OPTICAL TIME DIVISION DEMULTIPLEXING USING THE GAIN SATURATION EFFECT OF SEMICONDUCTOR OPTICAL AMPLIFIER

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Md Neamul Hasan

Department of Electrical and Electronic Engineering

Bangladesh University of Engineering and Technology

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Abstract

A novel model for an OTDM demultiplexer based on Cross Gain Modulation in a SOA is developed. Analysis is carried out to evaluate the performance of the OTDM demultiplexer in terms of output signal corresponding to '0' and '1' bit of the desired OTDM channel. Expression is developed for the output signal current and noise currents when an optical direct detection receiver used to receive the demultiplexed signal. The expression for Signal to Noise Ratio and Extinction Ratio and BER are also derived. Performance results are evaluated numerically for operation at different bit rates of a particular channel considering Amplified Stimulated Emission (ASE) and photo detector (shot) and receiver (thermal) noise. The results are presented in terms of BER versus pump power at different bit rates for various input signal power level. The receiver sensitivity at specific BER and the output ER are also evaluated for different bit rate. It is found that at a given signal input power the BER can be reduced by increasing the pump power and the required pump power is higher at higher level of input power. It is noticed that BER decreases with increase in pump power at a given signal power level. It is also found that at a given BER the required signal power is higher when the pump power is increased. It is clearly found that the required values of signal power are within the normal operational range of signal levels in a direct detection receiver. It is further, noticed that there is significant increase in extinction ratio at higher bit rate as it requires higher pump power at a given signal power at higher bit rates at a given BER (say, 10^{-9}).

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List of Symbols

$a_{k,j}$	k-th bit of j-th OTDM channel frame
A_{eff}	Effective core area
B_o	Optical Bandwidth
B_e	Receiver Bandwidth
E	Electric field
g_0	Gain coefficient per unit length
G	Gain of SOA
G_s	Single pass gain
k	Boltzman constant
$I(z)$	Optical intensity
I_s	Saturation intensity
I_p	Photo current
I_d	Dark current
L	Fiber length
L_{eff}	Effective fiber length
N	Number of channels
n_g	Group index of the cavity
n_{sp}	Population inversion factor
P_{sat}	Saturated optical power
P_s	Average optical signal power
P_{cross}	Crosstalk power
P_{sp}	Spontaneous emission power
q	Electron charge
R	Reflection coefficient of cleaved facet
T	Absolute room temperature in degree Kelvin
ε	Extinction ratio
$h\upsilon$	Photon energy

σ_{th}^2	Thermal noise
σ_{shot}^2	Shot noise
Γ	Optical Confinement factor
$\Re$	Responsivity
α	Attenuation constant of fiber
λ	Wavelength

List of Abbreviations

ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
CDMA	Code Division Multiple Access
DMUX	Demultiplexer
DWDM	Dense Wavelength Division Multiplexing
dB	decibel
FDM	Frequency Division Multiplexing
FPA	Fabry-Perot Amlifier
LASER	Light Amplification by Stimulated Emission of Radiation
MUX	Multiplexer
NF	Noise Figure
OA	Optical Amplifier
OFA	Optical Fiber Amplifier
OTDM	Optical Time Division Multiplexer
SCM	Subcarrier Multiplexing
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
TDM	Time Division Multiplexing
TWA	Traveling Wave Amplifier
WDM	Wavelength Division Multiplexing

Chapter-1

Introduction

Advancement in communications technology and communications services has triggered a global voracious appetite for bandwidth. Yesterday, downloading an image over the Internet, even it took several minutes, was exciting; today, one or more mere seconds are annoying. Yesterday, accessing scanty news from a distant country by clicking the mouse was a challenge; today, broadcasting the news as it happens with real time video is normal thing even in remote and ragged areas. Contrasting today's and yesterday's advancements can go on and on. Yet, today's advancements are made possible because of ever shrinking electronics, increasing processing power at lower cost, making it possible new services to emerge for mobility and easy access and because of optical technology that enables network to transport over a single strand of fiber a huge aggregate bandwidth. However, we should keep in mind that today is yesterday's future and tomorrow's past.

Optical communications is an extremely fast growing technology driven mainly by increasing need for global expansions of the Internet and multimedia communications [1-4]. Fiber optic communications have provided us with high speed communications with enormous bandwidth potential. Only the huge bandwidth of optical fiber seems to be able to accommodate the increasing amount of network traffic today and much more in the future.

The efficient use of this finite optical bandwidth is of imperative importance in order to meet the future data capacity needs. The wavelength Division Multiplexing (WDM) technique is a very promising solution for the effective exploitation of the optical spectrum. Use of WDM technology can simply and cost effectively multiplies the capacity of the already installed fiber infrastructure by increasing the number and spectral efficiency of the employed wavelength channels.

1.1 Optical Multiplexing Schemes

In order to maximize the information transfer over an optical fiber communication link it is usual to multiplex several signals on a single fiber. There are several types of multiplexing techniques in optical communication system as discussed below [1-3].

1.1.1 Optical Frequency Division Multiplexing

In OFDM optical carriers are modulated by baseband signal and a number of optical channels are combined by frequency division multiplexing (FDM) and passed through the same fiber [1-3]. In FDM the optical channel bandwidth is divided into a number of nonoverlapping frequency bands and each signal is assigned one of these bands of frequencies.

1.1.2 Optical Time Division Multiplexing

Digital pulse modulation schemes may be extended to multichannel operation by time division multiplexing (TDM) narrow pulses from multiple modulators under the control of a common clock [1]. Pulses from the individual channels are interleaved and transmitted sequentially, thus enhancing the bandwidth utilization of a single fiber link. A block schematic of an OTDM system is shown in figure 1.1. The principle of this technique is to extend time division multiplexing by optically combining a number of lower speed electronic baseband digital channels. In figure 1.1, the optical multiplexing and demultiplexing ratio is 1:4, with a baseband channel rate of 4 Gbit s^{-1}. Hence the system is referred to as a four channel OTDM system.

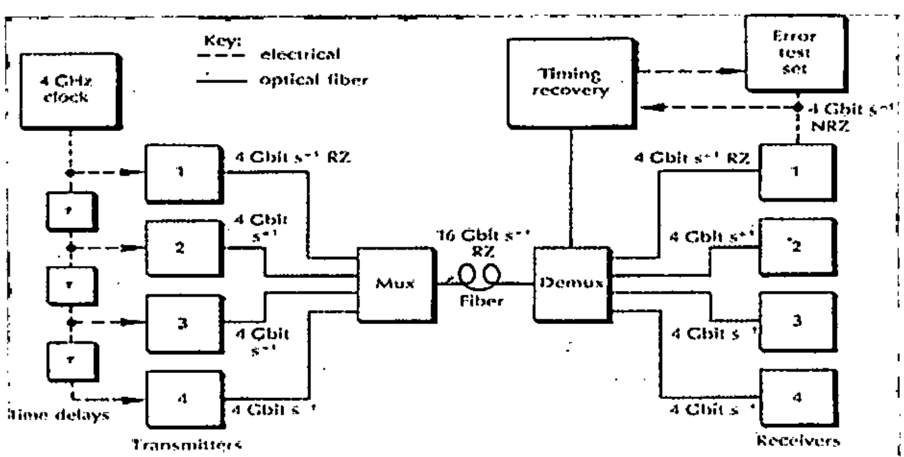

Figure 1.1: Four channel OTDM fiber optic transmission system

1.1.3 Subcarrier Multiplexing

The utilization of substantially higher frequency microwave subcarriers multiplexed in the frequency domain before being applied to intensity modulate a high speed injection laser source has generated a significant interest. Such microwave subcarrier multiplexing (SCM) enables multiple broadband signals to be transmitted over single-mode fiber and appears particularly attractive for video distribution system [1].

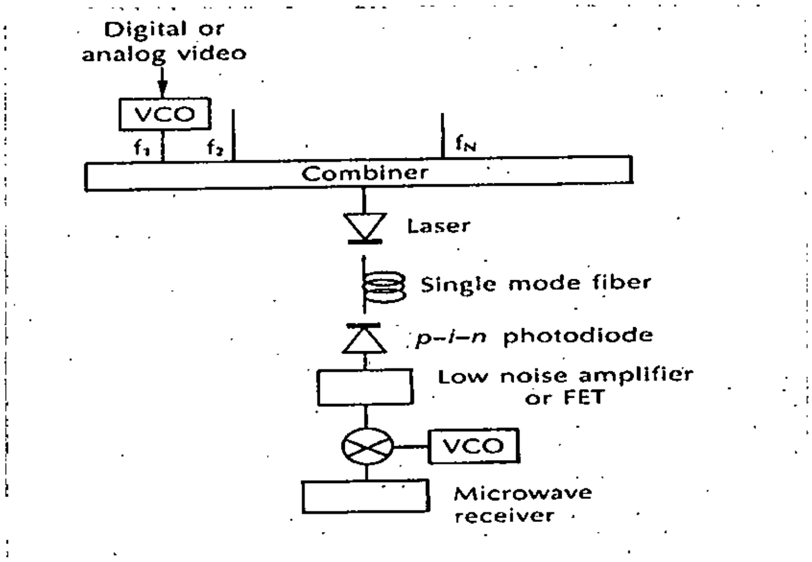

Figure 1.2: Basic subcarrier multiplexed (SCM) fiber system

1.1.4 Wavelength Division Multiplexing

It is also possible to utilize a number of optical sources each operating at a different wavelength on a single fiber link. Wavelength division multiplexing (WDM) involves the transmission of a number of different peak wavelength optical signals in parallel on a single optical fiber [2].

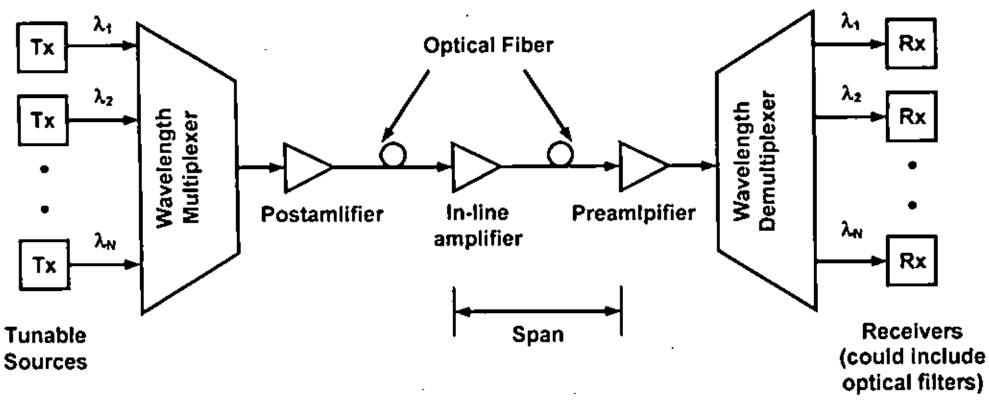

Figure 1.3: A typical WDM network containing various types of optical amplifier.

WDM enables the utilization of a significant portion of the available fiber bandwidth by allowing many independent signals to be transmitted simultaneously on one fiber, with each signal located at a different wavelength. A key feature of WDM is that discrete wavelengths from an orthogonal set of carriers that can be separated, routed and switched without interfering with each other.

In a simple WDM system, each laser must emit light at a different wavelength, with all the laser's light multiplexed together onto a single optical fiber. After being transmitted through a high-bandwidth optical fiber, the combined optical signals must be demultiplexed at the receiving end by distributing the total optical power to each output port and then requiring that each receiver selectively recover only one wavelength by using a tunable optical filter.

The implementation of WDM networks requires a variety of passive and active devices to combine, distribute, isolate and amplify optical power at different wavelengths.

Passive Devices require no external control for their operation, so they are somewhat limited in their application in WDM networks. These components are mainly used to split and combine of top off optical signals. They include N×N couplers, power splitters, power taps and star couplers.

The performance of active devices can be controlled electronically, thereby providing a large degree of network flexibility. Active WDM components include tunable optical filters, tunable sources and optical amplifiers. Fig 1.3 shows the use of such components in a typical WDM link containing various types of optical amplifiers.

1.1.5 Optical Code Division Multiple Access

Output bit stream of data sources are coded through optical CDMA encoder using optical correlators and passed through optical coupler. Each user has its own signature sequence and output of the encoders are passed to a star coupler is distributed among users. Each user can decode the data from an optical channel using optical correlator receivers.

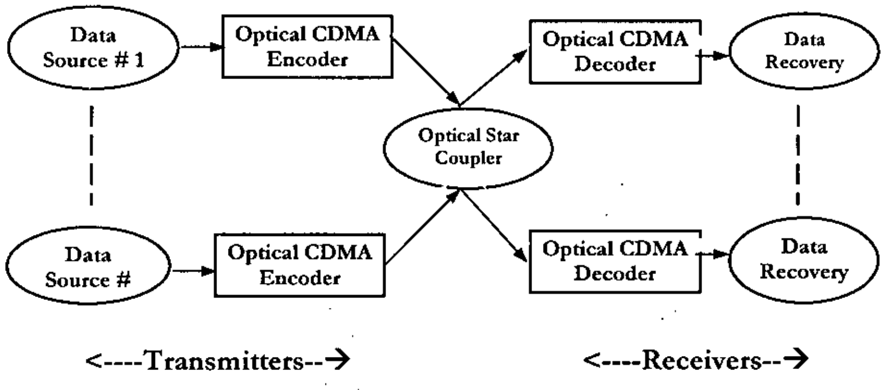

Figure 1.4: Optical CDMA network

1.2 Evolution of DWDM

Until the late 1980s, optical fiber communications was mainly confined to transmitting a single optical channel. Because fiber attenuation was involved, this channel required periodic regeneration, which included detection, electronic processing, and optical transmission. Such regeneration caused a high speed optoelectronic bottleneck and could handle only a single wavelength. In the early 90's optical amplifier ware developed, which enabled us to accomplish high speed repeater-less single channel transmission. Several different independent wavelengths can be transmitted simultaneously down a fiber to fully utilize the enormous optical bandwidth. WDM was emerged as a promising technique for opening the Terahertz transmission bandwidth in optical networks.

In WDM transmission, different data channels are modulated into the optical fiber with unique wavelength each [1]. Thus each data channel can be used to carry data independently with its own independent rate without any independence from other channels. Moreover, the overall bandwidth supported by the optical fiber is the sum of all the bandwidth supported by the individual data channels.

The first WDM systems only combined two signals, one channel is at 1.33 μm and the other is at 1.55 μm. Modern systems can handle up to 160 signals and can thus expand a basic 10 Gbps fiber system to a theoretical total capacity of over 1.6 Tbps over a single fiber pair.

1.3 **Optical Amplifiers.**

Optical signal experience attenuation as they propagate in a medium they are. In communications, any transmission medium be it wire, wireless or optical (other than purely free space), is characterized by certain amount of attenuation per unit length. Thus as the source transmits a known optical power level and the receiver at the other end of the path expects a lower power level because of attenuation. The optical power must be at a measurable level such that the signal is detected reliably and at an expected low bit error rate (~10^{-9} to ~10^{-11}).

Optical media (such as fiber) are characterized by *attenuation per kilometer*, or attenuation coefficient, α, provided in dB/km. Consequently knowing the power level at the source, P_S, and the expected power level at the receiver, P_R, one can easily calculate the total attenuation and translate it into an acceptable fiber length. If for simplicity we neglect other types of losses (due to dispersion, polarization, etc.) the fiber length is calculated as [4]:

$$L = (P_S - P_R) / \alpha \text{ (km)} \qquad (1)$$

Thus attenuation puts a limit on fiber length between source and receiver unless the optical power of the signal is amplified, typically every 40 to 80 km, compensating for losses and extending the source receiver distance.

Amplification of optical signal is a multistep process. The traditional way of doing it would first convert the optical signal to an electronic signal; the electronic signal would be retimed, reshaped and amplified (an operation known as 3R); and then it was converted back to an optical signal. This function is known as *regeneration.*

Direct amplification technologies have been developed and used, known as *optical amplifier* (OA), to directly amplify a weak optical signal. To date, the best-known are four, *semiconductor optical amplifier* (SOA), *optical fiber amplifier* (OFA), *Stimulated Raman amplifiers* and *Stimulated Brillouin amplifiers* [2]. Depending on application, each structure has its own advantages and disadvantages.

The key common characteristics of optical amplifiers are *gain, gain efficiency, gain bandwidth,* the *gain saturation* and *noise, polarization sensitivity* and *output saturation power.* Other characteristics are *sensitivity (gain and spectral response) to temperature* and other environmental conditions, *dynamic range, cross talk, noise figure, physical size,* and others.

- *Gain* is the ratio of output power to input power (measured in dB).
- *Gain efficiency* is the gain as a function of input power (dB/mW).
- *Bandwidth* is a function of frequency, and as such *gain bandwidth* is the range of frequencies over which the amplifier is effective.
- *Gain saturation* is the maximum output power of the amplifier, beyond which it cannot increase despite the input power increase.
- *Noise* is an inherent characteristic of amplifiers. In electronic amplifiers noise is due to (random) spontaneous recombination of electron-hole pairs that produces an undesired signal added to the information signal to be amplified. In optical amplifiers, it is due to the spontaneous light emission of excited ions.
- *Polarization* sensitivity is the gain dependence of optical amplifiers on the polarization of the signal.
- *Output saturation* power is defined as the output power level for which the amplifier gain has dropped by 3 dB.

Optical amplifiers introduce noise that contaminates the optical signal and thus decreases the signal-to-noise ratio (SNR) and influences the overall system performance. Therefore, it is important that noise characteristics of any amplifier be specified.

The noise figure (NF) of an amplifier is the dimensionless ratio of input SNR to output SNR of an amplifier [3]

$$NF = SNR_{in} / SNR_{out} \qquad (2)$$

In fiber optics communication systems, problems arise from the fact that no fiber material is perfectly transparent. The visible lights of infrared beams carried by a fiber are attenuated as they travel through the material. This necessitated the use of repeaters in spans of optical longer than above 100 kilometers.

1.3.1 Repeaters versus amplifiers

A conventional repeater puts a modulated optical signal through three stages: (i) optical-to-electrical conversion, (ii) electrical signal amplification, and (iii) electrical-to-optical conversion. Repeaters of this type limit the bandwidth of the signals that can be transmitted in long spans of fiber optic cable. This is because, even if a laser beam can transmit several gigabits per second of data, the electronic circuit of a conventional repeater cannot.

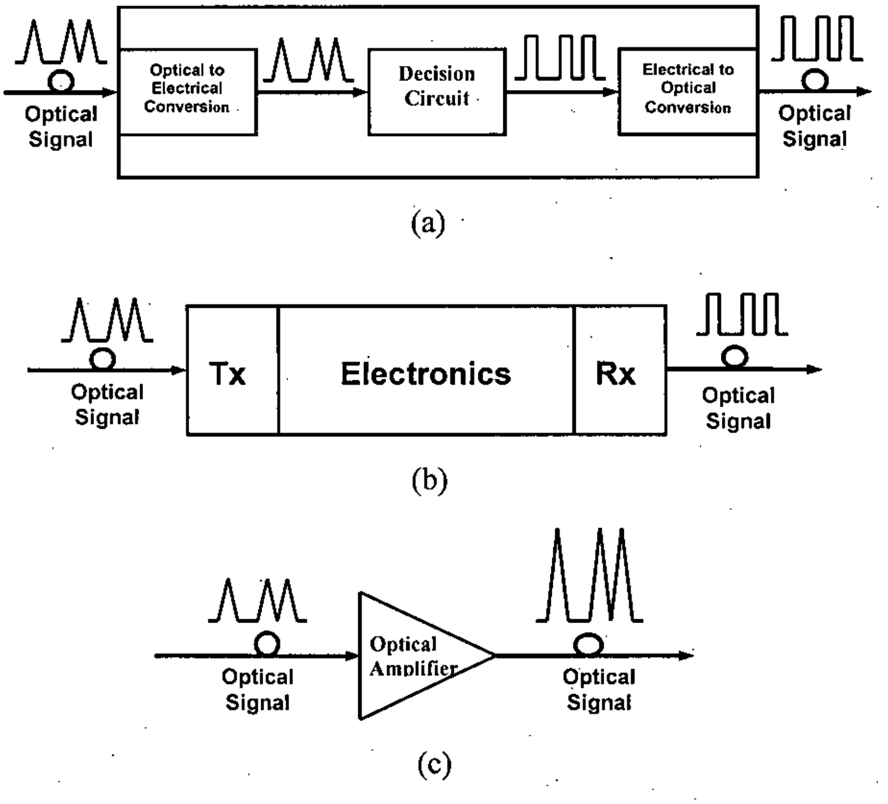

Figure 1.5: Repeaters and optical amplifiers, (a) functional block diagram of a repeater, (b) simplified diagram of a repeater, (c) optical amplifier.

On the other hand, optical amplifiers simply strengthen the optical signal, as shown in fig. 1.5. Optical amplifiers work without having to convert an optical signal into electrical from and back. This feature leads to two great advantages optical amplifiers over repeaters. First, optical amplifiers support any bit rate and signal format because, they simply amplify the received signal. Secondly, they support not just a single wavelength,, as the repeaters do, but the entire region of wavelengths.

1.3.2 Basic applications of optical amplifiers

Optical amplifiers are categorized in terms of the function they perform. The three basic types are boosters, in-line amplifiers and preamplifiers.

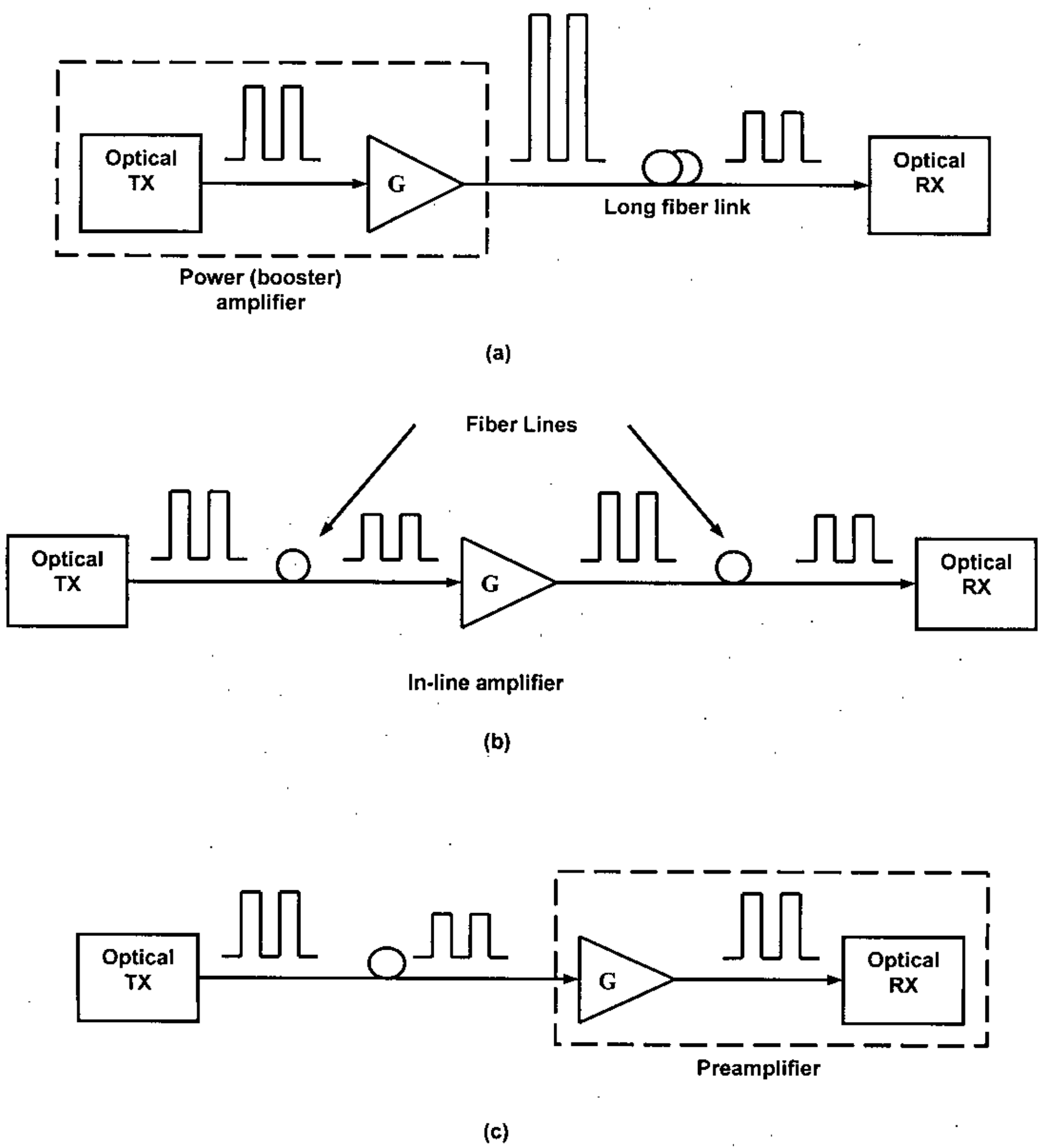

Figure 1.6: Applications of optical amplifier, (a) booster of transmitted power, (b) in-line amplifier to increase transmission distance, (c) preamplifier to improve receiver sensitivity.

A booster or post-amplifier is a power amplifier that amplifies a transmitter signal before sending it down a fiber. A booster raises the power of an optical signal to the highest level, which maximizes the transmission distance. The main requirement of this amplifier is to produce maximum output power, not maximum gain, since the input signal here is relatively large as it comes immediately from a transmitter.

A preamplifier amplifies a signal immediately before it reaches the receiver. This type of optical amplifier operates with a week signal. Hence, good sensitivity, high gain, and low noise are major requirements here. Noise becomes an extremely important feature of a preamplifier because a receiver's performance is limited by its own noise as well as by the noise of a preamplifier [2].

1.3.3 Types of optical amplifier

Two major classes of optical amplifiers are semiconductor optical amplifiers (SOA) [1] and fiber optical amplifier (FOA). A semiconductor optical amplifier is an active medium of semiconductor laser diode without or with very low optical feedback. The two basic SOA types are the Fabry-Perot amplifier (FPA) [1] and the traveling wave amplifier (TWA) [1]. A fiber optic amplifier is quite different from a semiconductor optical amplifier. It is a piece of fiber spliced with a transmission fiber and connected to a pump laser. Erbium doped fiber amplifier (EDFA) is of this kind. Both SOA and FOA work on the principle of stimulated emission.

There are other types of optical amplifiers which use nonlinear effects for amplification rather than stimulated emission. Two types of optical fiber amplifiers that are close to reaching practical implementation use the Raman and Brillouin effects. Using these effects would make it possible to build distributed, but not lump, amplification of an optical signal.

1.3.4 Semiconductor optical amplifiers

Semiconductor optical amplifiers (SOA) [1] are based on conventional laser principles; an active wavelength region is sandwiched between a p-region and an n-region. A bias voltage is applied to excite ions in the region and create electron-hole pairs. Then, as light of the specific wavelength is coupled in the active wavelength, stimulation takes place and causes electron hole-pairs to recombine and generate more photons (of the same wavelength as the optical signal), and hence optical amplification is achieved. In a different implementation, the active region is illuminated with photonic energy to cause the necessary excitation in the active region. For best coupling efficiency of the optical signal in the active region, the SOA end walls have been coated with an anti reflecting material.

Depending on the actual structure, SOAs are distinguished as:

- Semiconductor traveling wave laser optical amplifiers
- Fabry-Perot laser amplifiers
- Injection current distributed feedback (DFB) laser amplifiers

Semiconductor optical amplifiers (SOA's) are important components for optical networks. In the linear regime they can be used for both booster and in-line amplifiers, e.g., in the 1.3- m window [21]. On the other hand, potential use of SOAs' nonlinearities for all-optical signal processing has led to research in various application fields [11] and [16]. One application is demultiplexing and switching with use of an SOA as a nonlinear element in a short fiber loop, a configuration also known as terahertz optical asymmetric demultiplexer (TOAD) or semiconductor laser amplifier in a loop mirror (SLALOM) [5-6]. The potential of SOA's has led to the development of various theoretical models, e.g., [8-9]. A quite successful description of the SOA gain dynamics that includes the ultrafast gain dynamics and its saturation has been presented by Mecozzi and Mørk in [15]. One of the assumptions there is the spectral independence of the gain. A time-domain amplifier model based on the gain (and index) dynamics *and* taking into account the spectral gain profile for investigating and optimizing the performance of an SOA in a system environment.

1.3.5 **Cross-gain modulation**

When high optical power is injected into the active region and the carrier concentration is depleted through stimulated emission, *gain saturation* occurs and the optical gain is reduced. Based on this, let two wavelengths injected into the active region of an optical amplifier. Wavelength λ_1 is of high power and is on-off keying modulated with binary data, whereas wavelength λ_2, the target signal, is of lesser power and is continuous. When the input bit in λ_1 is logic 'one' the power is high and depletion occurs such that blocks λ_2, hence, λ_2 is at logic 'zero'. When the bit in λ_1 is logic 'zero' (no power), depletion does not occur and λ_2 passes at full power; hence λ_2 is logic 'one'. Thus a transfer of inverted data from λ_1 to λ_2 takes place. This is known as cross-gain modulation (XGM).

1.3.6 Limitations of optical amplifier

One of the severe disadvantages of optical amplifiers is that, they amplify the signal noise along with the signal itself. Moreover, the optical amplifier generates its own noise. The dominant noise generated in an optical amplifier is amplified spontaneous emission (ASE). Optical amplifiers are often to over come fiber losses in a log-haul light wave system. The buildup of amplifier induced noise is the most critical factor for such systems. Because, in a cascaded chain of optical amplifiers, the ASE accumulates over many amplifiers and degrades the optical signal to noise ratio (SNR) as the number of amplifiers increases. Again, as the level of ASE grows, it begins to saturate optical amplifiers and reduced the gain of amplifiers located further down the fiber link. The net result is that the signal level drops further while the ASE level increases and if the number of amplifiers is large, the SNR will degrade so much at the receiver that the bit error rate (BER) will become unacceptable. To achieve a required BER, the number of cascaded amplifiers will be limited when ASE noise level is increased [3].

Using optical fibers has other disadvantages like signal crosstalk between different wavelength channels when several channels are amplified simultaneously. The gain of amplifier is also dependent on intensity of input signal. The fluctuation of signal gain at other wavelength is a source of crosstalk when the amplifier is in saturation.

1.4 Literature Review

Optical amplifiers have become increasingly important in modern optical communication systems. Semiconductor optical amplifiers are excellent candidates for optical amplifications due to their advantages of simple structure and ease of integration. Significant amount of research works are reported in literature on the various applications of optical amplifiers [5-7]. There have been several research works on development of optical TDM (OTDM) multi/demultiplexers some of which are based on SOA [10-40]. Some recent research works on OTDM are outlined below.

J. P. Sokoloff et al. [5] presented a new device capable of demultiplexing Tb/s pulse trains. It requires less than one picojoule of switching energy and can be integrated on a chip. The device consists of an optical nonlinear element asymmetrically placed in a short fiber loop, Its switching time is determined by the off-center position of the nonlinear element within the loop, and therefore it can use the strong, slow optical nonlinearities found in semiconductors, which all other fast demultiplexers seek to avoid.

M. Eiselt et al. [6] presented detailed investigations on a device, which utilizes a semiconductor laser amplifier in a loop mirror configuration (SLALOM). Different modes of operation are reported like nonlinear single pulse switching and two-pulse switching at different operation speeds (1-100 Gb/s). Furthermore, a number of applications of the SLALOM in photonic systems, like pulse shaping, decoding, retiming and time-division demultiplexing, are presented.

S. J. B. Yoo [7] demonstrated various wavelength conversion techniques, discusses the advantages and shortcomings of each technique, and addresses their implications for transparent networks.

Liu Deming et al. [8] proposed and demonstrated a simple and new scheme of wavelength conversion in which the cross-gain modulation of amplified spontaneous emission of a semiconductor optical amplifier is used to convert the pump signal wavelength by means of the spectrum-spliced method. This technology allows pump wavelength to be converted into any other wavelength without using any probe light source.

T. Durhuus et al. [9] presented an advanced dynamic model for multi section semiconductor optical amplifier which account for the carrier and field distributions in the longitudinal direction as well as for the facet reflectivities. The crosstalk and intermediation distortion due to cascaded amplifiers are found to accumulate by adding together in amplitude which limits the number of cascaded amplifiers in multi channel systems.

G. Toptchiyski et al. [10] presented an advanced time-domain dynamical model for the investigation of semiconductor optical amplifiers (SOA). The model accounts for the ultrafast gain dynamics, the gain saturation and the gain spectral profile. It is also suitable for analyzing the amplifier in a system environment. The model can be applied to the investigation of other optically timedivision multiplexed (OTDM) applications.

S. Kawanishi et al. [11] presented recent progress in optical time-division-multiplexed (TDM) transmission technologies is reviewed including optical short pulse generation, time-division multiplexing/demultiplexing, timing extraction, and waveform measurement. The latest 400-Gbit/s transmission experiments based on optical signal processing are presented and the possibility of terabit/second TDM transmission is discussed.

R. Hess et al. [12] demonstrated a novel high-performance monolithic integrated Mach–Zehnder interferometer with semiconductor optical amplifiers (SOA's) in its arms and 80-Gb/s all-optical demultiplexing has been realized. Penalty-free operation for 40–10 Gb/s demultiplexing has also been achieved. A theoretical model which takes into consideration amplifier gain dynamics and pulse propagation describes the demultiplexing experiments and predicts the device performances also at higher bit rates.

A. A. M. Saleh et al. [13] showed that the nonlineanty inherent in semiconductor optical amplifiers can cause adverse system effects, such as intermodulation distortion (IMD) in FDM systems, crosstalk in on/off-keying WDM systems, and pulse distortion in multi-Gbit/s on/off keying systems. A practical, feed-forward linearization scheme that is capable of reducing these effects significantly is presented. A two-tone experiment confirms the reduction of the IMD by about 14 dB.

G. P. Agrawal [14] presented an analytic expression for the channel gains of a travelling-wave amplifier is used to discuss and compare the crosstalk for ASK and FSK systems. The relatively short carrier lifetime in high-gain amplifiers may ultimately limit the channel spacing of such multichannel systems.

A.Mecozzi and J. Mork [15] derived a very general and compact description of the amplifier dynamics in terms of an integral equation.

C. Joergensen et al. [16] experimentally analyzed that semiconductor optical amplifiers are used for efficient wavelength conversion up to 4 Gb/s. The rise and fall time as well as extinction ratio are. System performance at 4 Gb/s is evaluated showing a penalty of only 1.5 dB for the converted signal for conversion over 17 nm.

T. Durhuus et al. [17] presented an in depth analysis of cross gain and cross phase wavelength conversion in semiconductor optical amplifiers. The cross gain modulation scheme shows extinction ratio degradation for conversion to longer wavelengths. The first results for monolithic integrated interferometric wavelength converters are reviewed, and the quality of the converted signals is demonstrated by transmission of 10 Gb/s converted signals over 60 km of nondispersion shifted single mode fiber.

C. Joergensen et al. [18] presented the prospects for high-speed all optical wavelength conversion using the simple optical interaction with the gain in semiconductor optical amplifiers (SOA's) via the interband carrier recombination. Experiments at bit rates up to 40 Gb/s are presented for both cross-gain modulation (XGM) and cross-phase modulation (XPM) in SOA's demonstrating the high-speed capability of these techniques.

J. M. Tang et al. [19] have investigated the operating characteristics of the terahertz optical asymmetric demultiplexer (TOAD) devices subject to picosecond control pulses taking into account gain saturation and nonlinear gain compression, due to carrier heating and spectral hole burning.

J. M. Tang and K. A. Shore [20] investigated the propagation of strong picosecond optical pulses in semiconductor optical amplifiers (SOA's) numerically by taking into account carrier heating, spectral hole burning, and two-photon absorption, as well as ultrafast nonlinear refraction.

S. Reichel et al. [21] presented optical system simulation of a field trial at 1.3 m including attenuation, fiber dispersion, fiber nonlinearity and amplification by in-line semiconductor optical amplifiers (SOA's), amplifier noise and filtering. For the first time, simulation results in terms of saturation effects due to SOA's are compared with measurements obtained during a field trial in the network of the Deutsche Telekom, and show very good agreement.

P. Brosson, [22] introduced the spatial dependence of the material gain in the model of a semiconductor optical amplifier. Analytical expressions of the profiles of the carrier density, spontaneous emission, and amplified fields are obtained for amplifiers with arbitrary facet reflectivities. The model predicts the output saturation power and gain ripple, with good agreement with experimental results in resonant and traveling-wave amplifiers. Very low-gain ripple measured in low facet reflectivities amplifiers is explained by the model.

C. Henry [23] presented a theory of spontaneous emission noise based on classical electromagnetic theory. Unlike conventional theories of laser noise, this presentation is valid for open resonators. The theory is illustrated with applications to traveling wave and Fabry-Perot amplifiers and Fabry-Perot lasers. Several new results are found: optical amplifier noise increases inversely with quantum efficiency; spontaneous emission into the lasing mode is enhanced in lasers with low facet reflectivities; and the linewidth of a Fabry-Perot laser with a passive section decreases as the square of the fraction of the cavity optical length that is active.

C. Henry [24] presented a theory of the spectral width of a single-mode semiconductor laser and used to explain the recent measurements of Fleming and Mooradian on AlGaAs lasers It is found that the linewidth to be inversely proportional to power and to have a value of 114 MHz at 1 mW per facet.

K. Uchiyama et al. [25] investigated experimentally and theoretically the signal-to-noise ratio (SNR) characteristics of 100 Gbit/s all-optical demultiplexing using a nonlinear optical loop mirror (NOLM). The analysis takes into account two effects that degrade the SNR associated with NOLM demultiplexing. First is channel crosstalk originating from the leakage of non-target channels. Second is the intensity fluctuations of demultiplexed signals caused by the combined effects of timing jitter and a profile of the switching window. Considering these two effects, power penalties associated with NOLM demultiplexing are theoretically evaluated using the conventional noise theory of an optical receiver followed by an optical preamplifier. Experimental results of bit error rate measurements for 100 Gbit/s demultiplexing using three different NOLM's with different intrinsic crosstalk values, defined by signal transmittance in the absence of control pulses, show that the power penalties are in good agreement with the evaluation based upon proposed analysis.

I. Glesk et al. [26] reported the first demonstration of all-optical demultiplexing of TDM data at 250 Gbit/s. The demultiplexer, called a 'TOAD, is compact and requires sub-picojoule switching energy. Crosstalk measurements of pseudorandom data in adjacent, 4ps- width time slots, exhibit a BER of less than 109, with strong jitter immunity.

A. D. Ellis and D. M. Spirit [27] used a polarisation insensitive GaInAsP near travelling wave semiconductor laser amplifier as the nonlinear element in a nonlinear optical loop mirror. With this compact configuration. the authors demonstrated a continuously tunable switching window, and report, for the first time using semiconductor materials, error ratio measurements for a demultiplexing operation from 40 to 10 Gbit/ s. with a receiver sensitivity of -23 dBm.

K. Uchiyama et al. [28] presented a novel all-optical time-division demultiplexer capable of simultaneously outputting multiple channels at speeds of > 100Gbitk. Its operation is based on time-wise local chirp compensation of a down-chirped clock pulse through cross-phase modulation (XPM) induced by a signal pulse stream. Error-free, simultaneous six-channel-output, 100 to 6.3 Gbit/s demultiplexing is successfully demonstrated.

T. Morioka et al. [29] successfully demonstrated error-free 100 Gbit/s to 10 Gbit/s all-optical demultiplexing based on four-wave mixing (FWM) in a 300m polarisation-maintaining dispersion-shifted optical fiber is utilising low-noise 1 ps super continuum pulses with ultra-low timing jitter of < 100 fs.

T. Yamamoto et al. [30] successfully demultiplexed and routed for a TDM signal with two channels (2.62 Gbit/s × 2), each channel by using stimulated four-wave mixing in a dispersion-shifted fiber and a novel wavelength router consisting of optical circulators and fiber gratings. The advantages of this wavelength router are a sharp spectral edge and low insertion loss.

M. Eiselt et al. [31] demonstrated a novel, purely optical technique for demultiplexing high speed time division multiplexed data. The technique uses the SLALOM (semiconductor laser amplifier in a loop mirror). The data rate is not limited by the gain recovery time of the semiconductor laser amplifier. The same technique can also be used for multiplexing.

1.5 Objectives

The objectives of this research work are:

(i) To develop a novel analytical model of all optical TDM demultiplexer based on XGM of a SOA using the gain saturation effect.

(ii) To carryout the analysis of the OTDM demultiplexer considering intensity modulated OTDM signal and to find the expression for the output of the OTDM demultiplexer.

(iii) To carryout analysis to find the output of an optical IM/DD receiver to receive the demultiplexed optical signal and to find the output signal to noise ratio (SNR) taking into account the optical amplifier's spontaneous emission (ASE) noise.

(iv) To evaluate the bit-error-rate (BER) performance results at different bit rates for several system parameters.

(v) To find the optimum system parameters of an OTDM system using the OTDM demultiplexer.

1.6 Organization of the thesis

Chapter-2 gives the detailed analytical model and theoretical analysis of an OTDM demultiplexer with gain saturation effect of semiconductor optical amplifier along with the effect of amplified spontaneous emission noise.

Chapter-3 presents the results and discussion based on the theoretical analysis presented in Chapter-2.

Chapter-4 presents the conclusive remarks of this thesis work along with the scope of future work.

Chapter-2

Theoretical Analysis

In this chapter a brief description of the operating principle of semiconductor optical amplifier is given which is followed by the detailed theoretical analysis of the gain saturation characteristics of SOA. The crosstalk due to gain saturation and ASE noise present in amplifier are described with mathematical equations.

2.1 Semiconductor Optical Amplifier

2.1.1 Spontaneous and stimulated emission

Spontaneous means that radiation occurs without external cause. Excited electrons from the conduction band fall without any external inducement to the valence band, which result in spontaneous radiation.

A different process occurs if an external photon hit and excited electron as shown in the fig 2.1. Their interaction includes and electron transition and the radiation of a new photon. The induced emission is stimulated by an external photon. In this stimulated emission an external photon forces a photon with similar energy to be emitted.

The stimulation process is enhanced by placing mirrors at the ends of an active layer. According to fig 2.1 (c), two photons, one external and one stimulated, are reflected back by the mirror and directed to the active layer again. These two photons now work as external radiation and stimulate the emission of two other photons. The four photons are reflected by a second mirror, which is positioned at the other end of active layer. When these photons pass the active layer, they stimulate emission of another four photons. These eight photons are reflected back into the active layer by the first mirror and this process continues. Thus, the two mirror provide optical feed back and the mirrors constitute a resonator.

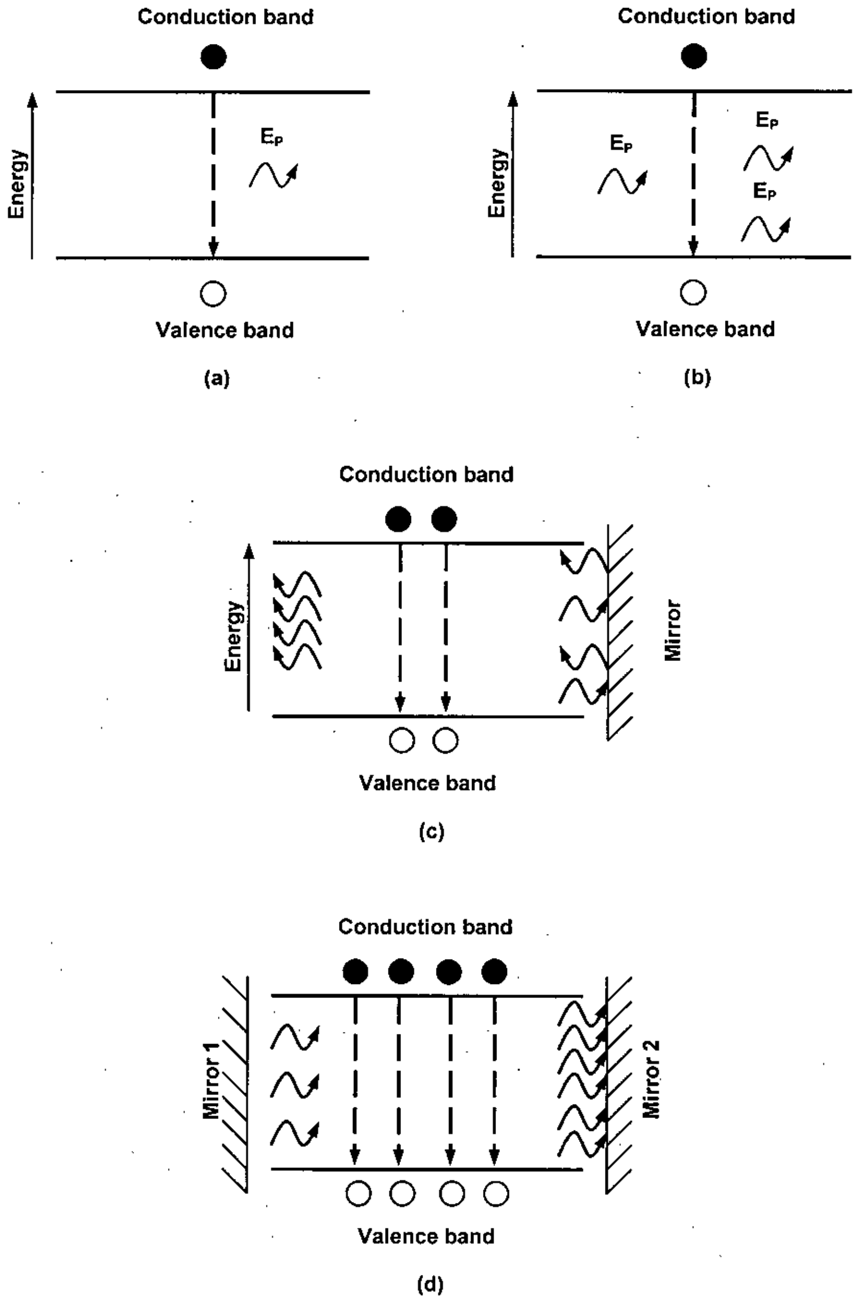

Figure 2.1: (a) spontaneous radiation, (b) Stimulated radiation, (c) and (d) Light amplification and positive feedback.

2.1.2 Principle of operation of a semiconductor optical amplifier

A SOA uses the principle of stimulated emission to amplify and optical information signal. How a SOA is connected to a fiber link is shown schematically in fig 2.2. An optical input signal carrying original data enters the semiconductor active region through coupling optics. Injection current delivers the external energy necessary to pump electrons at the conduction band. The input signal stimulates the transition of electrons down to the valence band and the emission of photons with the same energy i. e. the same wavelength that the input signal has. Thus, the output is an amplified optical signal.

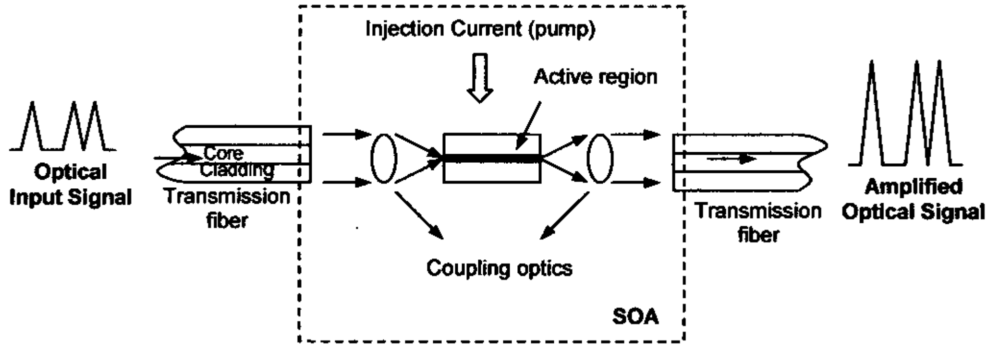

Figure 2.2: Semiconductor Optical Amplifier (SOA)

In Fabry-Perot amplifier, light entering the active region is reflected several times from cleaved facets and, having been amplified leaves the cavity. This is depicted in Fig. 2.3 (a), where different paths of a reflected beam are shown.

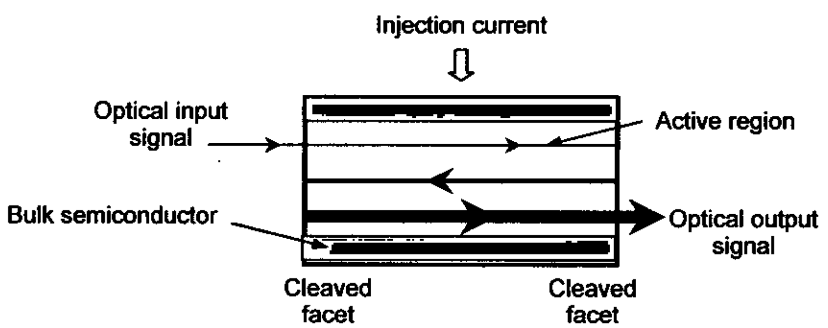

Figure 2.3(a): Fabry-Perot semiconductor optical amplifier

A traveling-wave amplifier is essential an active medium without reflective facets so that an input signal is amplified by a single passage through the active region, as shown Fig.2.3 (b).

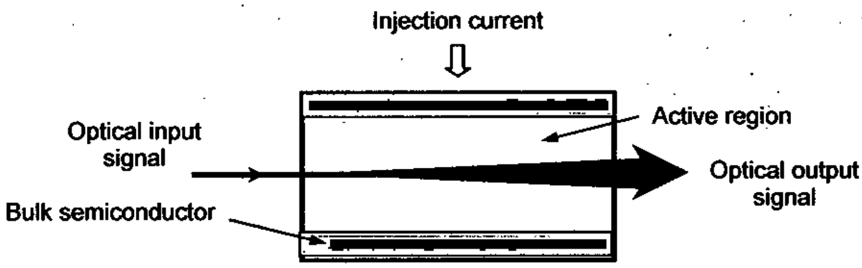

Figure 2.3(b): Traveling-wave semiconductor optical amplifier

2.2 Gain of FPA and TWA

If we denote the power reflection coefficients of cleaved facets as R_1 and R_2, the length of an active region as L, the effective group index of the cavity as n_g, and the single-pass power amplification factor as G_s, then the gain (G) of an FPA can be expressed as [1][3],

$$G_{FPA} = \frac{P_{out}}{P_{in}} = \frac{(1-R_1)(1-R_2)G_s}{\left(1-G_s\sqrt{R_1R_2}\right)^2 + 4G_s\sqrt{R_1R_2}\sin^2\phi(L)} \quad (1)$$

Where, $\phi(L) = 2\pi n_g L(1/\lambda - 1/\lambda_0)$ (2)

If $R_1=R_2=R$, then (1) can be written as,

$$G_{FPA} = \frac{P_{out}}{P_{in}} = \frac{(1-R)^2 G_s}{(1-RG_s)^2 + 4RG_s\sin^2\varphi(L)} \quad (3)$$

λ And λ_0 are the current and centre wavelength respectively.

A single passage amplification factor or single pass gain G_s is assumed to have a Gaussian shape dependence on frequency (wavelength) as shown in Fig. 2.4. An FPA exhibits peaks of gain, called gain ripple, at resonant frequencies (wavelengths). These are frequencies that a resonator, made from facets separated by distance L, can support. The resonant wavelengths can be expressed as [3],

$\lambda = 2L/N$ (4)

Where, N is integer and L is the length of the active region that is equal to resonator length.

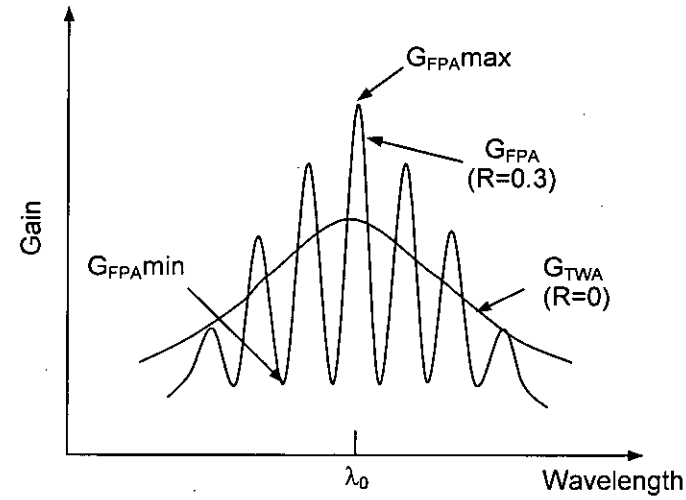

Figure 2.4: Gain of FPA and TWA as a function of wavelength

Using a Fabry-Perot resonator, which provides optical feedback, can significantly increase the gain of an SOA. The higher the reflectance (*R*), the higher the gain at the resonant frequencies. But increasing the reflectance beyond a certain point will turn the amplifier into a laser.

A traveling –wave amplifier is essentially an active medium without reflective facts so that an input signal is amplified by a single passage through the active region, as shown in Fig.2.3. The gain of a traveling-wave amplifier is given by (1), where, the reflectance (*R*) is zero. Hence,

$$G_{TWA} = \frac{P_{out}}{P_{in}} = G_s \qquad (5)$$

A single pass gain (G_s) can be expressed through the parameters of an SOA as follows,

$$G_s = \exp[(\Gamma g_0 - \alpha_0)L] \qquad (6)$$

Where, Γ is the confinement factor that accounts for the guiding of radiated photons by the waveguide structure of an active region, g_0 (1/cm) is the gain coefficient of an active region per unit of length, and α_0 (1/cm) is the loss coefficient of a cavity per unit of length. The gain of a TWA can be increased by increasing Γ, g_0 and L or decreasing α_0.

2.3 Gain Saturation of SOA

The gain coefficient (g) depends on the frequency and power of the signal being amplified as well. The power dependence is given by [1-3],

$$g = \frac{g_0}{1 + P/P_{sat}} \quad (7)$$

where P_{sat} is the saturation optical power. When the signal power becomes too high, the gain coefficient start to decrease, thus reducing the power of the signal undergoing amplification. This effect is called gain saturation.

The physics behind gain saturation effect is that high optical power involves all the electrons from the conduction band so that a further increase in the number of external photons will not stimulate any further transition of electron down to the valence band i.e. it will not produce additional stimulated photons.

In terms of signal intensity (*I*), the value of gain coefficient (*g*) at a position *z* along the optical axis is expressed as [3],

$$g(z) = \frac{g_0}{1 + I(z)/I_s} \quad (8)$$

I(z) is the optical intensity in the active layer and I_s is the saturation intensity. Thus, when gain saturation occurs, in place of (6), the signal pass gain is given by,

$$G_s = \exp[\int(\Gamma g(z) - \alpha_0)dz] \quad (9)$$

2.4 Crosstalk due to Gain Saturation Effect

To amplify several channels (wavelengths) simultaneously in WDM system, the major problem is crosstalk, which is any distortion of channel caused by the crosstalk and cross saturation or gain saturation. In this thesis work, crosstalk due to gain saturation has been analyzed.

Gain saturation occurs when a semiconductor amplifier works in the saturation mode, i.e. the power of the input signals is above the saturation value. When one channel changes from ON OFF, the gain undergoes an opposite change. When one channel results in variations in the amplification of another signal because, all signals share the same gain produced by one active medium. Fig.2.5 illustrated this point.

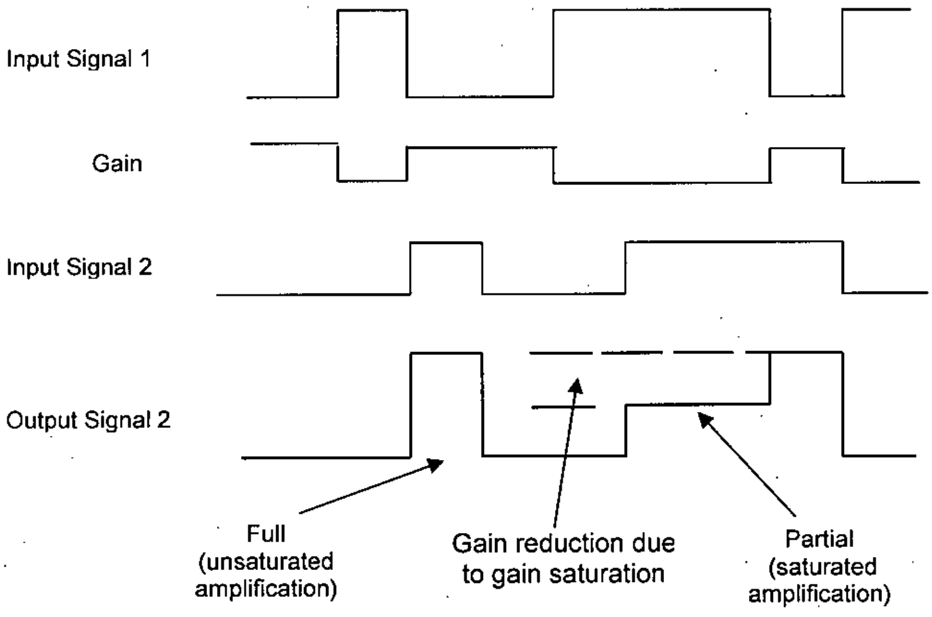

Figure 2.5: Crosstalk in SOA due to gain saturation

2.5 Amplified Spontaneous Emission (ASE) Noise in SOA

The noise generated by an active medium of an optical amplifier is caused primarily by amplified spontaneous emission (ASE). The vast majority of excited carriers are forced by stimulated emission to fall to a lower level, although some of these carriers do so spontaneously. When they decay, these carriers radiate photons spontaneously. The spontaneously emitted photons are in the same frequency rangy range as the information signal, but they are random in phases and directions. The spontaneously emitted photons that follow in the direction of the information signal are amplified by an active medium. The spontaneously emitted and amplified photons constitute amplified spontaneous emission. Since they are random in phase, they do not contribute to the information signal but generate noise within the signal's bandwidth [3].

The spontaneous emission depends on the relative population of the upper and lower energy levels. A spontaneous emission factor or population inversion factor n_{sp} can be defined as [3],

$$n_{sp} = \frac{N_2}{N_2 - N_1} \tag{10}$$

where, N_2 and N_1 are population of the excited and lower levels respectively. The higher the spontaneous emission factor, the greater the power the power of the amplified spontaneous emission generated by an optical amplifier.

The spontaneous emission power at the output from an optical amplifier is given by,

$$P_{sp} = n_{sp}(G-1)h\nu B_0 \tag{11}$$

Where, $h\nu$ is photon energy, G is amplifier gain and B_0 is the optical bandwidth of the amplifier.

2.6 OTDM System Model

The block diagram of an OTDM transmission system is shown in Fig.2.6.

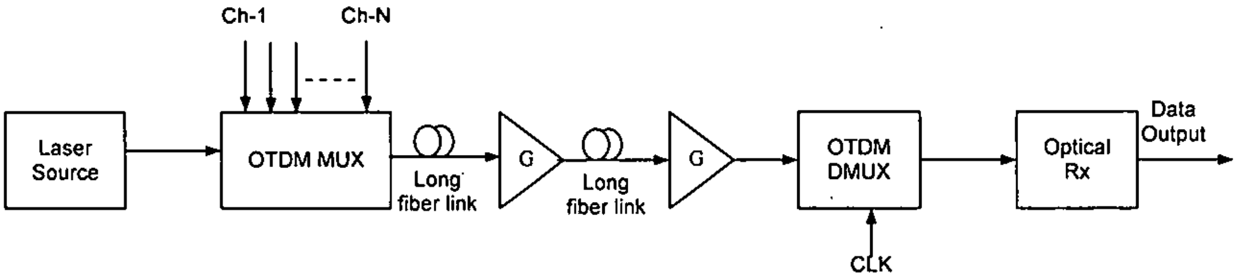

Figure 2.6: Block diagram of an OTDM transmission system

The principle of optical time division multiplexing (OTDM) is depicted in Fig.2.7. The block diagram of the proposed OTDM demultiplexer based on SOA is shown in Fig2.8. Here two Semiconductor Optical Amplifier stages are used for theoretical analysis as shown in Fig.2.8. The gain versus input power characteristic is shown in Fig.2.9 and the operation of OTDM demultiplexer is depicted graphically in Fig.2.10.

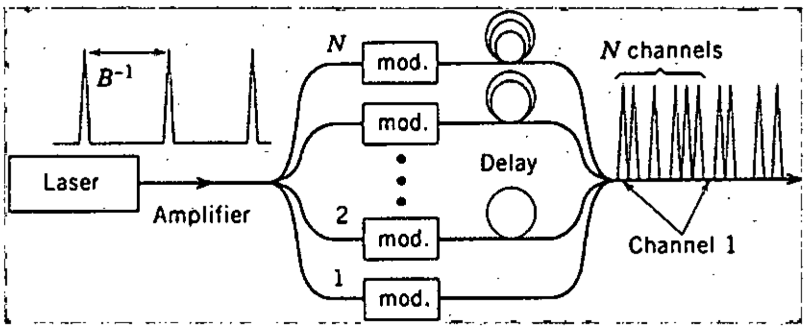

Figure 2.7: Principle of optical time division multiplexing

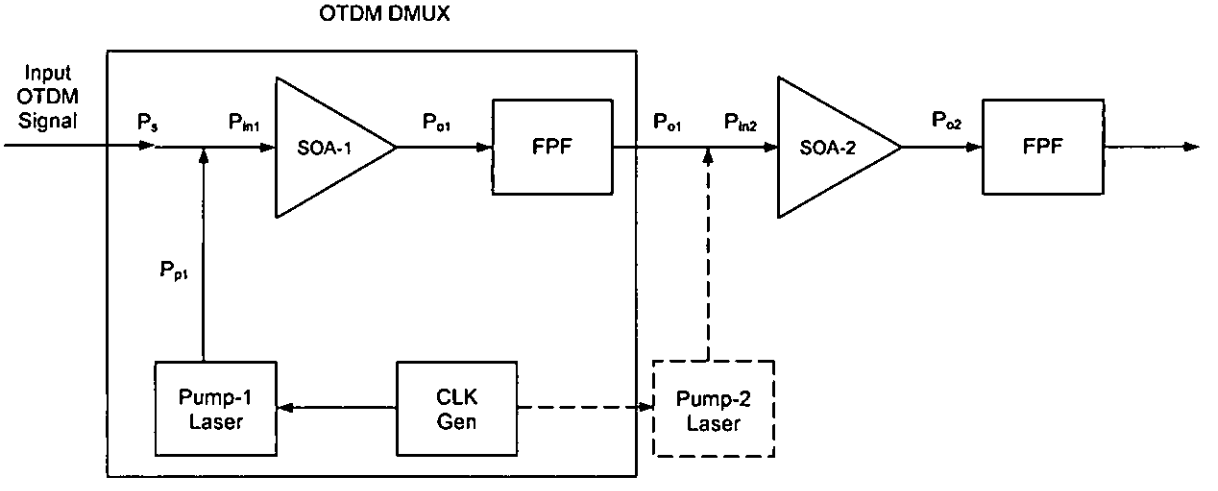

Figure 2.8: Block diagram of an OTDM demultiplexer based on SOA

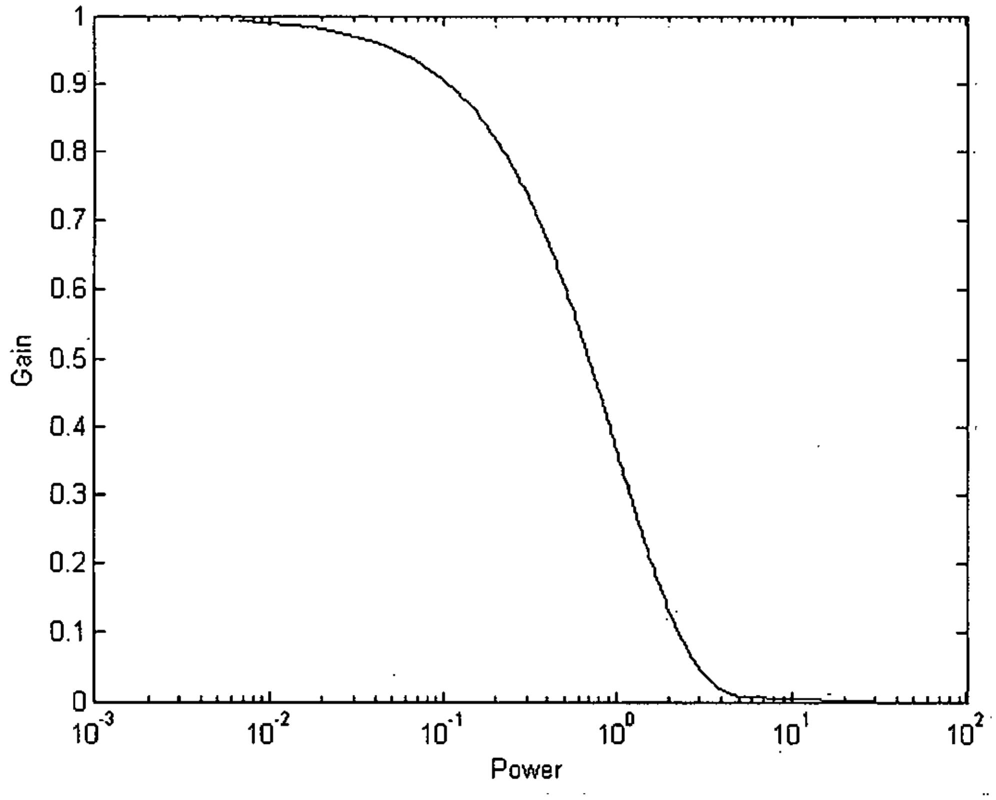

Figure2.9: Plot of gain versus input power of a SOA

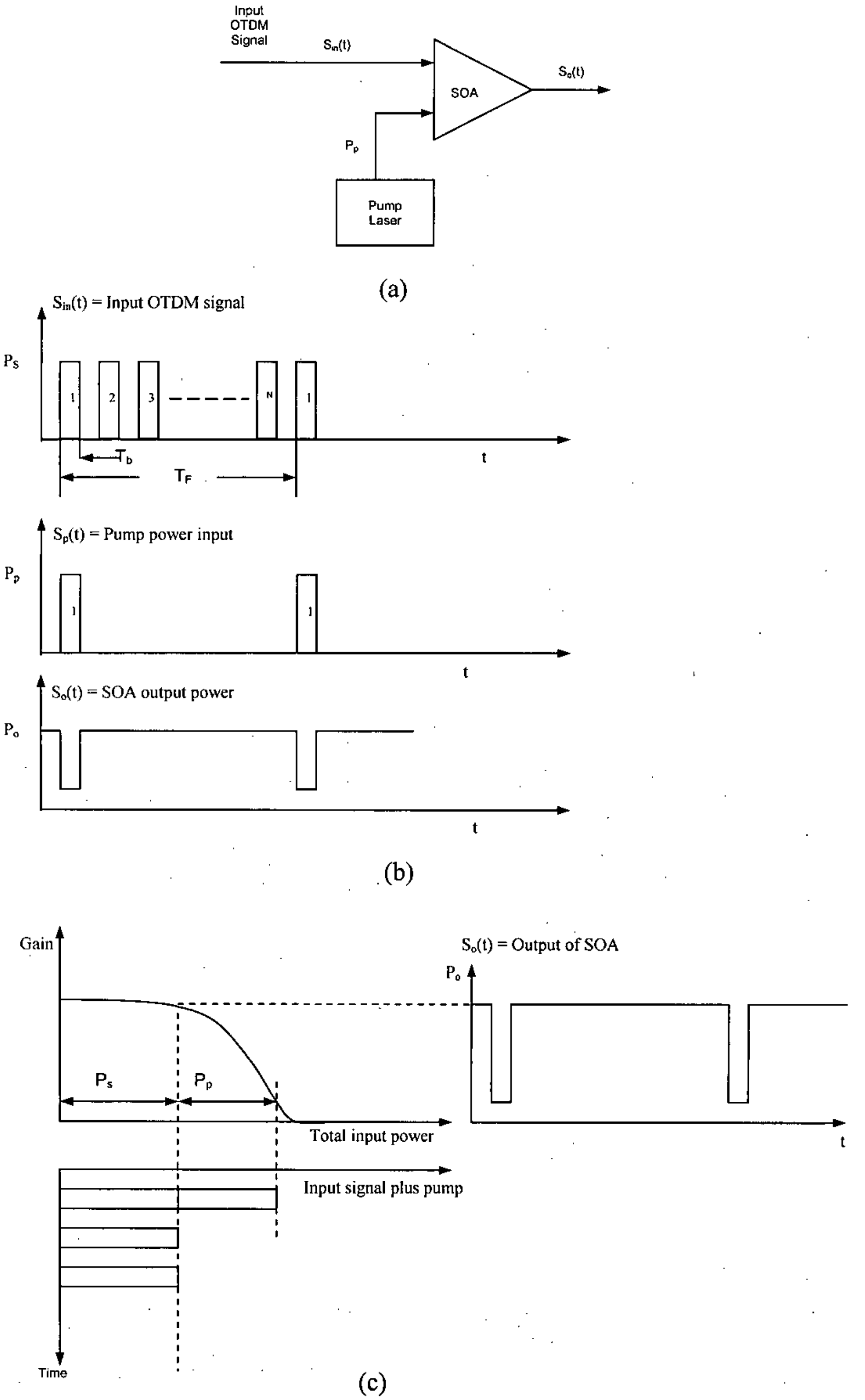

Figure 2.10: SOA input and output curves

The input OTDM signal is mixed with the pump signal of pump laser-1 and is fed to the SOA-1. The presence of the pump power causes the SOA-1 to go to the saturation which results in a low gain of the SOA-1. The pump is driven by the clock signal from a clock generator to select the desired OTDM channel. When the clock is high, the SOA-1 goes to saturation and the output goes to lower level, otherwise the output remains high. Thus during the desired channel slot time, the output of SOA-1 is low if a bit '1' is present in the time slot. If the bit is '0', the SOA-1 does not go to saturation and the output remains high. Thus the output of the SOA-1 is high for a '0' bit in the desired channel slot and is low for a '1' bit in the desired channel slot. The output of SOA-1 is given input to SOA-2 which acts as an inverter as it goes to saturation giving low output for a '1' bit (high) input and remains at higher output level for a '0' input bit (low input level) due to gain saturation effect caused by the input power level. The pump power of SOA-2 is selected to adjust the total input power of the amplifier to achieve gain saturation corresponding to high input power level. The output of the OTDM demultiplexer is given input to an optical direct detection receiver to receive the transmitted data bits of the desired channel.

2.7 Performance Analysis of the OTDM Demultiplexer

The OTDM signal can be represented as:

$$E_s(t) = \sqrt{2P_s} \sum_{j=0}^{\infty} \sum_{k=0}^{N-1} a_{k,j} p(t - kT_b - jT_F) \times e^{j\omega_c t} \qquad (12)$$

where, $\{a_{k,j}\} = \{0,1\}$, N is the number of OTDM channels, $a_{k,j}$ is the k-th bit of the j-th OTDM frame. P_s is the average optical signal power of the OTDM channel. The pump signal given input to SOA-1 at nth time slot is given as:

$$E_{p1}(t) = \sqrt{2P_{p1}} \sum_{j=0}^{\infty} p(t - jT_F - nT_b) \times e^{j\omega_p t} \qquad (13)$$

n is the channel index to be demultiplexed = {0, N-1} and ω_p is the angular frequency of the pump laser with power P_{p1}.

The total power input signal given to SOA-1 is then given by

$$E_{in1}(t) = E_s(t) + E_{p1}(t) \qquad (14)$$

Total input to the SOA-1 is then given by:

$$P_{in1} = P_s + P_{p1} \tag{15}$$

The electric field at the output of SOA-1 is given by:

$$E_{o1}(t) = [\sqrt{2G_1(t)P_s}\sum_{j=0}^{\infty}\sum_{k=0}^{N-1} a_{k,j}\,p(t - kT_b - jT_F) + \sqrt{2G_1P_{p1}}\sum_{j=0}^{\infty} p(t - jT_F - nT_b)] \times e^{j\omega_c t} \tag{16}$$

where, ($\omega_c = \omega_p$), $a_{k,j}$ represents k-th bit of the j-th OTDM frame, and P_{p1} is the pump power of the pump laser-1 corresponding to the n-th bit of the j-th frame.

The instantaneous gain of the SOA-1 depends on the input power level and can be expressed as:

$G_1(t) = G_1$ for k = n, $a_k = +1$
$= G_2$ for k = n, $a_k = 0$
$= G_2$ for $k \neq n$

For $a_{n,j} = +1$

$$E_{o1}(t) = \sqrt{2G_1(P_s + P_{p1})}\sum_{j=0}^{\infty} a_{k,j}\,p(t - nT_b - jT_F) \times e^{j\omega_c t} \tag{17}$$

If G_s represents the single pass gain, then $G_1 < G_s$, $G_2 = G_s$

For $a_{n,j} = 0$, $E_{o1}(t) = \sqrt{2G_2P_{p1}} \times e^{j\omega_c t}$ (18)

For $n \neq k$, $G_{11} < G_{12}$ and $G_1 < G_2$,

$$E_{o1}(t) = \sqrt{2G_2P_s}\sum_{j=0}^{\infty}\sum_{\substack{k=0 \\ k\neq n}}^{N-1} a_{k,j}\,p(t - kT_b - jT_F)e^{j\omega_c t}\ ,\ (0<t<T_F) \tag{19}$$

$G_1 << G_2 = G_s$, so that $G_1(P_s+P_{p1}) < G_2P_{p1n}$

So output $P_{o1} = G_1(P_s + P_{p1})$ (20)

$P_{o2} = G_2P_{p1}$ (21)

As $G_2 >> G_p$, $P_{o2} > P_{o1}$

So the dynamic range and the extinction ratio of the demultiplexed signal at the output of SOA-1 can be represented as:

Dynamic Range = DR = $P_{o2} - P_{o1}$ (22)

Extinction Ratio = ε = P_{o1}/P_{o2} (23)

The demultiplexed signal of the output of SOA-1 is fed to the input of SOA-2 with pump input power P_{p2}. The input signal to the SOA-2 is given by:

$$E_{in2}(t) = E_{01}(t) + E_{p2}(t) \tag{24}$$

where, $E_{01}(t)$ is given by equation (16), (17), (18) and (19) and $E_{p2}(t)$ is the electric field input to SOA-2 from the pump laser-2 and is given by:

$$E_{p2}(t) = \sqrt{2P_{p2}}\sum_{n=0}^{\infty} p(t - jT_F - nT_b)e^{j\omega_c t} \tag{25}$$

The output signal of the SOA-2 is then given by:

$$E_{o2}(t) = \sqrt{2[G_1(P_s + P_{p1}) + P_{p2}]} \times \sqrt{G_{21}}\sum_{j=0}^{\infty} p(t - jT_F - nT_b)e^{j\omega_c t} \tag{26}$$

where, G_{21} is the gain of SOA-2 corresponding to low input power level.
For k = n and a_k = +1

$$E_{02}(t) = \sqrt{2G_2(P_{p1} + P_{p2})} \times \sqrt{G_{22}}e^{j\omega_c t} \tag{27}$$

for k = n and a_k = 0

$$E_{02}(t) = \sqrt{2[G_1(P_s + P_{p1}) + P_{p2}]} \times \sqrt{G_{22}}\sum_{n=0}^{N-1}\sum_{j=0}^{\infty} P(t - jT_F - nT_b)e^{j\omega_c t} \tag{28}$$

where, G_{22} on the gain of the SOA-2 corresponding to high levels of the input signal and $G_{22} < G_{21}$.

Thus output power levels of SOA-2 are:

$$P_1 = 2[G_1(P_s + P_{p1}) + P_{p2}]G_{21} \quad \text{for '1' bit} \qquad (29)$$

$$P_0 = 2(G_2 P_{p1} + P_{p2})G_{22} \qquad \text{for '0' bit} \qquad (30)$$

2.8 Optical Receiver Model

In practice, the vast majority of installed optical fiber communication systems use incoherent or direct detection optical receiver in which the variation of the optical power level is monitored and no information is carried in the phase or frequency content of the signal.

The output signal of the OTDM DMUX is fed to a direct detection optical receiver. The block diagram of the receiver is shown in Fig.2.8.

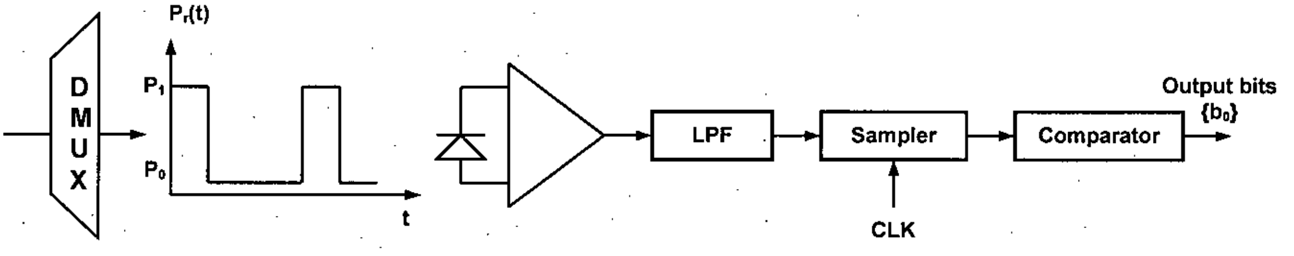

Figure 2.11: Block diagram of a direct detection optical receiver

The receiver optical signal at the output of the OTDM Demultiplexer is given by:

$$r(t) = E_s(t) + E_{sp}(t) \qquad (31)$$

where, $E_s(t) = \sqrt{2P_2}e^{j\omega_c t}$, for '1' bit (32)

$= \sqrt{2P_1}e^{j\omega_c t}$, for '0' bit

and $E_{sp}(t)$ is the spontaneous emission noise of the optical amplifiers in cascade.

2.9 Noise in Optical Receiver

The term noise is used to describe unwanted components of an electric signal that tend to disturb the transmission and processing of the signal in a physical system.

The noise is caused by the spontaneous fluctuations of current or voltage in electric circuits. The two most common samples of these spontaneous fluctuations are shot noise and thermal noise. Fig. 2.3 shows a simple model of a photo detector receiver and a block schematic of the front end of an optical receiver with various noise sources associated with it.

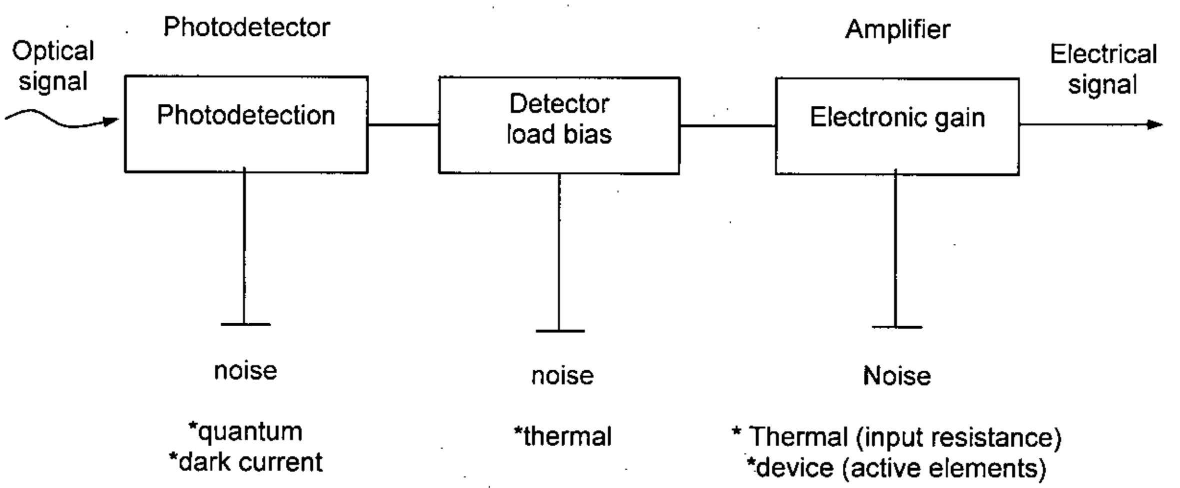

Figure 2.12: Block schematic of the front of an optical receiver showing the various sources of noise.

2.9.1 Shot noise

The shot noise arises from the statistical nature of the production and of photoelectrons when an optical signal is incident on a photodetector. The two main source of noise in photodiodes without internal gain are dark current noise and quantum noise, both of which may be regarded as shot noise on photocurrent. Dark current is a small reverse leakage current which flows from the device terminals when there is no optical power incident on the photodetector. The total shot noise is given by [3],

$$\langle i_{shot}^2 \rangle = \sigma_{shot}^2 = 2qB_e(I_p + I_d) \tag{33}$$

where, B_e is the receiver bandwidth, q is the charge of electron, I_p is the photocurrent due to optical incident power and I_d is the dark current.

2.9.2 Thermal noise

Thermal noise arises from the random motion of electrons in a conductor. When the photodiode is without internal gain, thermal noise from the detector load resistor and from active elements in the amplifier tends to dominate. The thermal noise due to the load resistance R_L is given by,

$$\langle i_{th}^2 \rangle = \sigma_{th}^2 = \frac{4kTB_e}{R_L} \tag{34}$$

where, k is Boltzman constant, T is absolute room temperature in Kelvin.

2.10 Analysis of Signal of Noise Ratio (SNR) and Bit Error Rate (BER)

The different types of noises in optical receiver are briefly described in section 2.7. Since ASE originates ahead of the photodiode, it gives rise to three different noise components in an optical receiver in addition to the other receiver noises. This occurs because the photocurrent consists of a number of beat signals between the signal and the optical noise field, in addition to the squares of the signal field and the spontaneous emission field.

If the total optical field is the sum of the signal field E_s and the spontaneous emission field E_{sp}, then the total photo detector current i_{tot} is proportional to the square of the electric field of the optical signal,

$$i_{tot} \propto (E_s + E_{sp})^2 = E_s^2 + E_{sp}^2 + 2E_sE_{sp} \tag{35}$$

Here the first two terms arise purely from the signal and noise respectively. The third term is a mixing component i.e. a beat signal between the signal and noise, which can fall within the bandwidth of the receiver and degrade the signal to noise ratio.

The mean signal currents corresponding to '1' or '0' bits are given as:

$I_{s1} = \Re.P_1$ and $I_{s0} = \Re.P_0$

Considering ASE noise, and neglecting dark current noise, the total shot noise current is given by [3],

$$\left\langle I_{shot}^2 \right\rangle = \sigma_{shot}^2 = \sigma_{shot-s}^2 + \sigma_{shot-sp}^2 = 2qB_e(I_{s1} + I_{sp}) \quad \text{- '1'} \tag{36}$$

$$= 2qB_e(I_{s0} + I_{sp}) \quad \text{- '0'}$$

where, $I_{s1} = \Re.P_1$, $I_{s0} = \Re.P_0$ and $I_{sp} = \Re.P_{sp}$, $\Re$ is the responsivity of the photodiode, G is the amplifier gain and $P_{sp} = n_{sp}(G-1)h\upsilon B_0$, n_{sp} is the spontaneous emission factor and $h\upsilon$ is the photon energy.

The other two noises arise from the mixing of the different optical frequencies contained in the light signal and the ASE, which generates two sets of beat frequencies. Since the signal and the ASE have different optical frequencies, the beat noise of the signal with the ASE is [3],

$$\sigma_{s-sp}^2 = 4(\Re G P_{in})(\Re P_{sp} \frac{B_e}{B_0}) \tag{37}$$

In addition, since the ASE spans a wide optical frequency range, it can beat against itself giving rise to the noise current as [3],

$$\sigma^2_{sp-sp} = (\Re P_{sp})^2 B_e \frac{(2B_0 - B_e)}{B_0^2} \tag{38}$$

The total noise variance at the output of the receiver LPF is given by:

$$\sigma^2 = \sigma^2_{th} + \sigma^2_{shot-s} + \sigma^2_{shot-sp} + \sigma^2_{s-sp} + \sigma^2_{sp-sp} \tag{39}$$

The noise variance corresponding to a '1' bit is given by:

$$\sigma_1^2 = \sigma^2_{th} + 2qB_e(I_{s1} + I_{sp}) + 4(\Re G P_1)(\Re P_{sp}.\frac{B_e}{B_0}) + \sigma^2_{sp-sp} \tag{40}$$

and that corresponding to a '0' bit is given by:

$$\sigma_o^2 = \sigma^2_{th} + 2qB_e(I_{so} + I_{sp}) + 4(\Re G P_o)(\Re P_{sp}.\frac{B_e}{B_o}) + \sigma^2_{sp-sp} \tag{41}$$

The signal to noise ratio (SNR) at the output can be expressed as:

$$SNR = \frac{I_{s1} - I_{s0}}{\sigma_1 + \sigma_o} \tag{42}$$

The extinction ratio (ER) is then given by,

$$\varepsilon = \frac{I_{s0}}{I_{s1}} \tag{43}$$

The bit error rate (BER) can be expressed as [1-3],

$$BER = 0.5erfc\left[\frac{SNR}{\sqrt{2}}\right] \tag{44}$$

In most cases of practical interest, thermal noise dominates receiver performance, i.e. $\sigma_{th}^2 >> \sigma_{shot}^2$ [1-3]. Neglecting the shot noise terms in (41), SNR becomes,

$$SNR = \frac{(\Re GP_{in})^2}{2qB_e \Re P_{cross} + \frac{4kTB_e F_n}{R_L}} \tag{45}$$

When the receiver performance is dominated by shot noise, i.e. $\sigma_{shot}^2 >> \sigma_{th}^2$ and $\sigma_1^2 >> \sigma_0^2$, the SNR becomes,

$$SNR = \frac{(\Re GP_{in})^2}{2qB_e \Re(GP_1 + P_{sp} + P_{cross}) + 4(\Re GP_1)(\Re P_{sp}\frac{B_e}{B_0}) + (\Re P_{sp})^2 B_e \frac{(2B_0 - B_e)}{B_0^2} + \frac{4kTB_e F_n}{R_L}} \tag{46}$$

In a multiple span system, where N numbers of amplifier are cascaded, the crosstalk power (P_{cross}) and the spontaneous emission power (P_{sp}) in (44) is to be replacement by NP_{cross} and NP_{sp} respectively in order to obtain cumulative effect of crosstalk and amplified spontaneous noise.

2.11 Summary

Theoretical analysis of an OTDM DMUX based on semiconductor optical amplifier with gain saturation effect is given in this chapter. Analytical expression for the output SNR is derived and the BER expression is presented including the effect of ASE noise, shot noise and thermal noise of the receiver along with crosstalk.

Chapter-3

Results and Discussions

3.1 Results and Discussions

Following the theoretical analysis presented in chapter-2, the performance results of an OTDM demultiplexer based on gain saturation effect are evaluated at different bit rates and system parameters. System parameters used for computation are shown in the table 3.1.

Table 3.1: System Parameters used for computation

Parameter Name	**Typical Value**
Bit rate, R_b	5 ~ 25 Gbps
Temperature, T	300° K
Fiber attenuation, α	0.24 dB/Km
Responsivity, $\Re$	0.85 A/W
Current intensity, I_{th}	10×10^{-12} ampere
Load resistance, R_L	50 ohm
Gain, G_1	20 dB
Gain, G_2	10 dB
Boltzman's constant, k	1.38×10^{-23}
Electron charge, e	1.602×10^{-19} coulombs

Other results are presented in terms of signal to noise ration (SNR) and bit error rate (BER) and extinction ratio at the output of the demultiplexer followed by a direct detection receiver.

The variation of the gain of SOA with input power obtained by simulation is depicted in Fig.3.1. It shows that as the input power increases, the gain of the amplifier goes towards saturation. This characteristic of the SOA is used for demultiplexing a channel from an OTDM signal.

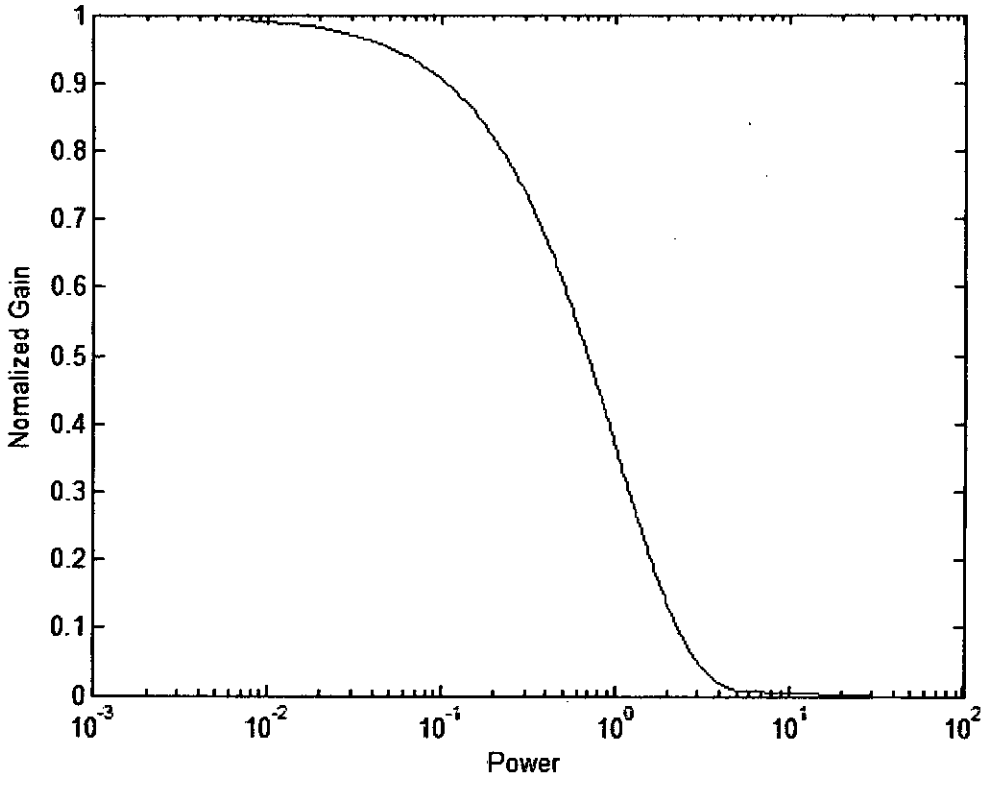

Figure 3.1: Gain versus input power Pin (dBm) of a SOA

The plots of BER of the OTDM system versus pump power of SOA-1 are depicted in Fig.3.2 for signal power Ps = -45 dBm and -37 dBm. It is noticed that the bit error rate decreases with increase in pump power at a given signal power level. At higher signal power level the BER is higher. The receiver sensitivity in terms of P_p(dBm) at a BER of 10^{-9} is found to be -40.85 dBm and -39.93 dBm corresponding to P_s = -45 dBm and -37 dBm respectively.

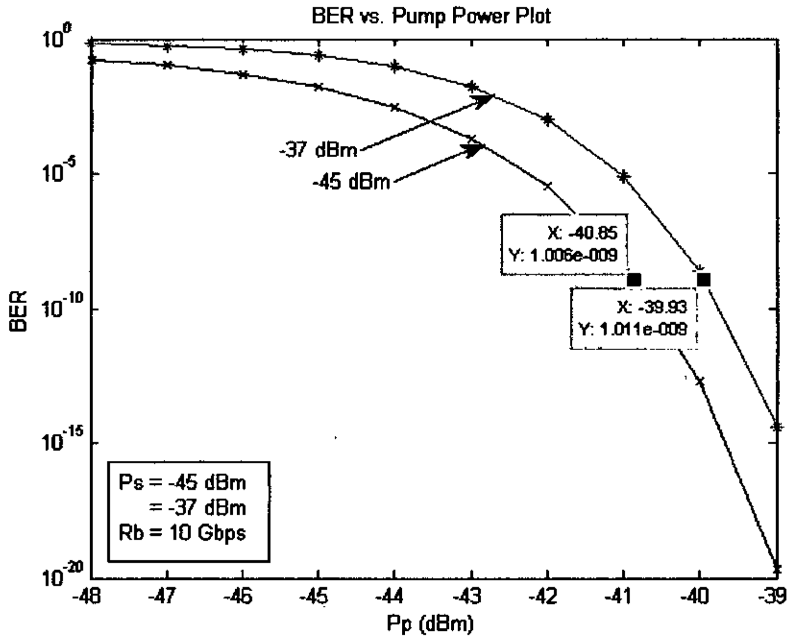

Figure 3.2: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a bit rate of 10 Gbps with signal power P_s as a parameter

Similar plots of BER versus P_p (dBm) for P_s = -39 dBm and -43 dBm are shown in Fig.3.3.

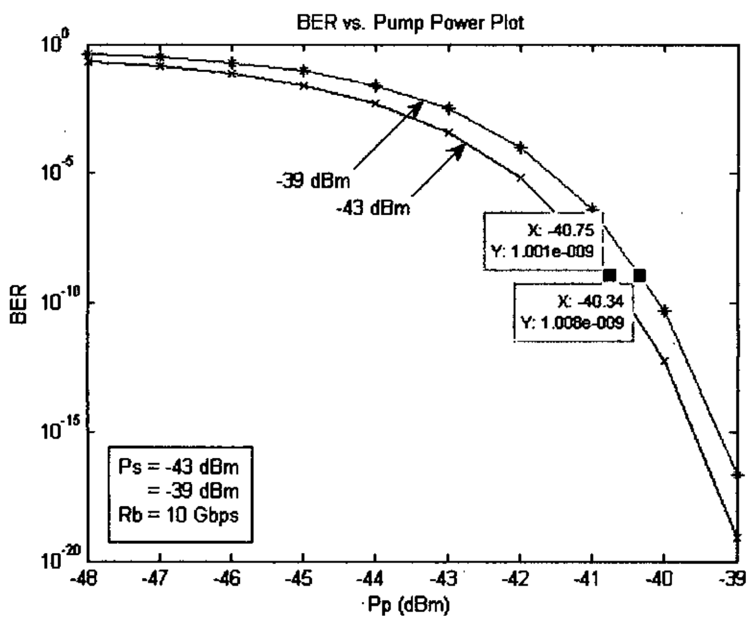

Figure 3.3: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a bit rate of 10 Gbps with signal power P_s as a parameter

It is noticed that at a given BER the required signal power is higher when the pump power is increased. This is due to the increased shot noise at higher pump power input. Plots of BER versus P_p(dBm) with Ps(dBm) as a parameter are also shown in Fig.3.4 to Fig.3.5 and similar observations are found.

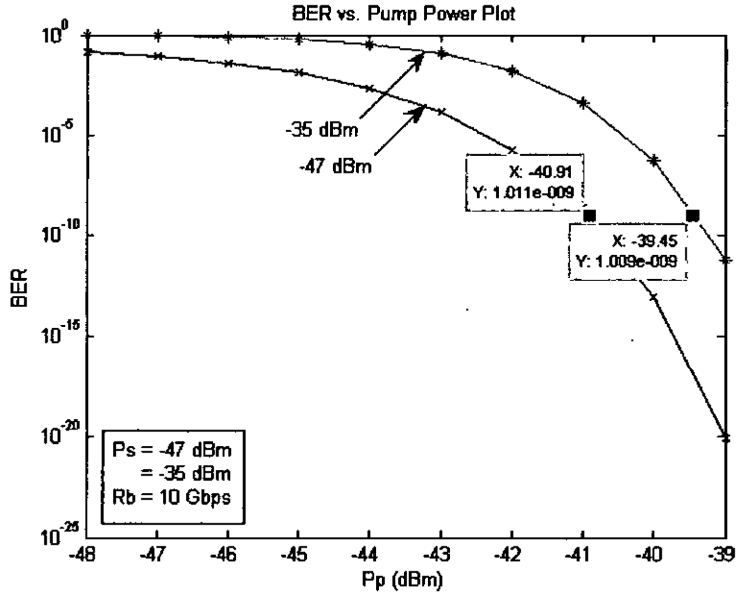

Figure 3.4: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a bit rate of 10 Gbps with signal power P_s as a parameter

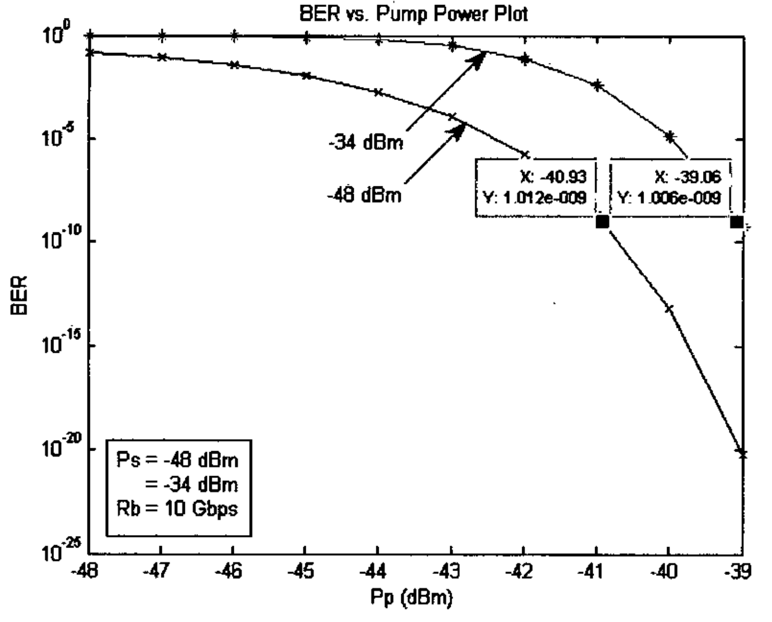

Figure 3.5: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a bit rate of 10 Gbps with signal power P_s as a parameter

The relationship between the required value of P_s(dBm) to achieve a given BER of 10^{-9} corresponding to a given P_p(dBm) is depicted in Fig.3.6 for operation at a bit rate of 10 Gbps. It is clearly found that the required values of P_s(dBm) are within the normal operational range of signal levels in a direct detection receiver.

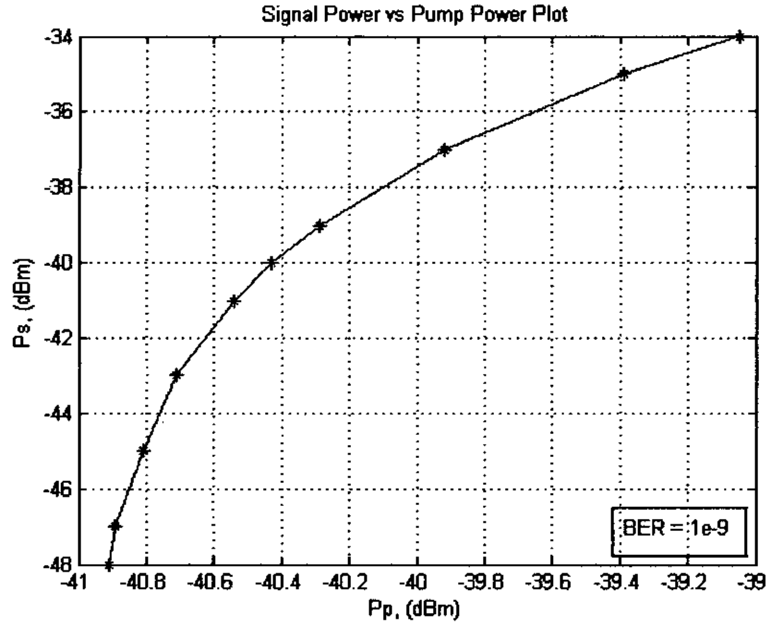

Figure 3.6: Plot of required signal power versus pump power of an OTDM link to achieve BER = 10^{-9} and operating at R_b = 10 Gbps

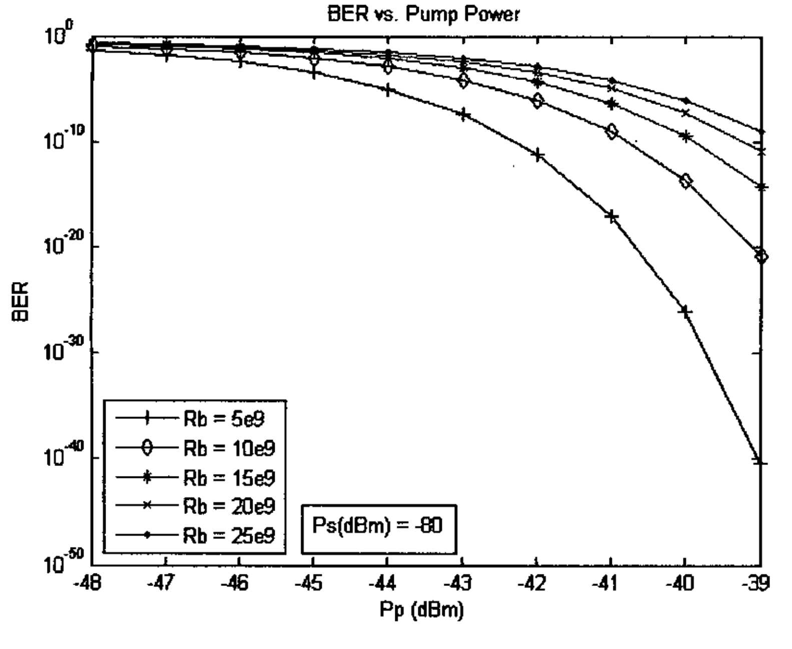

Figure 3.7: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a signal power P_s = -80 dBm with bit rate as a parameter

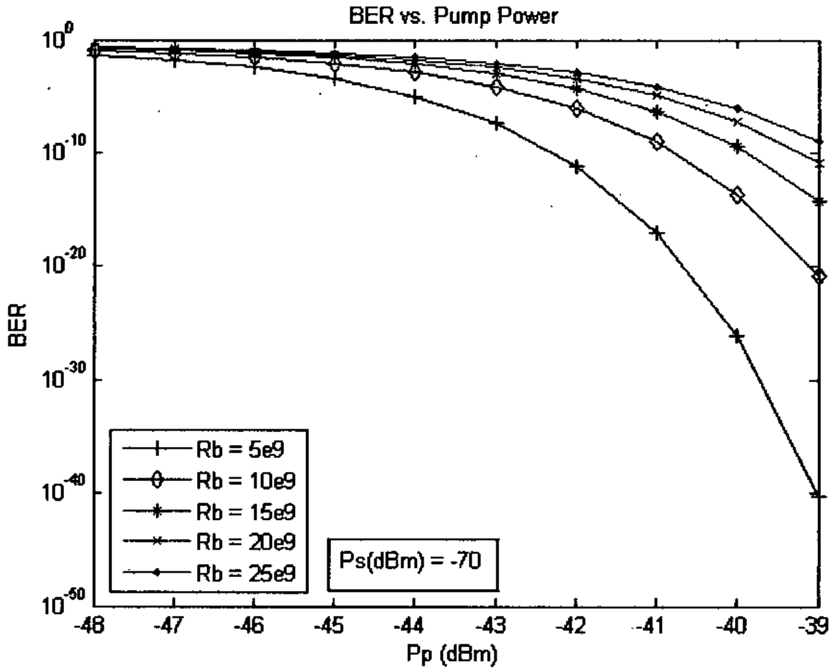

Figure 3.8: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a signal power P_s = -70 dBm with bit rate as a parameter

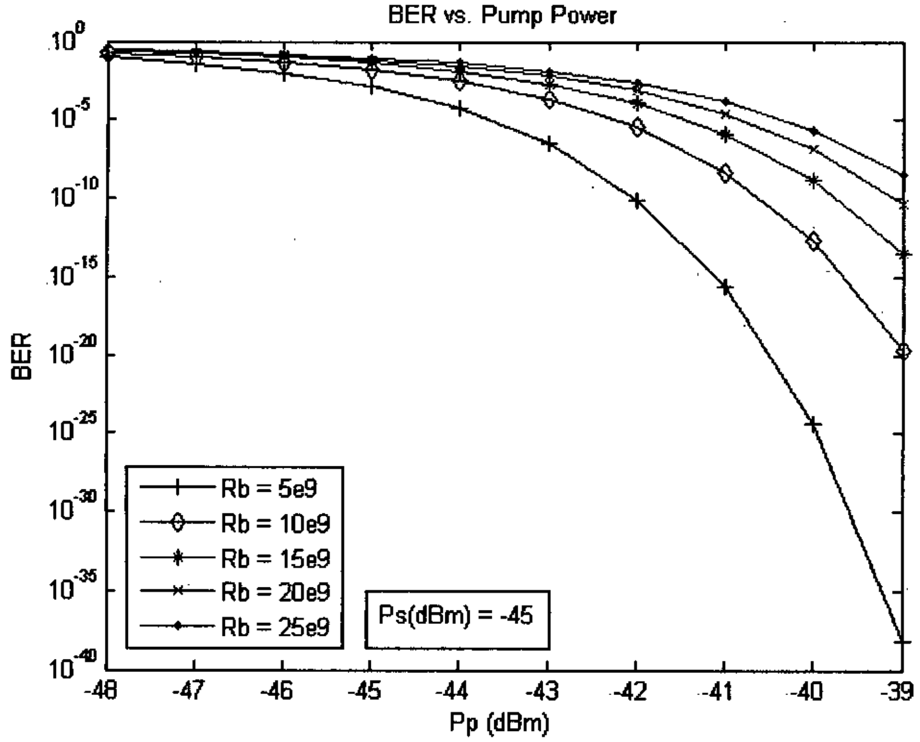

Figure 3.9: Plot of BER versus pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a signal power P_s = -45 dBm with bit rate as a parameter

Fig.3.7 through Fig.3.9 depict the plots of BER versus pump power of SOA-1 with bit rate R_b as a parameter. The plots are shown for R_b = 5 Gbps to 25 Gbps for P_s = -80 dBm, -70 dBm and -45 dBm respectively. The plots reveal that at increased bit rate, the required pump power is higher to achieve a specific BER (say, 10^{-9}). Thus the required receiver sensitivity is higher at higher bit rate due to increased receiver noise.

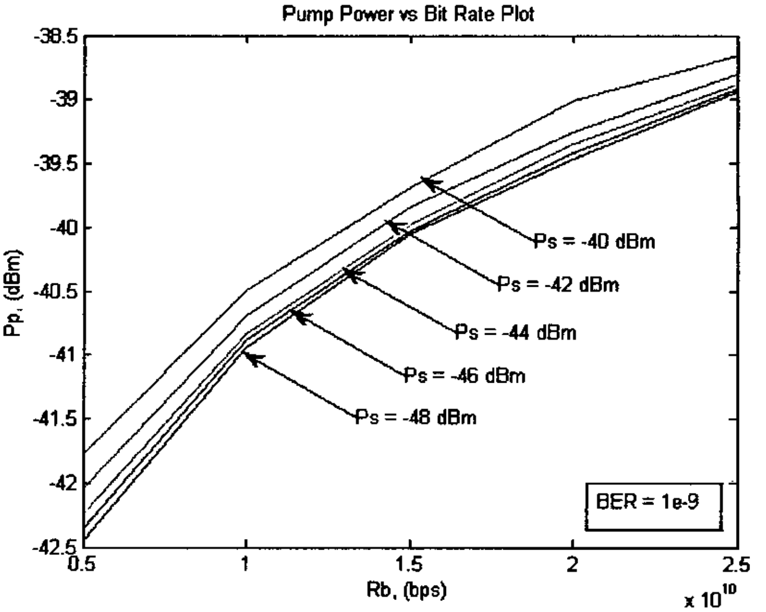

Figure 3.10: Plot of pump power versus bit rate at a BER = 10^{-9} with signal power as a parameter (varying from -48 to -40 dBm)

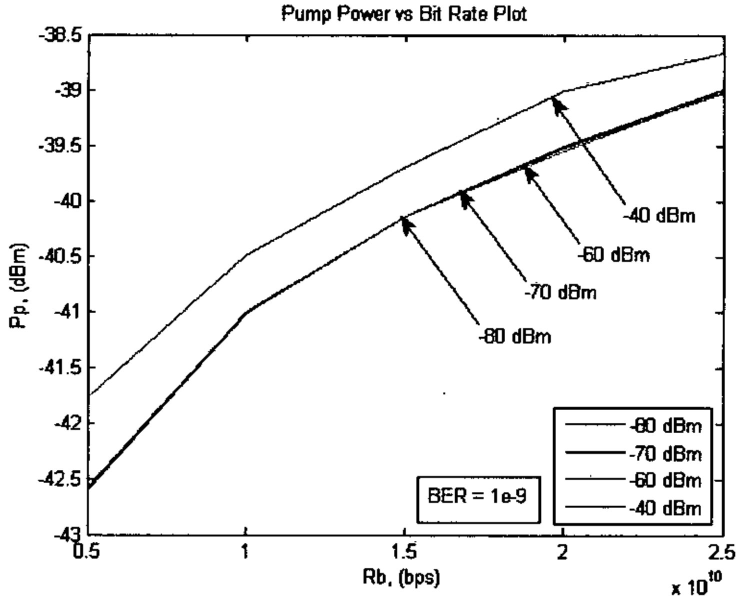

Figure 3.11: Plot of pump power versus bit rate at a BER = 10^{-9} with signal power as a parameter (varying from -40 to -80 dBm)

The plots of required receiver sensitivity in terms of P_p(dBm) as a function of R_b are shown in Fig.3.10 and Fig.3.11 with P_s as a parameter corresponding to BER = 10^{-9}. It is noticed that the required value of P_s(dBm) is higher at high bit rate at BER = 10^{-9} due to increased value of P_p(dBm). The Fig.3.10 shows the results for smaller range of values of P_s and Fig.3.11 shows the results for higher values of P_s.

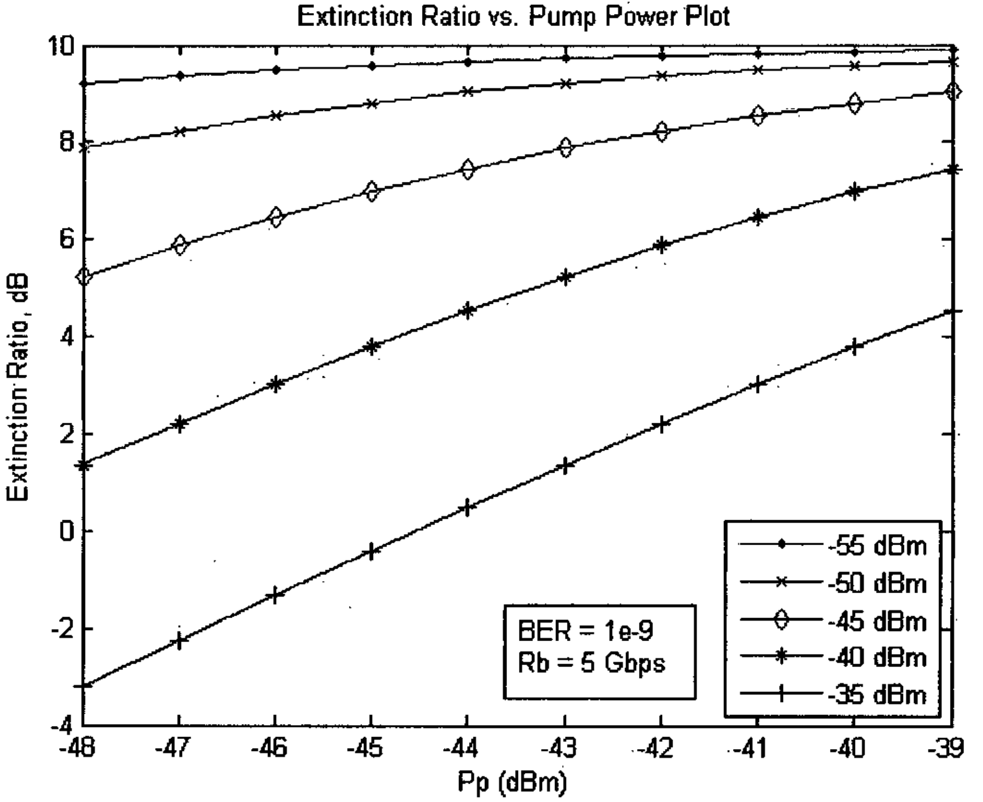

Figure 3.12: Plot of extinction ratio versus pump power at R_b = 5 Gbps, BER = 10^{-9} with signal power as a parameter (varying from -35 to -55 dBm)

The dependence of extinction ratio at the output of the OTDM DMUX with pump power of SOA-1, P_p(dBm) is depicted in Fig.3.12 at a bit rate of 10 Gbps at a BER = 10^{-9} with P_s(dBm) as a parameter. The figure clearly depicts how the degradation in extinction ratio occurs at higher values of signal power P_s(dBm) due to gain saturation effect of SOA. This is due to the fact that at higher signal power input, the dynamic range between the signal levels for '1' and '0' bits is reduced. At low input signal power, there is a significant improvement in extinction ratio. Similar results are shown in fig.3.12 at R_b = 5 Gbps.

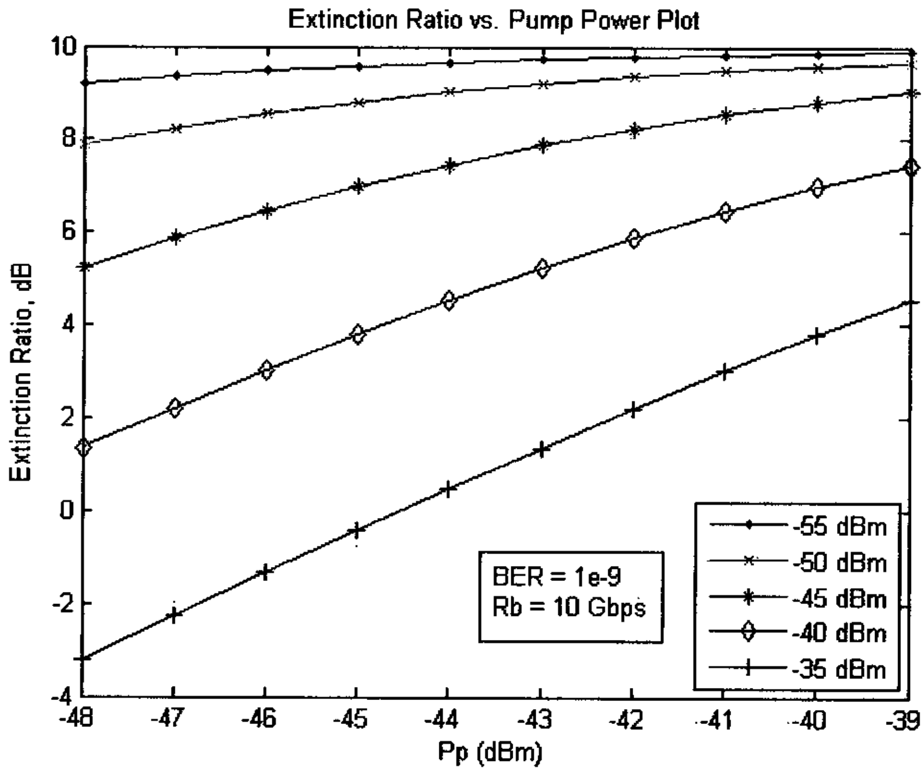

Figure 3.13: Plot of extinction ratio versus pump power at $R_b = 10$ Gbps, BER = 10^{-9} with signal power as a parameter (varying from -35 to -55 dBm)

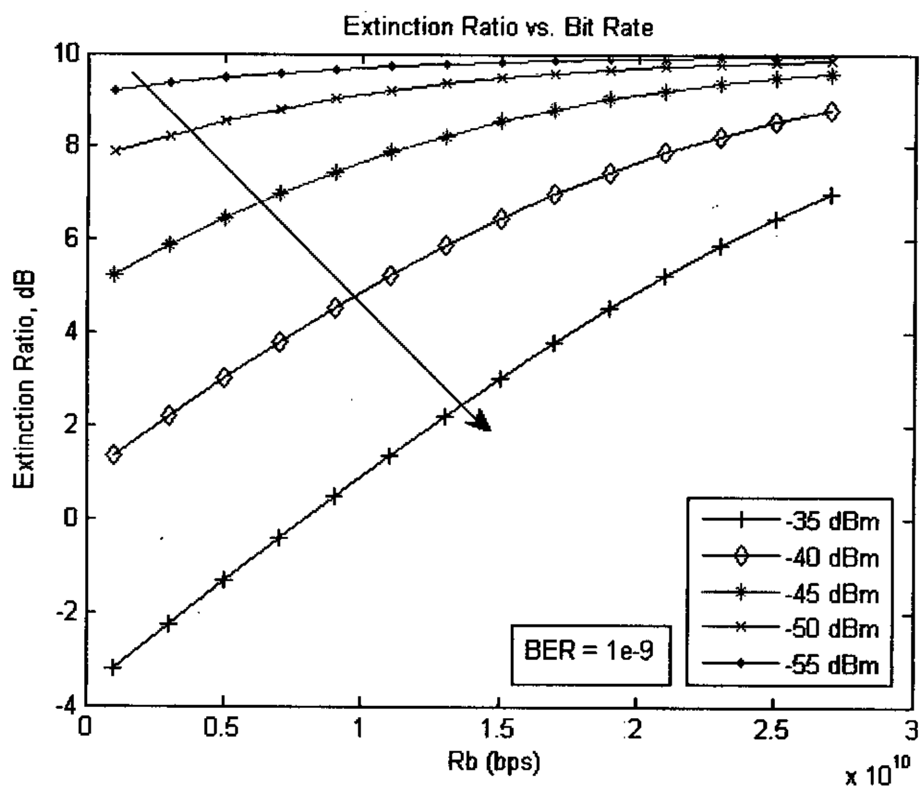

Figure 3.14: Plot of extinction ratio versus bit rate with signal power as a parameter (varying from -35 to -55 dBm)

The variation of extinction ratio with increase in bit rate is depicted in Fig.3.13 for several values of P_s(dBm) and P_p(dBm). It is noticed that there is significant increase in extinction ratio at higher bit rate as it requires higher pump power at a given signal power at higher bit rates at a given BER (say, 10^{-9}).

Chapter-4

Conclusion

4.1 Conclusion

A model is developed for an OTDM demultiplexer based on Cross Gain Modulation (XGM) in a Semiconductor Optical Amplifier (SOA). Analysis is carried out to evaluate the performance of the OTDM demultiplexer in terms of output signal corresponding to '0' and '1' bit of the desired OTDM channel. Expression is developed for the output signal current and noise currents when an optical Direct Detection (DD) receiver used to receive the demultiplexed signal. The expression for Signal to Noise Ratio (SNR) and Extinction Ratio (ER) and Bit Error Rate (BER) are also derived.

Performance results are evaluated numerically for operation at different bit rates of a particular channel considering Amplified Stimulated Emission (ASE) and photo detector (shot) and receiver (thermal) noise. The results are presented in terms of BER versus pump power at different bit rates for various input signal power level. The receiver sensitivity at specific BER and the output ER are also evaluated for different bit rate.

It is found that at a given signal input power the BER can be reduced by increasing the pump power and the required pump power is higher at higher level of input power.

It is noticed that the bit error rate decreases with increase in pump power at a given signal power level. At higher signal power level the BER is higher. For instance the receiver sensitivity in terms of P_p(dBm) at a BER of 10^{-9} is found to be -40.85 dBm and -39.93 dBm corresponding to P_s = -45 dBm and -37 dBm respectively.

It is also noticed that at a given BER the required signal power is higher when the pump power is increased. This is due to the increased shot noise at higher pump power input.

It is clearly found that the required values of P_s(dBm) are within the normal operational range of signal levels in a direct detection receiver. The relationship between the required value of P_s(dBm) to achieve a given BER of 10^{-9} corresponding to a given P_p(dBm) is determined for operation at a bit rate of 5 Gbps to 25 Gbps

The dependence of extinction ratio at the output of the OTDM DMUX with pump power of SOA-1 is noticed at a bit rate of 10 Gbps at a BER = 10^{-9} with P_s(dBm) as a parameter. The figure clearly depicts how the degradation in extinction ratio occurs at higher values of signal power due to gain saturation effect of SOA. This is due to the fact that at higher signal power input, the dynamic range between the signal levels for '1' and '0' bits is reduced. At low input signal power, there is a significant improvement in extinction ratio.

It is noticed that there is significant increase in extinction ratio at higher bit rate as it requires higher pump power at a given signal power at higher bit rates at a given BER (say, 10^{-9}).

4.2 Further Scope of Works

Further works can be carried out to evaluate the impact of crosstalk due to adjacent OTDM channels and due to the cross-gain modulation of SOA.

Further research can be initiated to carryout the simulation for the OTDM DMUX based on SOA and to compare with analytical results.

Works can be carried out to compare the performance of OTDM DMUX with other SOA-based OTDM DMUX and to find the optimum design parameters.

Further work can be carried out to evaluate the numerical results for operation at higher bit rates and to find the maximum number of OTDM channels as limited by crosstalk.

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