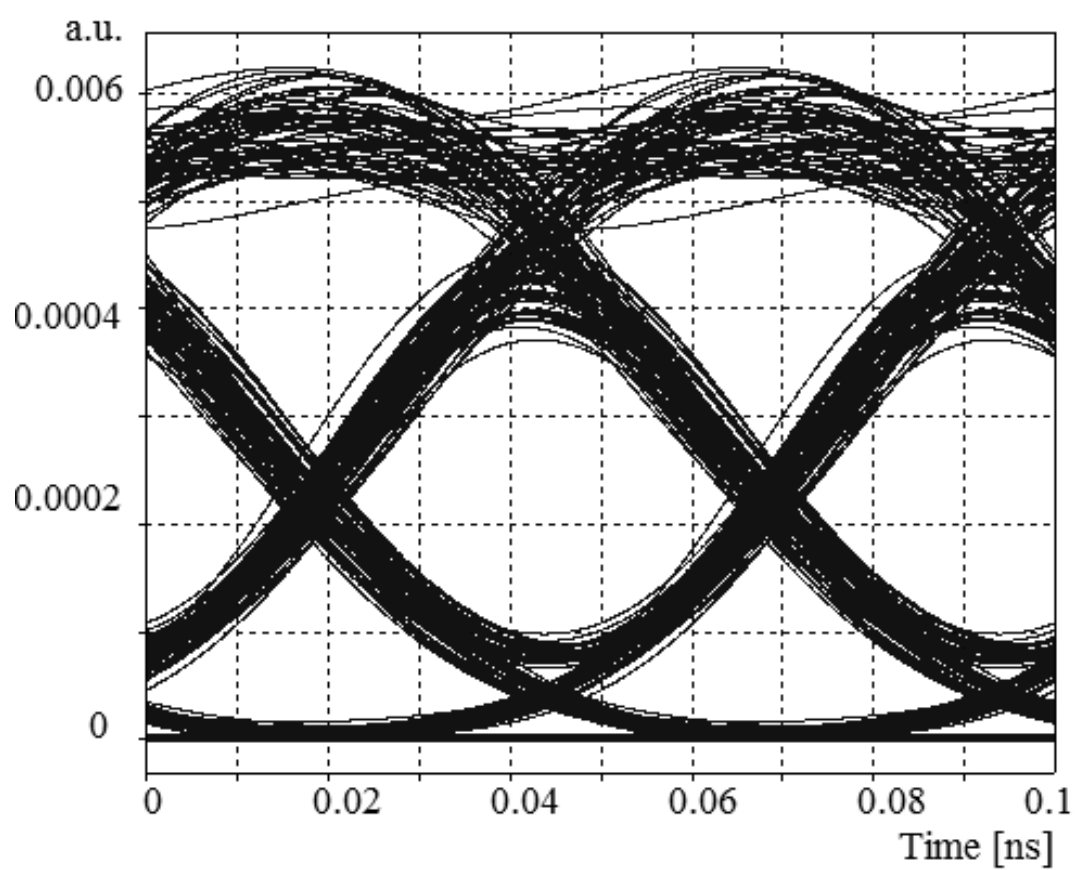
Figure 3.9: BER versus bit rate at 12.5 GHz of channel spacing.



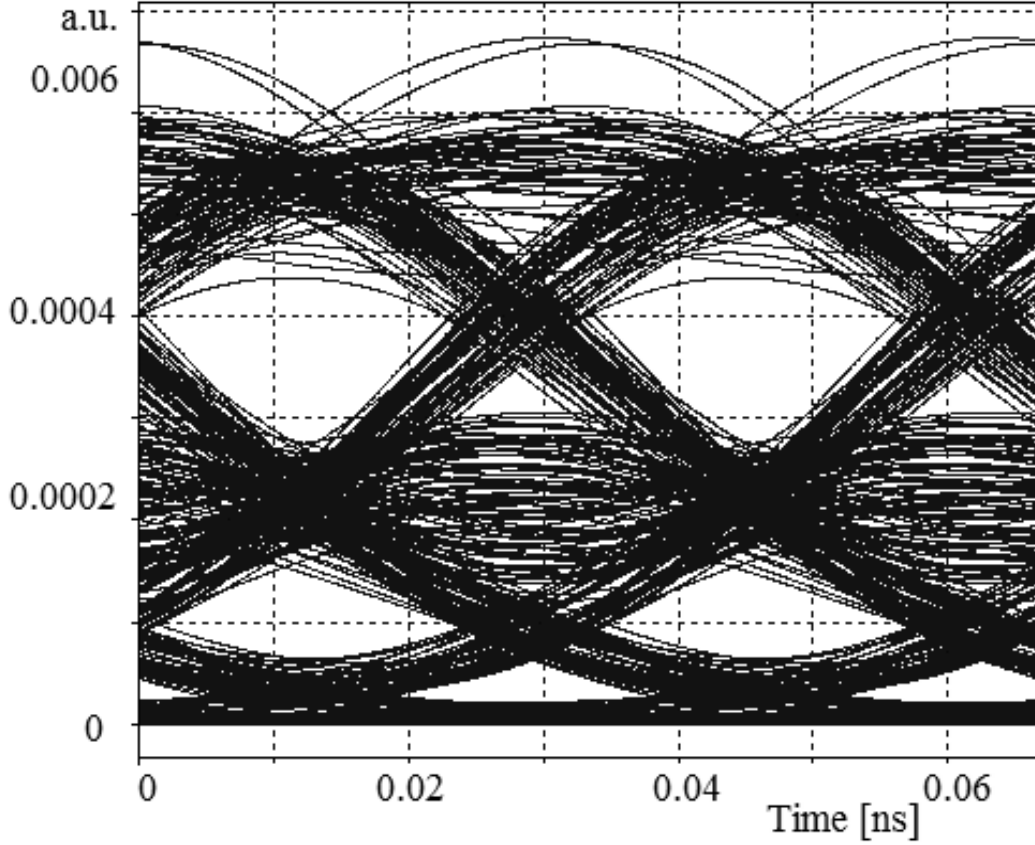
(a)



(b)



(c)



(d)

Figure 3.10: Eye diagrams at bit rate of: (a) 4 Gbps, (b) 10 Gbps, (c) 20 Gbps, (d) 30 Gbps.

3.3 Flat Gain Characteristics of Raman-EDFA HOA in DWDM System

In previous Section, it is reported that the hybrid Raman and EDFA shows superior results as compared to others. But still the gain flatness is the major issue for ultra-DWDM system. In literature, numerous gain clamping methods have been projected to decrease the gain variation among the effective channels, as also described in Section 2.2.1. Huri et al. [68] suggested a new way for further improving the gain flatness. To reduce gain variation and noise figure, the inline isolator was also used between the cascaded optical amplifiers. Chen et al. [80] proposed a structure of hybrid Raman amplifiers with high cost multiple pumps at precise wavelengths to achieve the flat gain characteristics with better performance. Unfortunately, all these investigations have been limited by the number of channels with larger channel spacing or expressively raise the cost and complexity of the system. In this section, the Raman-EDFA HOA is characterized in the denser and up-scaled version of previous scheme (See Figure 3.1) to

attain improved gain flatness without introducing costly techniques such as, multiple pumping, gain equalizer filters, midway isolator etc.

3.3.1 Gain Analysis of the Proposed Amplifier

In [81], the rate equation for the EDFA modeled as three level system is described. The EDFA gain is given as:

$$G_{EDFA} = G_{max}(L, \lambda_p, \lambda_s) = \exp \left[L \frac{r_p(\lambda_p) - r(\lambda_s)}{1 + r_p(\lambda_p)} \right]$$

which represents that G_{max} depends on pump wavelength (λ_p) and signal wavelength (λ_s). The dependence appears explicitly in the terms of cross-section ratios $r_p = \sigma_{pa}/\sigma_{pe}$ (pump absorption/pump emission); $r = \sigma_{sa}/\sigma_{se}$ (signal absorption/signal emission). The parameter $L = (L_{amp} \cdot \Gamma_s \cdot \sigma_{se} \cdot \lambda_s \cdot N_T)$ varies with signal wavelength, where, the physical length of the amplifier (L_{amp}) is constant and Γ_s represents signal to the core overlap.

In a Raman amplifier the power spectrum of the optical signal is affected by Raman pumping (only counter-propagation is considered here), Raman ASE noise and Rayleigh back-scattering. The set of two coupled equations govern the Raman-amplification process as described in [22] by including these effects. The signal gain is calculated as:

$$G_{Raman} = G(z) = \frac{P_s(z)}{P_s(0)} = \exp \left(g_R \int_0^z P_p(z) dz - \alpha_s z \right)$$

where P_s and P_p are the signal and pump power, respectively. On the other hand, longitudinal position (along fiber) is denoted by z and Rayleigh scattering coefficient is α_s .

In [65], it was reported that the total gain for HOAs is a multiplication individual amplifiers gain while placing in cascaded manner. Hence, total gain of proposed DRA-EDFA (G_{RE}) is calculated as:

$$G_{RE} = G_{Raman} \times G_{EDFA}$$

3.3.2 Setup and Results

The setup for the proposed system constituting 160 DWDM channels deploying continuous wave lasers in the frequency range of 187 THz to 190.975 THz with channel spacing of 25 GHz is shown in Figure 3.11. This system is investigated at different input

laser powers (P_{in}) of 3, 5, and 15 mW. To drive a sine squared amplitude modulator, a pre-coded data stream with a NRZ binary sequence is provided by a 10 Gbps pattern generator. Table 3.5 describes the parameters of different fibers. For the EDFA, the gain and noise figure is fixed at 25 dB and 4 dB respectively.

Table 3.5: Parameter values for the considered fibers.

Fiber	Loss dB/Km	Dispersion ps/nm/Km	Pump frequency THz	Pump Power mW
SMF	0.2	16	207	650
			201	250
DCF	0.5	-90	---	---

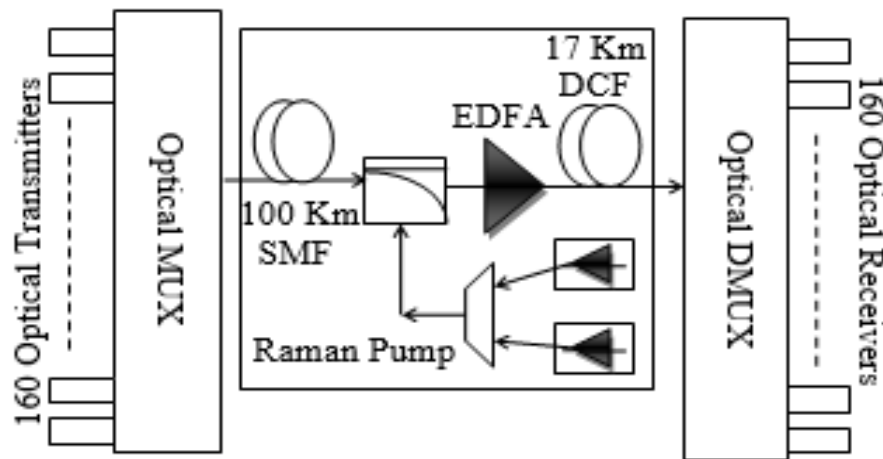


Figure 3.11: Proposed Hybrid Raman-EDFA for DWDM system.

Figure 3.12 demonstrates input optical spectrum of 160 DWDM channels with 25 GHz of interval. The gain spectrum of the Hybrid Raman-EDFA with different per channel input power is shown in Figure 3.13. It can be observed that, the gain decreases with the increase in input power. Also, due to nonlinearities and ASE noise induced by each amplifier, the gain variation over the effective bandwidth is not uniform.

From Figure 3.13, it can also be seen that the gain variation over the effective bandwidth, i.e. 3.97 THz (33.37 nm), increases with respect to increment in input power; this is because of the nonlinearities in fiber. A better performance in terms of the gain flatness (4.5 dB) with input power level at 3 mW is achieved over [68], [80]. On the other hand, the gain variation is increased to 5.4 and 11.6 dB for 5 and 15 mW of input power/

channel, respectively. This large variation along the fiber length is caused due to local gain variations or local inversion introduced by pump power. Moreover, the amplifier saturation due high input power is also the major reason behind it.

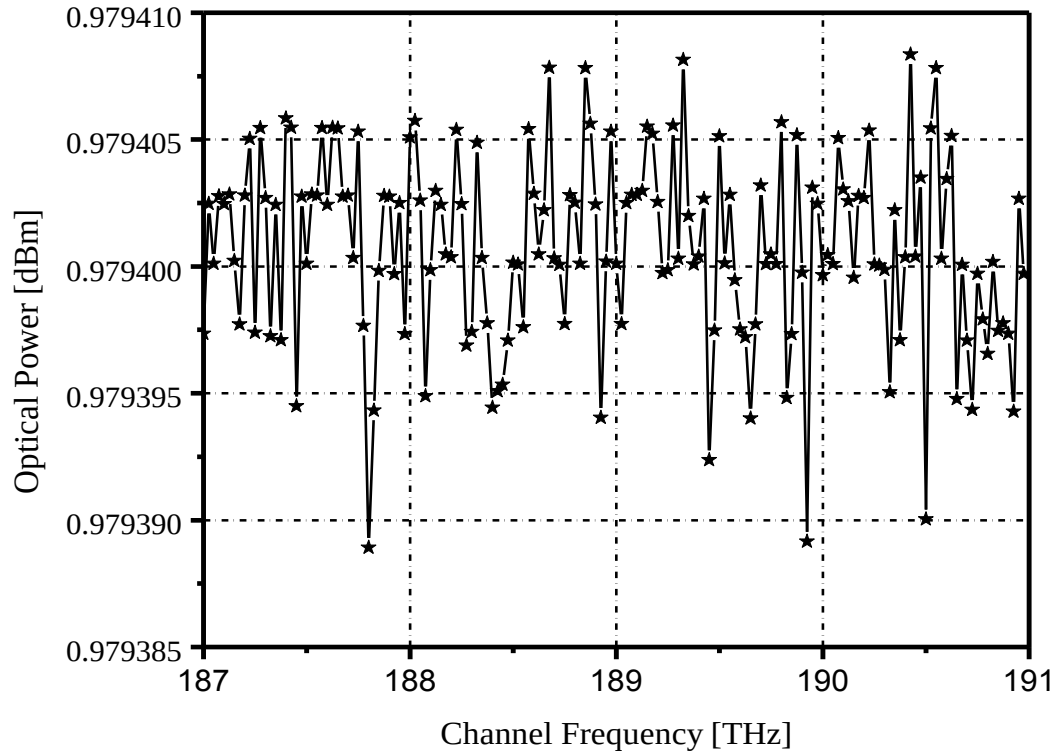


Figure 3.12: Input signal optical spectrum for DWDM system (with $P_{in} = 3$ mW).

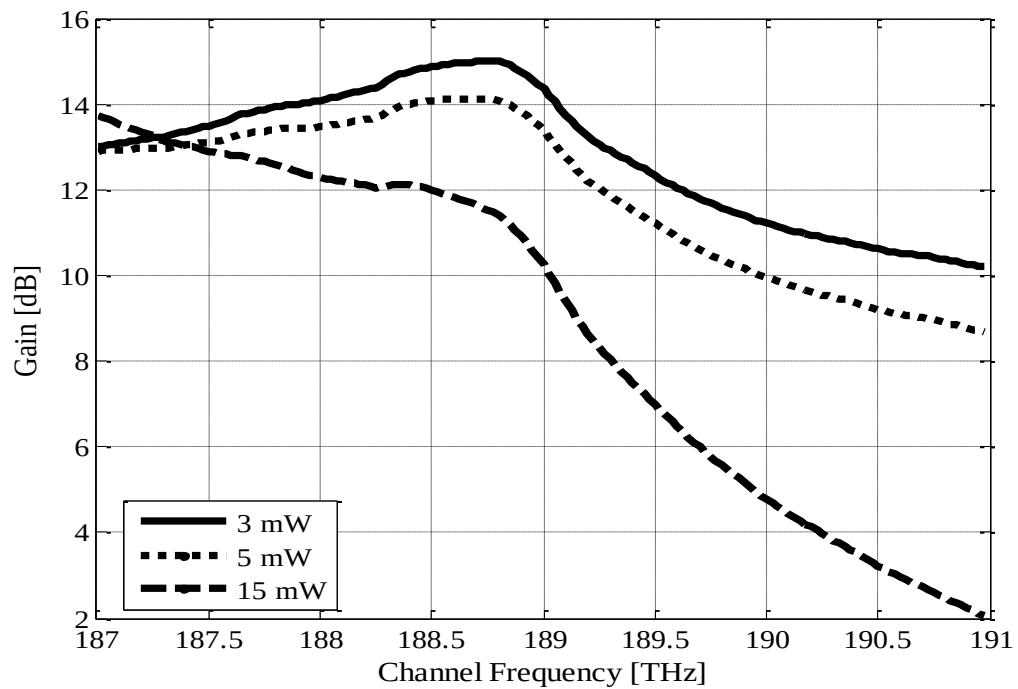


Figure 3.13: Gain spectra (with $P_{in} = 3, 5$ and 15 mW) of HOA.

In the proposed system, the received power after the Raman-EDFA HOA increases with increasing input power as shown in Figure 3.14. At 3 mW of input power, the smooth power spectrum of different channels is obtained with 4.8 dBm variations. On the other hand, maximum gain variation is observed with respect to the large input power.

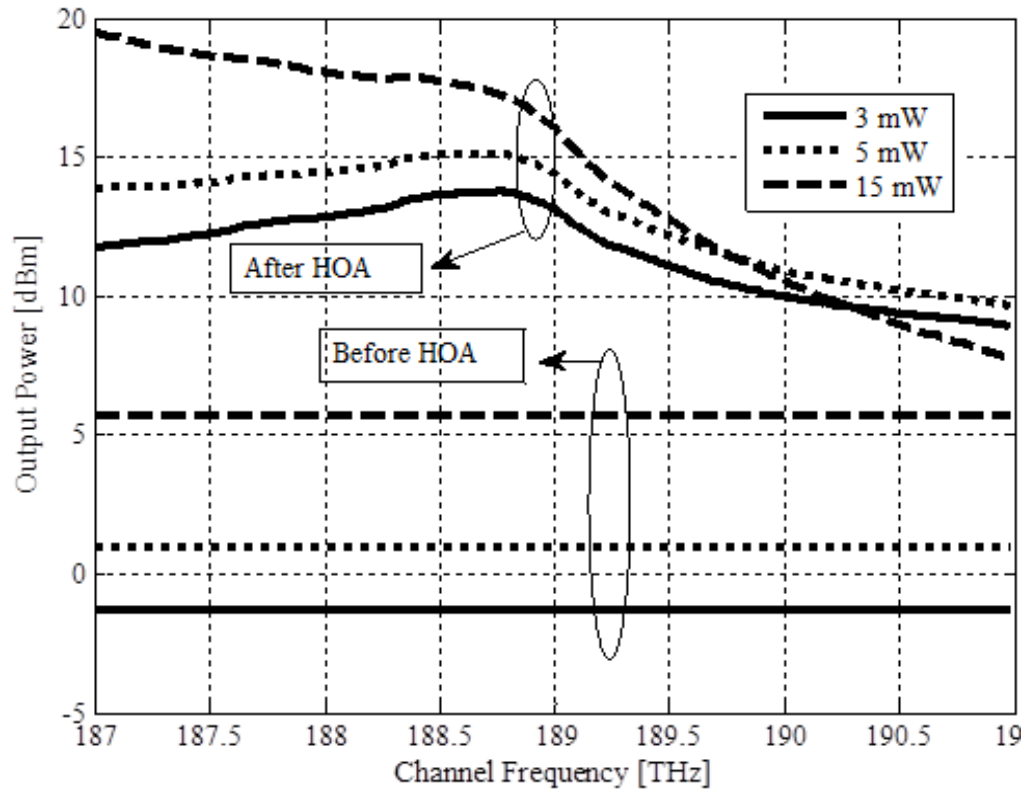


Figure 3.14: Optical spectra at Receiver of HOA with P_{in} = 3, 5 and 15 mW.

The investigation of Q-factor of the electrical signals obtained after PIN photodetector is also done for the proposed HOA. Optical signal quality with different per channel input power is shown in Figure 3.15. There is an increase in the quality factor variations over the bandwidth due to contribution of the inter-channel crosstalk between highly DWDM channels and non-linear effects at high input power, which limits the system performance.

3.4 Optimization of Raman-EDFA Hybrid Optical Amplifier

As discussed in Section 3.3, the Raman-EDFA HOA provides improved performance with large gain flatness. However, Raman amplifier has some disadvantages at high input power which leads to induce the nonlinear impairments, such as FWM, SBS, and XPM, yield degradation in system performance [82]. On the other hand, the saturated EDFAs induce the non-uniform gain spectrum which further cause the decrease in the OSNR to

unacceptable values [83]. Thus, both the amplifiers and their realistic parameters must be carefully designed or chosen if we wish to install the hybrid amplifiers in DWDM system. So it is important to optimize the important parameters (such as Raman length, EDFA length and its pump powers etc.) before the HOA is deployed. In literature, various optimization techniques are considered for optimization of the parameters of HOAs for improving the system performance in the term of gain, gain flatness, transient effect etc. Carena et al. [65] presented the mathematical optimization to yield the optimal configuration of hybrid Raman/EDFA HOA for given target optical signal to noise ratio. It was reported that span distance is around 30 km when only EDFAs are used, while it is increased to 50–60 km in the case of HOA. In [84], Kaler investigated the simulation based DWDM system to optimize the Raman-EDFA HOA.

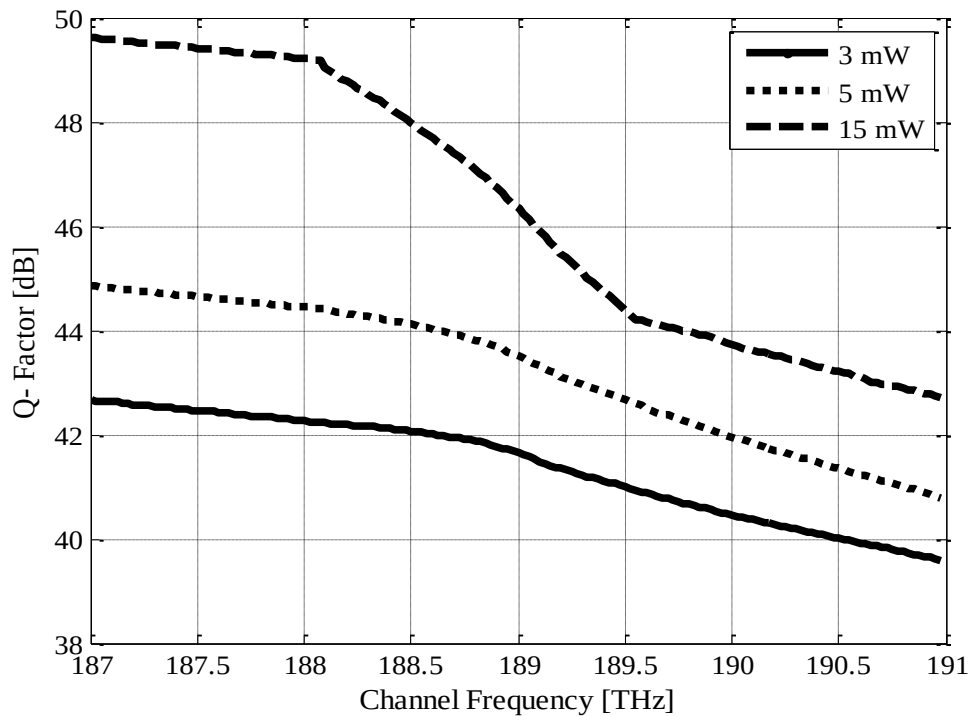


Figure 3.15: Q-factor variation over channel frequencies (after HOA) with P_{in} = 3, 5 and 15 mW.

Unfortunately, these investigations are based on single/ local parameter optimization (i.e. at single time only one parameter of HOA is varied). In previous research papers published as [85], [86], [87], [88] various global optimization techniques (such as genetic algorithm, hybrid genetic algorithm, neural network learning etc.) are presented to optimize the Raman and EDFA individually. Till now no global optimization technique is applied to optimize the Raman-EDFA HOA in optical communication system.

To address these issues, in this Section, a novel net gain analytical model of Raman-EDFA HOA is proposed and optimized the various parameters using genetic algorithm. Our method has shown to be robust in the simultaneous analysis of multiple parameters (Raman length, EDFA length and its pump powers). The optimized HOA is further investigated on system level for high speed DWDM system comprising 160 channels covering L-band with 25 GHz interval.

3.4.1 Analytical Net Gain Model of Raman-EDFA Hybrid Optical Amplifier

As the mathematical model of HOA is concerned, according to [65], [66] the total gain is the multiplication/ addition of individual gain of cascaded amplifiers. But in original the gain of second cascaded amplifier (net gain) is depend on the first amplifier gain as shown in Figure 3.16. So in this section, the net gain modal is derived by considering the actual conditions. The mathematical model is divided into two parts. In part A, an expression of variation in pump power and signal power along with EDFA length is determined while. On the other hand, in part B, after considering the effect of Raman output power on EDFA power, an expression for a net signal gain is established.

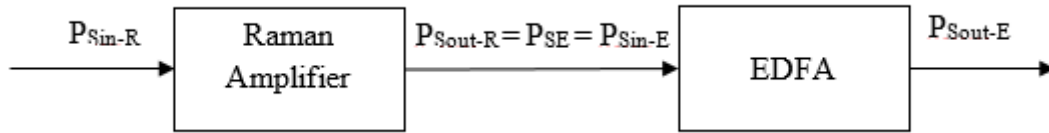


Figure 3.16: Net Gain/ Power evaluation.

A. Analytical computation of pump power and pump signal evolution along the EDFA length

The EDFA model is derived as multi-level system but due to high relaxation rate of pump level (E_3 , top level) remains almost empty, therefore

$$N_1 + N_2 = N_t \quad (3.1)$$

where N_1 and N_s are the is population density in ground and in metastable state, respectively, N_t is total erbium-ion density in the core of EDFA. Then the rate of change of population (N_1) at ground level (energy E_1) is given as [89]:

$$\frac{dN_1}{dt} = \frac{-\sigma_{pa} P_{PE} N_1}{a_p h \nu_p} - \frac{\sigma_{sa} P_{SE} N_1}{a_s h \nu_s} + \frac{\sigma_{se} P_{SE} N_2}{a_s h \nu_s} + \frac{N_2}{\tau_{sp}} \quad (3.2)$$

where P_{PE} is Pump power, P_{SE} is signal power, σ_{pa} is absorption cross-section at pump frequency ν_p , σ_{sa} is absorption cross section at signal frequency ν_s , σ_{se} is emission cross section at signal frequency ν_s , a_p is cross sectional area for fiber modes for λ_p , a_s is cross sectional area for fiber modes for λ_s , and τ_{sp} is spontaneous emission lifetime for transition from E_2 to E_1 .

On right hand side of equation (3.2) the first term $\frac{\sigma_{pa}P_{PE}N_1}{a_p h \nu_p}$ is the rate of absorption per unit volume from E_1 to E_3 due to pump, second term $\frac{\sigma_{sa}P_{SE}N_1}{a_s h \nu_s}$ is the rate of absorption per unit volume from E_1 to E_2 due to signal, third term $\frac{\sigma_{se}P_{SE}N_2}{a_s h \nu_s}$ is rate of stimulated emission per unit volume from E_2 to E_1 due to signal and fourth term $\frac{N_2}{\tau_{sp}}$ is rate of spontaneous emission per unit volume from E_2 to E_1 due to signal.

Similarly, the rate of change of population (N_2) at upper amplifier level is [89]:

$$\frac{dN_2}{dt} = \frac{\sigma_{pa}P_{PE}N_1}{a_p h \nu_p} + \frac{\sigma_{sa}P_{SE}N_1}{a_s h \nu_s} - \frac{\sigma_{se}P_{SE}N_2}{a_s h \nu_s} - \frac{N_2}{\tau_{sp}} \quad (3.3)$$

Under steady state condition $\frac{dN_2}{dt} = 0$. Put it into (3.3) and after rearrangement the expression becomes:

$$\frac{N_2}{\tau_{sp}} = \frac{\sigma_{pa}P_{PE}N_1}{a_p h \nu_p} + \frac{P_{SE}}{a_s h \nu_s} [\sigma_{sa}N_1 - \sigma_{se}N_2] \quad (3.4)$$

By neglecting the contribution of spontaneous emission, variation of pump power P_p and signal power P_s along the length of amplifier is calculated as:

$$\frac{dP_{SE}}{dz} = \Gamma_s(\sigma_{se}N_2 - \sigma_{sa}N_1)P_{SE} - \alpha_s P_{SE}$$

$$\pm \frac{dP_E}{dz} = \Gamma_P(-\sigma_{pa}N_1)P_{PE} - \alpha' P_{PE}$$

α and α' are fiber losses and can be neglected for small erbium fiber length, therefore these equations can be written as:

$$\frac{dP_{SE}}{dz} = \Gamma_s(\sigma_{se}N_2 - \sigma_{sa}N_1)P_{se} \quad (3.5)$$

$$\pm \frac{dP_{PE}}{dz} = \Gamma_P(-\sigma_{pa}N_1)P_{PE} \quad (3.6)$$

B. Analytical Computation of Net Gain

To drive the net gain, first it is required to calculate the Raman output power and then final gain is calculated by putting this power into equation (3.5) and (3.6). The Raman-amplification technique is directed by the following set of equations by considering single continuous wave pump beam to amplify an optical signal [90].

$$\frac{dP_{SR}}{dz} = \frac{g_R P_{PR} P_{SR}}{a_p} - \alpha_S P_{SR} \quad (3.7)$$

$$\pm \frac{dP_{PR}}{dz} = \frac{\omega_P}{\omega_S} g_R \frac{P_{PR} P_{SR}}{a_p} - \alpha_P P_{PR} \quad (3.8)$$

where P_{SR} is signal power for Raman amplifier, g_R is Raman gain coefficient, P_{PR} is Pump power for Raman amplifier, a_p is cross-sectional area of pump beam inside the fiber, α_S , α_P is fiber losses at signal and pump frequencies ω_S & ω_P , '+' and '-' sign for forward and backward, '-' sign for backward pump. For practical situations, pump power is so large as compared to signal power. The pump depletion can be neglected by setting $g_R=0$ in equation (3.8) and considering forward pump only [22],

$$\frac{dP_{PR}}{dz} = -\alpha_P P_{PR} \quad (3.9)$$

Solving equation (3.9):

$$\frac{dP_{PR}}{P_{PR}} = -\alpha_P dz$$

Integrating both sides,

$$\int_{P_{Pin-R}}^{P_{Pout-R}} \frac{dP_{PR}}{P_{PR}} = -\alpha_P \int_0^z dz$$

$$\frac{P_{Pout-R}}{P_{Pin-R}} = e^{-\alpha_P z}$$

From above equation the Raman output power can be calculated as:

$$P_{PR} = P_{Pout-R} = P_{Pin-R} \exp(-\alpha_P z) \quad (3.10)$$

By substituting the value of $P_{PR} = P_{Pout-R}$ in equation (3.7),

$$\frac{dP_{SR}}{P_{SR}} = -\alpha_s dz + \frac{g_R}{a_p} P_{Pin-R} \exp(-\alpha_p z) dz$$

Integrating both sides,

$$\int_{P_{sin-R}}^{P_{sout-R}} \frac{dP_{SR}}{P_{SR}} = \int_0^{L_R} -\alpha_s dz + \int_0^{L_R} \frac{g_R}{a_p} P_{Pin-R} \exp(-\alpha_p z) dz$$

$$\frac{P_{sout-R}}{P_{sin-R}} = \exp \left[-\alpha_s L_R + \frac{g_R}{a_p \alpha_p} [1 - \exp(-\alpha_p L_R) P_{Pin-R}] \right]$$

Now the net gain (G_{net}) can be calculated as:

$$G_{net} = P_{sout-R} = P_{sin-R} \exp \left[\frac{g_R P_{Pin-R} L_{eff}}{a_p} - \alpha_s L_R \right] \quad (3.11)$$

$$\text{where } L_{eff} = \frac{[1 - \exp(-\alpha_p L_R)]}{\alpha_p}$$

Now dividing and multiplying the second term of (3.11) by L_R :

$$P_{sout-R} = P_{sin-R} \exp \left[\frac{g_R P_{Pin-R} L_{eff} L_R}{a_p L_R} - \alpha_s L_R \right]$$

$$P_{sout-R} = P_{sin-R} \exp[g_0 L_R - \alpha_s L_R]$$

$$\text{where } g_0 = \frac{g_R P_{Pin-R} L_{eff}}{a_p L_R}$$

Also, $P_{sout-R} = P_{SE}$ is a input signal to EDFA

Put value of P_{SE} in (3.5) and after rearranging it becomes as:

$$\frac{dP_{SE}}{P_{sin-R}} = \Gamma_s (\sigma_{se} N_2 - \sigma_{sa} N_1) \exp[g_0 L_R - \alpha_s L_R]$$

For convenience of solving above equation, let us denote signal power by P_s only,

$$\frac{dP_s}{P_s} = \Gamma_s (\sigma_{se} N_2 - \sigma_{sa} N_1) \exp[g_0 L_R - \alpha_s L_R] dz$$

Integrating both sides for L_E as length of EDFA,

$$\int_{P_{sin-E}}^{P_{sout-E}} \frac{dP_s}{P_s} = \int_0^{L_E} \Gamma_s (\sigma_{se}N_2 - \sigma_{sa}N_1) \exp[g_0L_R - \alpha_sL_R] dz$$

From equation (3.1), the $N_1 = N_t - N_2$

Using value of N_1 in above eq.,

$$\int_{P_{sin-E}}^{P_{sout-E}} \frac{dP_s}{P_s} = \int_0^{L_E} \Gamma_s (\sigma_{se}N_2 - \sigma_{sa}(N_t - N_2)) \exp[g_0L_R - \alpha_sL_R] dz$$

After the long calculation and taking exponential both side:

$$G_{Total} = \exp \left\{ \frac{-\Gamma_s \sigma_{sa} [\exp(g_0L_R - \alpha_sL_R)] N_t L_E + \Gamma_s (\sigma_{sa} + \sigma_{se}) \exp[g_0L_R - \alpha_sL_R] N_{2avg}}{\Gamma_s (\sigma_{sa} + \sigma_{se}) \exp[g_0L_R - \alpha_sL_R] N_{2avg}} \right\} \quad (3.12)$$

$$\text{where } N_{2avg} = \frac{N_t [\omega_p + \omega_{sa}] L_E}{\left[\frac{1}{\tau_{sp}} + \omega_p + \omega_{sa} + \omega_{se} \right]}, \text{ pump rate } \omega_p = \frac{\sigma_{pa} P_{PE}}{a_p \hbar \nu_p},$$

ω_{sa} is stimulated absorption rate,

ω_{se} is stimulated emission rate.

3.4.2 Multi-parameter Optimization using Genetic Algorithm

The GA is a global search optimization algorithm based on biological evolution. Evolution is a method of searching among a large number of possibilities for solutions. A GA permits a population composing many individuals to be evolved to the state that maximizes “fitness” under specified selection rules [91]. Before the starting of optimization, the population of individuals is generated randomly and updated further by making the other generation.

The implementation of GA begins with the initialization of the several constraints for GA i.e. population size, number of generations, mutation probability and Cross over probability. Here population magnitude defines the amount of individuals contained by population for a particular constraint. Further, each of the various parameters to be optimized is initialized randomly [92]. Each of these random valued parameters forms the gene. A collection of all these random values is collectively called as the population. In this paper, haploid reproduction is introduced for the chromosome generation. In contrast to this, the algorithm uses one dimensional array with its each row representing a

chromosome. The objective function is called as a subprogram, within the main program, to calculate the fitness values for the whole population. The set of random initialized values for each parameter is passed in the function call to evaluate the objective function. A track of fitness value for each set of parameters is kept and further compared with each of the other fitness values throughout the population owing to reach the maximum fitness. A new generation of chromosomes, which is an improved form of the previous generation, is presented. During each generation, total number of individuals i.e. chromosomes remain unchanged, however only their values are changed according to their fitness. The successive generations lead to improvement of fitness value by selecting the set of parameters converging to the optimal solution with maximum fitness. Applying this simple GA for optimization of HOA can be broadly sub-divided into following steps and their sequence can be represented by a flow diagram as shown in Figure 3.17.

Step 1: Initialization of GA parameters and population for various system parameters i.e. Raman length, EDFA length and its pump powers. During this stage, the range for the parameters i.e. the limits of the search space is defined. The parameters for the GA and range of values for HOA are as given in Table 3.6 and 3.7 respectively. Set the number of generations after which the algorithm will converge to optimum solution.

Table 3.6: Parameters for the GA.

Parameter	Value
Cross over Probability	80%
Mutation Probability	2.5%
Tournament selection Parameter	75%
Number of generations	20
Population	400 individuals
Fitness function	Maximum gain

Table 3.7: Range of values for HOA parameters.

Number of pumps	1
Pump powers (mW)	500
Maximum Raman length(Km)	200
Maximum EDFA length(Km)	30

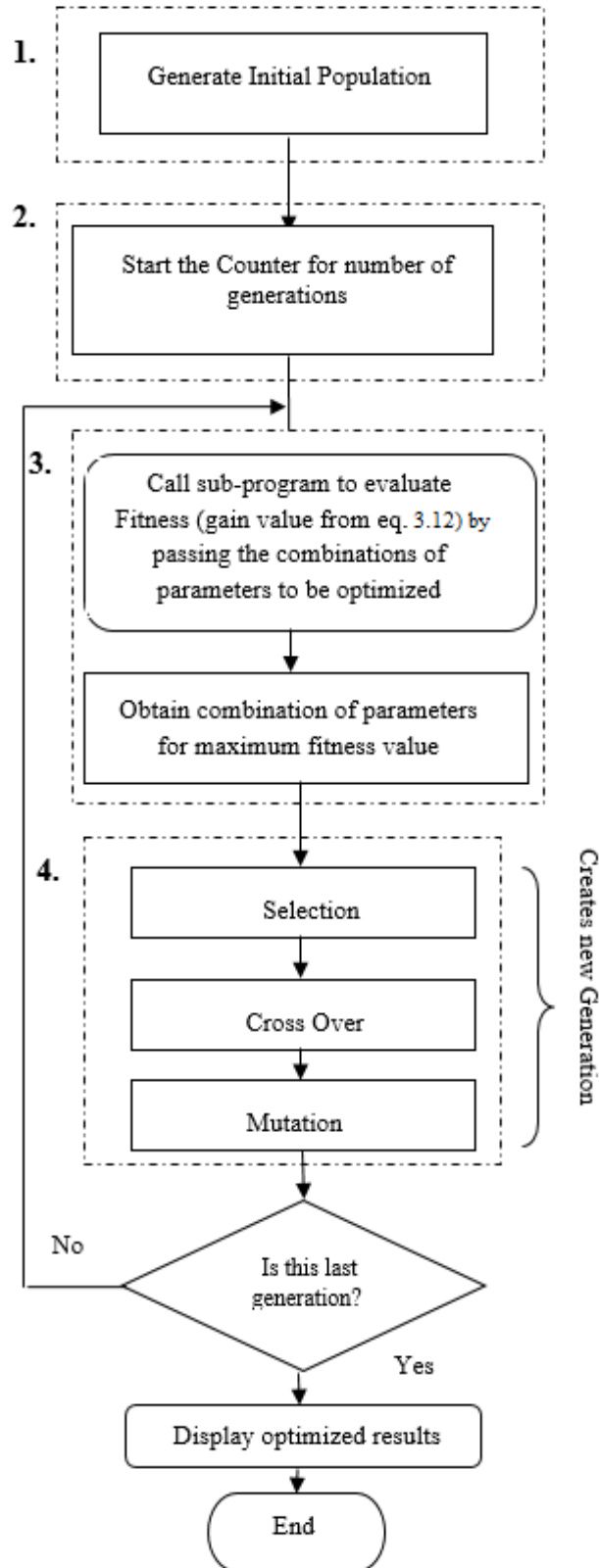


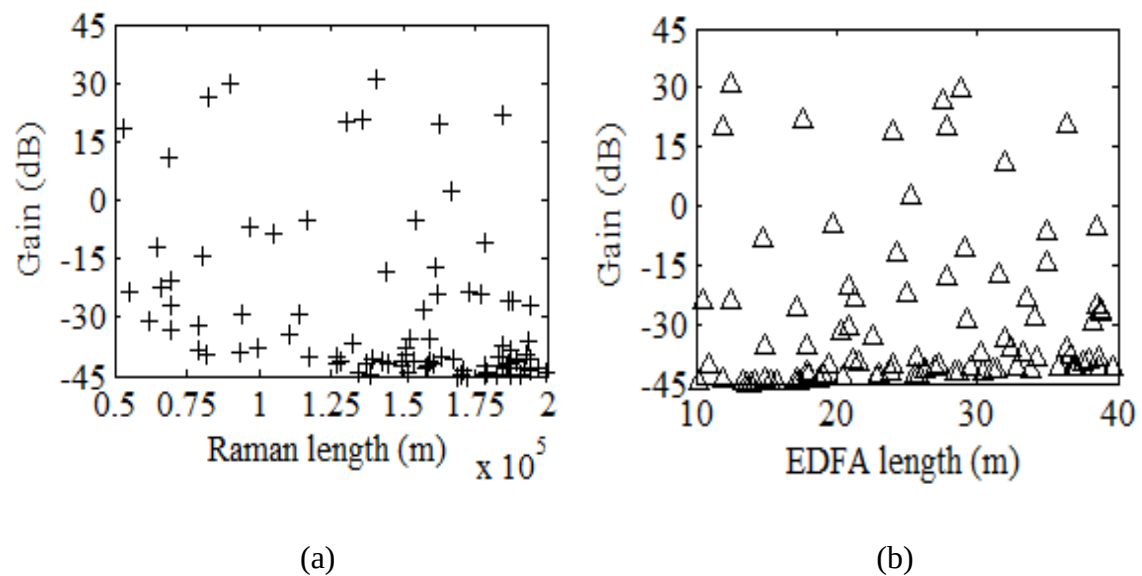
Figure 3.17: GA applied for Raman-EDFA HOA optimization.

Step 4: During the next sub-stage, the current population of individuals is modified by appropriately employing tournament selection. The fitness value and tournament select

probability are passed to call the function. Here the fitness is an array of gain values respective to the set of all parameters in current population. Tournament selection chooses a random value for chromosomes depending upon small probability as defined in Table 3.6. New chromosome pairs are obtained from these selected chromosomes by crossover method. These newly generated chromosomes form a temporary new population which replaces the original population after performing a mutation operation on each of the new chromosomes. Finally a new improved population is obtained.

Again *step 3* followed by *Step 4* is repeated until the final generation is reached. It can be determined that amplifier gain increases with the succession of the generations. Since, the proposed method of employing GA includes tournament selection, crossover method and mutation adopted collectively, so it converges towards maximum gain in a few generations and then further modification is not desirable.

Figure 3.18 illustrated the values of the gain versus Raman length, EDFA length, pump power for Raman amplifier and for EDFA during the progress of the algorithm through last generation. In the 2D plots, the Gain value is plotted versus a single parameter, but in each case the gain is obtained with the particular combination of the four optimized parameters. Table 3.8 shows the results obtained from genetic algorithm as a function of the expected gain of more than 30 dB. The maximum gain (31.1 dB) is obtained with the optimum solution presented in Case 5. For further investigation, the proposed Raman-EDFA HOA has been considered with these optimized parameters called optimized HOA.



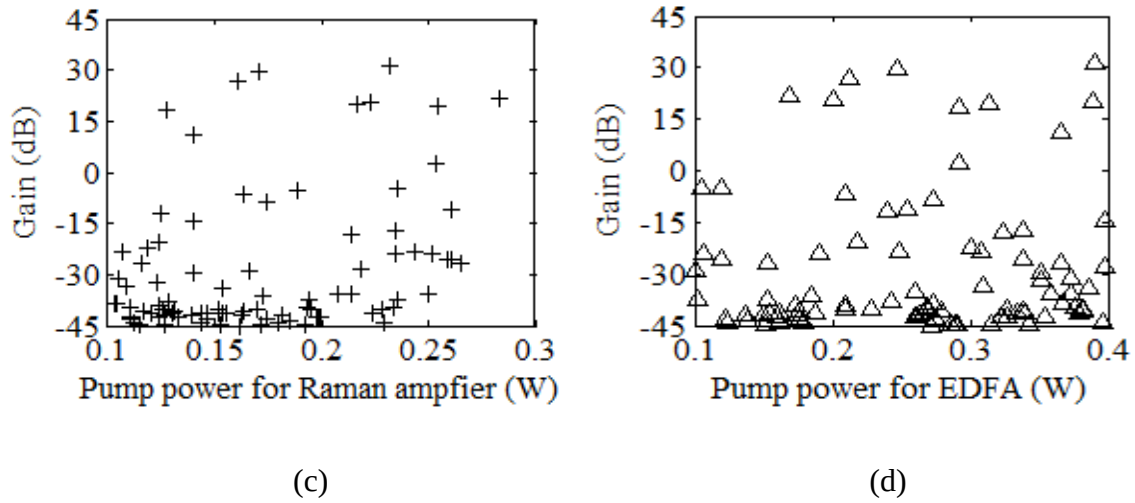


Fig. 3.18: Convergence of the GA obtained for (a) Raman length, (b) EDFA length, (c) Raman pump power and (d) EDFA pump power.

Table 3.8: Gain obtained from various combinations of parameters (Cases).

Case	Raman Length(km)	EDFA length(m)	Raman Pump Power (mW)	EDFA Pump Power (mW)	Gain(dB)
1	162.44	27.88	254.66	313.26	19.64
2	184.827	17.62	283.17	168.32	21.72
3	82.32	27.48	160.76	212.58	26.62
4	90.244	28.8	170.76	247.51	29.65
5	140.44	12.53	232.33	390.60	31.10

3.4.3 Analogy of Genetic Algorithm to Proposed Optical Communication System

In this section, the analogy of GA is described with optical communication system. In general GA is biological evolution method of searching among large number of possibilities for solution by varying the range as well as combinations of individuals. As proposed optimization technique is inspired from GA we have taken the individuals as HOA parameters (such as Raman Length, EDFA Length, Raman pump power and EDFA pump power). In the current investigation by using GA selection rules the individuals/ amplifiers parameters are varied until the maximum gain will be achieved. The flow chart shown in Figure 3.19 clearly represents the analogy of GA in which following terms (GA terms and optical system terms) are associated to each other: individual's $\leftrightarrow$ HOA parameters, fitness $\leftrightarrow$ gain calculated from equation (3.12), generation $\leftrightarrow$ combinations of individuals/ amplifier parameters.

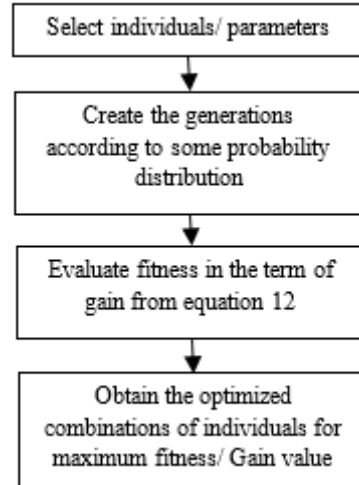


Figure 3.19: Analogue of GA with Optical system optimization.

3.4.4 System Setup and Results

The numerical simulation representation of optimized Raman-EDFA HOA is also carried out in the scenario of high speed DWDM system. The DWDM system contains 160 channels starting from 187 THz to 190.975 THz with channel spacing of 25 GHz in L-band is shown in Figure 3.20. This system is explored with -20 dBm of per channel input power. To drive a sine squared amplitude modulator, a pre-coded data stream with NRZ binary sequence is generated from a 10 Gbps pattern generator. The optimized parameters for the considered fibers and pumps are taken from Case 5, described in Table 3.8.

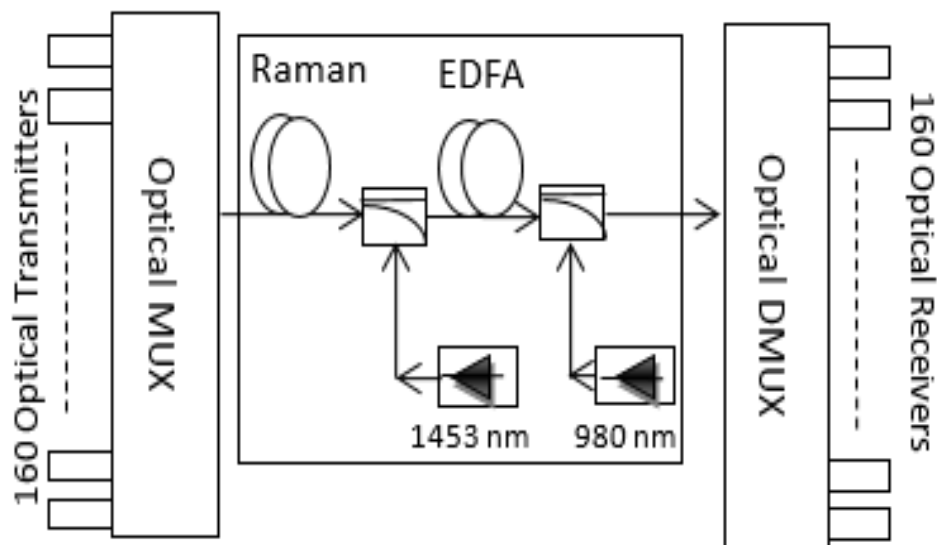


Figure 3.20: Proposed DWDM system with optimized Raman-EDFA HOA.

The Gain/noise figure spectrum of optimized Raman-EDFA HOA over 160 channel DWDM system is as shown in Figure 3.21. Since each amplifier induces its own ASE noise and nonlinearities [23], hence the gain variation with different wavelength is observed to be non- uniform. It can be observed that each frequency has a gain of more than 17.5 dB.

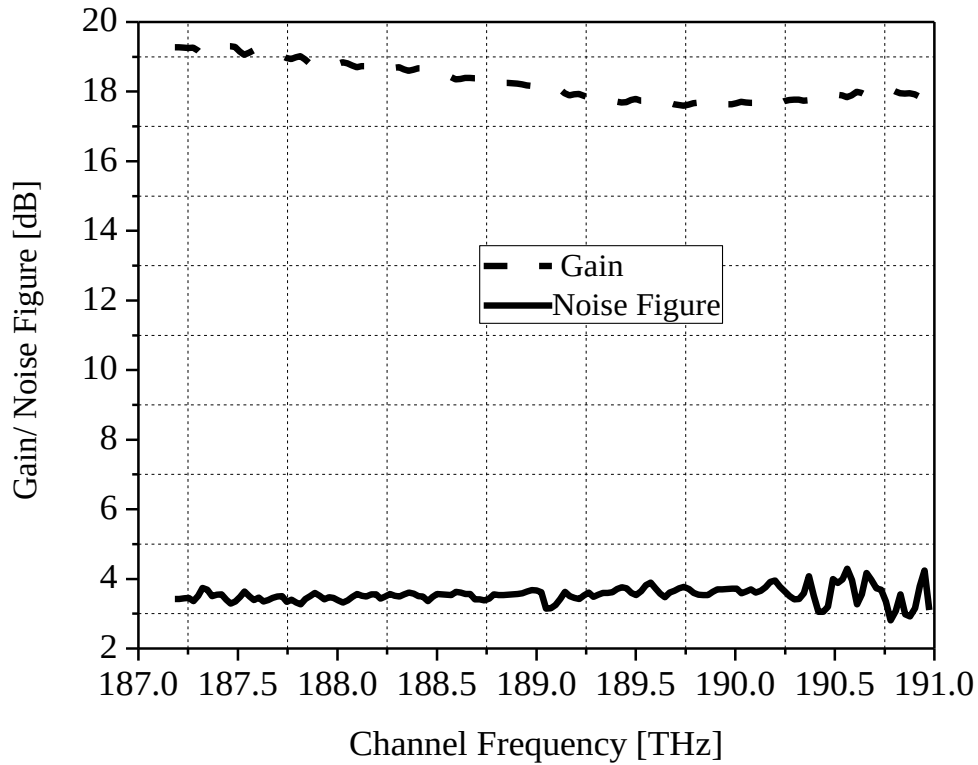


Figure 3.21: Gain and noise figure spectra of optimized Raman-EDFA HOA.

In simulation results various nonlinear effects are considered, such as, ASE, four wave mixing etc. unlike the mathematical analysis represented in GA. This is the reason behind the reduction of gain in the case of simulation. Using optimized parameters, the gain flatness of ~ 1.48 dB is obtained with noise figure of less than 4 dB, which shows improvement over [93], [94].

3.5 Conclusion

In this chapter, various configurations of optical amplifiers have been proposed. The several techniques are addressed for achieving better gain flatness without using high cost multiple pumping or gain equalizers. With respect to overall performance in the transmission system, among the four types, the Raman-EDFA HOA is found to show the

best performance and achieved maximum single span distance of 220 km with acceptable BER (4×10^{-10}), Quality factor (15.8 dB) and eye closure (2.23 dB). After investigating the Raman-EDFA for 160 channel DWDM system it is observed that, with 3 mW of input signal, a flat gain (>10 dB) is achieved in the frequency range from 187 THz to 190.975 THz having a small variation in gain (< 4.5 dB). Further, a new analytical gain model for Raman-EDFA HOA is proposed and the final gain equation is illustrated to optimize the multiple parameters using GA. It is observed that, the optimized HOA with optimum parameters (i.e. Raman length: 140.4 Km, EDFA length: 12.5 Km, Raman pump power: 232.3 mW and EDFA pump power: 390.6 mW) provides a flat gain of >17.5 dB in the frequency range from 187 THz to 190.975 THz having a small variation in gain (< 1.48 dB). The noise figure obtained for the proposed Raman-EDFA HOA is also the lowest value (< 4 dB/ channel) ever reported for the Raman-EDFA HOA DWDM system at such reduced channel spacing. In further investigations, these proposed hybrid amplifiers are illustrated in various high speed applications to identify its new areas. Also, the techniques are addressed to control the transience and crosstalk effect.

Chapter 4

Hybrid Optical Amplifier in DWDM System/ Network Applications

4.1 Introduction

In this Chapter, the new areas of optical communication and networks are identified where the proposed HOAs, in Chapter 3, are used as inline for seek better performance. In first application, the hybrid Raman and EDFA are investigated for a 16×40 Gbps high speed differential phase shift keying (DPSK) modulated system. The investigation has been done by considering different channel spacing. An improvement has been reported as compared to the current state-of-the-art schemes. Also, by virtue of efficient utilization of bandwidth, a new optical data format has been proposed. It is based on simultaneously modulating polarization-shift-keying and non-return-to-zero. The new proposed data format has also been investigated for Raman-EDFA HOA as high speed DWDM applications. Further, an optimal and heuristic solution is introduced for the scaled-up and denser version of sample MAN. The solution is based on placing hybrid optical amplifiers for high capacity DWDM links and by placing conventional optical amplifiers over local links with the aim of minimizing the total count of optical amplifiers needed in the network and hence the cost is reduced effectively. The performance evaluation of proposed HOA has also been checked in the scenario of high capacity long haul DWDM communication system. It is reported that, 70 km is the optimum span distance at which the Raman-EDFA (R-E) HOA achieves a 2450 km transmission distance with acceptable performance. To further improve the utilization of bandwidth the Raman-EDFA HOA is also investigated as high speed DWDM-OTDM system.

4.2 Raman-EDFA HOA for High Speed DPSK Modulated System

In present, the DPSK is the promising modulation format which is liable in achieving better performance for high-speed optical communication system or networks at low cost. As per as the degradation in signal quality or in amplitude level is present due to various losses, the optical amplifiers are important to use at optimal position. Unfortunately, the investigation of hybrid amplifiers being used for optical system with DPSK modulation is not yet examined. The literature has presented various investigations on long- and short-haul DWDM systems in the presence of low cost hybrid amplifiers, see Section 2.2.4.

Downie et al. [5] presented an error-free transmission of DPSK signals at 43 Gbps using DWDM system in reference to further increase the data rate. The transmission was demonstrated for DWDM at 50-GHz channel spacing over 1200 km without considering any inline dispersion compensation. But the work has been reported for a limited number of channels and also described specific data rate per channels is 10 Gbps. Also, in these investigations, only conventional amplifiers are used. In this Section, the previous work has been extended by investigating the Raman-EDFA HOA in scenario of high speed DPSK modulated WDM system.

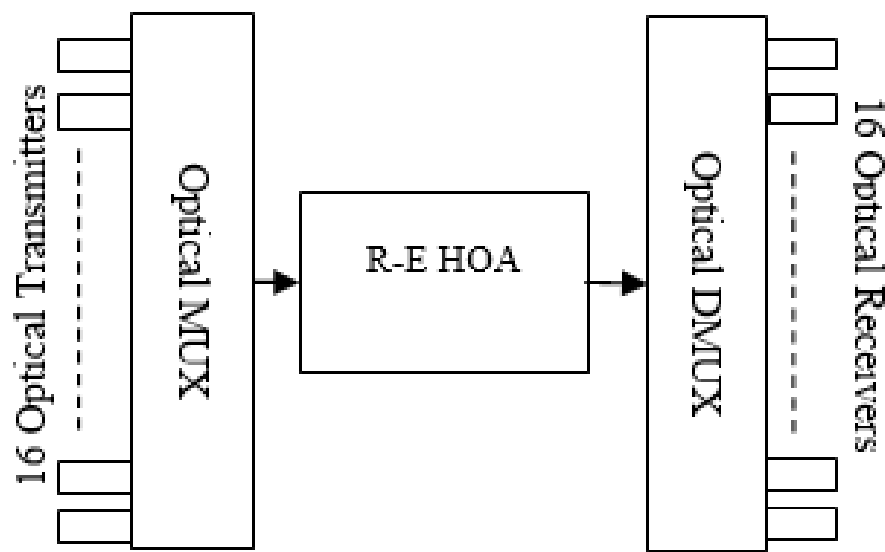


Figure 4.1: DPSK modulated system with R-E HOA.

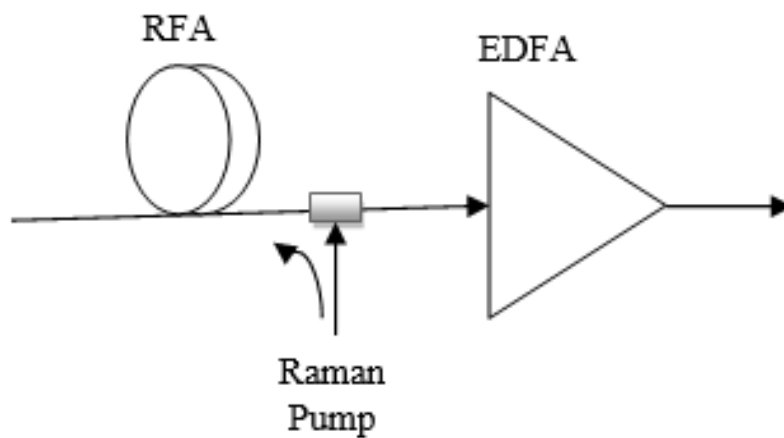


Figure 4.2: Arrangement of proposed two stage HOA.

4.2.1 Numerical Simulation Setup

The proposed Raman-EDFA (R-E) HOA as DWDM system is shown in Figure 4.1 and 4.2. The numerical simulation is performed by deploying Raman pump unit offering 650 mW of output power at 1448.2 nm, which has also been used in Section 3.3. In the various R-E configurations, the Raman amplification stage is made to operate with the counter-propagating pump geometry so that the signal is having a smaller pump noise coupling [95], [96]. In this reported work, an EDFA with a 25 dB of fixed gain and with a 4 dB of noise figure is considered. The PIN diode is considered with responsivity of 0.875 A/W. The various parameters of Raman amplifier are specified in Table 4.1.

In this system, the transmitter's source comprising of 16 continuous wave lasers has been used by carefully selecting the central frequency. Here, the input power of each signal probe is tuned to -10 dBm, because rise in the input power means degradation in the quality of received signal due to induced non-linearities [97]. To drive an optical modulator, a pre-coded data stream with DPSK binary sequence; generated by a pattern generator at 40-Gbps, is used.

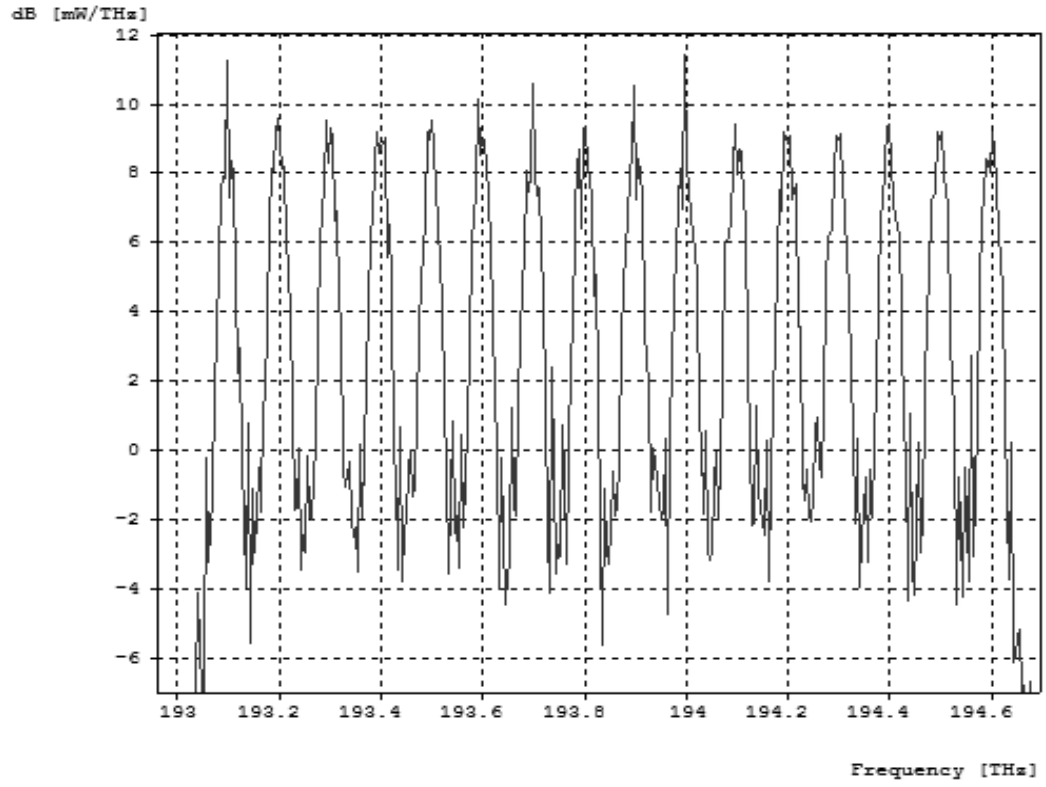
Table 4.1: Raman fiber amplifier parameters.

Parameters	Value
Fiber length	100 Km
Fiber attenuation	0.2 dB/Km
Dispersion	16 ps/nm/Km
Operating Temperature	300 K
Pump Wavelength	1448.2 nm
Pump power	650

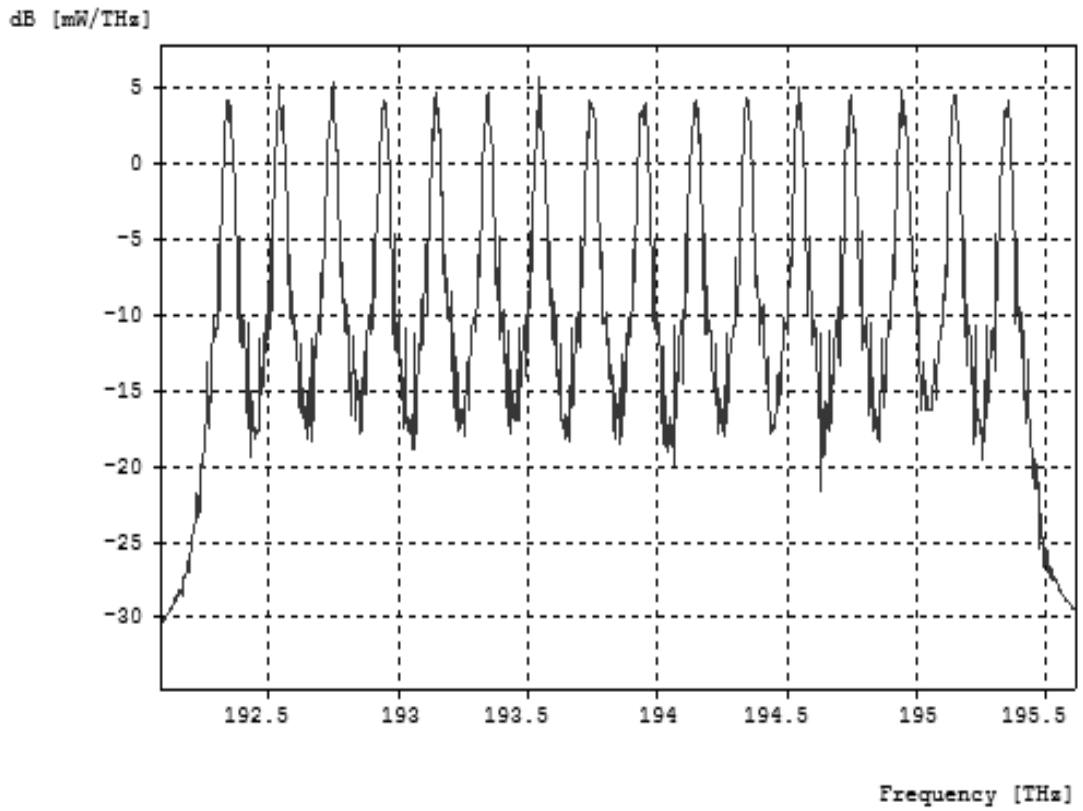
4.2.2 Result and Discussion

A. Influence of wavelength spacing on the HOA

In this scenario, 16×40 Gbps DPSK modulated WDM channels has been used having 0.1 THz and 0.2 THz of channel spacing covering the bandwidth from 193.1 THz to 194.6 THz and from 192.35 THz to 195.35 THz, respectively. The characterization of proposed hybrid amplifier has been done in the terms of Q-factor, gain, optical power etc. In Figure 4.3, the optical spectrums just after the transmitter are shown for 0.1 THz and 0.2 THz of channel spacing, respectively.

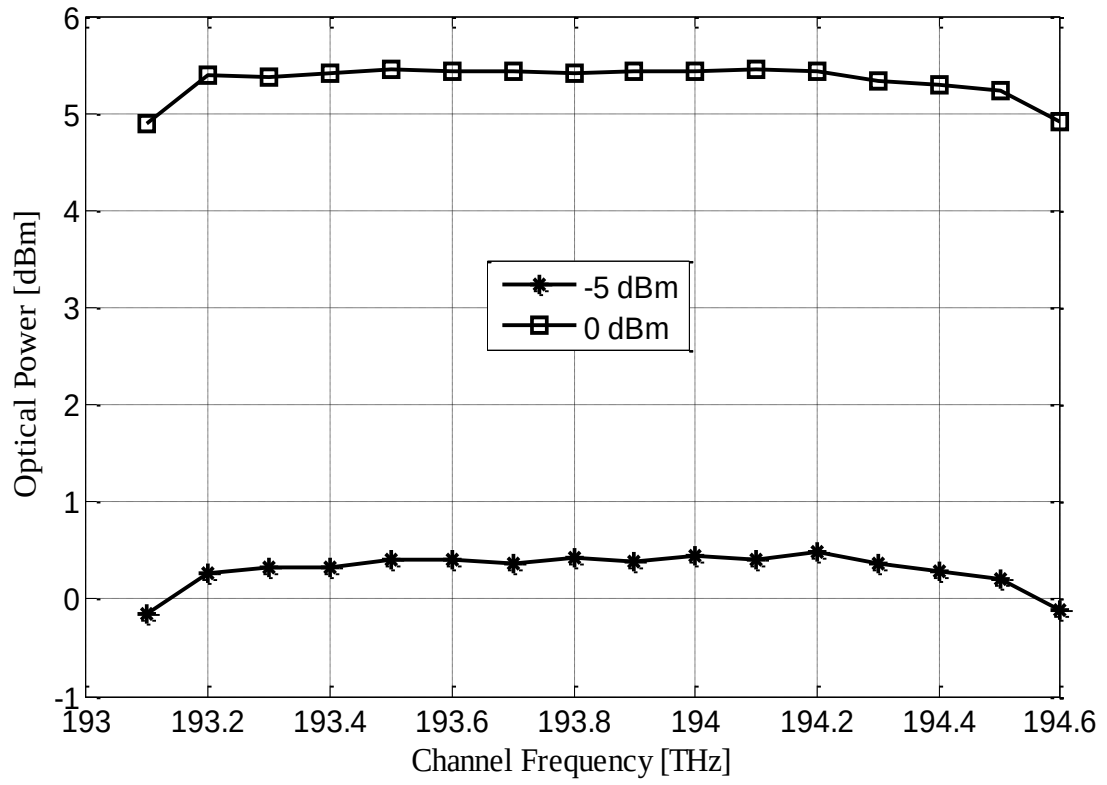


(a)

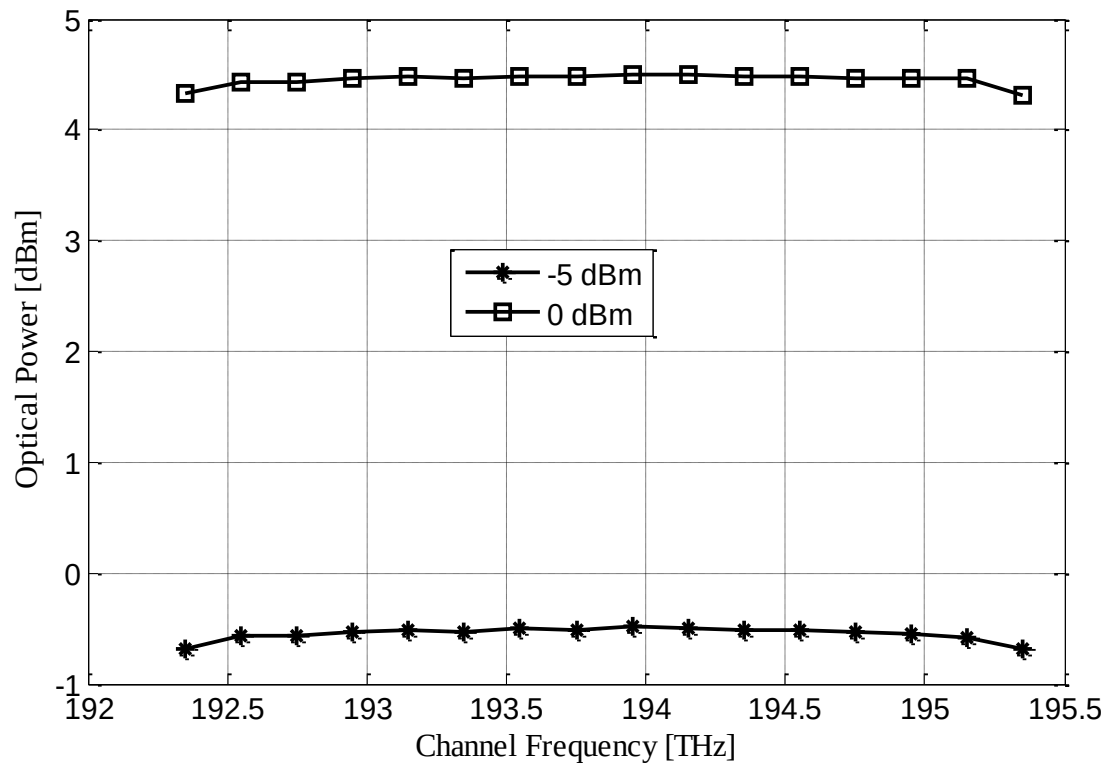


(b)

Figure 4.3: DPSK modulated WDM spectrum at different, (a) 0.1 THz and (b) 0.2 THz, channel spacing.



(a)



(b)

Figure 4.4: Variations in Power over the effective channels with (a) 0.1 THz, (b) 0.2 THz of channel spacing.

In this section, first task is to observe the variations in output power for varying channel spacing and for different input power. From Figure 4.4 (a), it is observed that an acceptable received power is provided by the R-E. The observed power is > 4.8 dBm and > -0.1 dBm for an input power of 0 dBm and -5 dBm, respectively, at a channel spacing of 0.1 THz. In addition, Figure 4.4 (b) presents the outcomes at channel spacing of 0.2 THz, which are also in the acceptable range.

Table 4.2: Gain variation (in decibel) at different input power and channel spacing over selected number of channels.

Channel Spacing	0.1 THz of channel spacing		0.2 THz channel spacing	
Input power per channel	-5 dBm	0 dBm	-5 dBm	0 dBm
Ch. 1	14.4	15.1	8.2	9.2
Ch. 3	12.4	12.5	9.4	9.8
Ch. 5	12.1	12.9	9.1	10.3
Ch. 7	12	12.6	9.37	10.42
Ch. 9	12.3	12.4	9.85	10
Ch. 11	12.05	12.4	9.33	10.2
Ch. 13	12.1	12.9	9.22	10.61
Ch. 15	13.5	13.5	9.08	9.8
Ch. 16	14.8	14.9	8.1	9.1

Table 4.3: Quality factor variation (in decibel) at different input power and channel spacing over selected number of channels.

Channel Spacing	0.1 THz of channel spacing		0.2 THz channel spacing	
Input power per channel	-5 dBm	0 dBm	-5 dBm	0 dBm
Ch. 1	18.71	19.84	20.85	20.78
Ch. 3	18.91	18.63	22.13	21.82
Ch. 5	17.46	19.19	22.14	22.04
Ch. 7	17.46	19.41	21.83	22.07
Ch. 9	18.35	18.14	21.97	21.99
Ch. 11	15.8	18.83	21.38	21
Ch. 13	17.57	16.25	19.84	20.26
Ch. 15	18.48	18.07	18.35	18.44
Ch. 16	16.9	17.1	17.67	17.6

The gain and optical signal quality variation among the selected channels for the R-E HOA with different input powers and channel spacing are described in Tables 4.2 and

4.3. It has been observed that as the channel spacing is decreased, the quality of the received signal also decreases. This degradation occurs due to the fact that each amplifier is introducing nonlinear effects and inter-channel crosstalk of WDM channels, as discussed in [98]. It demonstrates that with increase in the number of amplifiers (in cascade manner), the nonlinear effects become largely dominating in the system. The crosstalk that is induced by proposed R-E HOA is also calculated and presented in Section 7.6.

B Comparison of the performance parameters of Proposed R-E HOA with Current State-of-Art Schemes

In this section, a comparison is carried out between the various important performance parameters (input and output) of the proposed HOA, with the current state-of-the-art schemes. The comparison is described in Table 4.4.

Table 4.4: Comparison of the proposed HOA with the current schemes (state-of-art) of HOAs.

State-of-the-art HOA schemes →	Raman+EDFA + FBG+DCF Ref. [99] (2011)	Raman (pumped DCF)+ EDFA. Ref. [69] (2012)	Raman+EDFA+ DCF Section 3.3	Raman+EDFA, Raman+EDFA+Raman, EDFA+Raman+EDFA Section 3.2	Current Investigation
Parameter ↓					
Gain Bandwidth	80 nm	35 nm	3.97 THz	3 nm	#1.5 THz for 1 THz of channel spacing #3 THz for 2 THz of channel spacing
Gain ripple (dB)	< 0.5	-----	< 4.5	-----	< 3 for all investigations
Channels	26	18	160	16	16
Speed per channel (Gbps)	10	20 and 40	10	10	40
Overall speed (Gbps)	260	960 for 20 Gbps 1920 for 40 Gbps	1600	160	640
Modulation Format	-----	Intensity	NRZ	NRZ	DPSK
Crosstalk (dB)	-----	> -3.52	-----	< -6 for all investigations	<-14 for all investigations
Dispersion Compensating Module	Used	Used	Used	Not Used	Not Used

Table 4.4, presents the description of the various state-of-the-art HOAs arrangements currently published during 2011 to 2013. The table clearly concludes that the proposed HOA shows improvement over the current schemes because: (i) better performance has been achieved with minimum bandwidth utilization, even when DPSK signals at 640 Gbps are being transmitted over 100 km; (ii) the presented results are conducted with an advanced modulation technique, i.e. DPSK, as this technique is resistance to nonlinearity, in specific, the polarization mode dispersion which is a major factor for limiting the capacity in communication networks; (iii) it also leads to inducing lesser crosstalk as described in Section 7.6; and (iv) the cost effectiveness of the system since the dispersion compensating fiber is not used.

4.3 Raman-EDFA HOA in the Scenario of Orthogonal Modulated DWDM System

In high capacity multi-terabit optical communication system, the choice of modulation pattern is the first key factor in determining the channel speed, dispersive tolerance, spectral efficiency, transmission quality of the system [100]. Also the advanced modulation patterns are the present and very hot research area to enhance system capacity with improved performance [101]. In [102], it was reported that the advanced hybrid or orthogonal modulation formats shows better performance over conventional patterns (i.e. NRZ, RZ, DPSK etc.) in the term of speed, capacity, efficient bandwidth utilization etc. This is because it can transmit more than one pattern of data over single channel by modulating more than one parameters of single channel simultaneously, which enhance the number of users and further the system capability. In the literature, several orthogonal modulation schemes are suggested. Ohm et al. [103] proposed a new orthogonal modulation technique which is an arrangement of amplitude shift keying (ASK) and DPSK signals. Unfortunately, these investigations are limited to single channel only. Moreover, the effects of optical amplifiers were not deliberated, as these are important attentions for high capacity long-haul communication systems.

In previous work reported in Chapter 3, the proposed HOAs are investigated as highly DWDM system with conventional modulation formats (such as NRZ, RZ and DPSK) using 10 Gbps per channel of speed. On the other hand, in Section 4.2, the DPSK modulation is used with the speed of 40 Gbps per channel. Unfortunately, this investigation has been done with less number of channels and with large channel spacing, which is not a bandwidth efficient technique. So to increase the data rate per channel with

that much reduced channel spacing, the hybrid modulation technique is the best alternative than other single dimensional modulations. In this Section, a new hybrid modulation technique is proposed and addressed the various relative issues, such as spectral efficiency with high data rate at reduced channel spacing to improve the performance of previously proposed amplifier in Chapter 3. Further, the performance of 8×20 Gbps and 20×20 Gbps DWDM system has been checked with proposed modulation format and characterized in terms of optical power, Q-factor and BER.

4.3.1 Hybrid Modulation Signal Transmitter and Receiver

The schematic of proposed signal generator is shown in Figure 4.5. The sine square optical modulator is used in push-pull state to modulate the optical signal (generated by CW laser) with respect to NRZ encoded data. Then the polarization state of this amplitude modulated signal changed to 45 deg by polarizer (PC) for further modulation. The polarizer modulator consists of a polarization splitter (PS) and a polarization combiner (PCB). The phase modulator is placed between their horizontal ports, while their vertical ports are directly connected.

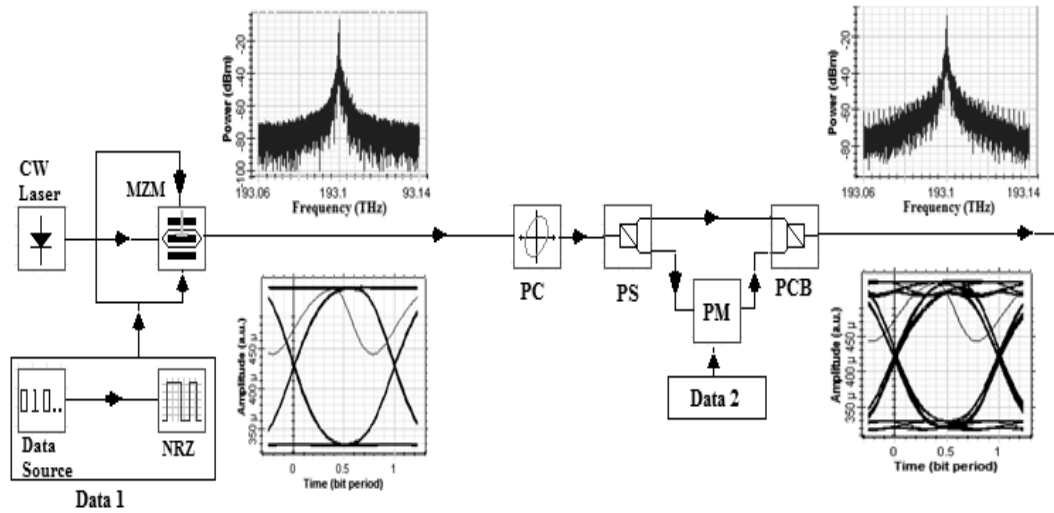


Figure 4.5: Representation of single channel hybrid modulated transmitter.

At the output side, the hybrid NRZ/ PolSK modulated signal is generated having two types of data with different users. The shown eye diagrams are evident for the same and present different eye opening or closure penalty. The second eye diagram shows a smaller amount of eye opening because it has been detected from the signal which has two types of data on two different parameters of signal (i.e. amplitude and polarization state), means

more the number of bits on to the signal then more the lines available in eye diagram, see Figure 4.5. These eye diagrams have been observed at the side of single channel transmitter only.

At the receiver side two independent paths are used to regenerate the transmitted signals, as shown in Figure 4.6. To recover the NRZ signal the direct detection has been used, which consists of the optical filter and PIN photo-detector only, where the PIN photodetector is used with a responsivity of 0.875 A/W and dark current of 0.1 nA. On the second path, the PolSK modulated data is demodulated by suitably amending the received polarization state on which the second data is present. The PolSK receiver consists of a PS followed by a balanced PIN photo-detector.

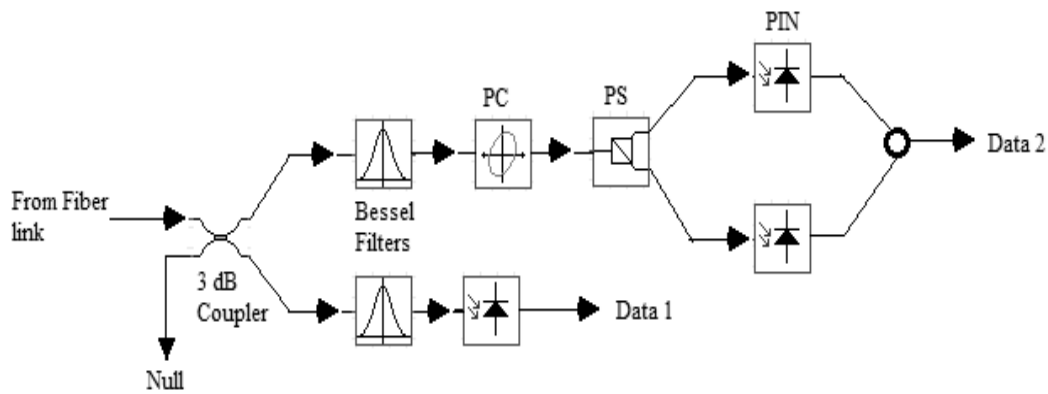


Figure 4.6: Representation of single channel hybrid modulated receiver.

4.3.2 System Setup and Results

Figure 4.7 represents the proposed 8×20 Gbps DWDM system. In this setup eight CW signals ranging from 193.1 THz to 194.85 THz are used at 25 GHz of spacing. Each signal is generated and received using proposed transmitter and receiver, respectively, by just tuning the appropriate frequency of used CW lasers and optical filters, as shown in Figure 4.6 and 4.7. This system has been examined with different per channel input laser powers (that is variation from -10 dBm to 20 dBm). The data stream from a 10-Gbps (Data 1) pattern generator with a NRZ binary sequence is pre-coded and drives a sine-squared amplitude modulator. This NRZ modulated signal is further modulated by a PolSK modulator with another 10 Gbps of data (Data 2). It revenues that each channel has 20 Gbps of aggregated speed, means two users can transmit their different data simultaneously over single channel which yields great reduction in cost. Further, these

high-speed orthogonal-modulated signals are amplified by a Raman-EDFA HOA. The parameters of these amplifiers have been taken from Section 3.3.

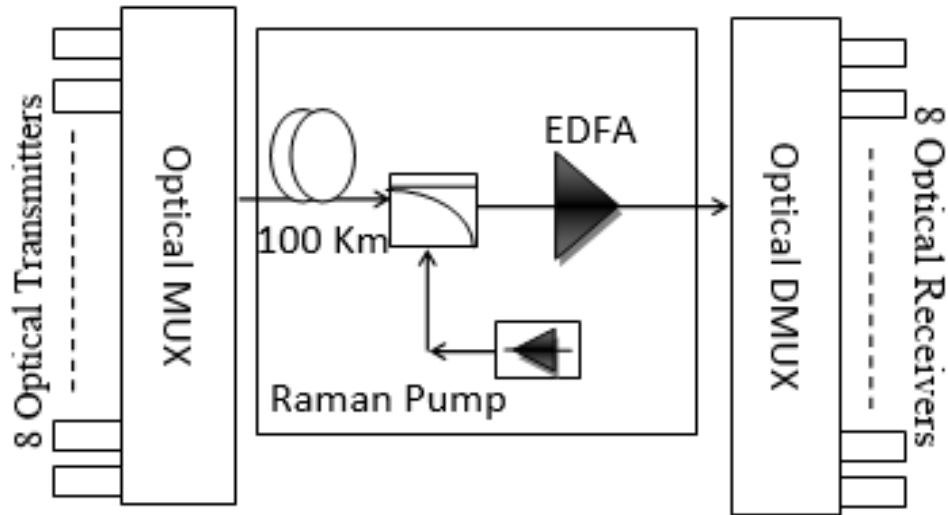


Figure 4.7: Proposed DWDM orthogonal modulated system.

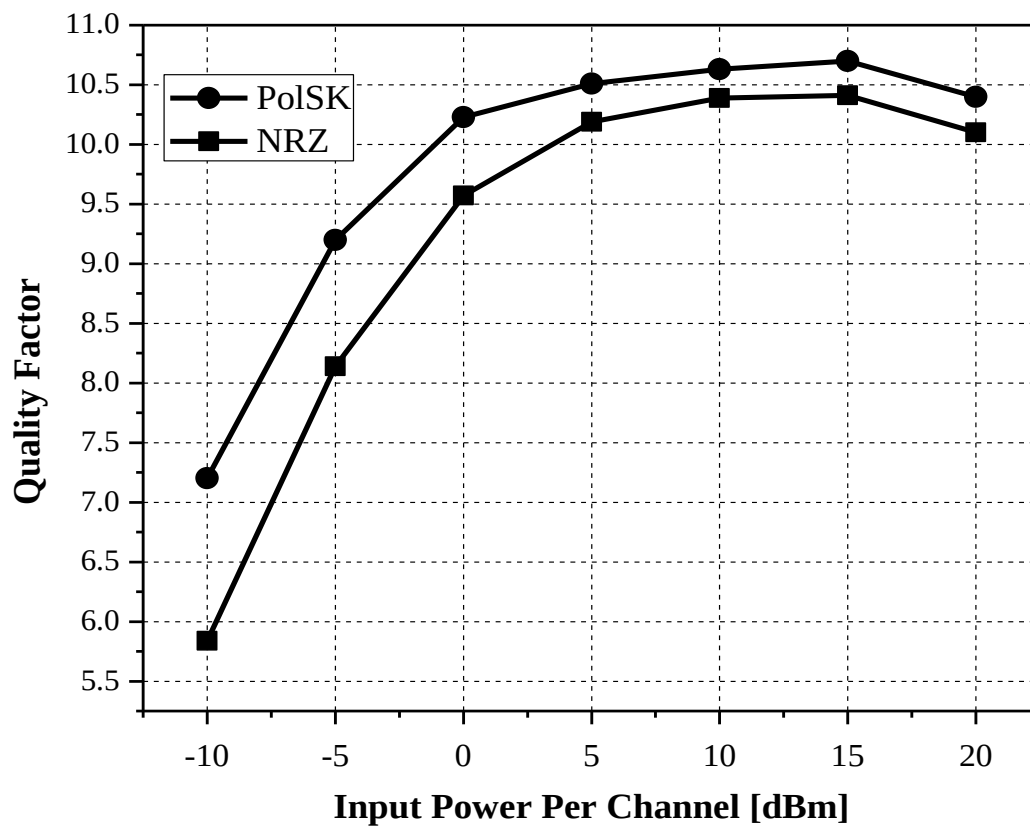


Figure 4.8: Q-factor variation with respect to the input power for proposed setup.

The two curves representing the Q-factor and BER for the two modulation formats (i.e. amplitude and PolSK) on single channel is compared in Figures 4.8 and 4.9. The Q-factor and the BER are measured at the first channel (i.e., 193.1 THz) only. As represented in Figure 4.8, at the same input powers, the effect on the Q-factor in the NRZ signal is slightly more. The reason behind it is, the output optical signal has greater high-level power because of the duty cycle is small; hence, lower receiver sensitivity is observed in the amplitude path which yields the degradation in Q-factor; this is also reported in [104].

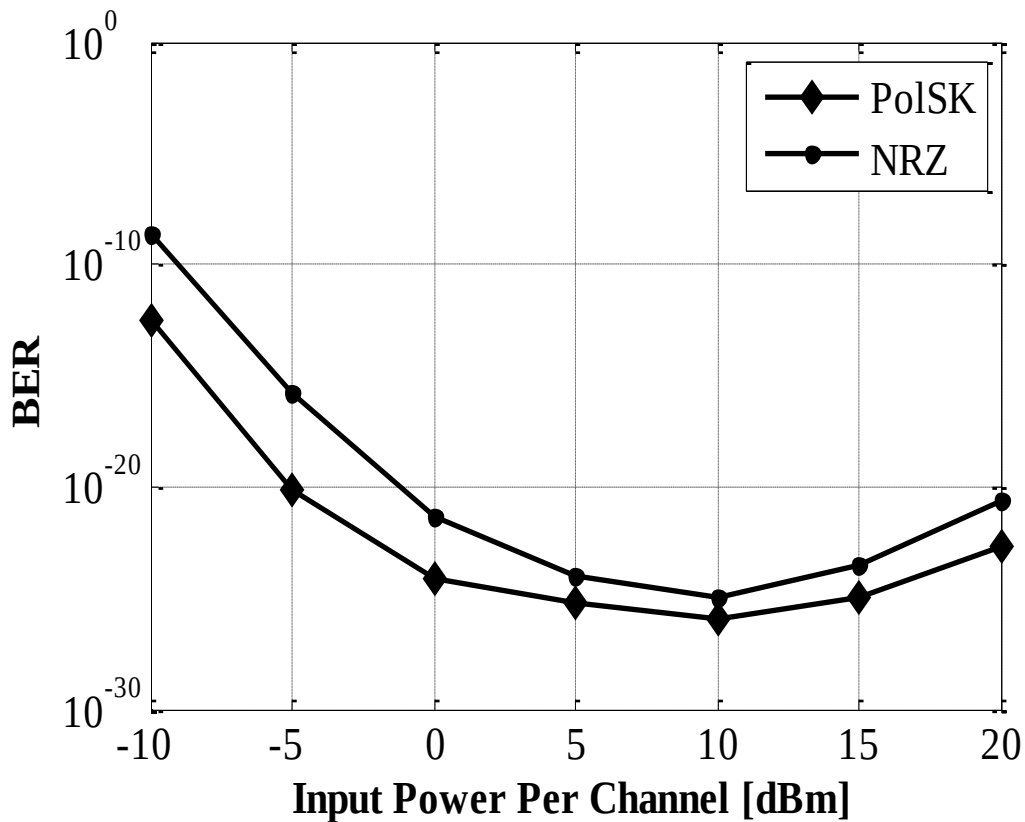


Figure 4.9: BER variation with respect to the input power for proposed setup.

The eye diagrams has also been taken after 100 Km for both orthogonal modulation patterns at 10 dBm of input power, as shown in Figure 4.10. The same investigation has also been performed for a 20×20 Gbps DWDM system. The 20 channels lie in the optical spectrum ranging 1552.5 nm to 1571.7 nm with 0.8 nm of channel spacing and hence covering a bandwidth of 19.2 nm. The input power per channel is set to 0 dBm during this investigation. From Figure 4.11, the non-uniform power spectrum is observed after hybrid Raman and EDFA as each amplifier induces its own ASE noise and nonlinearities, as also described in [105] and [86]. But still the proposed amplifier

provides virtuous output power with a smaller amount of variation (~ 0.056 dBm) among the effective channels.

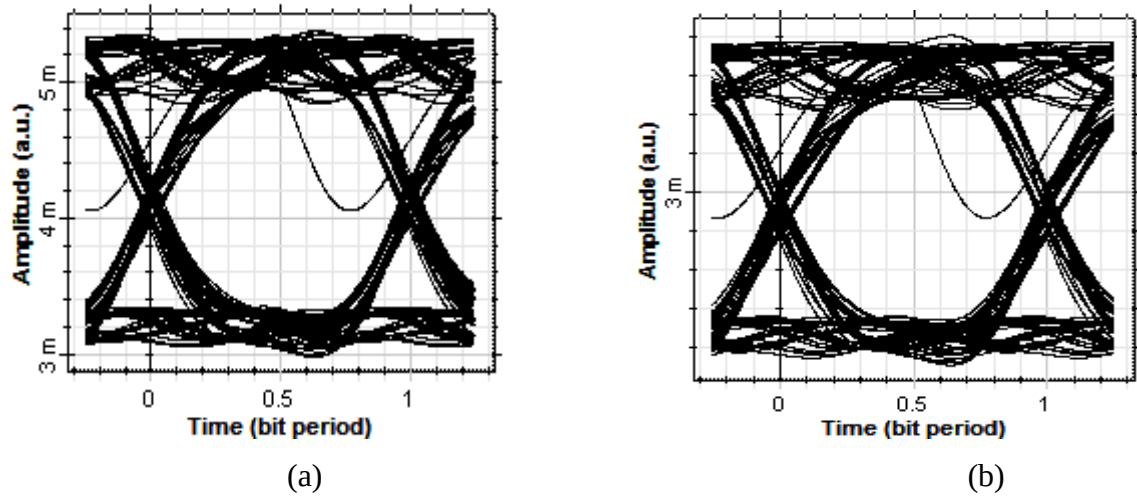


Figure 4.10: Eye diagrams for (a) NRZ and (b) PolSK modulation format.

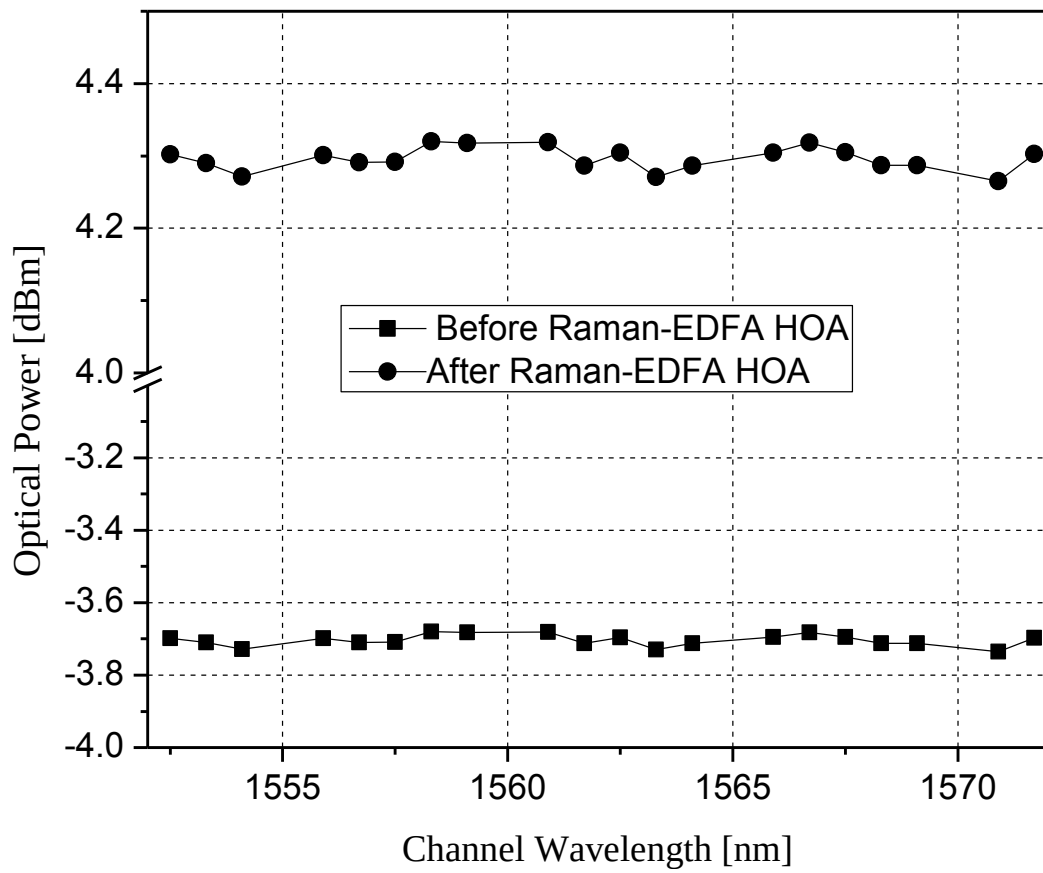


Figure 4.11: Power variation over the effective channels for proposed setup.

Table 4.5: Gain, BER and Q-factor variation over different channels.

Channel Wavelength	NRZ		PolSK		Raman-EDFA HOA Gain (dB)
	Q-Factor	BER	Q-Factor	BER	
1552.5	8.89	2.8×10^{-19}	10.1	3.08×10^{-24}	7.92
1555.9	9.01	9.7×10^{-20}	9.982	8.5×10^{-24}	7.9
1558.3	9.35	4.3×10^{-21}	9.607	3.69×10^{-22}	7.925
1561.7	9.36	3.78×10^{-21}	9.569	5.3×10^{-22}	7.935
1564.1	4.4	2.4×10^{-21}	9.64	2.67×10^{-22}	7.95
1567.5	9.24	1.18×10^{-20}	9.1	9.98×10^{-20}	7.93
1570.9	10.29	1.18×10^{-26}	11.82	2.1×10^{-29}	8.08
1571.7	8.23	9.14×10^{-17}	9.64	2.49×10^{-22}	8.01

In Table 4.5, the Q-factor and BER values observed for the NRZ and PolSK formats are compared. The values are with respect to the varying channel wavelengths used for the investigation. It is observed that the proposed setup provides an acceptable as well as better BERs ($<10^{-19}$) and Q-factors (>7) among all the channel wavelengths. It can also be observed that for the proposed HOA (Raman-EDFA), a flat gain (>7 dB) is obtained with a small gain variation of nearly 0.23 dB without incorporating any of the gain-flattening techniques.

4.4 Placements of Hybrid/ Conventional Optical Amplifiers in a Multi-wavelength Dense Metropolitan Area Network

The continuous increase in the demand of multimedia services makes DWDM systems to be one of the enabling techniques to improve present structures and to efficiently utilize the fiber bandwidth [106]. In order to increase the transmission distance, the optical amplifiers has made the DWDM system a feasible technology. In industry, various optical amplifiers are available, but the most widespread-used ones are the EDFAs. Despite their advantages, such as high gain, high bandwidth and low noise figure, EDFAs have some disadvantages. The EDFAs are not only the expensive devices but they also need maintenance [90]. Because of these restrictions the designers have to develop techniques to minimize the number of amplifiers into the system or network. In literature, various algorithms are proposed to find an optimal solution to resolve this problem [107], [108], [109], [110].

In our previous work or in literature, the HOAs are investigated in point-to-point optical system. As today's technology is shifted towards multipoint network it is beneficial to take the advantage of HOAs by placing it into the networks.

In this Section, the previous work has been extended by designing the up-scaled and denser version of MAN network with the help of hybrid and conventional optical amplifiers for low cost solution. However, the HOAs are used to amplify the back-bone (large DWDM signals or star-to-star link) link, on the other hand, conventional optical amplifier are used to amplify the local network signals (between 10 to 20 Km). The proposed network shows improved/ cost-effective performance over other algorithms by reducing number of amplifier into network.

4.4.1 Problem Definition

In general, due to the different power levels of different channels (called near far effect) arriving at an amplifier results in ineffective exploitation of a specific amplifier. Due to the near far effect, the higher-powered channels might saturate the amplifier and bound the gain perceived by the channels at low power. The near-far effect is mostly present between two passive stars connection (back bone connection) as many wavelengths from local stations are combining or splitting by these passive stars. In literature, various researches are evident that the HOAs are the good alternative to achieve better gain flatness with minimum power variation among the effective wavelengths. Also the HOA is the best for broadband amplification as the conventional optical amplifiers (such as EDFA, SOA etc.) are restricted to the wavelength band. The basic aim is to propose the approach using which the exact placement of conventional and hybrid amplifier can be determined with its minimum utilization.

This work offers the methods to reduce the quantity of optical amplifiers over local links and backbone connections using mixed integer linear program (MILP) and optimized HOAs, respectively. The method works as follows (as also shown in Figure 4.12): (i) determine the feasibility of the network by calculating the various parameters such as power budget, receiver sensitivity etc.), (ii) Optimize the HOA for corresponding transmission distances for broadband amplification with less variation of power, (iii) generate the constraints for local links, (iv) calculate the number of amplifier over the local links using MILP solver, and (v) conclude the precise locations of the amplifiers.

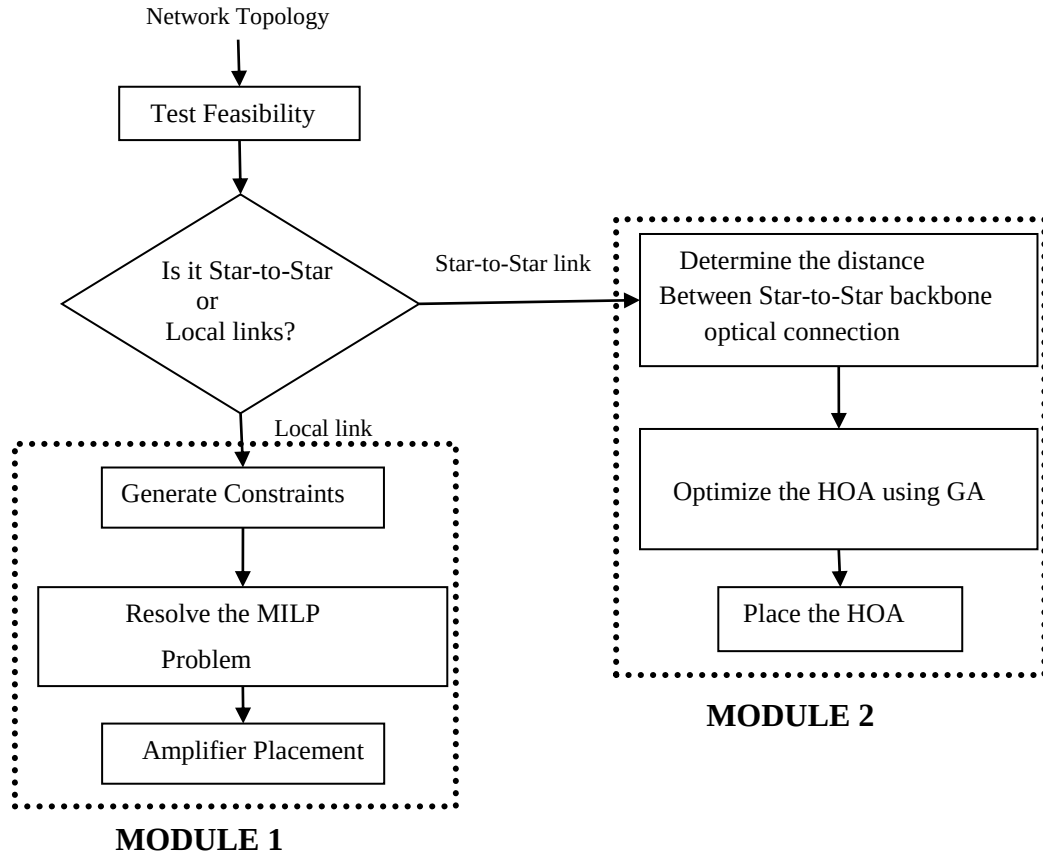


Figure 4.12: Flow diagram of proposed algorithms for optimal placement of optical amplifiers.

4.4.2 Solution Approach

The solution approach is divided into two modules after checking feasibility of network. *Module 1* corresponds to optimize the placement of conventional optical amplifiers for local connection (< 20 Km). On the other hand under *Module 2* the HOA is optimized for star-to-star link broadband amplification with less variation of power.

A. Testing of Feasibility of the Network:

The feasibility check insures that signals from users must be capable to reach at the desired receiver with sufficient power level and receiver sensitivity. To achieve this objective, number of amplifiers are used to compensate the attenuation (induced by splitter, combiner, splicer etc.) suffered by the signals. In this investigation the passive stars hubs have been used to combine or split the signals without any internal amplification. During this testing, it is ensured that the power level of each signal on every link is enough to guarantee that the signal power level is maintained of at least $P_{\min}$,

so that it can be recognised, as also reported in [107]. The test for feasibility can thus be written as follows:

$$P_{\max} - 10 \log_{10} (S_i - 1) - 10 \log_{10} (|\lambda_n|) - 10 \log_{10} (S_p) \geq P_{\min} \quad (4.1)$$

The description of various notations of parameters is described in Table 4.6. Means if the equation (4.1) for each star i in the network and for each input link j into this star is achieved then the network is feasible otherwise the replacement of optical amplifiers will be required.

B. Selection of link type

In this step, the two types of links are treated individually. The placement of optical amplifier in local links, which connects the users to the star, is done by using MILP approach. On the other hand the optimization of Raman-EDFA HOA for back-bone link, which connects the two stars placed at long distance, is done by using GA.

C. Generate the Constraints

(i) Computation of $g_{\max}$ (star to star)

The available gain at an amplifier is a function of the maximum small-signal gain of the amplifier ($G_{\max}$), the total input power aggregated across all wavelengths (P_{Total}), and the total internal saturation power of the amplifier (P_{sat}). For any link n :

$$g_{\max n} = G(P_{\text{Total}}, G_{\max}, P_{\text{sat}}) \quad (4.2)$$

In this study, the amplifier EDFA gain modal has been taken from [107] for the case of local links. On the other hand the Raman-EDFA HOA gain has been calculated from equation (12), see **Chapter 3**, for the case of back-bone link.

For any back-bone link which connects star to star, there are $|\lambda_n|$ wavelengths in the link and hence the total power (P_{Total}) can be calculated as:

$$P_{\text{Total}} = P_{\min} + 10 \log_{10} (|\lambda_n|) \quad (4.3)$$

From equation (4.2)

$$g_{\max n} = G(P_{\min} + 10 \log_{10} (|\lambda_n|), G_{\max}, P_{\text{sat}}) \quad (4.4)$$

(ii) Link Constraints (from station to star or star to station)

For any link n from any station x to the star y we can bound the power p_y by following expression:

$$P_{\max} - \alpha \cdot L_l - 10 \log_{10}(S_y - 1) + g_{\max_n} \cdot A_l \geq p_y \quad (4.5)$$

For any link n from star y to the station p , the received power of each wavelength should accept the following sensitive condition, i.e.

$$P_y - \alpha \cdot L_l + g_{\max_p} \cdot A_l \geq p_{\min} \quad (4.6)$$

In the other hand, to check the feasibility of output power can be calculated as:

$$P_{\max} - 10 \log_{10}(S_y - 1) - 10 \log_{10}(|\lambda_n|) \geq p_y \quad (4.7)$$

Table 4.6: Description of used parameters.

Notation	Description
$P_{\max}$	Amplifier output power (dBm)
S_i	Number of output splitter ports
$ \lambda_n $	Number of channels over link n
S_p	Splicer loss
$P_{\min}$	Minimum power required on a wavelength for detection in dBm.
$g_{\max_n}$	Maximum per-wavelength gain that can be offered by an amplifier on link n .
$G_{\max}$	Maximum small-signal gain of the amplifier
P_{Total}	Total input power aggregated across all wavelengths
P_{sat}	Total internal saturation power of the amplifier
P_n	Output power of star n on each wavelength.
α	signal attenuation in dB/km.
L_l	Transmission distance
A_l	Number of amplifiers placed in the link
A	Total number of conventional amplifiers used in the network
B	Total number of HOAs used in the network
N	Total number of stations/ users
M	Total number of passive star

(iii) Star-to-Star Constraint

Under the star constraint for each incoming link n into star y , it should be ensured that the required output power p_y is feasible, i.e.

$$P_{\max} - 10 \log_{10} (S_y - 1) - 10 \log_{10} (|\lambda_n|) \geq p_y \quad (4.8)$$

First the transmission distance has to be estimated then by multi-parameter optimization using global optimization technique (i.e. GA) has been done to achieve large gain with less power variation. The implementation of GA is described in Chapter 3.

(iv) Objective Function

Our objective is to minimize total number of amplifier:

$$(A) = \sum_n A_n \quad (4.9)$$

Where number of amplifiers and per wavelength output power is variable.

D. Placement of conventional and HOAs

(i) Case 1: Placement of Conventional Optical Amplifier in Local Links (station-to-star or star-to-station)

The constraints (4.1)–(4.7) are found to be linear and can be fed to a MILP solver (linear program solver version 1.11 has been used) to obtain the optimum values of the p_n 's and A_n 's. These MILP solvers typically employ branch-and-bound strategies to handle the integrality constraints, thereby significantly cutting down the exponential search space [111]. For the placement of conventional optical amplifier in local link, the As-Soon-As-Possible algorithm has been used, as explained in [112]. This method helps in reducing the amplifiers.

(ii) Case 1I: Placement of Hybrid optical Amplifier (Star-to-Star)

After determining the transmission distance and multi-parameter optimization the distributed Raman-EDFA HOA is placed between two stars. For multi-parameter optimization the Pump powers of Raman and EDFA has been considered. For the cost effective solution only one laser has been used as pump laser for Raman and EDFA, respectively. By adjusting the pump power the desired gain with better performance can be achieved.

4.4.3 Numerical Example of Metropolitan Area Network

Figure 4.13 presents the sample network which is a dense and scaled-up version of previous MAN networks [107], [108], [109]. The network has $N=80$ stations and $M=5$ passive stars. The operation of the two modules with this sample network is described below. The input network topology is subdivided into the two modules after checking feasibility of the network. The feasibility of the network has been checked by determining whether the inequality of equation (1) holds good for this network. The feasibility is also checked according to the parameters with its value as described in Table 4.7. *Module I* is used to optimize the placement of conventional optical amplifier for local links (i.e ≤ 20 km).

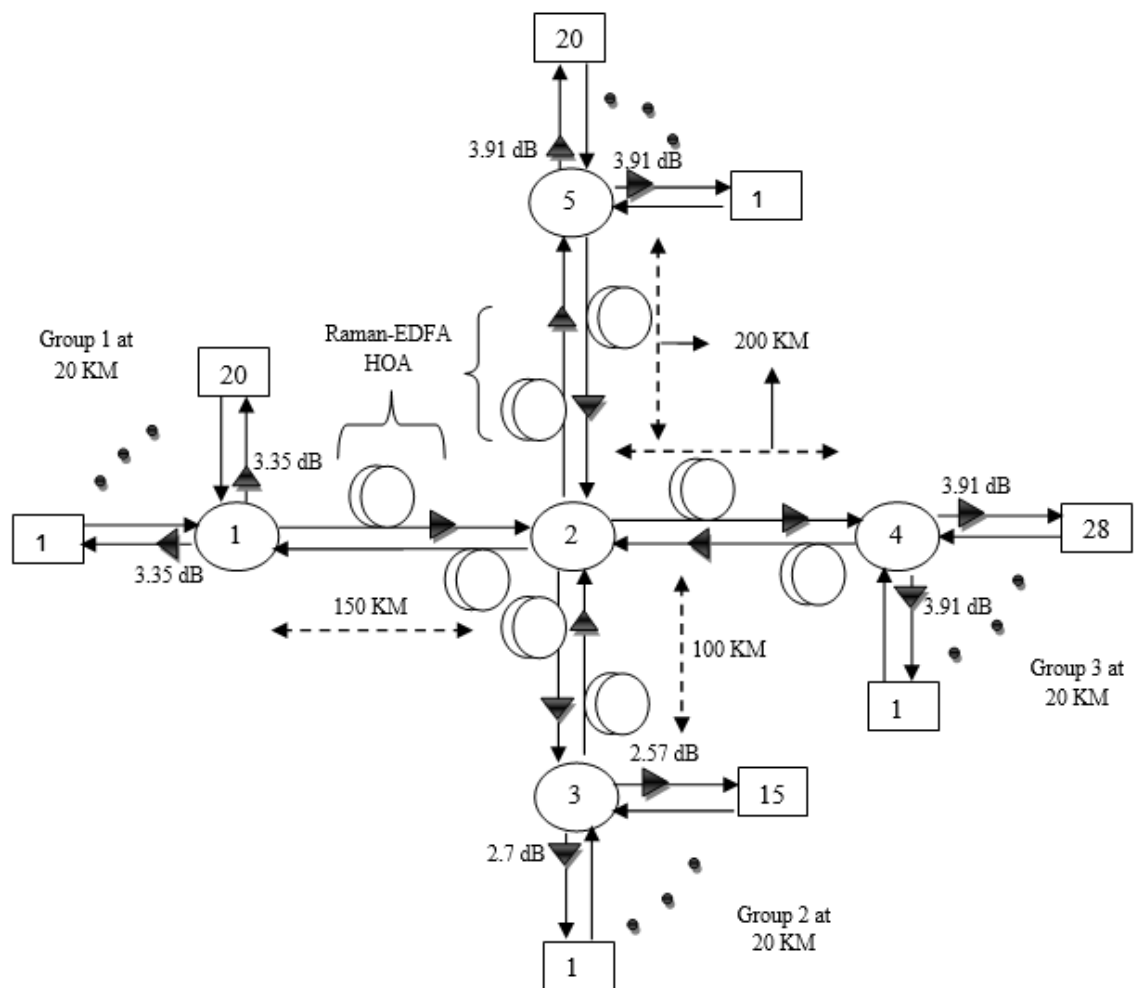


Figure 4.13: Placement of hybrid and conventional optical amplifiers in high capacity MAN, scaled-up and denser version of [107], [108], [109].

In Module 1 it produces the restrictions from the input for this network and contains the MILP solver and outputs the optimum value of the objective function. The complete MILP formulation and other related details of amplifier placement can be found in [22].

At the end, the optimized placement of optical amplifier has been done as shown in Figure 4.13. *Module II* is used to optimize the Raman-EDFA HOA for back bone star-to-star link which consist of maximum number of channels. Under this module first the distance between two stars should be determined and optimize the pump powers of Raman and EDFA using GA to achieve maximum gain (> 20 dB) with lesser variation (see Chapter 3). After that this optimized HOA is placed into the backbone network. From Figure 4.13 it can be observed that to compensate the splitting loss in advance proposed optimum method pushes the conventional amplifiers toward the upstream side of the stars.

Table 4.7: Important parameters used in this investigation.

Parameters	Range	Used value
$P_{\min}$	-20 to -40 dBm [2]	-30 dBm
$G_{\max}$	≤ 25 dB [19]	20 dB
α	-----	0.2 dB/Km
P_{sat}	-----	1.5 dBm

Table 4.8: Comparison of amplifier placement algorithms.

Sample Network	Number of stars and distance between them	Total number of stations/users	Number of used optical amplifiers for back-bone link	Used Algorithm
Ref. [107], Fig. 12	4 (100 to 150 Km)	68	14 (for 6 back-bone link)	MILP
Ref. [108], Fig. 10	5 (10 to 20 Km)	~60	~6 (for 8 back-bone link)	MILP
Ref. [113], Fig. 11	4 (100 to 150 Km)	63	13 (for 6 back-bone link)	Distributed ASAP
Ref. [113], Fig. 12	5 (100 to 200 Km)	29	16 (for 8 back-bone link)	Distributed ASAP
Current Work	5 (100 to 200 Km)	80	8 HOAs (for 8 back-bone link)	MILP + GA

4.4.4 Cost Analysis

Table 4.8 described the comparison between our proposed network with other sample networks reported in literature. It can be clearly observed that our proposed algorithm shows cost effectiveness as compared to other even in the scenario of high capacity with large transmission distance. As from [69], it is evident that the combination of distributed Raman amplifier plus EDFA for large transmission distance is better as well as cost

effective as compare to other conventional and hybrid optical amplifiers. In the sample network the number of conventional optical amplifiers has been reduced (see Table 4.8) by using only eight HOAs instead of 14 [107], 16 [113] . For local links the number of conventional optical amplifiers is same.

4.5 Raman-EDFA HOA in Long Haul Communication System

The system setup for long haul communication using R-E HOA is shown in Figure 4.14. The DWDM transmitter transmits 98 optical channels with 0.2 nm of interval. Each individual channel has a speed of 2.488 Gbps. The long haul system composed of N_{spans} has been considered, each span length with different cases is described in Table 4.9. Each span is made up of a stretch of SMF with 16 ps/nm/km dispersion, DCF with -96 ps/nm/km dispersion, a fixed output power EDFA with 22 dB of fixed gain, a Fiber Bragg Grating (FBG) with -550 ps/nm of compensating dispersion at reference frequency. Fiber length parameters are L_{span} for the SMF, and L_{DCF} for the DCF. The total link is:

$$L_{\text{total}} = N_{\text{spans}} \times (L_{\text{span}} + L_{\text{DCF}})$$

As shown in Figure 4.14 the DCF is backward pumped at 1448.2 nm with 650 mW of power, called as pumped DCF (PDCF) in order to get Raman amplification and dispersion compensation in parallel [47]. For better compensation of dispersion following formula is used to determine the DCF and SMF length:

$$L_{\text{DCF}} = - \left(\frac{D_{\text{span}}}{D_{\text{DCF}}} \right) \times L_{\text{span}}$$

where D_{span} and D_{DCF} is dispersion for SMF and DCF, respectively.

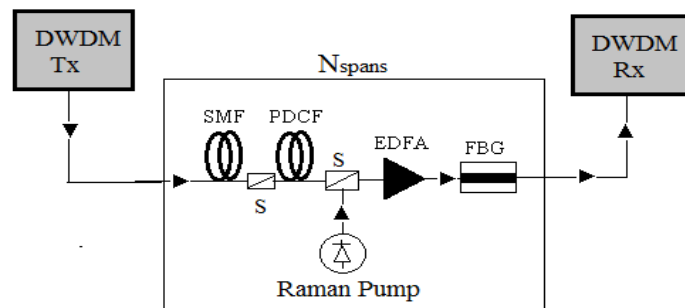


Figure 4.14: Setup for long haul communication using R-E HOA.

Table 4.10 describes the results of the maximum reachable distance L_{max} as a function of L_{span} , given a target Q factor > 15 dB and bit rate < 10^{-9} . At L_{span} of 70 Km (using case 4), the L_{total} is around 2450 Km (35 spans of case 4) when Raman-EDFA (R-E) is used. In

the view of these results, we recommend that the R-E HOA can be used in long haul communication at large L_{span} for better performance, these results have good agreement with [65] and shows an improvement over the result reported in [7]. Figure 4.15 displays the eye diagram for DWDM system consisting R-E after 2450 Km.

Table 4.9: Different combinations of SMF and DCF.

Case	DCF (km)	SMF (km)
1	4	24
2	6	36
3	8	48
4	10	60
5	12	72
6	14	84

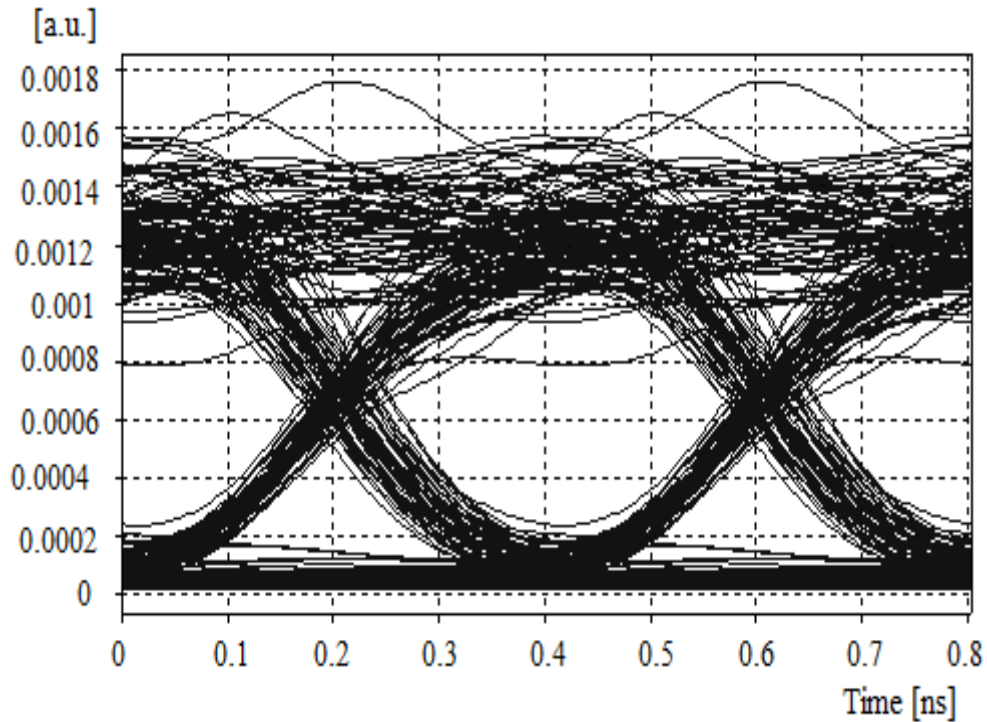


Figure 4.15: Eye Diagram after 2450 Km using R-E as inline amplifier.

4.6 Raman-EDFA HOA in High Speed Hybrid DWDM-OTDM System

In previous Sections, various advanced modulation and multiplexing techniques are addressed to increase the capacity of installed fiber without changing it. To change the fiber as per the need of capacity is very complex, time consuming and expensive. So, as per the above said issues, the advance multiplexing techniques i.e. hybrid OTDM and DWDM is the best alternative. Using this technique, the high capacity can be easily

achieved by just changing the transmitter and receiver characteristics without changing the fiber type. In literature, various researchers had proposed the numerous hybrid WDM-TDM techniques to increase the capacity of the system and networks [114], [115]. Gousia et al. [116] realized the parallel bus architecture using hybrid WDM-TDM technique. It was reported that this hybrid multiplexing technique is born with features of high scalability, high spectral efficiency and bandwidth elasticity. But the described recommendations are restricted to number of users, channel spacing, bit rate etc.

Goyal et al. [117] evaluated the performance of hybrid OTDM and WDM in the scenario of high capacity passive optical networks. It was recommended that the proposed hybrid multiplexing technique is a feasible technology which can adopt the triple-play service of audio, video and data. Unfortunately, all these studies are restricted to number of channels, bit rate and the conventional optical amplifier is used to boost the signals, as the hybrid Raman-EDFA is best and cost effective solution to amplify the high capacity signal with least non-linearities. Moreover, the major issue i.e. efficient utilization of bandwidth at ultra-narrow channel spacing was not addressed.

In this work, we have extend our work described in previous Sections, by investigating the performance of Raman-EDFA HOA in the scenario of bandwidth efficient hybrid DWDM-OTDM system and further evaluate its performance in the term of gain, noise figure, OSNR etc.

Table 4.10: Variation of output parameters corresponding to cases using R-E.

Case	Spans	$L_{\max}$ (Km)	Q-Factor (dB)	BER
1	23	644	15.19	9.07×10^{-9}
2	29	1218	15.20	5.92×10^{-9}
3	24	1344	15.41	2.7×10^{-9}
4	35	2450	15.63	1.09×10^{-9}
5	28	2352	15.47	2.19×10^{-9}
6	23	2254	15.43	1.61×10^{-9}

4.6.1 System Setup and Results

The system setup consists of 8 hybrid DWDM-OTDM channels covering the bandwidth starting from 1550 nm to 1551.4 nm in a 0.2 nm spacing is shown in Figure 4.16. Figure 4.17 shows the 4×10 Gbps OTDM transmitter. Four channels at wavelength 1550 nm are RZ-modulated with different PRBS pattern, have a 3-dB pulse width of 5 ps and

further drive the sine squared amplitude modulator. Before multiplexing every subsequent channel is delayed by 25 ps. The parameters of Raman-EDFA have been taken from Section 3.4. The optical spectrum analyzer has been recycled to indicate the gain, noise figure etc.

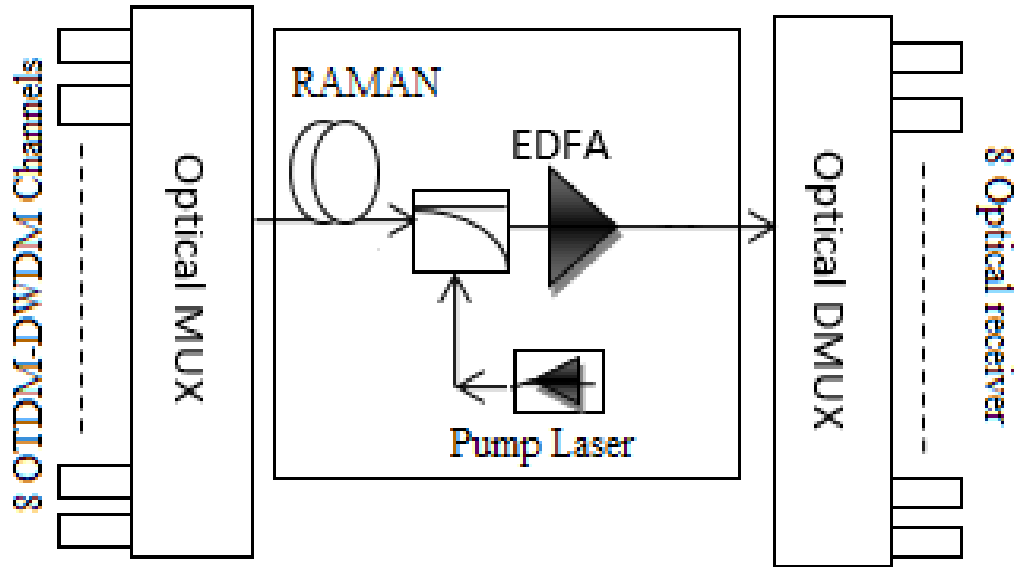


Figure 4.16: Proposed 8x40 Gbps hybrid DWDM-OTDM System.

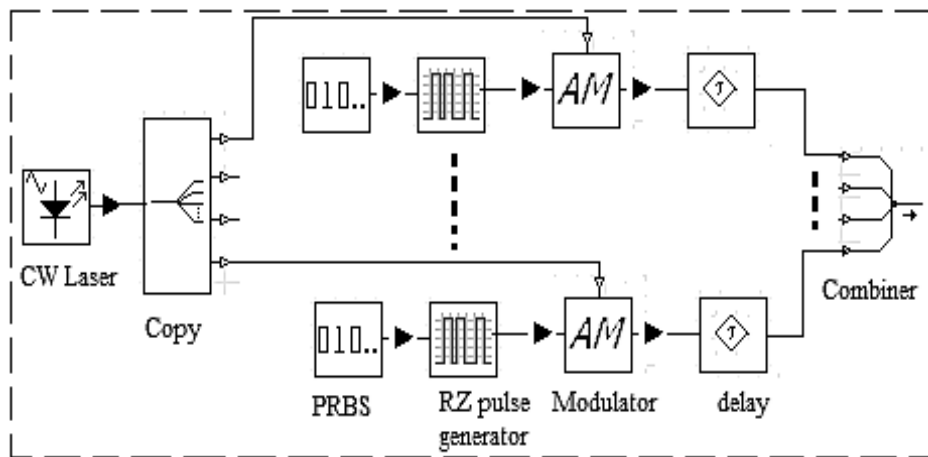
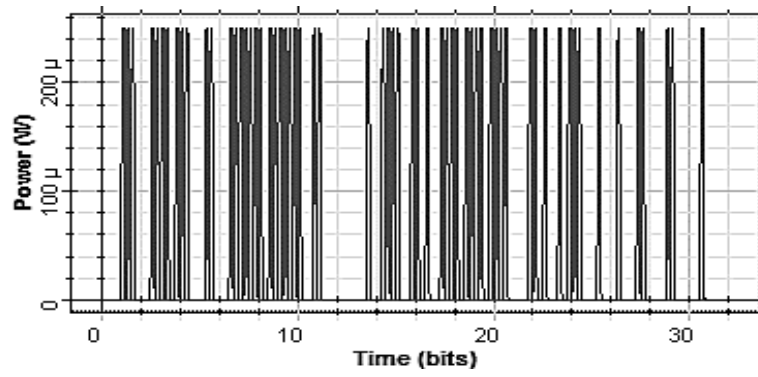
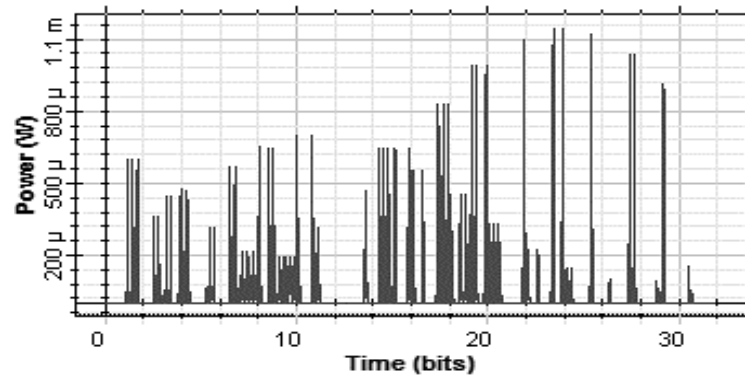


Figure 4.17: Single channel OTDM transmitter used in system setup.

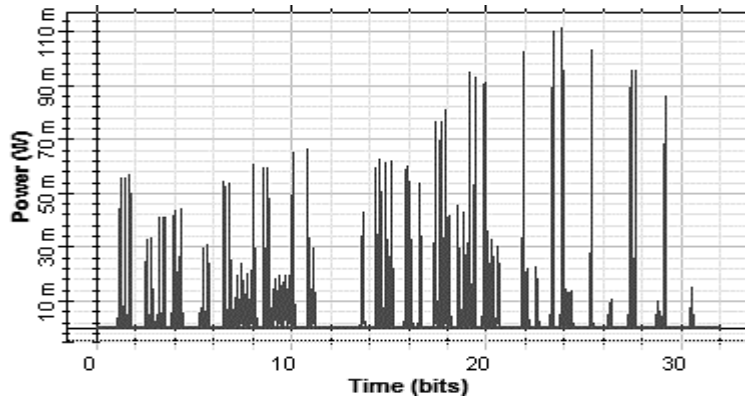
Figure 4.18 shows the power level of bits with respect to the time at different stages i.e. after single channel, after optical multiplexer (when all the eight channels are present) and after Raman-EDFA HOA. It can be observed that the power level is varies if more number of channels is added that induces the crosstalk or transience effect which degrades the system performance. On the other hand after HOA (see Figure 4.17 (c)) the variation is same but with high power.



(a)



(b)



(c)

Figure 4.18: Power variation among the bits after (a) first channel, (b) 8 OTDM-DWDM channels, (c) After Raman-EDFA HOA.

Figure 4.19 shows the gain spectrum of proposed hybrid DWDM-OTDM system using Raman-EDFA HOA. It can be observed that the gain variation with wavelength is not uniform. But still our proposed HOA provides the better gain (> 19.64 dB) with less variation (< 0.02 dB) and with good OSNR (> 26.8 dB), see Table 4.11. Moreover, the

obtained noise figure is also the lowest value (< 5.06 dB/ channel) ever reported for a Raman-EDFA HOA at narrow wavelength spacing.

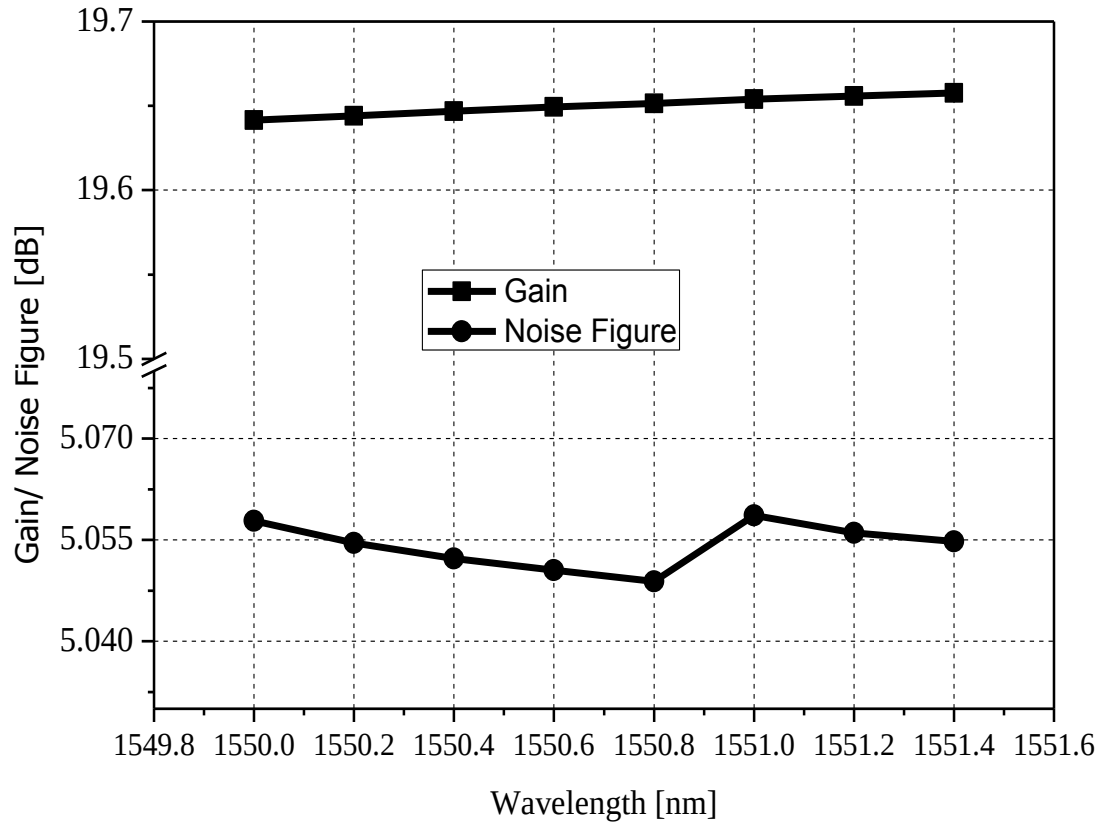


Figure 4.19: Gain and noise figure spectra of Raman-EDFA HOA.

Table 4.11: OSNR performance from proposed hybrid DWDM-OTDM system.

Wavelength [nm]	OSNR [dB]
1550	26.83
1550.2	28.82
1550.4	28.21
1550.6	25.55
1550.8	27.61
1551	29.48
1551.2	27.18
1551.4	29.9

4.7 Conclusion

Four recently investigated applications of Raman-EDFA HOA have been presented in this chapter. In first application, the Raman-EDFA HOA is investigated as a 16×40 Gbps DPSK-modulated system with different channel spacings. Secondly, a new optical modulation transmitter is proposed that transmits the NRZ/PolSK signals and further investigated its impact on Raman-EDFA HOA is investigated. It is observed that the proposed two-dimension orthogonal modulation formats have a more compact spectrum and are more tolerant to noise than conventional modulation formats (i.e. NRZ, RZ, DPSK etc.). The method provides a simple way to enhance the capacity of the system using minimum utilization of bandwidth with acceptable performance (in the term of optical power, Q-factor and BER) in the scenario of 8×20 and 20×20 Gbps DWDM systems. Further, the amplifier placement problem with multiple types of amplifiers is presented. It is observed that, using the optimized low cost Raman-EDFA HOA the number of conventional optical amplifiers are reduced over back-bone high capacity link. It is recommended that the Raman-EDFA HOA can be a good candidate even for future denser, high speed and up-scaled multipoint network. In the view of reported results, we recommended that the R-E HOA also can be used in long haul communication at large span distance which achieves 2450 km transmission distance with 70 km of span distance. After evaluating the performance of hybrid DWDM-OTDM, it is observed that our offered Raman-EDFA HOA provides the virtuous results even in the scenario of 320 Gbps data signals over narrow bandwidth (1.4 nm) with reduced channel spacing (0.2 nm).

These applications are investigated in the presence of fiber amplifier. However, the waveguide amplifiers are also the good as well as cost effective way to boost the signals, as also discussed in Chapter 1. So in further study, to take the advantage of such integrated amplifiers we have proposed the various new configurations to achieve better performance in cost effective solution.

Chapter 5

Hybrid Configurations of Optical Waveguide Amplifiers for DWDM System

5.1 Introduction

The development of integrated optics is current and hot research topic in which several optical components (such as lasers, multiplexers, couplers, modulator etc.) are fabricated on a single substrate, which yields in significant reduction in system size and cost. The integrated optical waveguide amplifier is one next step to further improve this technology by compensating the losses from the other integrated optical components. In this chapter, the various configurations have been proposed using these low cost waveguide amplifiers. In first configuration, a novel flat-gain amplifier is proposed in a hybrid configuration with an Er-Yb co-doped waveguide amplifier (EYDWA) and a SOA for 100×10 Gbps DWDM system at 0.2 nm interval. It is observed that when the proposed hybrid amplifier is used as a booster for hybrid distributed Raman and EDFA (proposed in Section 3.3), the gain variation is reduced from 2.01 to ~ 1.15 dB efficiently with acceptable bit error rate. On the other hand, in second architecture a new split-band hybrid waveguide amplifier (HWA) is projected to amplify the dual C plus L-band using two different amplifiers, i.e. EDWA and EYDWA, in parallel structure. This HWA plays a role to boost the DWDM signals and giving a larger gain while keeping the little power/gain variations over effective gain bandwidth product.

5.2 Flat-Gain Hybrid Amplifier for DWDM System

In Chapter 3 and 4, it is demonstrated that the hybrid Raman-EDFA is an enabling and promising technology for high speed DWDM systems as it provides large gain with minimum gain variation. Besides the superior immunity to gain variation as compared to a gain clamped optical amplifiers, the waveguide technology has the potentiality of integration with other functions. Such an integrated block offers small footprint and low mass production cost [118]. Among the several technologies, silicon photonics provides a powerful platform for the dense integration of several components, among which integrated amplifiers play a fundamental role [119]. In literature, for integrated optical waveguide amplifiers, several gain clamping techniques have been developed to achieve large flat-gain bandwidth, as also discussed in Section 2.2.3. Ennser et al. [120]

established an optical gain clamped waveguide amplifier which plays a role to reduce the transience phenomenon in all-optical WDM ring network. It was reported that the gain or power excursion is directly proportionate to the injected pump power, means higher the power stouter the gain stabilization. C. H. Yeh et al. [121] proposed a new way to suppress the transience phenomenon and validate results experimentally. In this work, the optical feedback technique is used to stabilize the gain dynamics of EDWA. Unfortunately, all these methods expressively increased the complexity and price of the optical system, as many opto-electronics components are used to mitigate the transience. In this section, these schemes are improved by further increasing the gain flatness devoid of any expensive gain stabilization approaches. The EYDWA-SOA hybrid amplifier (HA) is used as a booster providing higher gain with less gain variation to address typical necessities in LAN/ MAN. The original contribution of this investigation is to propose a flat-gain hybrid amplifier based on cheapest standard optical/waveguide amplifiers which are suitable for the next generation DWDM networks.

5.2.1 Proposed Setup and Results

In this Section, a new configuration based on flat-gain EYDWA-SOA HA is proposed. This setup consists of 100 DWDM channels covering the bandwidth starting from 1554 nm to 1574 nm in a 0.2 nm spacing using continuous wave lasers as shown in Figure 5.1. Each laser radiates the light with -20 dBm of power. The parameters of optical modulator, driver and data source has been taken from Section 3.3. The parameters of waveguide amplifier are described in Table 5.1. The optimized SOA with small facet reflectivity is considered as a cascaded amplifier and the parameters are same as reported in [68]. In the proposed hybrid amplifier, first the signal go into the EYDWA stage before experiencing additional amplification in the cascaded SOA called hybrid EYDWA-SOA.

Table 5.1: Parameters of EYDWA.

Parameter	EYDWA
Waveguide Length	0.03 m
Er Ion Density	$2 \times 10^{26} \text{ m}^{-3}$
Er Pump Excess Loss	37.3 dB/m
Yb Ion Density	$1 \times 10^{27} \text{ m}^{-3}$
Yb Pump Excess Loss	44.95 dB/m

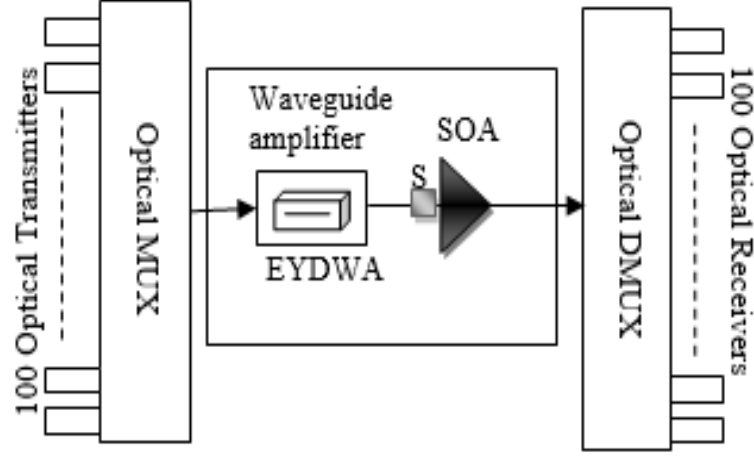


Figure 5.1: Proposed HA for DWDM system, s: splicer.

Figure 5.2 shows the gain spectrum of 100×10 Gbps DWDM system using single EYDWA and hybrid EYDWA-SOA. For both amplifiers, the gain variation with wavelength is not uniform as each amplifier induces its own nonlinearities and ASE noise. The reported gain has been measured in the presence of various losses (such as coupling, splicing, nonlinear etc.). The DWDM system with single EYDWA exhibits gain variation of ~1.83 dB over the whole effective gain-bandwidth (20 nm) while ~0.75 dB is observed with EYDWA-SOA HA. These results provide cost effectiveness and improvement over [122] in the terms of gain and gain bandwidth product. In [122], the flat gain of >8 dB (in our case it is >14 dB) was obtained across the bandwidth (1580 nm to 1597 nm) with a gain variation of the order of 0.1 dB using high cost broadband Raman pump, which makes the system expensive. It is clearly evident from the graph that the EYDWA-SOA HA provides better gain flatness as compared to single EYDWA because of a cascaded SOA. An optimized SOA provides large output power or gain with lesser variation, as also reported in [68].

From reported results it is recommended that the cascaded configuration of EYDWA and SOA can be used as a booster which provides large gain with lesser variation. The same investigation has been conducted on our previous proposed DRA-EDFA HOA in Section 3.3 to take the advantage of EYDWA-SOA HA as booster. Figure 5.3 represents the gain curve from single DRA-EDFA HOA that excludes various losses (such as coupling, splicing etc.). These results are different from the previously reported results in Section 3.3, as this investigation has been done using different number of channels (i.e. 100×10 Gbps instead of 160×10 Gbps) with different frequency band and input power.

Similarly Figure 5.4 represents the gain spectra of DRA-EDFA HOA when the proposed EYDWA-SOA HA is used as a booster.

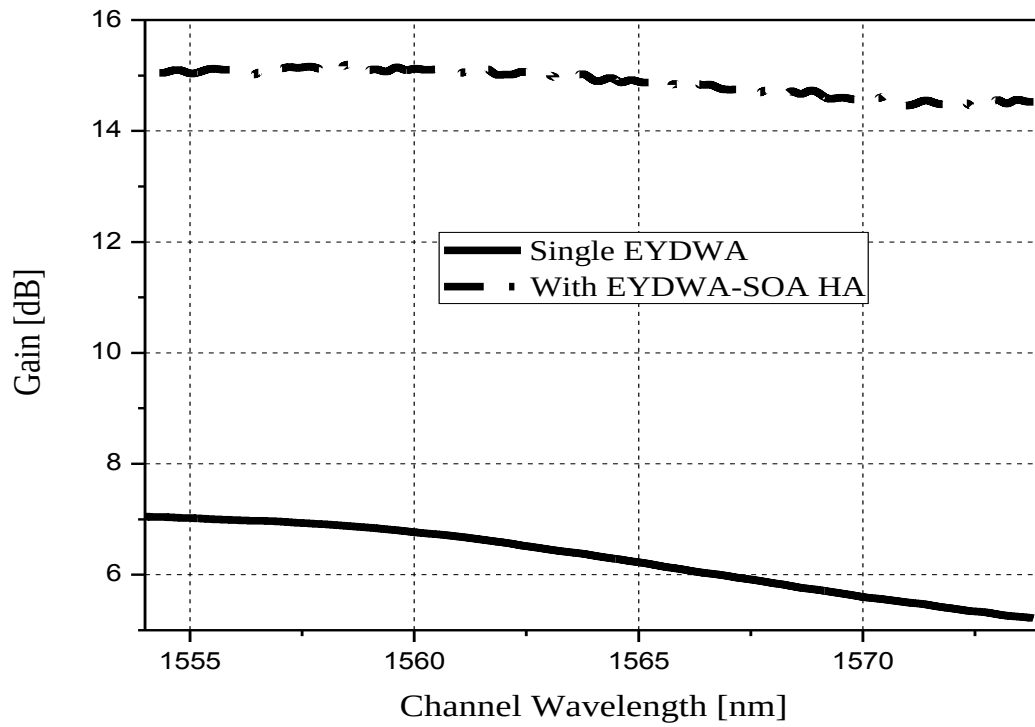


Figure 5.2 Gain spectra of proposed amplifiers.

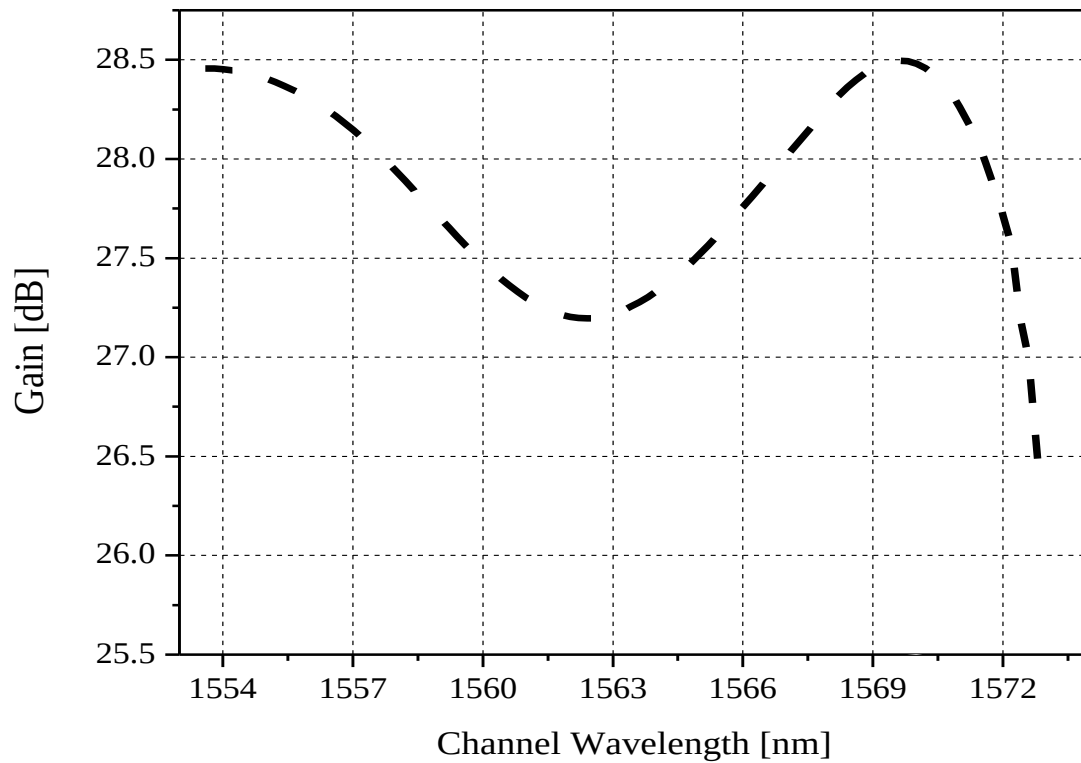


Figure 5.3: Gain spectra of single DRA-EDFA HOA proposed in Section 3.3 for 100×10 Gbps DWDM system excluding coupling, splicing losses.

From Figure 5.3 and 5.4 it can be seen that, both the amplifiers have similar gain profiles with a peak gain at 1570 nm but with a small drop in gain of proposed HA. The net gain in Figure 5.4 is measured including the effects of various losses (such as coupling, splicing etc.). In particular, nonlinear losses also mitigate the optical gain, including excited-state absorption and up-conversion in erbium-doped with free-carrier absorption [119]. From these Figures, it can also be observed that the gain variation of DRA-EDFA HOA over the wavelengths ranging from 1553 nm to 1573 nm is reduced from 2.01 to 1.15 dB when proposed HA is used as a booster, which shows improvement over previous results in Section 3.3 and in [68], [123]. We have also examined the crosstalk performance of proposed DWDM system. It is observed that the variation of BER among the DWDM channels is detected due to crosstalk between the data symbols but still the acceptable BER is measured (see Section 7.5).

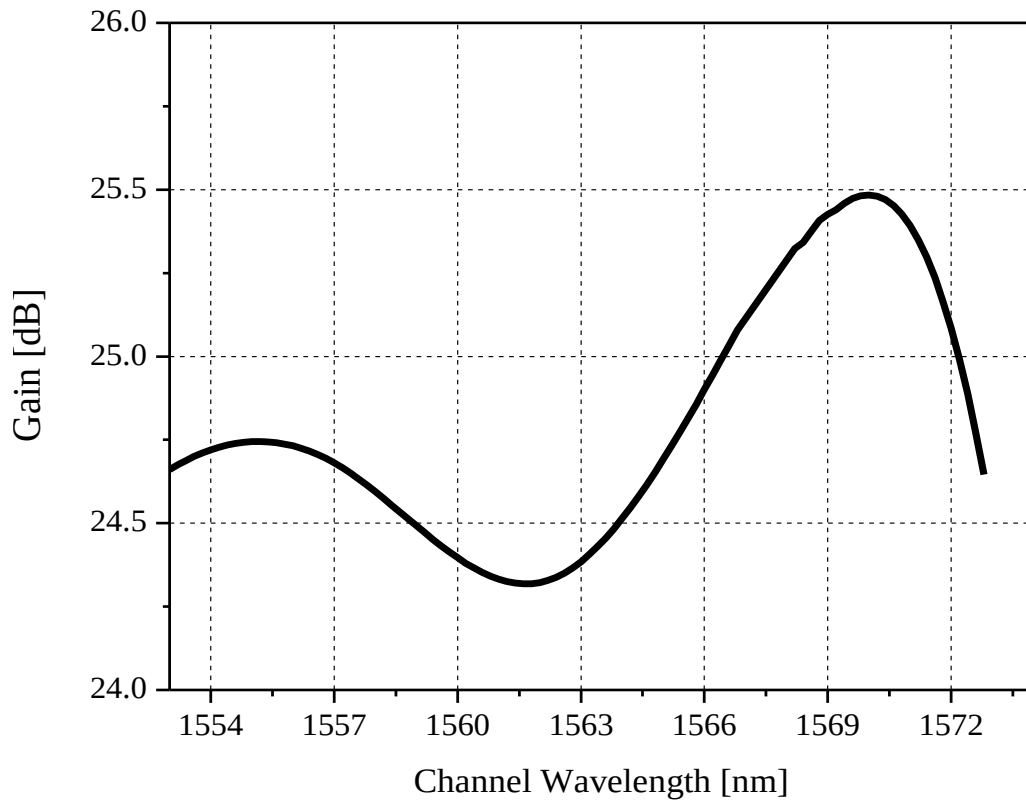


Figure 5.4: Gain spectra of DRA-EDFA HOA proposed in Section 3.3 using EYDWA-SOA HA as booster for 100×10 Gbps DWDM system including coupling, splicing, nonlinear losses.

Table 5.2 describes the comparison of important performance parameters (output and input) of our proposed HA with current state-of-the-art schemes. This evaluation has been prepared to define the level of facts and the progress accomplished in a system. In this

Table, currently published 2011 to 2013 snapshots of the various HOAs state-of-the-art schemes are presented. After evaluation it can be determined that our offered HA demonstrations development over existing state-of-the-art schemes and over our previous work presented in Section 3.3 and Section 4.2 because: (i) the better performance has been achieved even when 100×10 Gbps DWDM channels are communicated over hundred kilometer of Raman fiber; (ii) it excludes gain clamping techniques; and (iii) the dispersion compensating fiber and other gain flattening techniques are not considered, which strongly reduce the cost.

Table 5.2: Comparison of our proposed HA with current state-of-the-art schemes.

Parameter	L-Band Raman+EDFA HOA (2011) [124]	Raman+EDF A+FBG+DCF (2011) [99]	Raman+EDFA+ DCF (2013) (Section 3.3)	Raman+EDFA (2013) (Section 4.2)	Current investigation (HA+DRA- EDFA)
Gain	> 12 dB	> 4 dB	>10 dB	>11dB	>24dB
Gain Flatness	~1.2 dB	< 0.5 dB	< 4.5 dB	< 3 dB	~1.15 dB
Number of channels/ channel spacing	Channels:35 Spacing: 1 nm	Channels: 26 -----	Channels: 160 Spacing: 25 GHz	Channels: 16 Spacing: 0.1 THz	Channels: 100 Spacing: 0.2 nm
Gain Bandwidth	23.5 nm	80 nm	3.97 THz	1.5 THz	20 nm

5.3 Split Band Hybrid Waveguide Amplifier for DWDM System

In general, hybrid amplifier combines several amplifiers with different gain bandwidths to extend the gain bandwidth product of the optical amplifiers. The several configurations are possible to propose a HOA, such as cascaded and parallel combination. In parallel arrangement, first the DWDM channels are de-multiplexed according to the required bands and then these bands are amplified by the corresponding suitable amplifier.

Recently, the waveguide amplifiers concerned more and more attention in fiber optics communication as it provides large gain even with much compact and low cost structure. This planar amplifier can be used as pre- and post- amplifier to boost the power level after transmitter and before receiver, respectively. Now a days the integrated DWDM transmitters are used to transmit multiple signals at ultra-narrow wavelength spacing. The

advantage of waveguide amplifier is that, it can easily be fabricated with DWDM transmitter on same substrate, which will strongly reduce coupling losses or cost. But still the gain variation over the channels are present which degrades the system performance. Numerous mechanisms had been dedicated to flatten the amplifier gain by electronic and optical means [125]. Now a days, to achieve large gain stabilization over compact DWDM signals is the extreme operation condition to solve. In previous investigations, numerous gain-stabilising procedures have been described, such as the all-optical gain-clamped technique [126], or different optical filters including FBG filters and fiber acousto-optic filters [127], [128]. Unfortunately, all of them expressively increased the complication and cost of the definite optical modules. Moreover, these techniques are not bandwidth efficient as these are restricted to number of channels and large channel spacing was used to place the channels which directly degrade the fiber capacity.

In this Section, the various issues are addressed, such as gain bandwidth product, gain flatness, cost etc., and improves the performance of the system by offering the new flat gain hybrid waveguide amplifier (HWA). With respect to earlier investigations described in Chapter 3 and 4, a split-band HWA comprising parallel EDWA and EYDWA is used with higher gain to address classic necessities in up scaled and denser version of the systems. In addition, this work has also been examined on the observation of additional much smaller gain variation brought by our earlier projected hybrid Raman-EDFA described in Section 3.3.

5.3.1 Proposed HWA and Results

In our previous work reported in Section 3.3, an R-E HOA has been investigated which was able to decrease gain variation even without costly gain flattening methodologies. Unfortunately, the conventional optical amplifiers, such as EDFA and Raman, have been considered which are expensive as compared to integrated amplifiers. In this section, the previous work has been extended to increase the gain bandwidth product and gain flatness using integrated waveguide amplifiers. Figure 5.5 shows the representation of DWDM system in the presence of proposed HWA. In this system the 130 channels are used with 0.2 nm of channel spacing, where 70 channels (ranging from 1565 nm to 1578.8 nm) and 50 channels (ranging from 1540 nm to 1549.8 nm) are assigned from L-and C-band, respectively. Further these C-and L-bands are amplified by EDWA and EYDWA, respectively, after fragmentation through band splitter. Each laser releases the light signal with 3 mW of power. The PRBS sequences are generated with 10 Gbps of speed and

formatted as NRZ pattern using electrical driver, which further control the output of an optical modulator. The parameters of waveguide amplifiers are described in Table 5.3. Both amplifiers are counter-pumped with 980 nm having 300 mW of power.

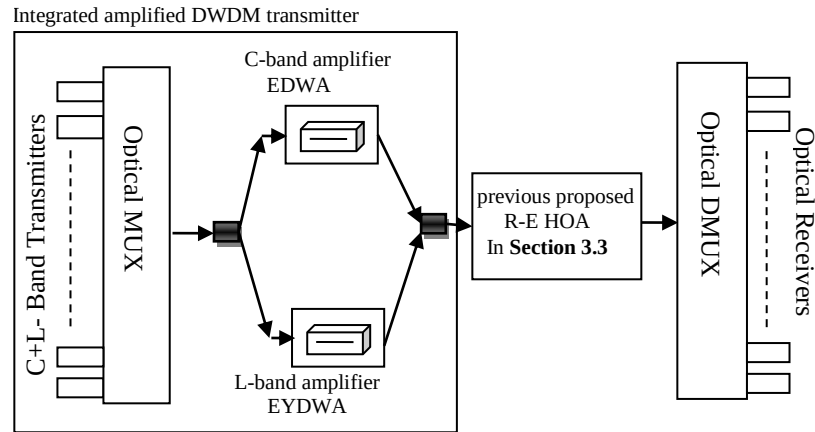


Figure 5.5. Arrangement of HWA for DWDM system; S: C and L band splitter, C: C and L band combiner.

In Figure 5.6, two different curves are indicated the non-uniform gain spectrum over C- and L-band of proposed HWA in the scenario of 130×10 Gbps DWDM system at 0.2 nm of spacing. This undesired gain variation is due to the ASE noise and planar or rectangular setting of used waveguide amplifiers. It can be observed that the gain grasped its supreme level (> 14.3 dB) over C-band and abruptly dropped as the signal wavelength regulated across L-band, it shows good agreement with [67].

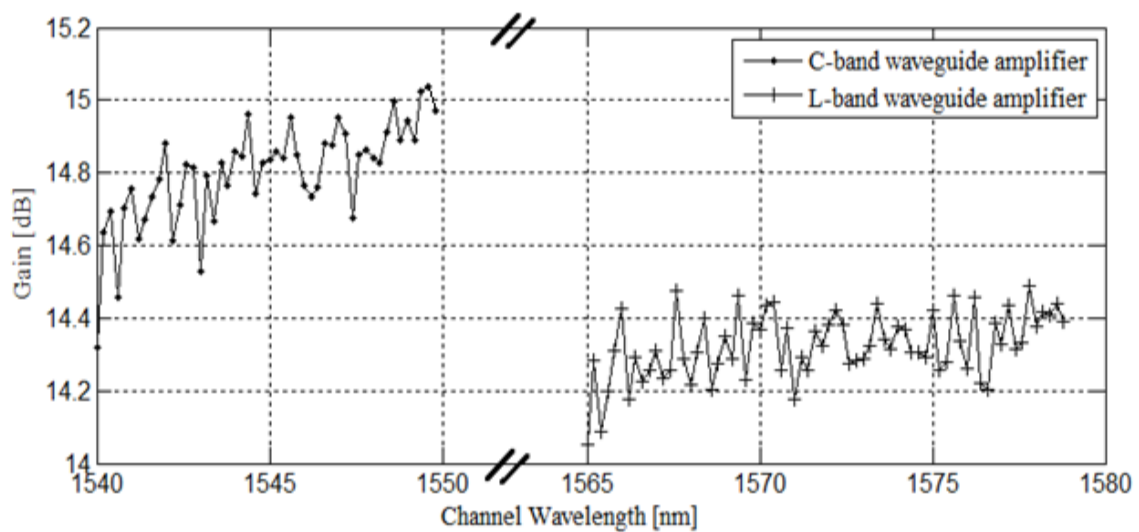


Figure 5.6 Gain spectra of proposed HWA over C+L- band DWDM system.

The proposed HWA plays a role to boost the compact DWDM channels and providing a high gain whereas keeping the little power or gain distinctions over operational bandwidth. The EDWA and EYDWA in parallel structure provides the high gain, i.e. > 14.3 dB and > 14 dB, over C- and L-band along with least gain variation of 0.9 dB and 0.5 dB, respectively. The above reported results show the performance of component level architecture only. For better investigation and to show the feasibility of proposed HWA as booster in communication system, we have considered the transmission distance using pumped SMF. To take the advantage of proposed HWA as booster, the same investigation has been conducted on the previous proposed R-E HOA in Section 3.3 to further increase the gain and gain flatness. From Figure 5.7, it can be observed that the gain flatness of 3.1 dB is achieved using proposed HWA as booster of R-E, with better performance over [80]. Moreover, without HWA, the R-E HOA induces 7.2 dB of gain variation when other type of amplifier is used as booster. From these results it is observed that the gain variation of previously proposed R-E HOA is reduced from 7.2 to 3.1 dB without using any costly gain clamping techniques. Also, the power variation of R-E HOA is reduced from 6.3 to 2.4 dBm using HWA as booster instead of conventional amplifiers, as shown in Figure 5.8.

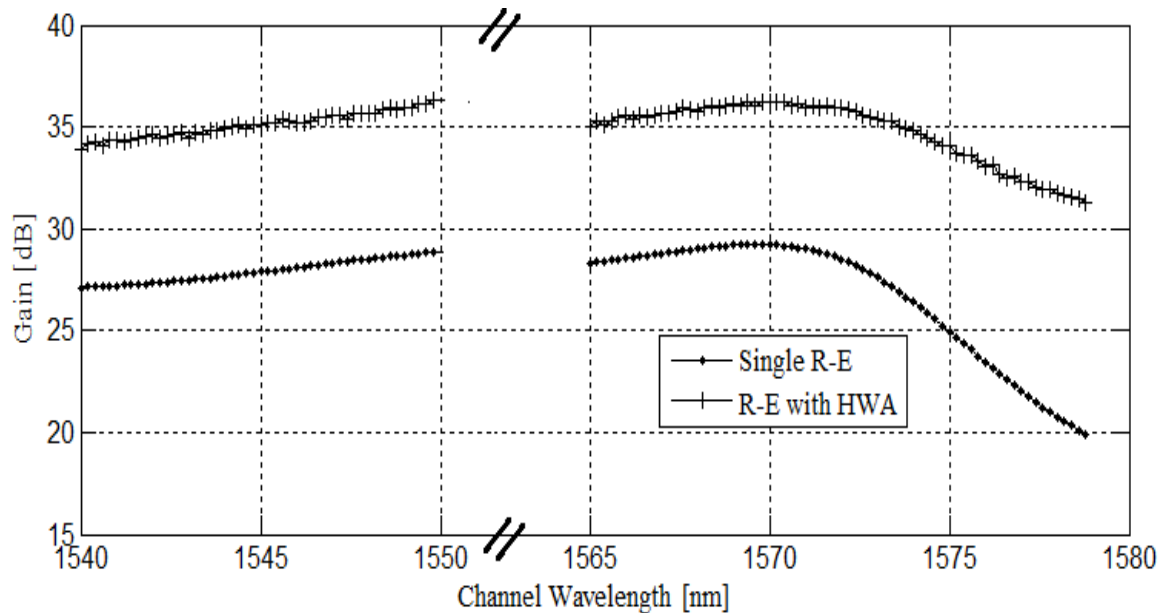


Figure 5.7: Gain variation of proposed HOAs over C and L band.

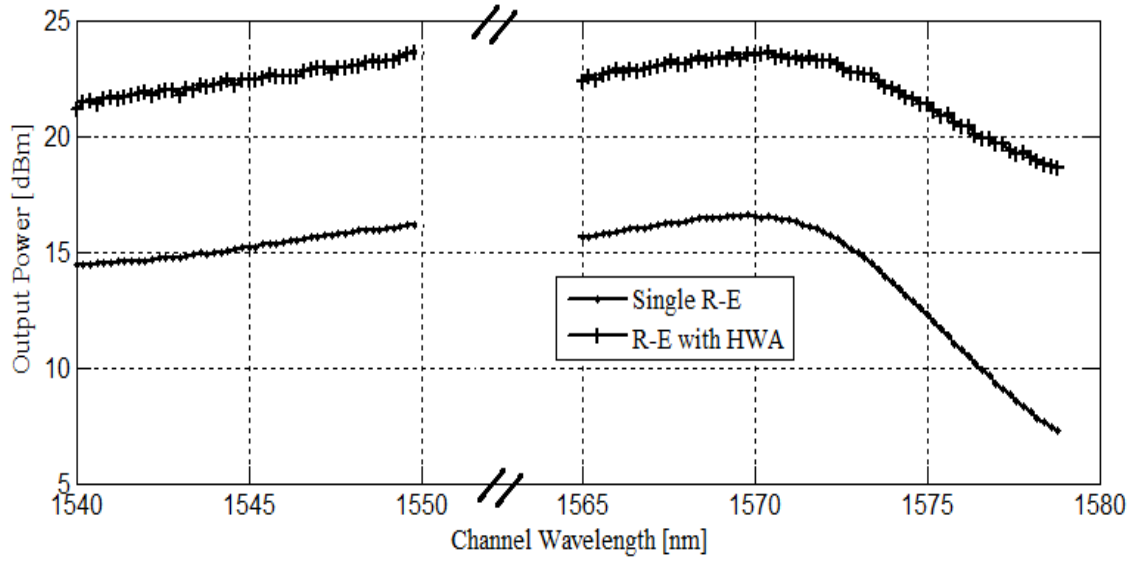


Figure 5.8: Power variation of proposed HOAs over C and L band.

5.3.2 Investigation of Various Parameters of EYDWA/ EDWA on Proposed DWDM System

In this section, the effect of EDWA/ EYDWA parameters (such as Pump power, amplifier length and Er/ Yb concentration) has been investigated and evaluated in the term of optical power measured after HWA and HOA. The results have been taken at 1565 nm of wavelength. Figure 5.9 presented the variation of optical output power after proposed HWA and HOA as function of the pump power of used waveguide amplifiers (EDWA/ EYDWA). It can be seen that, as the pump power of both EDWA and EYDWA increases the output power level is also increased because more the power level then high population inversion takes place. Similarly, Figure 5.10 shows the variation of power corresponding to the EDWA/ EYDWA length. As we increased the amplifiers length then the corresponding output power decreases this is due to the planar nature of waveguide amplifiers. The variation of power directly affects the gain of the HWA/ HOA.

Table 5.3: Constraints of waveguide amplifiers.

Parameter	EYDWA	EDWA
Length	0.09 m	0.07 m
Erbium Density	$2 \times 10^{26} \text{ m}^{-3}$	$2 \times 10^{26} \text{ m}^{-3}$
Erbium Pump Loss	37.3 dB/m	37.3 dB/m
Yttrium Density	$1 \times 10^{27} \text{ m}^{-3}$	----
Yttrium Pump Loss	44.95 dB/m	----

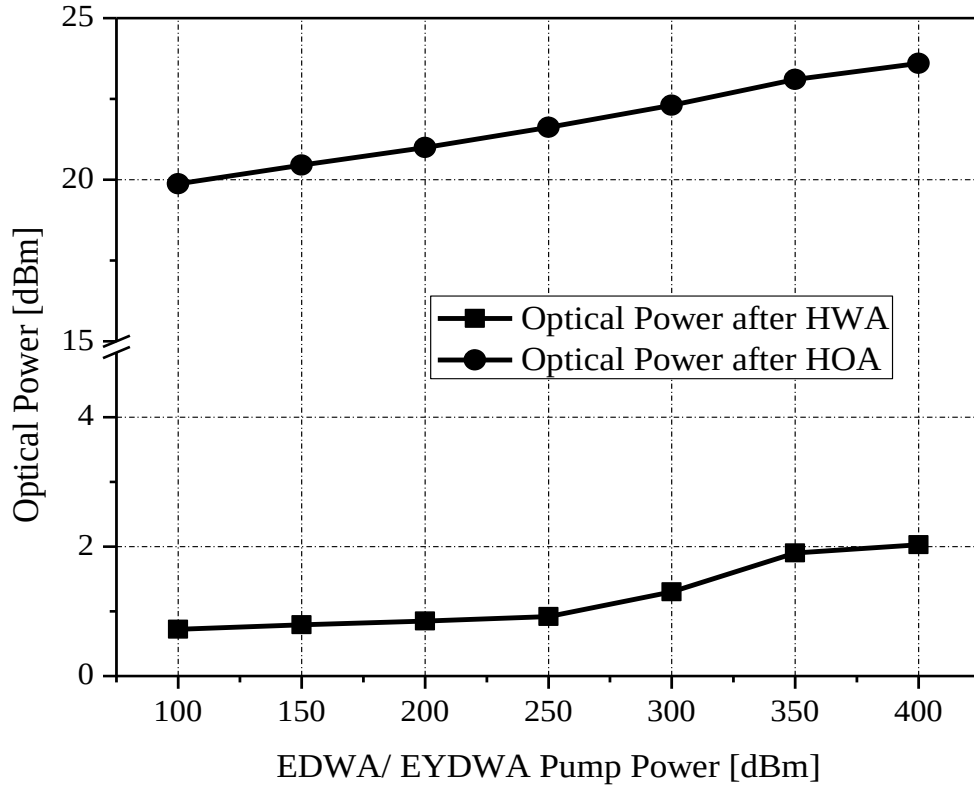


Figure 5.9: Pump power versus optical output power for proposed DWDM system.

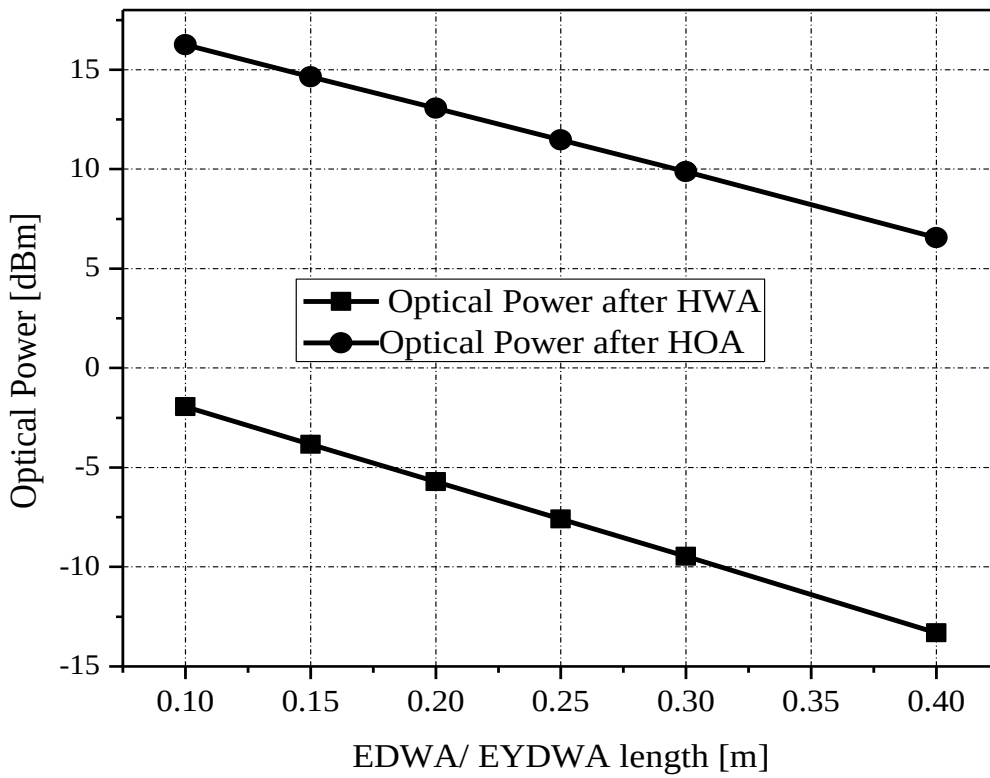


Figure 5.10: Waveguide amplifier length versus optical output power for proposed DWDM system.

Similarly, the same investigation has been conducted to check the impact of Er and Yb concentration on optical power. It can be observed from Table 5.4, that the output power increases as the value of concentration is incremented because higher the concentration more the conductivity (more the transformation of ions between higher and ground level).

Table 5.4: Variation of optical power after HWA and HOA with respect to Er and Yb concentration of used waveguide amplifiers.

Er concentration in EDWA/ EYDWA [m ⁻³]	Yb concentration in EYDWA [m ⁻³]	Optical Power after HWA [dBm]	Optical Power after HOA [dBm]
1×10^{26}	4×10^{27}	-3.1	14.54
2×10^{26}	5×10^{27}	2.4	19.14
3×10^{26}	6×10^{27}	6.3	22.98
4×10^{26}	7×10^{27}	11.1	28.5
5×10^{26}	8×10^{27}	15.6	32.3

5.4 Conclusion

In this chapter, the two configurations of HWAs, i.e. cascaded configuration of EYDWA plus SOA and parallel architecture of EDWA and EYDWA, have been proposed. These proposed amplifiers are further investigated for 100×10 Gbps and 130×10 Gbps DWDM system, respectively, with 0.2 nm of interval. The aim of this work is to achieve better gain flatness without using any costly components. With an EYDWA-SOA HA a flat gain of >14 dB is obtained across the effective bandwidth with a gain variation of ~0.75 dB, without using any gain clamping techniques. On the other hand, with a parallel EDWA and EYDWA configuration the gain and power variation due to the R-E HOA is reduced from 7.2 dBm to 3.1 dB and 6.3 dBm to 2.4 dBm, respectively. The improved performance have been shown in the terms of gain flatness, cost etc. We believe that this solution will bring excellent performance and will be suitable for the next generation DWDM network.

Till now the investigation has been done to increase the gain bandwidth with less variation. But various other relative issues; such as transience effect, non-linear crosstalk, power excursion etc.; are pending to address. In further study, presented in Chapter 6 and 7, these issues are investigated and further mitigated to seek of better performance.

Chapter 6

Investigation and Mitigation of Transient Phenomena in Hybrid Optical Amplifiers

6.1 Introduction

This Chapter deals with the third objective of this thesis work, which is to investigate the control techniques for HOA in order to suppress transient phenomena. This work is an expansion of our previous work presented in Chapter 3 to 5 by addressing the various control methods to mitigate abrupt change in overall power with respect to the time called transient effect. This objective is achieved and presented in different Sections as follows: in Section 6.2, the transient effect in two stage HOA is presented to show the combined dynamics of the distributed Raman amplifier (DRA) and the EDFA. To compensate this effect various important parameters (such as EDFA length and pump power) have been adjusted. In Section 6.3, to further reduce the transient phenomena a new hybrid control module is proposed by combining link control channel and power shaping techniques.

6.2 Power Transient and its Control in Raman- EDFA Hybrid Optical Amplifier

In saturated amplifiers, transient crosstalk is generated between adjacent channels, when the average power into the amplifier changes abruptly. This type of effect can be a serious problem in today's reconfigurable networks where reconfigurable optical add/drop multiplexers (ROADMs) and OXCs are used for dynamic routing and switching of individual channels. For better performance the gain dynamics should be controlled [129]. In general, transients are always unwanted in a system, as they impair the receiver sensitivity [130], can cause potential damage to system components and increase the effect from system nonlinearities during transmission. In literature, various control methods are proposed, which are briefly described in Section 2.2.2, to reduce the undesired amplifier transient effect.

Recently, various advanced control methods are also proposed to control the transient, including the use of reflective SOAs [131], gain clamped EDFA or discrete fiber Raman amplifier [132], [133] etc. J. H. Lee et al. [134] investigated the transient effect of Raman/EDFA hybrid amplifier. By using cost effective all optical FBG based gain

clamping technique they capably mitigate the transience phenomena. Unfortunately, these techniques are limited by small dynamic range and use an expensive component.

In our previous work presented in Chapter 3 to 5, the various HOAs are investigated for a DWDM system at narrow channel spacing and high bit rate. It was observed that the Raman-EDFA is the best combination to achieve better results. But the transient effect induced by the HOAs has not been investigated yet. In this section, the combined transient effects in Raman-EDFA HOA have been presented. Finally, the several solutions are evaluated to mitigating the power transients instead of costly or complex clamping techniques.

6.2.1 System Setup and Results

The schematic diagram to observe the HOA transient is shown in Figure 6.1. The eight-channel laser sources are used in which a few channels were modulated with a mach-zehnder modulator (MZM) to introduce add/drop operation. The laser array is transmitting the optical signals with input power of -3 dBm per channel. For add/drop operation, the data stream from a 10 Gbps pattern generator with an NRZ binary sequence is pre-coded and further drives the modulator. The signal wavelengths are adjusted from 1550 nm to 1551.4 nm with a 0.2 nm spacing. In DRA operation, the pump laser pumped a 50 km of SMF to produce Raman gain. A 10 m long EDF (Er concentration $1 \times 10^{25} \text{ m}^{-3}$) is used with an erbium metastable lifetime of 3.2 ms and numerical aperture of 0.24. The constraints of considered fibers are defined in Table 6.1. After the Bessel filter which is tuned at 1550 nm, the transient effects are observed using the time domain analyzer.

Table 6.1: Fiber parameters.

Fiber	Loss dB/Km	Dispersion ps/nm/Km	Pump wavelength Nm	Pump Power mW
SMF	0.2	16.75	1453	600
EDF	0.01	16	980	10

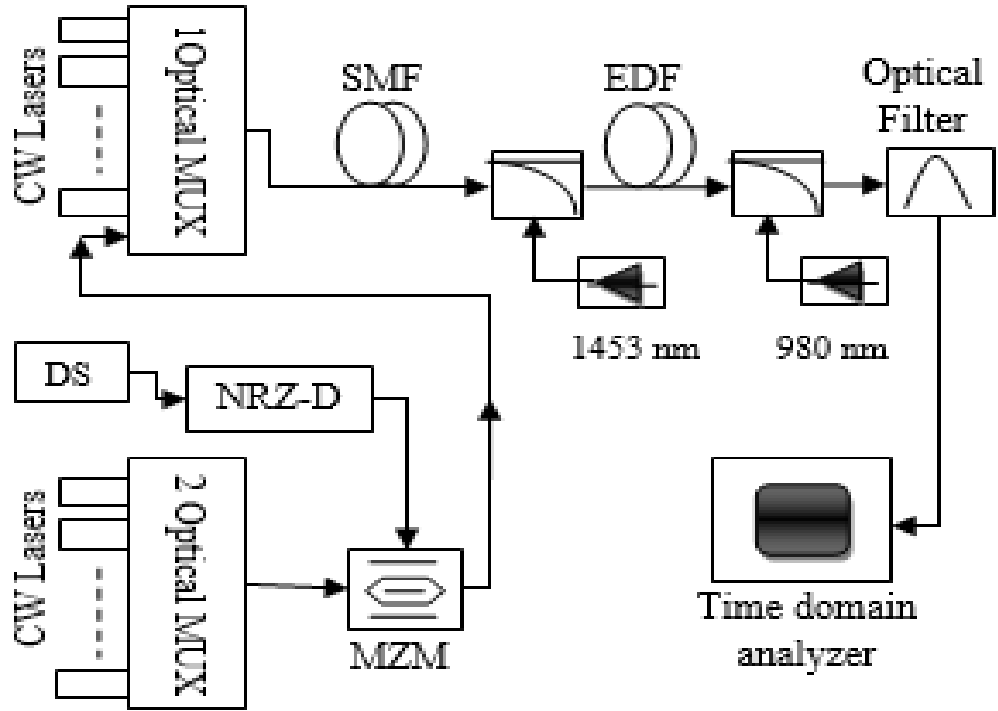


Figure 6.1: System setup to observe and control DRA-EDFA HOA transient effects; DS: data source, NRZ-D: NRZ- driver.

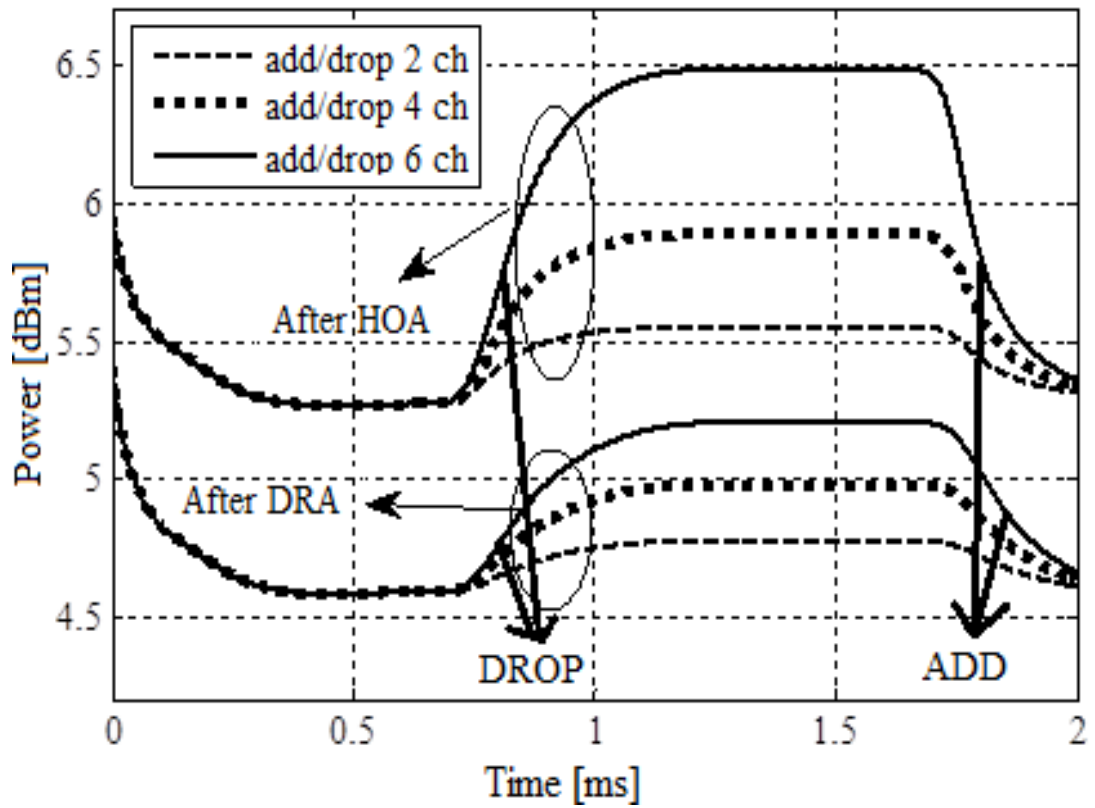


Figure 6.2: Output power of the surviving channel after DRA, and HOA when 2, 4 and 6 channels are added and dropped.

The power excursion is present for all the surviving channels when add/drop operation is activated. The power fluctuations for each of the surviving channels were essentially identical [135]. Figure 6.2 shows the power fluctuation in channel 1 (1550 nm), when last 2, 4, 6 channels are added or dropped, respectively. The large power excursion is observed when many channels are added or dropped. It is due to the input power of DRA-EDFA HOA is changed from 6.01 dBm to 5.4 dBm, 6.01 dBm to 4.7 dBm and 6.01 to 3.9 dBm when last 2, 4 and 6 channels are dropped, respectively, and vice versa when added. The response time for the output power after dropping six channels is measured to be 0.85 ms after DRA and 0.72 ms after EDFA.

The relatively fast and small changes at the event of add or drop of channels is originated from Raman-induced crosstalk among the signal channels. The transients after EDFA shows a larger output power variation than after DRA. From Figure 6.2 it can be observed that, the response time of DRA-EDFA HOA is governed by the response of EDFA because it has the fastest response time [136]. The output power deviation of DRA-EDFA HOA is mainly dependent on the dynamics of EDFA rather than DRA because of its high output power. As the power variation after DRA is smaller than after EDFA and the transients after DRA are relatively slower than after EDFA, there are input-power conditions that power of surviving channel can be controlled by adjusting the parameters of EDFA only. For further investigation, the worst case has been considered when six channels are added or dropped.

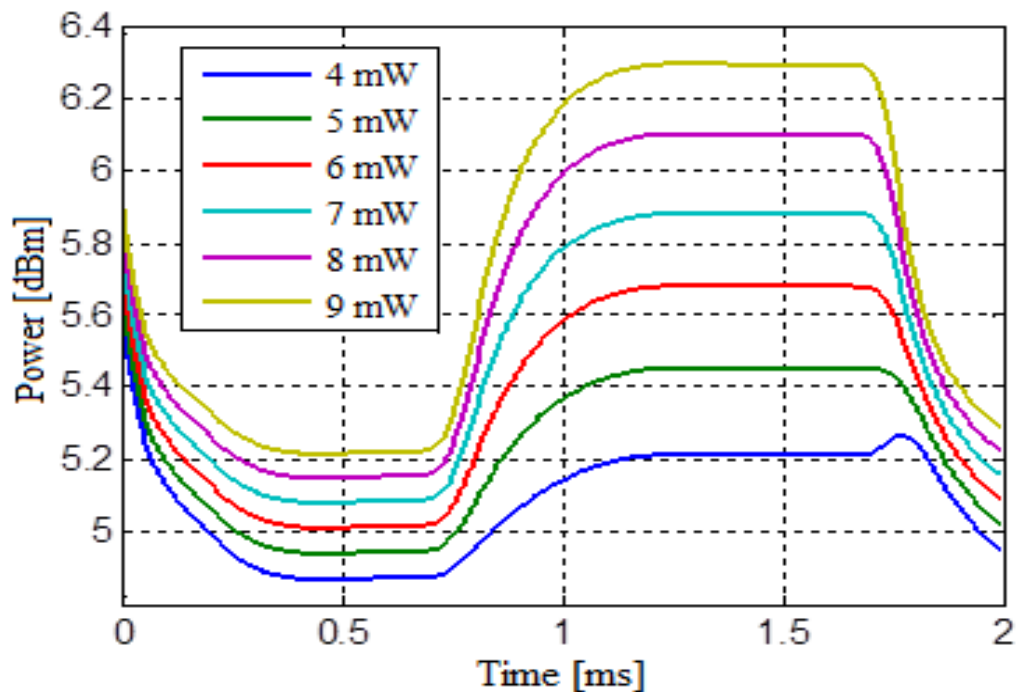


Figure 6.3: Reduction in power excursion using pump-power control, EDF is 10 m.

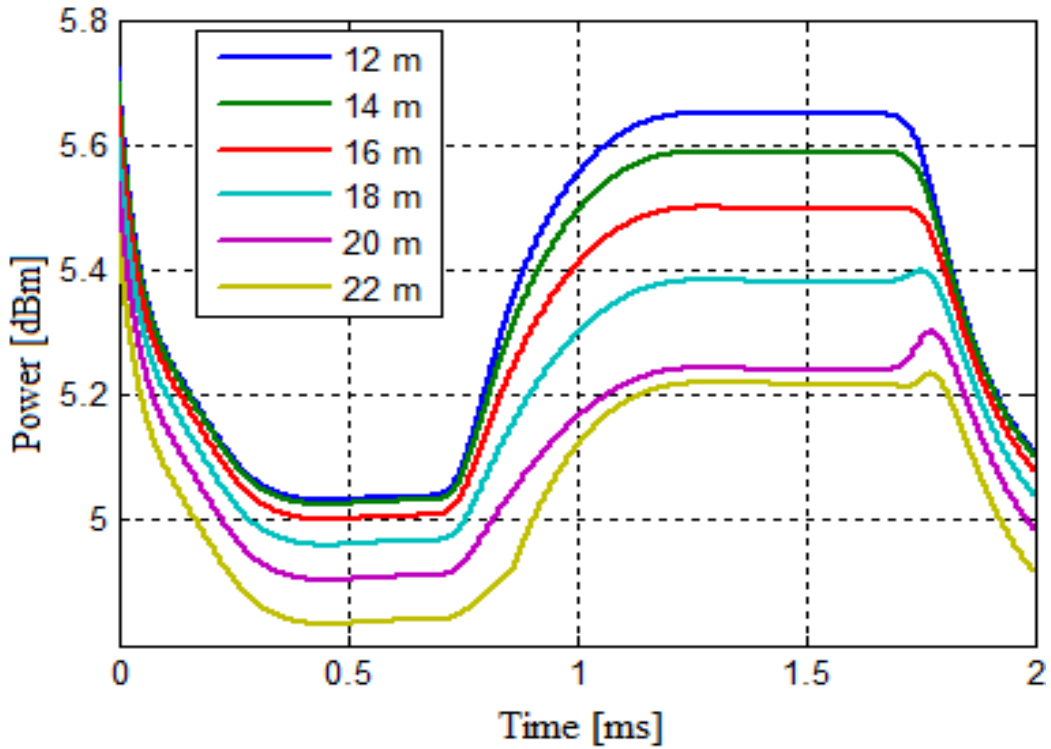


Figure 6.4 Reduction in power excursion using EDF length control, EDFA pump power is 8 mW.

In Figure 6.3 and 6.4, the pump power and length of EDFA is controlled where the parameters of the DRA is kept as it is. It can be observed that the power variation (peak to peak power excursion) reduces with decrease in the pump power and increase in the EDFA length. After 8 mW of pump power and 20 m of EDF length the power excursion is increased. When EDFA pump power and length is changed from 9 mW to 4 mW and 10 m to 20 m, total power of surviving channel decreases with an excursion from 1.07 dBm to 0.6 dBm and 0.62 dBm to 0.34 dBm, respectively. Table 6.2 and 6.3 described the overall characteristics of HOA at different EDF length and pump power. As expected these Tables confirm our results, the gain and OSNR reduces with decrease in the pump power and increase in the length of EDFA.

Table 6.2: Overall performance of HOA for different EDF length.

EDF Length (m)	Gain (dB)	OSNR (dB)
12	7.73	49.46
14	7.68	49.19
16	7.61	48.93
18	7.53	48.68
20	7.45	48.4
22	7.38	48.1

Table 6.3: Overall performance of HOA for different EDF pump power.

EDF Pump Power (mW)	Gain (dB)	OSNR (dB)
4	7.22	48.78
5	7.42	48.69
6	7.53	48.68
7	7.68	48.64
8	7.83	48.61
9	7.96	48.58

Further, the same investigation has been conducted to check the transience performance of Raman-EDFA HOA corresponding to the number of channels and input power. For this investigation the same system setup (shown in Figure 6.1) is used but with different number of channels and input powers. In all the cases, first two channels (tuned at 1550 and 1550.2 nm) are considered as a surviving channels, means the remaining number of channels are added or dropped. From Figure 6.5 it can be seen that the power excursion upturns with respect to the increment in number of channels. This is due to the sudden variation in the overall input power of HOA. Moreover, the power level of optical signal is increased as the input power increases.

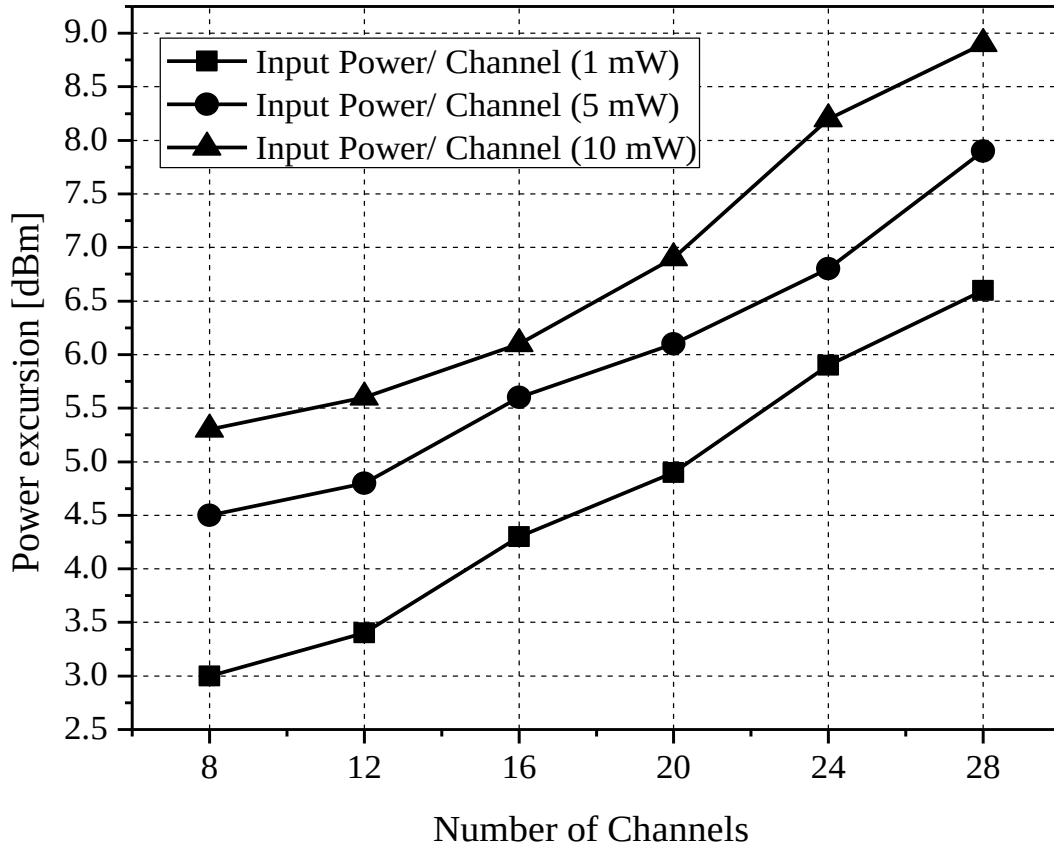


Figure 6.5: Power excursion with respect to the number of channels.

6.3 Control Methods for Hybrid Raman and EDFA in Order to Suppress Transient Phenomena

In Section 2.2.2, various control methods are briefly described to mitigate the transient effect that may require specialized and additional components. The power shaping has the advantage of being more economical as it mitigates the transience all optically. To further improve the system performance, Jackson et al. proposed an economical method based on power shaping where heads and tails are added to the beginning and end of a data which increases or decreases the power level gradually, which leads to mitigate the effects of EDFA transients [137].

In this Section, a new hybrid control technique is proposed to reduce the transience effect by combining link control technique with power shaping technique. Here a new approach, based on a complementary actuation of the link control channel and power shaping control techniques is demonstrated for cost effective solution by exempting expensive electronic controllers, regenerators etc.

6.3.1 Working Principle of Control Methods

Power shaping is defined as regulating and preserving the behavior of the power of a channel or connection all optically, as also explained in [137]. The approach is to increase or decrease the overall power gradually rather than abruptly. Figure 6.6, left side (data burst), shows the power profile of a channel as a function of time when no control method is applied. At the right side of Figure 6.6, i.e. data with head and tail, shows power shaping on a circuit-switched connection. Before the first traffic block and after the last traffic block, a head and a tail are inserted respectively. In this work, the added head and tail gradually increases or decreases the channel power by using a user defined bit sequence. These heads and tails are inserted by increasing the rise and fall time of the used NRZ pulses. The rise time and fall time of the input pulse is increased to 0.5 of a bit.

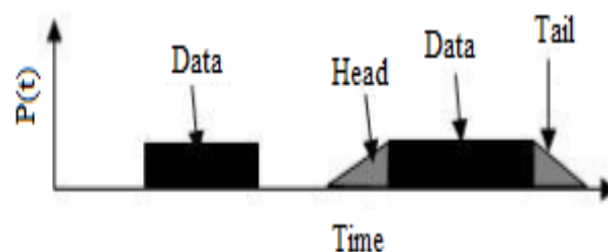


Figure 6.6: Power shaping [137].

While the link control technique was originally developed for the transient control in cascades of EDFA [138]. This technique allows the total power excursion to remain relatively constant along the cascade, by introducing a control channel to absorb any power variation in the cascade input.

In this work, the add/drop operation of used channels are done by bit pattern generator using NRZ pulse generator. To compensate the power transient (because of add/drop of channels) pattern of the bit sequence generator is inverted using NOT gate (See Figure 6.7). The control channel (which is tuned at 1541.3 nm with an input power of 0.32 mW) is modulated by the inverted envelope signal using the second modulator. This adds the control channel to the system when disturbing channels are dropped and vice versa i.e. when disturbing channels are added, at same time control channel gets dropped. Control channel absorb the total input power variation. Thus, the fluctuation of the optical power of the HOA input is reduced. As a result, transients in outputs of the HOA are suppressed effectively. In the case of hybrid control module both the control methods are used in parallel, as shown in Figure 6.7.

6.3.2 System Setup and Results

In this investigation, forty DWDM channels are considered with 0.4 nm of channel spacing. The eight surviving channels are allotted to different wavelength from 1553 nm to 1555.8 nm; while disturbing wavelengths are assigned from 1532 to 1544.8 nm. This is sufficient to show the dynamics of a Raman-EDFA HOA after dropping and adding the 32 channels out of 40. Add/drop of 32 channels is investigated by modulating the optical signal by a square wave at a low bit rate of 2.5 Gbps. A pseudorandom sequence is encoded on each add/drop channel using NRZ generator. These 32 channel light sources are modulated by an MZM optical modulator and further combined with 8 surviving channel using a multiplexer. The optimized parameters of Raman and EDFA are taken from Section 3.4. From OTDV the power excursion (peak to peak variation) has been observed.

From Figure 6.8 it can be seen that both the control methods (i.e. power shaping and link control channel) suppresses the large amount of power transient. Using only power shaping the power excursion is calculated to be ~ 1.3 mW. While when only link control technique is applied then calculated power excursion is ~ 1.55 mW. On the other hand, when the proposed hybrid control method is used then the power excursion is calculated to be 0.6 mW, as shown in Figure 6.9. Means using hybrid module the better

supersession, i.e. 0.6 mW and 0.9 mW, is observed as compared to power shaping and control channel, respectively.

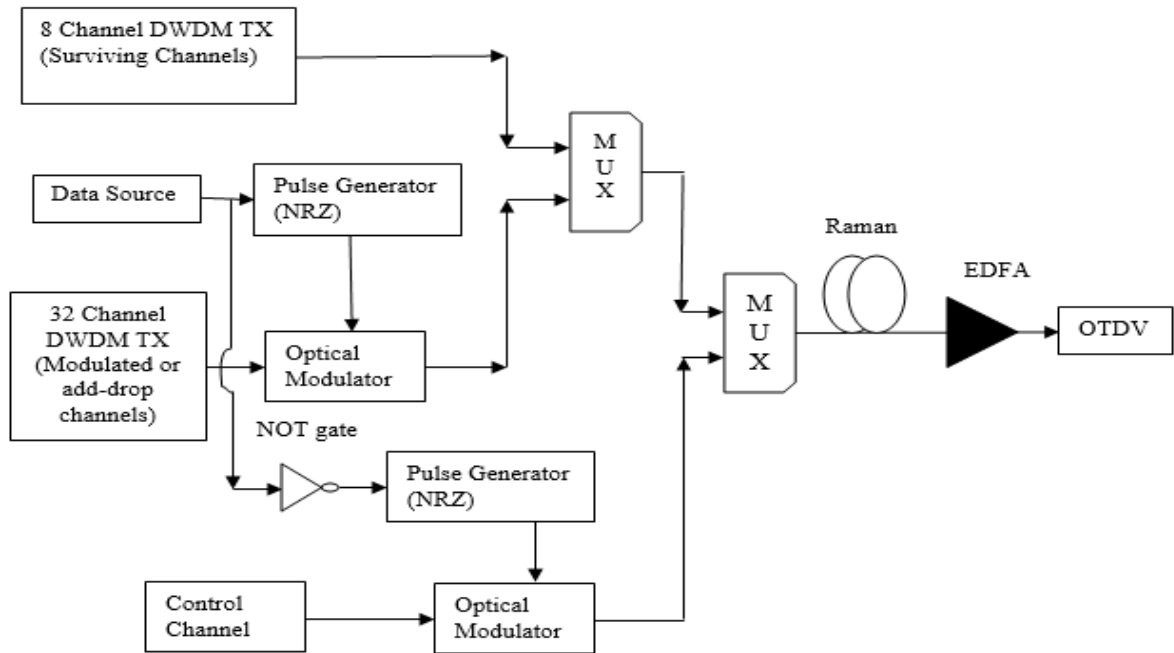


Figure 6.7: System setup for hybrid control technique to suppress the transient behavior (OTDV: Optical time domain visualizer).

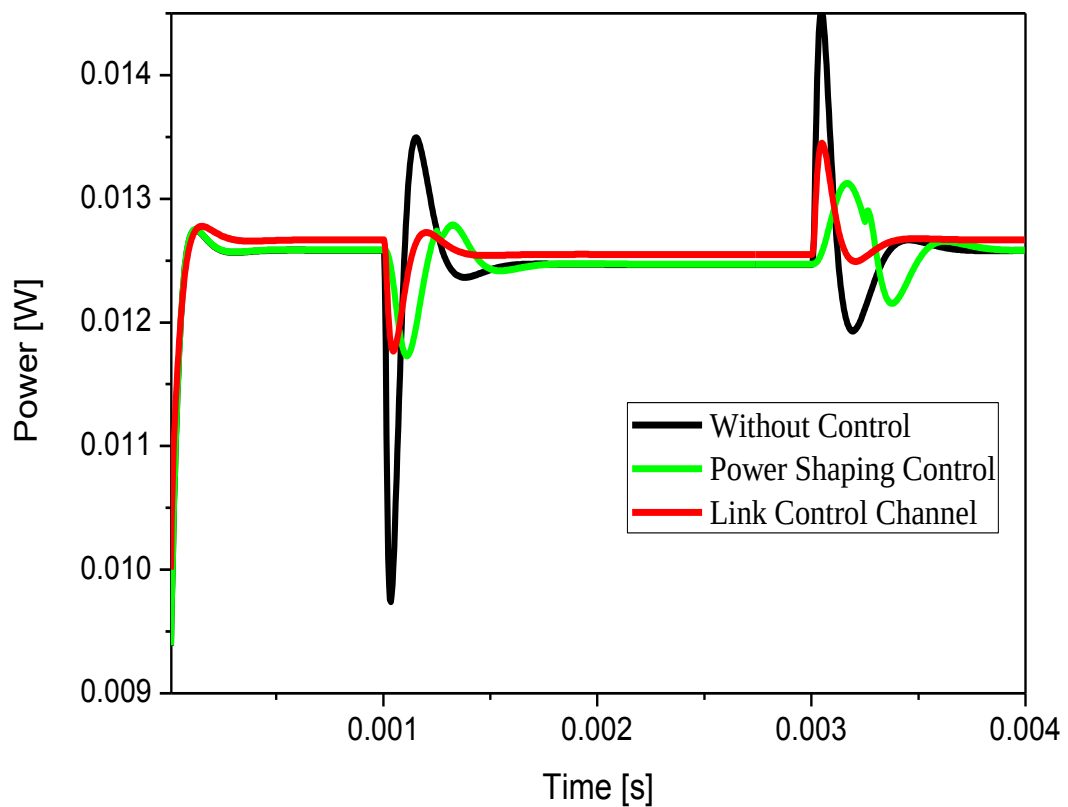


Figure 6.8: Comparison of Transient response with and without control methods.

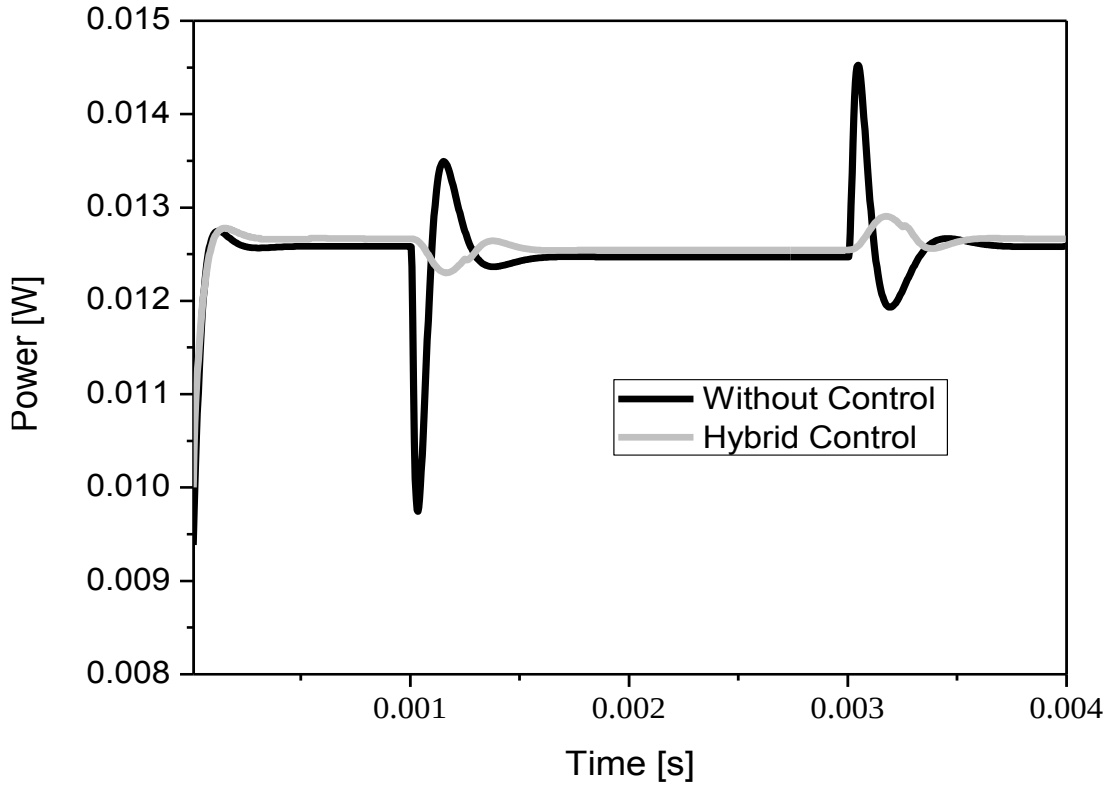


Figure 6.9: Supersession of transience response using hybrid control.

6.4 Conclusion

In this chapter, various control methods have been addressed in order to mitigate the transient phenomena induced from Raman-EDFA HOA. Firstly, after taking the variation of amplifier parameters it is observed that by adjusting the EDFA length and pump power the total power excursion of surviving channel is decreased from 1.07 dBm to 0.6 dBm and 0.62 dBm to 0.34 dBm, respectively. Then using the proposed hybrid control module, which is a combination of link control and power shaping, better suppression (i.e. 0.6 mW and 0.9 mW) is observed as compared to power shaping and control channel, respectively. But the transient is not only the effect to be examined, the non-linear crosstalk is also the important parameter to investigate and to confirm that the crosstalk induced by the proposed amplifiers are at acceptable level before its implantation into the system. In further study, the crosstalk effect has taken into the account and investigate the various sensitive parameters; such as input power, word length etc.; on which the crosstalk highly depends.

Chapter 7

Crosstalk Investigation of Hybrid Optical Amplifiers in DWDM System

7.1 Introduction

This chapter focuses on the crosstalk investigation of hybrid optical/ waveguide amplifiers in DWDM system at reduced wavelength spacing, which is related to the fourth objective of the research work. The basic aim of this work is to check the induced crosstalk level of the hybrid optical/ waveguide amplifiers (such as the different combinations of Raman and EDFA, EYWDA-SOA HA etc.) which is proposed in Chapter 3 and 4. Further, impact of input power and word length of bit pattern on nonlinear crosstalk has also been examined. It is observed that the proposed HOAs and HWAs induces acceptable level of crosstalk. On the basis of these investigations, the proposed amplifiers are recommended for future high capacity DWDM long haul applications.

7.2 Impact of the Input Power and Word Length on Nonlinear Crosstalk Induced by HOAs

In Chapter 3 and 4, various hybrid optical and waveguide amplifiers are designed, but still the distortion in data pulses are present because of crosstalk between the transmitted symbols. There are various reasons behind the crosstalk that is (i) it is induced due to the rapid gain excursion of optical amplifiers [139]. (ii) it is induced due to amplifier nonlinearities (such as SRS, FWM, SPM, XPM etc.) which changes the parameters of transmitted signal statically since it depends on the other remaining optical signal propagating through same fiber [140], [141], [142]. So it is mandatory to investigate the level of crosstalk before the implantation of proposed amplifiers in various applications. In Raman amplifier, the closely spaced channels are affected by the SRS which yield undesired nonlinear crosstalk. The power level of bit “1” in the individual pattern is changed due to amplification or attenuation as a result of SRS, which degrades the BER performance [143].

In optical communication system, generally the pseudorandom bit sequence (PRBS) are used as data signals for modulating the DWDM channels. The longer word length (WL) develops the more bit patterns in PRBS. The selection of number of bits in PRBS directly

affects the system performance because longer the WL means easy to evaluate the performance, on the other hand, shorter the WL means condense the calculation time and the memory requirements. Therefore, it is essential to illuminate how long the WL is vital to estimate the nonlinear crosstalk's precisely. In literature, various crosstalk investigations have been done by using several optical amplifiers, such as, SOA [144], EDFA [145], and Raman amplifier [146]. Unfortunately, these transmission systems are limited to some specific parameters only. The influence of input power and the WL of data sequence were not considered, as these are important and sensitive parameters. Also the exploration of crosstalk brought by HOAs is not yet done [147]. In Chapter 3, several configurations of the optical amplifiers are proposed for a DWDM system and investigated the impact of the high bit rates at reduced channel spacing. In this section, the previous schemes have been extended by examining the crosstalk performance of hybrid amplifiers for different input powers and WLs.

7.3 Crosstalk Calculation

In literature, various formulas have been derived to calculate the crosstalk between channels propagating through same fiber and/or same optical amplifiers. One alternative to calculate the amplifier crosstalk between two input channels is when only one of them is modulated. On the other hand, in other method the amplifier crosstalk can be calculated when both input signals are modulated. In this study, the second method is used to estimate the crosstalk prompted by the proposed hybrid amplifiers. In this method, crosstalk is just a variation in output power of first channel (λ_1) due to second when both are propagating and amplified through the same amplifier. Then the crosstalk can be calculated by [148]:

$$Crosstalk = \frac{p_{1,out}(p_{2,in} = off) - p_{1,out}(p_{2,in} = on)}{p_{1,out}(p_{2,in} = off)} \quad (7.1)$$

where $P_{1,out}$ is amplified output power, $P_{2,in}$ is input power, and index 1 and 2 are two signal wavelengths. Of course, P_1 and P_2 are all modulated signals.

As the previous formula is used to calculate the crosstalk between two channels only, the multichannel crosstalk can be calculated from [149]:

$$C_i = 10 \lg \frac{P_{C_i}(L, \omega_{0_i})}{P_i(L)} \quad (7.2)$$

where $P_{Ci}(L, \omega_{0i})$ is the crosstalk power in channel i which caused by other channels. ω_{0i} is the signal frequency of channel i .

7.4 System Setup and Results

The block diagram of proposed setup in the presence of different hybrid amplifiers is shown in Figure 7.1. In this Section, initially crosstalk is calculated by using equation (7.1) and then further the multichannel crosstalk can be calculated from equation (7.2). In first case, two CW lasers are considered as a light source to compute the amplifier crosstalk. The sine square amplitude modulator with excess loss of 3 dB is used to modulate the optical signal with respect to pre-coded NRZ data which is transmitted at 10 Gbps of speed. Further, these modulated signals are amplified by the proposed hybrid amplifiers (see Section 3.2).

The several parameters of EDFA and Raman are defined in Table 7.1 and 7.2. The optical signal analyzers are used to measure the power (just after and before the HOAs) as per the requirement of given formula in equation (7.1).

Table7.1: Parameters of Raman amplifier.

Parameters	Value
Single mode fiber length	100 Km
Attenuation	0.2 dB/Km
Pulse broadening factor	16 ps/nm/Km
Effective Temperature	300 K
Pump Wavelength	1453 nm
Pump power	500 mW

Table7.2: Parameters of EDFA.

Parameters	Value
EDFA type	Fixed output power
Output power	32 mW
Gain shape	Flat
Noise figure	4 dB
Maximum small signal gain	35

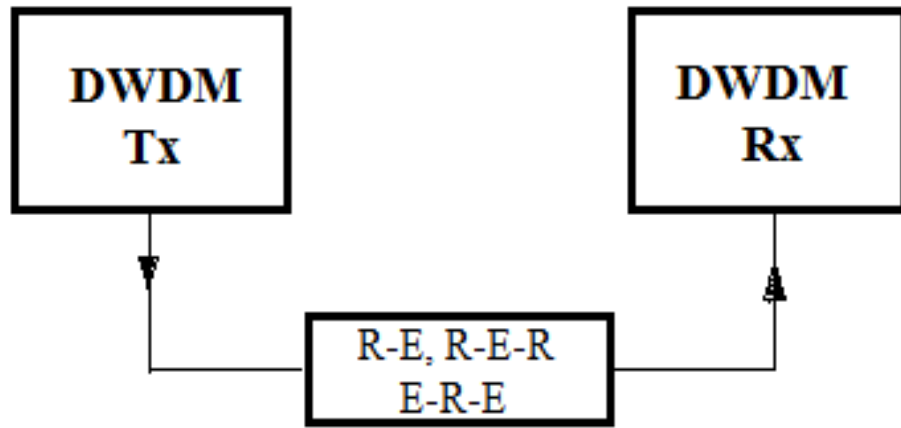
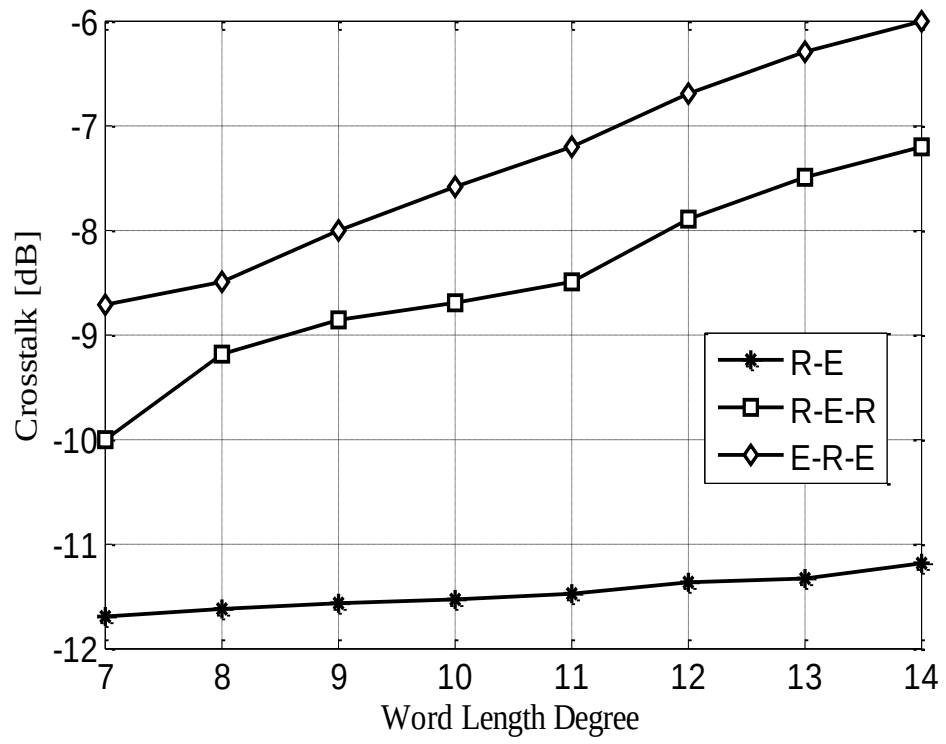


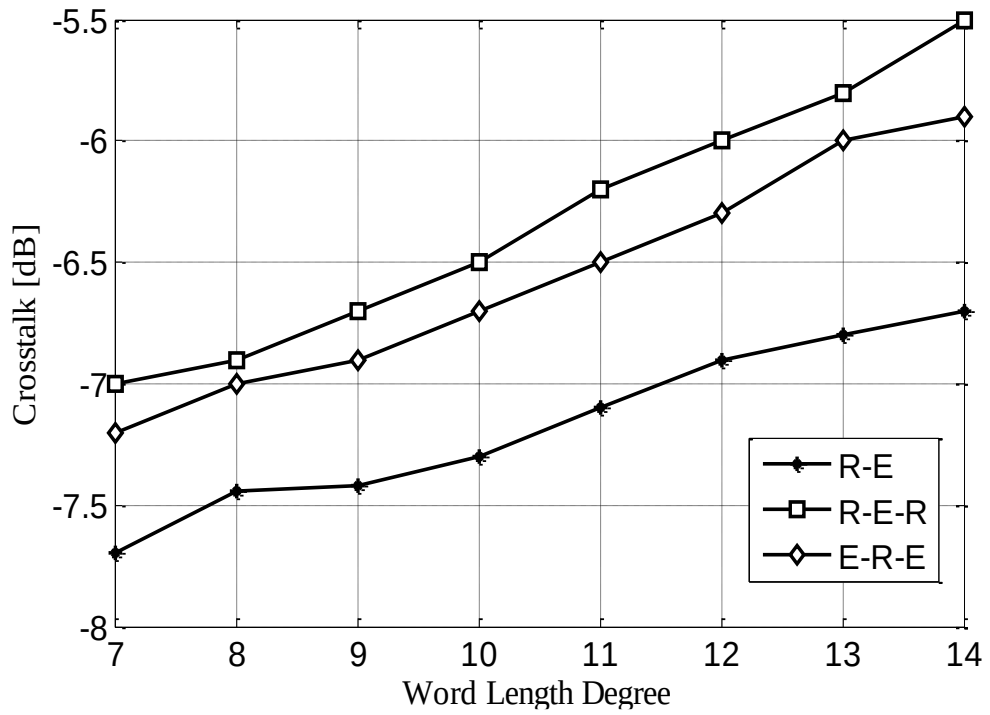
Figure 7.1: System setup.

7.4.1 Influence of Word Length and Input Power on Crosstalk Induced by HOAs

In this Section, the crosstalk from several HOAs has been calculated from equation (7.1) and (7.2) and further the impact of input power, channel spacing and WL is observed. In the scheme of 0.2 nm channel spacing the optical sources are tuned at 1550 nm and 1550.2 nm, respectively. On the other hand, 1550 nm and 1550.4 nm wavelengths are used in 0.4 nm of channel spacing. The crosstalk is calculated for different PRBSs with WLs of $2^{\text{degree}-1}$, where degree of the word length varies from 7 to 14 with single interval. Figure 7.2 (a) and 7.2 (b) shows the impact of WL and channel spacing on amplifier crosstalks, respectively. It can be observed that the crosstalk is sensitive to WL of PRBS sequence due to which the upturn in crosstalk with respect to increment in WL is observed. The major reason behind it can be the SRS, which depleted the “1” bit of a given channel due to the engrossment of other channel data (specifically “1” bit) propagating through same Raman fiber; it shows good agreement with [150], [151]. The SRS crosstalk can be increased due to the presence of successive number of “1” bits, which is directly proportional to the WL as it determines the maximum possible length of the successive ‘1’ bits. That means longer the WL, maximum the probability of occurrence in successive “1s”. From these results it can be reported that the Raman amplification dominates the optical communication system due to the error-generating mechanism yields from SRS crosstalk [152], [153].

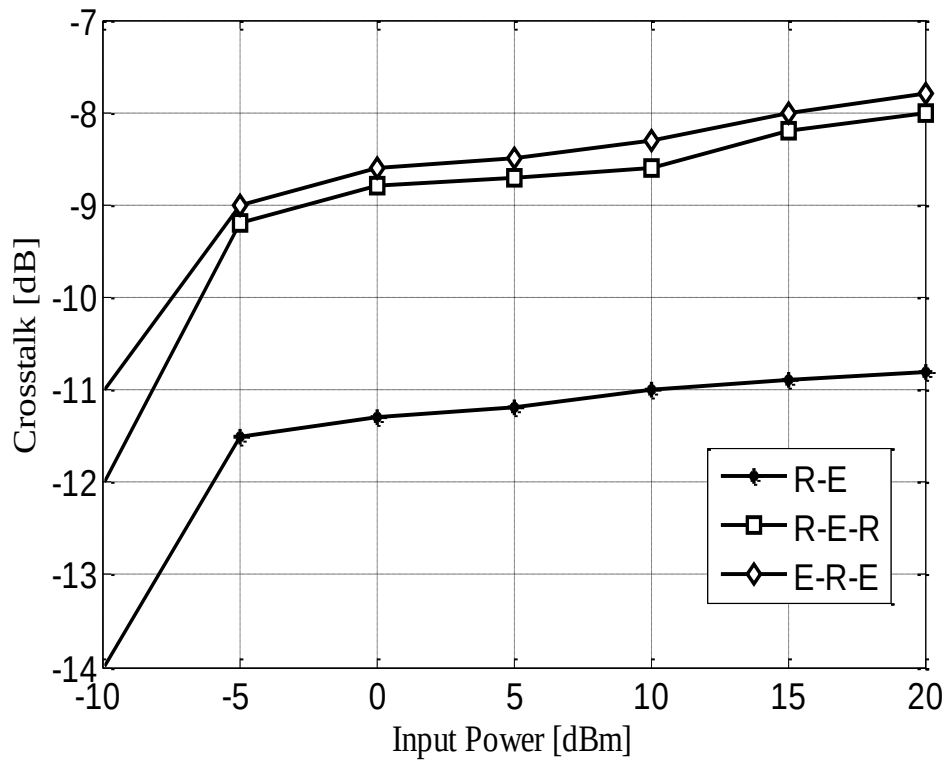


(a)

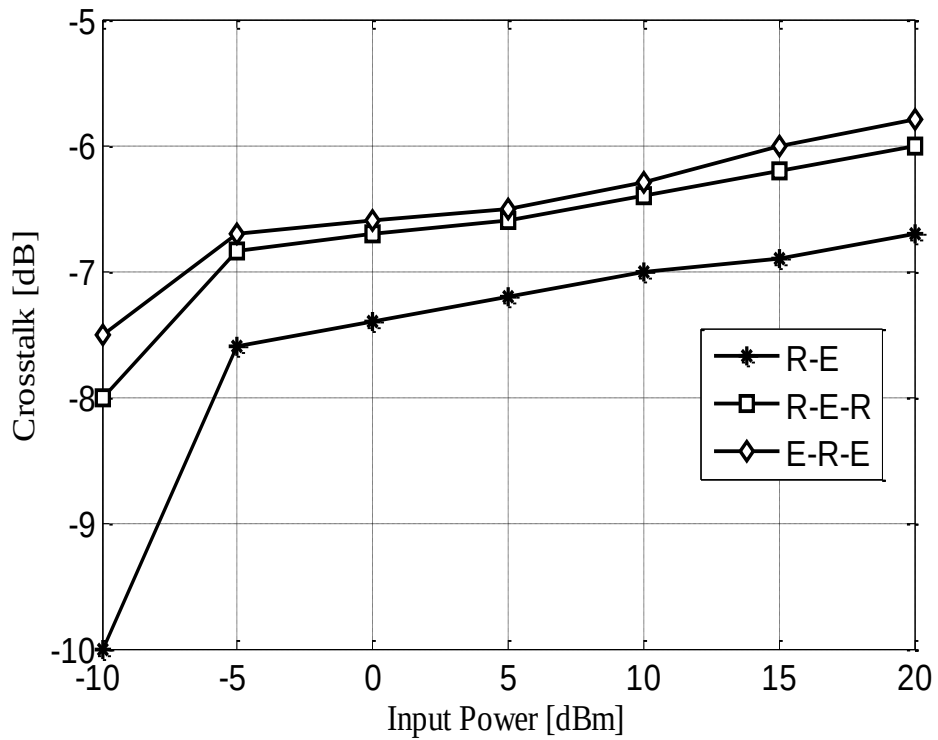


(b)

Figure 7.2: Crosstalk variation with respect to different WLs and channel spacing that is (a) 0.4 nm and (b) 0.2 nm.



(a)



(b)

Figure 7.3: Crosstalk variation with respect to input power and channel spacing that is
(a) 0.4 nm and (b) 0.2 nm

In this work, the other nonlinear effects (such as group velocity dispersion and XPM) have not been considered because of its little dependency on the WL [150]. After crosstalk comparison it is observed that the hybrid Raman and EDFA shows least crosstalk as compared to other configurations because it consists of less number of cascaded amplifiers. The same system setup has been considered with the WL of 2^7-1 to further check the impact of input power with different channel spacings on amplifier crosstalk. Figure 7.3 shows the variation in crosstalk as function of input power for R-E, R-E-R and E-R-E HOAs. The crosstalk increases with respect to the higher value of input power due to the gain saturation of used amplifiers, as also reported in [148]. Again R-E HOA shows the least crosstalk in the range from -14 dB to -11.2 dB and -10 to -7.2 dB for 0.4 and 0.2 nm of wavelength interval, respectively.

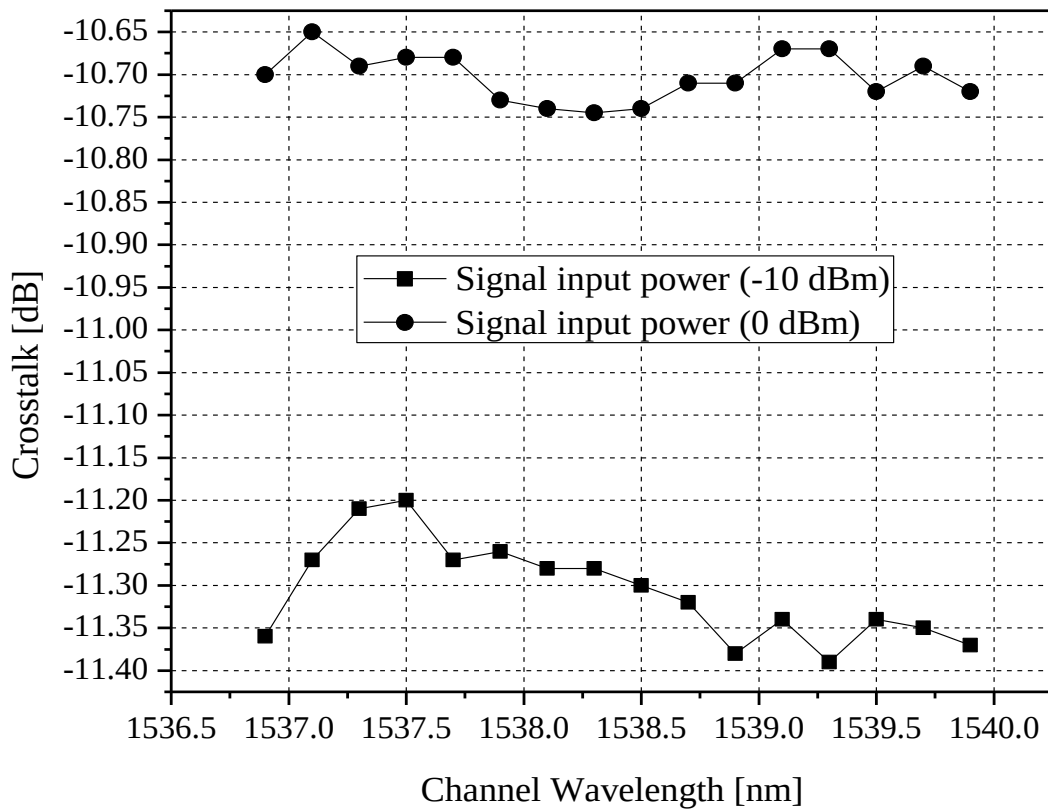


Figure 7.4: Variation in crosstalk over the effective bandwidth.

From above results it can be seen that the hybrid Raman-EDFA shows better results after reporting least crosstalk. This investigation shows the virtuous settlement with the results reported in Chapter 3. To further check the performance of proposed setup in electrical domain, the Tables 7.3 determined eye closure and Quality factor performance for both 0.4

and 0.2 nm of channel spacing, respectively. In this case, again R-E provides better results after reporting least eye closure (< 0.12 dB) and high Quality value (> 37 dB).

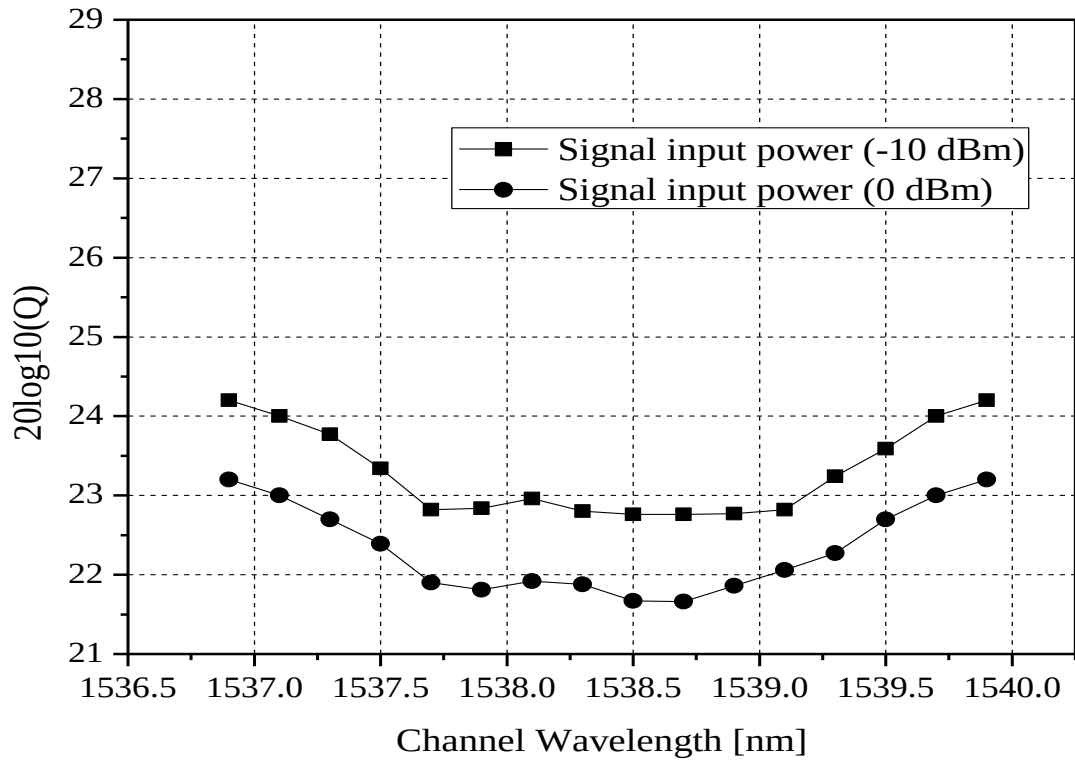


Figure 7.5: Variation in Quality values over the effective bandwidth.

Table 7.3: Variation of performance parameters of HOAs for 0.4 nm and 0.2 nm of channel spacing.

Amplifier name	0.4 nm of channel spacing		0.2 nm of channel spacing	
	Quality Factor (dB)	Eye Closure (dB)	Quality Factor (dB)	Eye Closure (dB)
R-E	39.34	0.12	37.99	0.15
R-E-R	34.18	0.23	20.60	1.36
E-R-E	35.76	0.16	26.44	0.53

To illustrate the performance of hybrid Raman-EDFA in DWDM application, the 16×10 Gbps system is deliberated at 0.2 nm of channel spacing. This system has been taken with $2^7 - 1$ of WL and -10 dBm of input power/ channel, rest of the parameters remain same. The multichannel crosstalk has been calculated using equation (7.2). Figure 7.4 represented the variation of hybrid R-E crosstalk among the used 16 DWDM channels. It can be observed that the crosstalk is not uniform among the wavelength grid. This is because of power

difference between used channels at input side of proposed Raman-EDFA HOA and further large variation is observed at the output side due to the rapid gain dynamics of both amplifiers. Still the proposed amplifier shows the acceptable crosstalk (< 10 dB) for all the channels and further better quality of signals are observed in Figure 7.5.

7.5 Crosstalk Investigation for Proposed Hybrid EYDWA-SOA Plus Raman-EDFA (in Section 5.2)

After characterizing the proposed amplifier, in the term of gain, gain flatness, the effect of crosstalk is presented in this Section. Due to the gain dynamics induced by EYDWA-SOA plus DRA-EDFA, the alteration of pulse profiles and then crosstalk among the data codes is present. The induced crosstalk directly affects the bit error rate performance of the system resulting from amplifier nonlinearities (such as XPM, FWM, SPM etc.). In Figure 7.6 the variation of bit error rate among the DWDM channels is detected due to crosstalk between the data symbols. But still, the proposed system provides acceptable bit error rate ($< 1 \times 10^{-9}$) over the effective bandwidth.

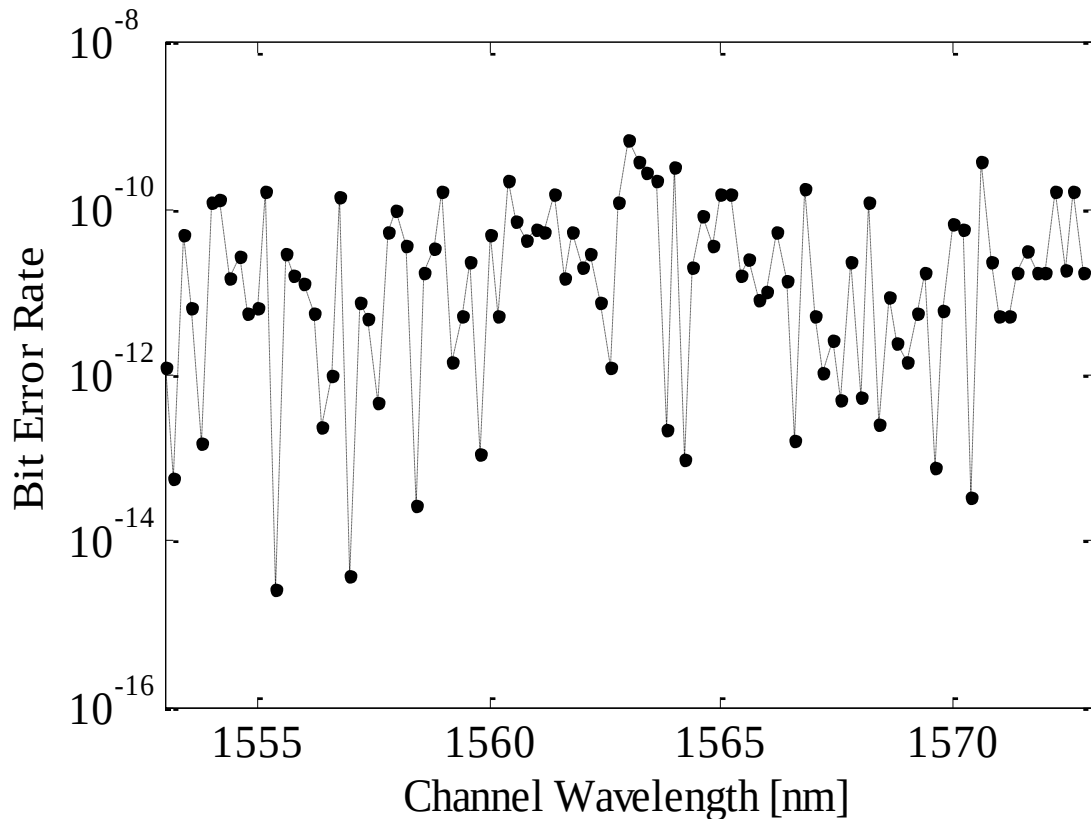


Figure 7.6. BER variation due to inter-channel crosstalk of DWDM channels induced by proposed setup.

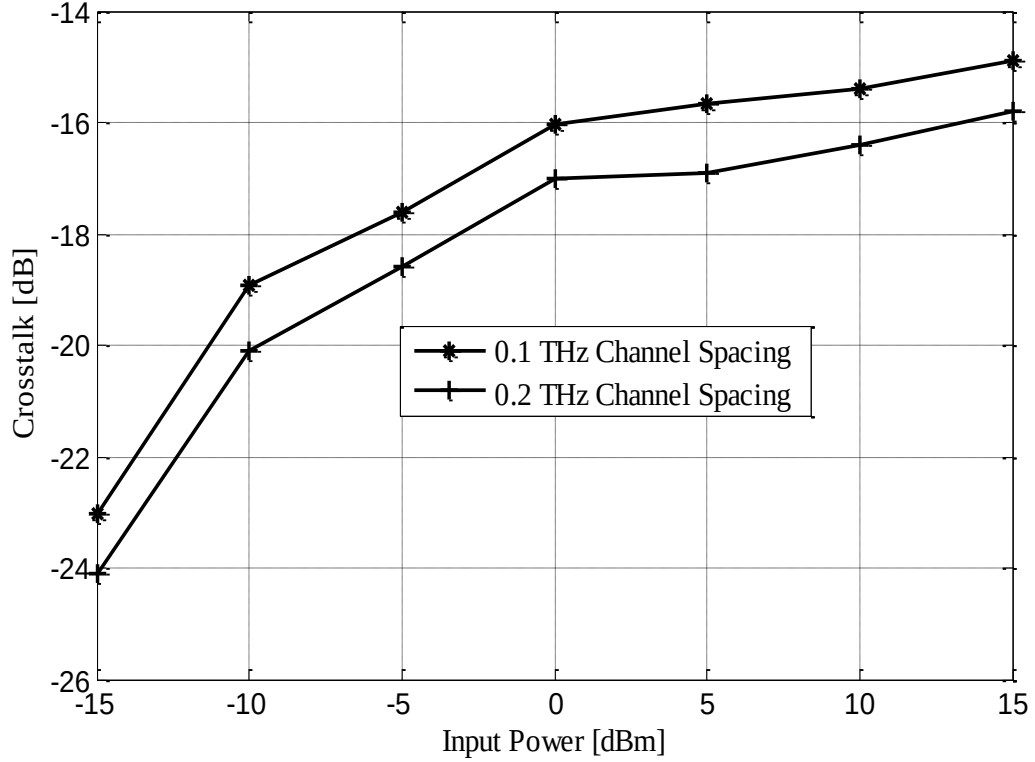


Figure 7.7: Crosstalk variations with different input laser power using R-E HOA.

7.6 Crosstalk Investigation for Proposed Raman-EDFA HOA in High Speed DPSK Modulating DWDM System (in Section 4.2)

To calculate the induced crosstalk the same concept and formula is used as in equation (7.1). The first two channels of proposed 16×40 Gbps DWDM system have been considered to compute the crosstalk. In this system, the hybrid Raman-EDFA induced its own crosstalk which varies at different channel spacings and input power. From Figure 7.7 it can be observed that the proposed HOAs induced acceptable crosstalk in the range from -23.1 dB to -15 dB and -24.1 dB to -15.8 dB for 0.1 THz and 0.2 THz of channel spacing, respectively. It is also observed that the crosstalk increases with respect to the higher value of input power due to the gain saturation of used amplifiers, as also reported in [148].

7.7 Crosstalk Investigation for Proposed Split C+L band Hybrid Waveguide Amplifier (in Section 5.3)

In this section, the crosstalk induced by proposed split band hybrid EDWA and EYDWA is presented for different input laser powers. To calculate the induced crosstalk the same concept and formula is used as in equation (7.1). As per previous results the same variation of

crosstalk is observed with respect to the input power, as shown in Figure 7.8. From this figure the little less crosstalk is observed in the case of EDWA.

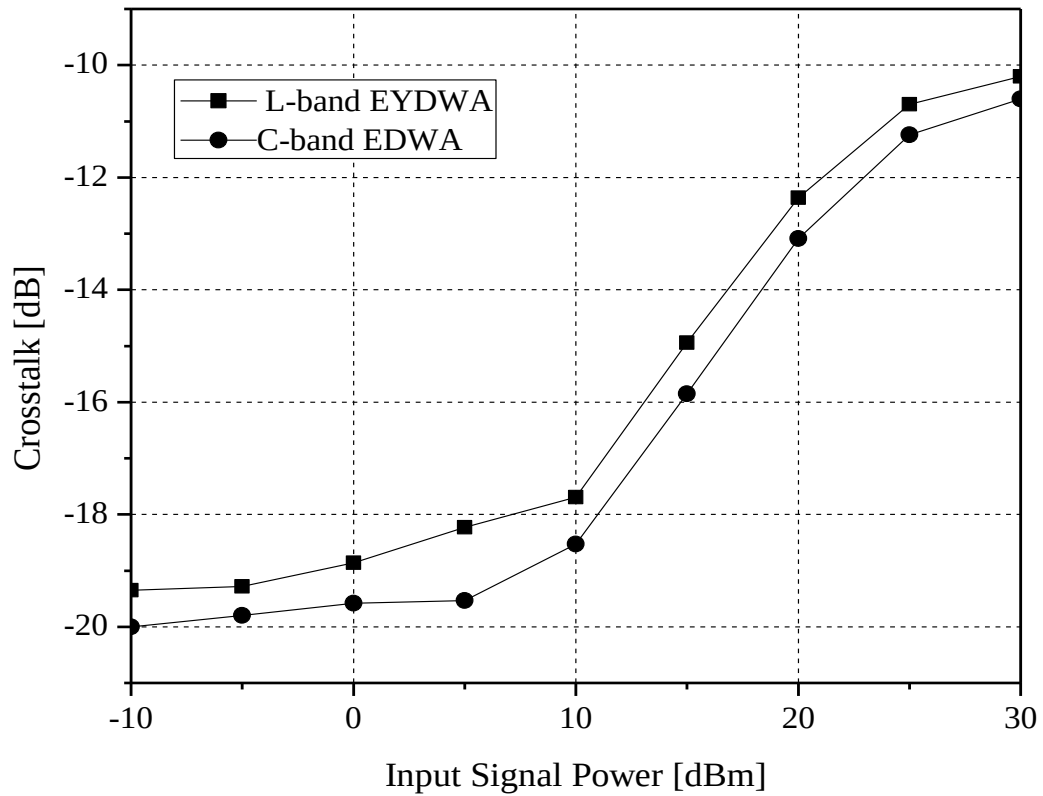


Figure 7.8: Crosstalk variation with different input power using split band HWA.

7.8 Conclusion

In this Chapter, the crosstalk effect has been investigated and confirmed that the proposed HOAs and HWAs induced lesser or acceptable crosstalk. Also the impact of input power and word length of bit sequence on induced crosstalk is studied. It is recommended that the hybrid Raman and EDFA is the best configuration as compared to other HOAs and can be used in a future high capacity DWDM system with lowest induced crosstalk even for longer WL and high input power. Moreover, the crosstalk induced by different proposed HOAs for various applications (such as Raman-EDFA in DPSK modulated system, EYDWA-SOA plus DRA-EDFA in DWDM system, split C+L band HWA for DWDM system etc.) have also been investigated.

Chapter 8

Conclusions, Recommendations and Future Scope

8.1 Conclusions

The hybrid optical amplifier is one of the possible way to amplify the broad gain bandwidth product with minimum gain variation among the channels. These amplifiers have been investigated with the purpose of identifying new applications and limitations for its use in future optical communication systems. This thesis focuses on the investigation of the various current problems (such as transient phenomena, gain variation, gain bandwidth product, crosstalk etc.) in HOAs for increasing the capacity, transmission distance and flexibility of DWDM communication system at reduced channel spacing.

The major results obtained from this study are summarized as follows:

1. The various HOAs are proposed for a DWDM system and the influence of reduced wavelength spacing is being explored. With respect to the overall performance in a transmission system, the Raman–EDFA HOA is brought out with being having the finest performance amongst the four types in the terms of eye closure, BER, quality factor etc. It is reported that the maximum single span distance of 220 km is achieved by the Raman–EDFA at acceptable BER (4×10^{-10}), quality factor (15.8 dB), and eye closure (2.23 dB). Then the best amplifier design, i.e. Raman-EDFA, has been investigated as 160×10 Gbps DWDM system to further characterize its performance in the term of gain, output power, gain tilt etc. With an input signal power of 3 mW, a flat gain of >10 dB is obtained for the frequency region 187 THz to 190.975 THz with a gain variation of less than 4.5 dB. This system is found to have a cost effective solution as the acceptable results has been obtained without using any expensive gain flattening techniques.

For optimization, a new analytical gain model of Raman-EDFA HOA is calculated and further the final gain equation is illustrated to optimize the multiple parameters using genetic algorithm. This algorithm has proven to be robust to refine the search of optimum Raman length, EDFA length and its pump powers required to the best configuration of proposed HOA. After simulation using optimum parameters (i.e. Raman length: 140.4 km, EDFA length: 12.5 m, Raman pump power: 232.3 mW and EDFA pump power: 390.6 mW) provides a flat gain

of >17.5 dB from the frequency region 187 THz to 190.975 THz with a gain variation of less than 1.48 dB.

2. In order to check the impact of proposed Raman-EDFA HOA in the scenario of high speed applications various system level investigations have been done to find the acceptable performance. The Raman-EDFA HOA has been investigated as a 16×40 Gbps DPSK-modulated system with different channel spacings. It is observed that the proposed HOA provides better performance even when 640 Gbps DPSK signals are transmitted over 100 km of Raman fiber amplifier without using dispersion compensating fiber. The improved performance is defined in the terms of speed, crosstalk, cost, crosstalk, gain flatness etc., after comparing it with the current state-of-the-art schemes.

For efficient utilization of bandwidth, a new optical modulation technique is suggested using which the two different data can be transmitted on the different dimensions of the single channel. Also the influence of hybrid Raman and EDFA on the proposed format has been checked. The offered two-dimension orthogonal modulation formats have a more compact spectrum and are more tolerant to noise than conventional modulation formats. The acceptable performance (in the term of BER, Q-factor and output power) is observed from even in the scenario of 8×20 and 20×20 Gbps DWDM systems. Further, the amplifier placement problem is studied with multiple types of amplifiers. It is observed that, using the optimized low cost Raman-EDFA HOA the numbers of conventional optical amplifiers are reduced over back-bone high capacity link. Although this increases the complexity of the amplifier-placement algorithm, but the numerical results show that certain networks do benefit significantly from this method by requiring fewer amplifiers.

3. The HA with flat-gain characteristics are proposed using a two stage configuration of EYDWA and SOA. With an EYDWA-SOA HA a flat gain of >14 dB is obtained across the effective bandwidth with a gain variation of ~ 0.75 dB, without using any gain clamping techniques. With the proposed EYDWA-SOA HA, the gain variation due to the DRA-EDFA HOA is reduced from ~ 2.01 dB to ~ 1.15 dB efficiently. We believe that this solution will bring excellent performance and will be suitable for the next generation DWDM network. To further increase the number of channels over multiple bands, a new HWA with flat gain characteristics is proposed using a two parallel stage

configuration of EDWA and EYDWA. With a hybrid EDWA and EYDWA, flat gain of > 14.3 dB is obtained across the effective bandwidth with a gain variation of 1.1 dB without using any gain clamping techniques. With the proposed HWA the gain and power variation due to the Raman-EDFA HOA is reduced from 7.2 dB to 3.1 dB and 6.3 dB to 2.4 dBm, respectively.

4. The transient effects resulting from the add-drop of channels in DRA-EDFA HOA have also been examined. It is observed that the dynamic response of the proposed HOA is mainly determined by the transients of the EDFA because it has the fastest response time. The surviving channel leads to about 0.4 dBm, 0.6 dBm and 1.25 dBm power excursion when 2, 4, and 6 channels are added/ dropped, respectively. To mitigate this problem, the EDFA pump power and length is changed from 9 mW to 4 mW and 10 m to 20m then the power excursion of surviving channel decreases from 1.07 dBm to 0.6 dBm and 0.62 dBm to 0.34 dBm, respectively. To further reduce the transience effect, a new hybrid control method is introduced by combining link control with power shaping technique. Using proposed control module better suppression, i.e. 0.6 mW and 0.9 mW, is observed as compared to power shaping and control channel, respectively.
5. To investigate the crosstalk effect induced by the HOAs, the impact of word length of bit pattern and input power has been checked. It is observed that the hybrid Raman-EDFA shows least crosstalk as compared to other proposed HOAs even for longer word length and high input power. Moreover, the crosstalk induced by different proposed HOAs for various applications (such as Raman-EDFA in DPSK modulated system, EYDWA-SOA plus DRA-EDFA in DWDM system, split C+L band HWA in DWDM system etc.) have also been investigated and confirmed that the proposed HOAs/HWAs induces acceptable level of crosstalk.

Therefore, this study establishes that the use of optimized HOAs in the optical communication networks results in revolutionary growth of internet traffic for large number of users and long transmission distance.

8.2 Recommendations

The following are some of the possible recommendations based on this research work.

1. The proposed configurations of HOAs are shown to be feasible alternative for DWDM system with a support of maximum number of channels at ultra-narrow channel spacing. Thus they can be used to amplify the backbone signals of future large scale networks which are spread over multiple bands (such as S, C and L etc.).
2. The proposed Raman-EDFA HOA is also suitable for high speed communication systems. Also, the offered hybrid modulation scheme is best, because it not only reduces the cost of the system, but also make the system bandwidth efficient with high bit rate which is not possible in the case of conventional modulation formats (such as NRZ, RZ etc.). It increases the number of users cost effectively, as two users can send their data on single channel simultaneously.
3. With the proposed Raman-EDFA HOA, the maximum transmission distance more than 2400 km is possible for 98 channel DWDM system at 25 GHz of channel spacing. Hence, this low cost amplifier configuration can be recommended for high capacity long haul DWDM transmission system as compared to complex or high cost regenerator and multi-pumped fiber amplifiers.
4. The hybrid distributed Raman and EDFA can also be used as broadband-amplifier to amplify backbone in up-scaled and highly dense LAN/ MAN.
5. After suppressing the transient effect using the proposed control methods, the designed Raman-EDFA HOA can be recommended in today's and future reconfigurable networks where the advanced band drop optical add drop multiplexers, optical cross connects etc. are used for dynamic routing and switching.

8.3 Future Scope

1. In the near future, we expect hybrid optical amplification to find use in long-haul systems using high bit rates of 40 Gbps per channel or more, where OSNR margins are small and HOAs can be effectively used to improve this margin and the reach of the system.
2. The new combination of Raman amplifier with other rare doped amplifier should be explored for covering much wider gain bandwidth product.

3. The research work can be extended by using residual pumping (single pump for both the amplifiers) which can further reduce the cost of the system.
4. As HOAs are having applications in wide area network as in-line amplifiers. The placement of optimum HOAs in different optical network topologies can be studied. The HOAs placement can also be explored in other broadcast topologies including multilevel topologies.
5. The simulation results for DWDM systems which were carried for systems with 98×2.488 Gbps of capacity for maximum transmission distance of 2450 km and channel spacing 0.2 nm using Raman-EDFA HOA in Chapter 4 can be enhanced further.
6. The leading challenges of HOAs in the coming years will continue to be the low power efficiency of the amplifier, the high cost of the pumps and issues related to safety and risks of having high optical powers in the field. The latter could be a major problem in access and FTTHs networks, where optical fibers are located in much more accessible areas (cable masts and interior boxes in houses) and human interaction with the fiber is more likely. Security and monitoring of these systems will be essential for a more widespread use of the HOAs in the coming years.

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