Performance Analysis of a DWDM Transmission System with Gain Saturation Effect of Semiconductor Optical Amplifier

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by

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The thesis titled **"PERFORMANCE ANALYSIS OF A DWDM TRANSMISSION SYSTEM WITH GAIN SATURATION EFFECT OF SEMICONDUCTOR OPTICAL AMPLIFIER"** submitted by **TANZINA KHALEQUE** Roll No.: 100606242P, Session: October 2006 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING** on July 18, 2009.

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List of Abbreviations

ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FOA	Fiber Optical Amplifier
FPA	Fabry-Perot Amplifier
SCR	Signal to Crosstalk Ratio
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
TWA	Traveling-wave Amplifier

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Abstract

A theoretical analysis of crosstalk due to gain saturation effect of semiconductor optical amplifier (SOA) is presented for a wavelength division multiplexed (WDM) system with optical amplifier in cascade. The analysis is carried out to evaluate the amount of crosstalk introduced by an optical amplifier while amplifying several channels simultaneously due to its gain fluctuation, induced by input power fluctuation, caused by random input bit patterns of input channels. The randomness of power fluctuation is approximated as a Gaussian process with crosstalk induced as the variance. The expression of signal to noise ratio (SNR) and bit error rate (BER) is developed with combined effect of crosstalk and amplified spontaneous emission (ASE) noise present in SOA. The results are computed by numerical computation. The results show that there is significant deterioration in BER performance due to the effect of gain saturation induced crosstalk which in turn limits the maximum allowable input power per channel. Performance results are evaluated for thermal noise limited and shot noise limited receiver operations. It is noticed that for thermal noise dominating operation, the maximum allowable input power is limited to a value which is much less than that for shot noise dominant case. Thermal noise dominating receiver allows more number of spans to be cascaded in the transmission system since the crosstalk effect is less at low power level. For example, when the receiver performance is dominated by thermal noise, the maximum allowable input power per channel of a two channel WDM system can be -23dBm which allows 150 spans in cascade to have BER 10^{-9}, but for shot noise dominated case, the input power per channel can be -13dBm which allows only 25 spans in cascade. Also, the maximum number of span that can be cascaded in the transmission system is determined to achieve BER 10^{-9} for different bit rates, input powers, and number of channels.

Chapter-1

Introduction

Optical communications is an extremely fast growing technology driven mainly by increasing need for global expansions of the Internet and Multimedia communications. 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 Evolution of Dense Wavelength Division Multiplexing (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 amplifiers were 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 a 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 1.33μm and the other is at 1.55 μm. Modern systems can handle up to 160 signals and can thus expand a basic 10Gbps fiber system to a theoretical total capacity of over 1.6Tbps over a single fiber pair.

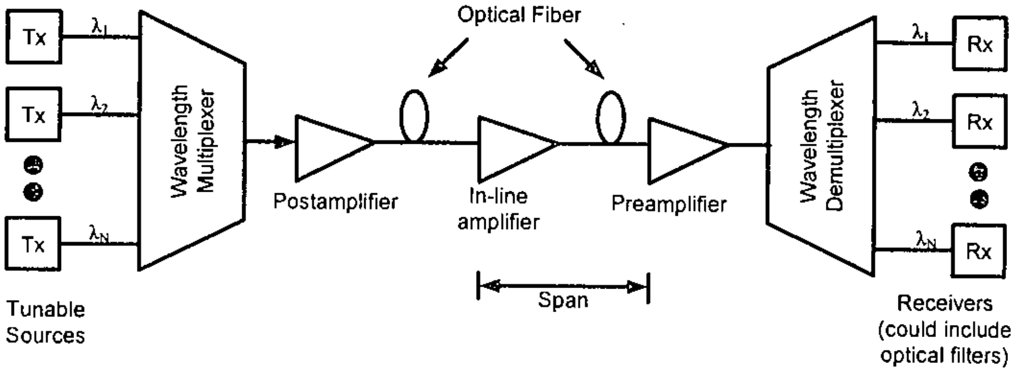


Fig. 1.1: Implementation of a typical WDM network containing various types of optical amplifier.

1.2 Components of a WDM System

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 the 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 lasers' 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/or active devices to combine, distribute, isolate and amplify optical power at different wavelengths [2].

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 tap 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. 1.1 shows the use of such components in a typical WDM link containing various types of optical amplifiers.

1.3 Optical Amplifiers

In fiber optics communication systems, problems arise from the fact that no fiber material is perfectly transparent. The visible light or infrared beams carried by a fiber are attenuated as they travel through the material. This necessitates the use of repeaters in spans of optical fiber 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 circuits of a conventional repeater cannot.

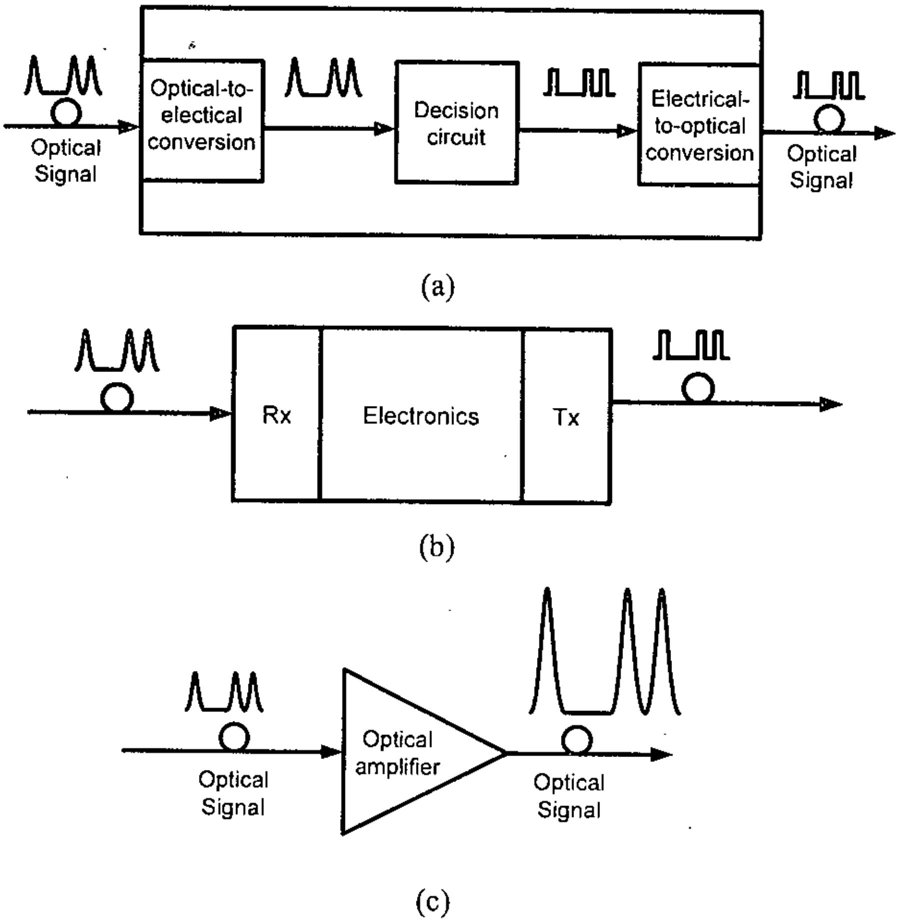


Fig. 1.2: Repeaters and optical amplifiers, (a) functional block diagram of a repeater, (b) simplified diagram of a repeater, (c) optical amplifier.

On the other hand, optical amplifiers simply strengthen the optical signal, as shown in Fig. 1.2. Optical amplifiers work without having to convert an optical signal into electrical form and back. This feature leads to two great advantages of 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.

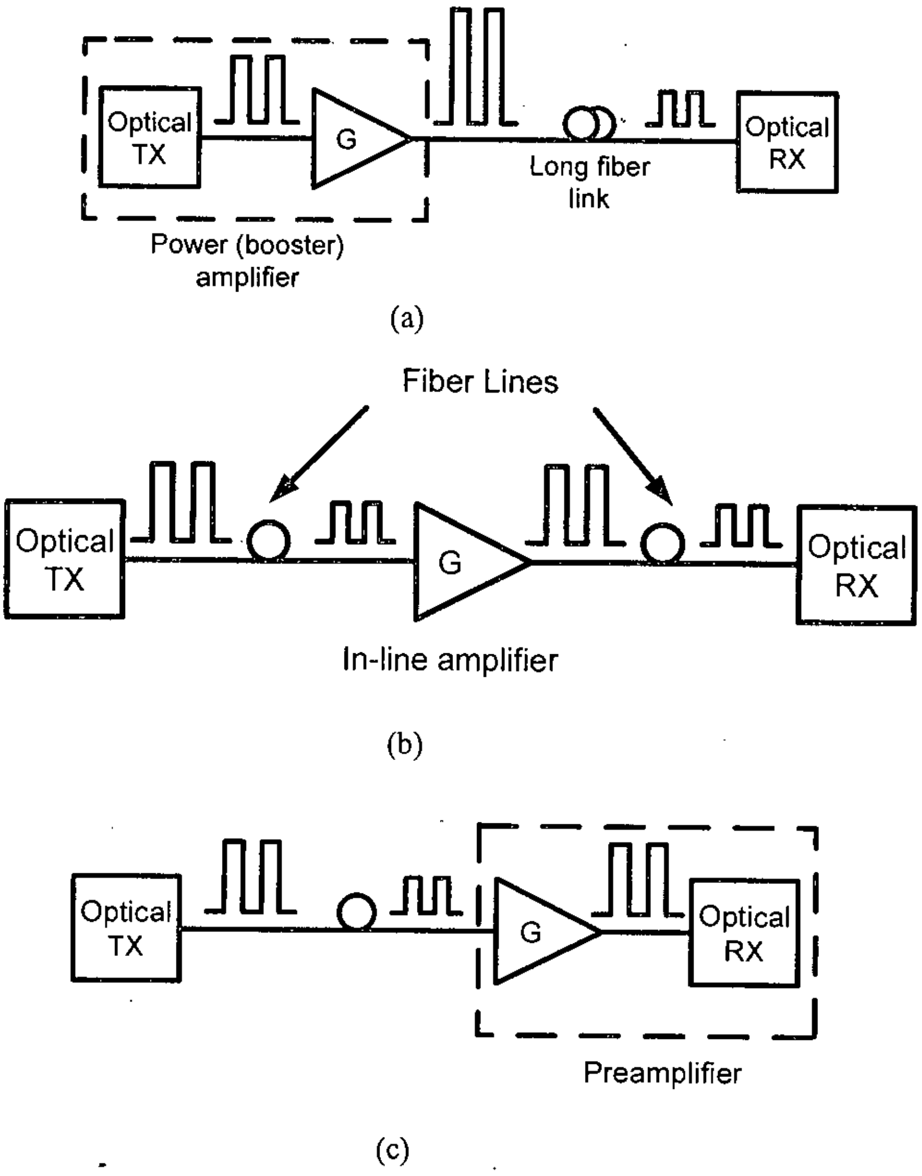


Fig. 1.3: Applications of optical amplifier, (a) booster of transmitted power, (b) in-line amplifier to increase transmission distance, (c) preamplifier to improve receiver sensitivity.

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.

An *in-line amplifier* operates with a signal in the middle of a fiber-optic link. Its primary function is to compensate for power losses caused by fiber attenuation, connections, and signal distribution in networks. Hence, the main requirement of this type of amplifier is stability over the entire WDM bandwidth. Since many in-line amplifiers may be cascaded, similarity in gain characteristics is also of concern when working with this amplifier. Keeping noise at the minimal level and performing good optical interaction with a transmission fiber are other requirements of this type of optical amplifier.

A *preamplifier* amplifies a signal immediately before it reaches the receiver. This type of optical amplifier operates with a weak 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 [3].

1.3.3 Types of optical amplifier

Two major classes of optical amplifiers are semiconductor optical amplifiers (SOA) 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) and the Traveling Wave Amplifier (TWA). A fiber optical 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 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 cascaded to overcome fiber losses in a long-haul lightwave system. The buildup of amplifier-induced noise is the most critical factor for such systems. Because, in a cascaded chain of optical amplifiers, shown in Fig. 1.1, 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 reduce 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 amplifiers 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 wavelengths 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.

Buus et al. [4] developed a simple model for the characteristics of Fabry-Perot type semiconductor laser amplifiers which leads to several simple analytic expressions. The theoretical results have been compared with measurements using a 1.3 μm laser as an amplifier.

Mukai et al. [5] investigated the signal gain saturation and crosstalk characteristics in two channel common amplification using a 1.5μm traveling-wave laser amplifier. Simultaneous amplification in the two channels causes gain saturation of the other, which results in an approximate 3dB reduction in saturation output power.

O'Mahony [6] discussed the application of semiconductor laser amplifiers to future long wavelength optical fiber systems. The basic equations defining laser amplifier characteristics are presented together with experimental results.

Ryu et al. [7] theoretically and experimentally presented the studies on long-haul coherent optical fiber communication systems with in-line optical amplifier repeaters. By theoretical calculation it is found that coherent systems can achieve wider dynamic range for an amplifier input power as compared with the intensity-modulation direct detection systems.

Gray et al. [8] investigated the effect of cross saturation on the frequency noise of the main mode which contain the nonlinear gain with both the self saturation and cross saturation. When cross saturation is stronger than self saturation, the frequency noise of the main mode is found to be significantly enhanced in the low frequency regime of less than 1GHz. An increase of more than 20dB is predicted due to a side mode suppressed by 15-20dB.

Öberg et al. [9] experimentally studied the performance of a 1.5μm Fabry-Perot type laser amplifier having two input signals at different wavelengths. Crosstalk between the two signals at the output of the amplifier is measured. A theoretical model taking gain saturation and wavelength shift of the amplifier spectrum into account is shown to explain the experimental results well. A theoretical model taking gain saturation and wavelength shift of the amplifier spectrum into account is shown to explain the experimental results.

Olsson [10] investigated fiber optic communication systems employing semiconductor laser amplifiers theoretically and experimentally. The noise and bit error rate characteristics of lightwave systems with optical amplifiers are calculated and the dependence of system performance on amplifier characteristics such as optical bandwidth, noise figure, gain is shown. Experimental results are presented on both a 4Gbps optical preamplifier as well as coherent and direct detection systems with four in-line amplifiers.

Inoue [11] presented theoretical study for channel crosstalk due to gain saturation in laser amplifier in multichannel transmission. Considering the probability distribution, the power penalty due to crosstalk is presented for practical system design. Calculation examples reveal that the power penalty is dependent on both the level of gain saturation and the number of multiplexed channels.

Durhuus et al. [12] presented an advanced dynamic model for multisection semiconductor optical amplifiers which accounts for the carrier and field distributions in the longitudinal direction as well as for the facet reflectivities. The crosstalk and intermodulation distortion due to cascaded amplifiers are found to accumulate by adding together in amplitude which limits the number of cascaded amplifiers in multichannel systems.

Liu et al. [13] investigated theoretically the effect of amplified spontaneous emission on the spatial distribution of the carrier density. Measures of the semiconductor optical amplifier performance, such as gain, saturation power and noise figure are derived. It is shown that the saturation due to the ASE strongly affects the SOA performance for device lengths>500μm.

Tangdiongga et al. [14] demonstrated the performance of linear optical amplifiers in a dynamic and reconfigurable wavelength division multiplexing system. Eight

WDM channels, each running at 10Gbps, are transmitted through two cascaded linear optical amplifiers and power transient immune add-drop capability is demonstrated by switching four of the eight channels at rates of 10-100kHz without affecting the bit error rate.

Lin et al. [15] demonstrated a new type of semiconductor optical amplifiers that can have a very low channel crosstalk. By arranging the order of the gain materials with different saturation power, the SOA crosstalk is greatly reduced. This new type of SOA can be an ideal gain material for WDM amplification.

The feature of gain saturation in semiconductor lasers is very important for multi-channel amplification since it gives rise to crosstalk which is strongly dependent on the input powers and on the signal gain. Crosstalk due to gain saturation in SOA reduces the signal to crosstalk ratio (SCR) and increases the bit error rate of the system and ultimately reduces the number of span that can be cascaded and also the number of WDM channels that can be amplified simultaneously in optical transmission system. Again, the ASE noise in SOA limits the performance of the system. So, it is important to investigate the combined effect of gain saturation induced crosstalk and ASE noise in a WDM system with optical amplifiers in cascade.

1.5 Objectives

The objectives of this research work are:

(i) To develop expression for the crosstalk in one channel due to gain saturation effect of a SOA caused by random input bit patterns in other channels.

(ii) To derive the SCR and signal to ASE noise ratio with the variation of input power and signal gain of a WDM system.

(iii) To develop an analytical expression for BER considering the statistics of the gain saturation induced crosstalk and the ASE noise due to SOA.

(iv) To find the performance results and limitations due to crosstalk and ASE noise and to find the maximum number of span for different signal gain, input power and number of channels of a WDM system.

1.6 Organization of the Thesis

Chapter 2 gives the detailed theoretical analysis of a DWDM transmission system 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 reported at chapter 2.

Chapter 4 presents the conclusive remarks of this thesis along with the limitation and 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 results in spontaneous radiation.

A different process occurs if an external photon hit an excited electron as shown in the Fig. 2.1. Their interaction includes an 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 the 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 mirrors provide positive optical feedback and the mirrors constitute a resonator.

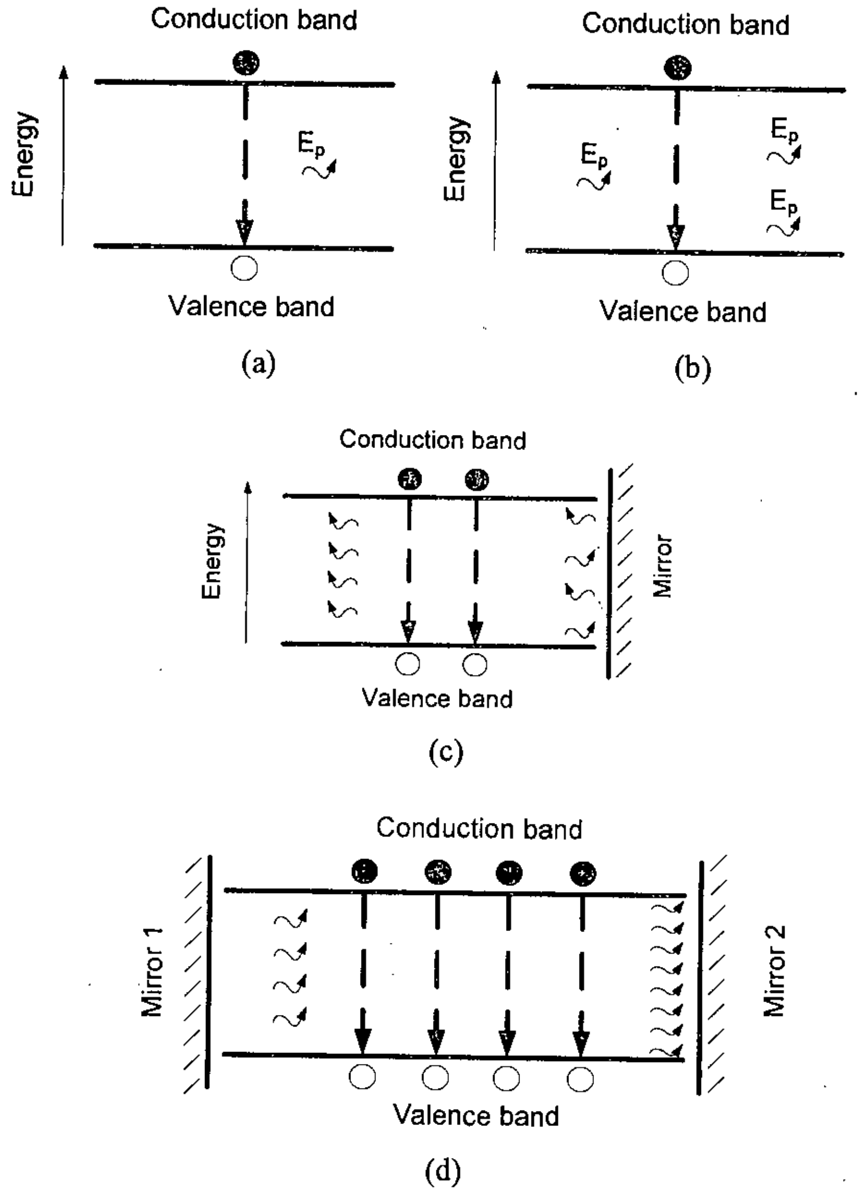


Fig. 2.1: (a) Spontaneous radiation, (b) stimulated radiation, (c)- and (d) light amplification and positive feedback.

2.1.2 Principle of operation of a semiconductor optical amplifier

An SOA uses the principle of stimulated emission to amplify an optical information signal. How an SOA is connected to a fiber link is shown schematically in Fig. 2.2. An optical input signal carrying original data enters the semiconductor's 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.

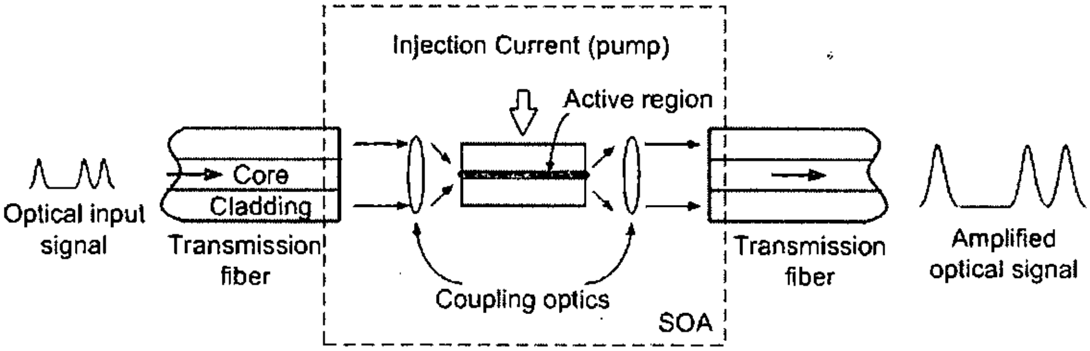
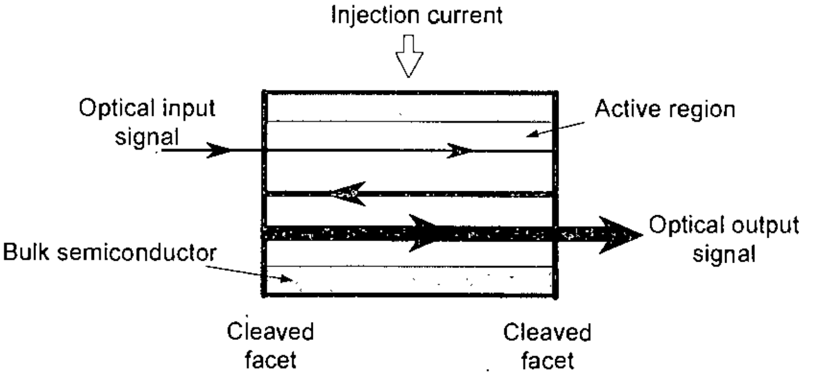
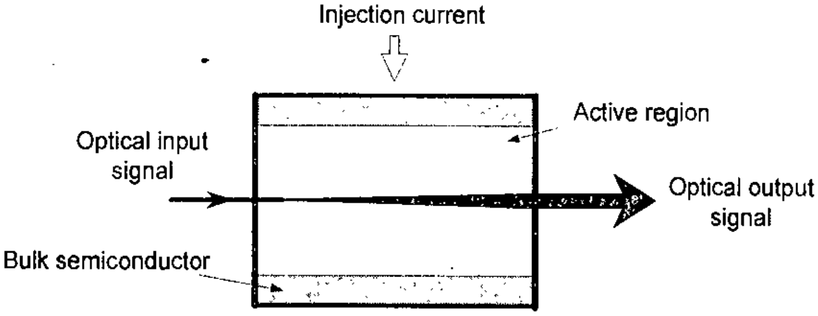


Fig. 2.2: Semiconductor optical amplifier (SOA).

2.1.3 Fabry-Perot and traveling-wave amplifiers



(a)



(b)

Fig. 2.3: (a) Fabry-Perot, (b) Traveling-wave semiconductor optical amplifier.

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.

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

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 [16][17],

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

where,

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

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

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

λ and λ_0 are the current and center 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],

$$\lambda_N = 2L/N \tag{4}$$

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

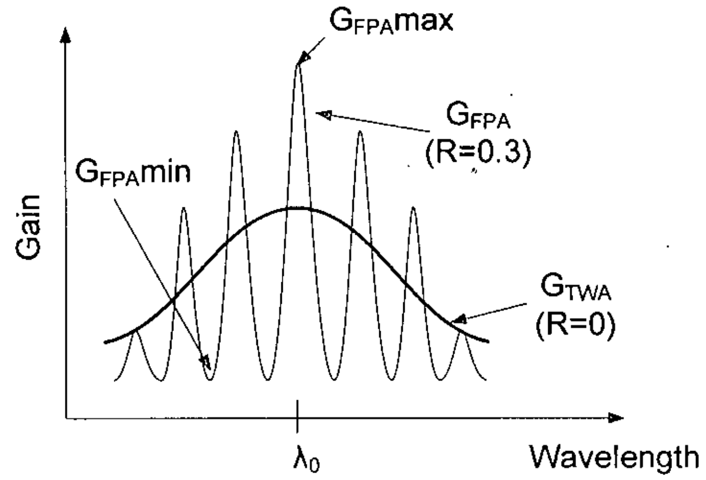


Fig. 2.4: Gain of FPA and TWA as a function of wavelength

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 facets 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,

$$G_{TWA} = \frac{P_{out}}{P_{in}} = G_s \tag{5}$$

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

$$G_s = \exp[(\Gamma g_0 - \alpha_0)L] \tag{6}$$

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 [17],

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

where, P_{sat} is the saturation optical power. When the signal power becomes too high, the gain coefficient starts 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 electrons 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 [9],

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

$I(z)$ 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 single pass gain is given by,

$$G_s = \exp[\int_0^L (\Gamma g(z) - \alpha_0) dz] \qquad (9)$$

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 a channel caused by the presence of another channel. There are two types of crosstalk in SOAs, interchannel 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 saturated mode, i.e. the power of the input signals is above the saturation value. When one channel changes from ON to OFF, the gain undergoes an opposite change. This gain change 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.

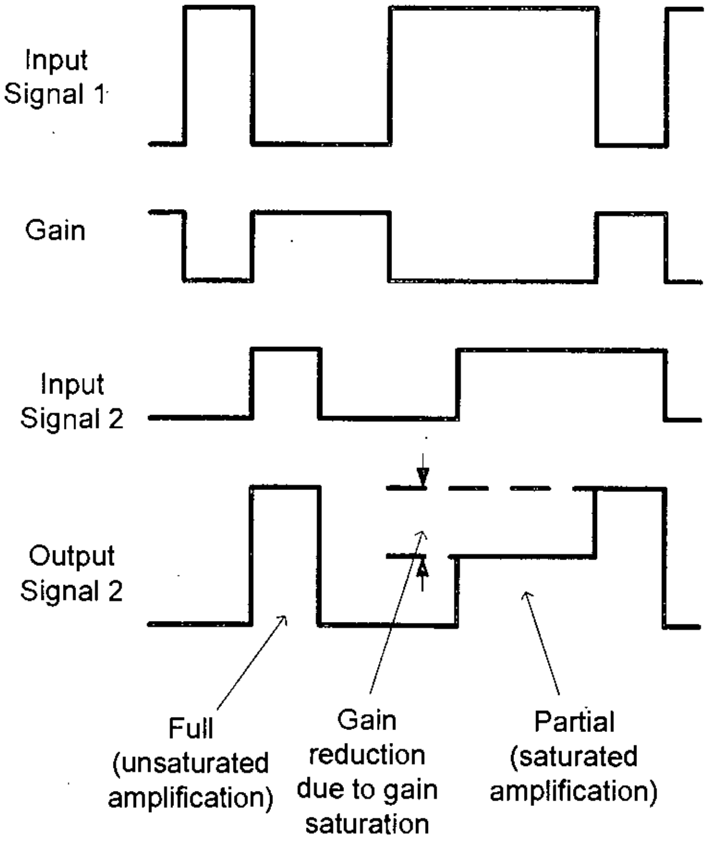


Fig. 2.5: Crosstalk in SOA due to gain saturation

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 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 [17],

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

where, N_2 and N_1 are populations of the excited and lower levels respectively. The higher the spontaneous emission factor, the greater 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,

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

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

2.6 System Model

The system model of a multiple span DWDM optical transmission system with in-line optical amplifiers used for theoretical analysis is shown in Fig. 2.6. Gain saturation at high input power levels in in-line amplifiers introduces crosstalk in a specific channel.

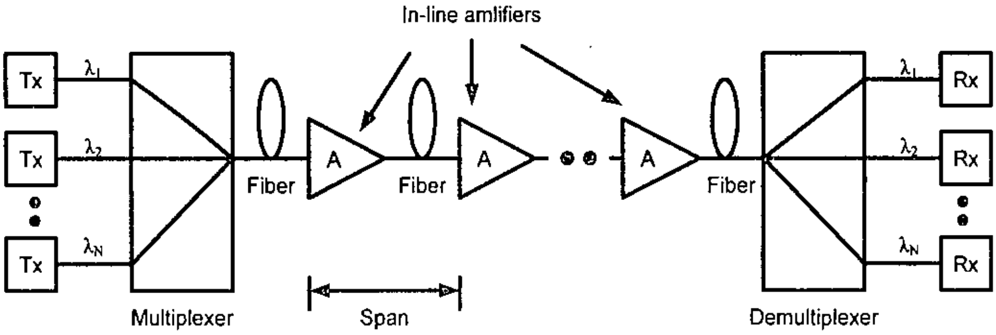


Fig. 2.6: Multiple span DWDM system architecture

2.7 Optical Receiver Model

In practice, the vast majority of installed optical fiber communication systems use incoherent or direct detection 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.

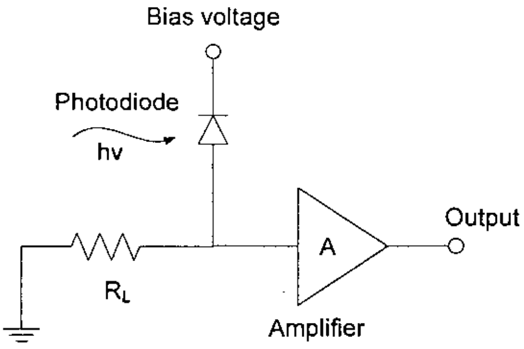


Fig. 2.7: Simple model of photodetector receiver

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. 2.7 shows a simple model of a photodetector receiver. A block schematic of the front end of an optical receiver with various noise sources associated with it is shown in Fig. 2.8.

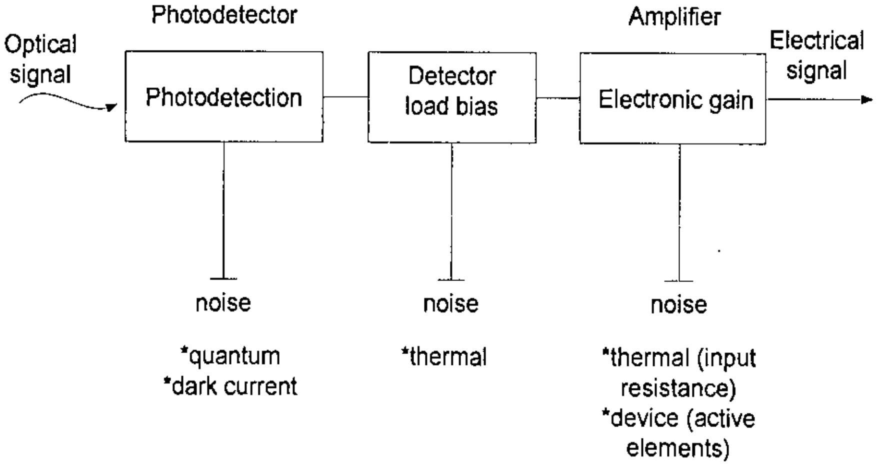


Fig. 2.8: Block schematic of the front end of an optical receiver showing the various sources of noise.

2.7.1 Shot noise

The shot noise arises from the statistical nature of the production and collection of photoelectrons when an optical signal is incident on a photodetector. The two main sources 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 [18],

$$\left\langle i_{shot}^2 \right\rangle = \sigma_{shot}^2 = 2qB_e(I_p + I_d) \qquad (12)$$

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.

2.7.2 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 [18],

$$\langle i_{th}^2 \rangle = \sigma_{th}^2 = \frac{4kTB_e}{R_L} \tag{13}$$

where, k is Boltzman constant, T is room temperature.

2.7.3 Signal to noise ratio (SNR) of an optical receiver

The SNR for the p-n or p-i-n photodiode receiver is obtained by summing all the noise contribution as [18],

$$\frac{S}{N} = \frac{I_p^2}{2qB_e(I_p + I_d) + \frac{4kTB_e}{R_L} + \langle i_{amp}^2 \rangle} \tag{14}$$

where, $\langle i_{amp}^2 \rangle$ is the total noise associated with the amplifier. However, when the noise associated with the amplifier is referred to the load resistor R_L, the noise figure F_n for the amplifier may be obtained. This allows $\langle i_{amp}^2 \rangle$ to be combined with the thermal noise from the load resistor $\langle i_{th}^2 \rangle$ to give,

$$\langle i_{th}^2 \rangle + \langle i_{amp}^2 \rangle = \frac{4kTB_eF_n}{R_L} \tag{15}$$

The expression for the SNR can be written in the form [18],

$$\frac{S}{N} = \frac{I_p^2}{2qB_e(I_p + I_d) + \frac{4kTB_eF_n}{R_L}} \tag{16}$$

2.8 Analysis of Crosstalk due to Gain Saturation Effect of SOA

(i) For Two Channel

At first we consider two input channels in a multiple span optical transmission system as shown in Fig. 2.6. To define crosstalk, we first consider, channel 2 with a constant power (P_{2in}) and channel 1 with varying power (P_{1in}) as shown in Fig. 2.9.

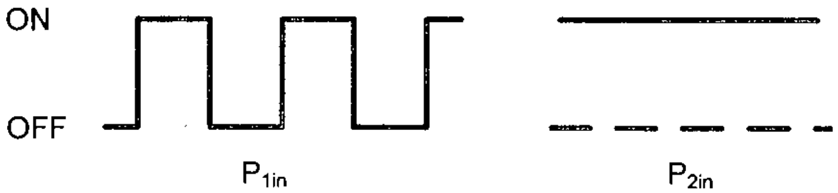


Fig. 2.9: Schematical drawing of two input signals in WDM system.

The two wavelengths are sufficiently far apart to neglect interchannel crosstalk, the maximum gain for two wavelengths are assumed to be same, the gain spectra is shown is Fig. 2.10.

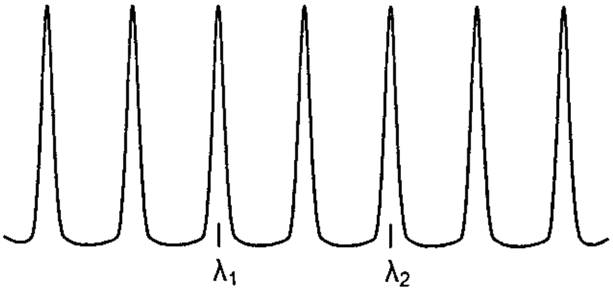


Fig. 2.10: The amplifier gain spectrum for two input signals at wavelength λ_1 and λ_2 respectively.

The total optical field inside the cavity is given by the sum of the fields traveling in the right and left directions. If no spontaneous emission is assumed to be present, the total field is given by [9],

$$E(z)=\frac{\sqrt{(1-R_1)}[\sqrt{G_{sr}(z)}\exp(-i\phi(z))+\sqrt{R_2G_sG_{sl}(z)}\exp(i\phi(z-L))]}{1-G_s\sqrt{R_1R_2}\exp(-2i\phi(L))}E_{in} \qquad (17)$$

Where, E_{in} is the incoming field and $G_{sr}(z)$ is the single pass gain for a wave traveling in the right direction from the input end to the position z. $G_{sr}(z)$ is given by (9) with the integration carried out from 0 to z. In the same way, $G_{sl}(z)$ is the single pass gain for a wave traveling in the left direction from the exit end to the position z, and is given by (9) with the integration carried out from z to L. $\phi(z)$ is the phase of the propagating field inside the cavity and is given by,

$$\phi(z)=2\pi n_g(z/\lambda-L/\lambda_0) \qquad (18)$$

For two input signals, (17) can be written as,

$$E(z)=\frac{\sqrt{(1-R_1)}[\sqrt{G_{sr}(z)}\exp(-i\phi(z))+\sqrt{R_2G_sG_{sl}(z)}\exp(i\phi(z-L))]}{1-G_s\sqrt{R_1R_2}\exp(-2i\phi(L))}\sqrt{(E_1^2+E_2^2)} \qquad (19)$$

If the amplifier gain is G when both the channels share the amplifier simultaneously, and is G_2 when only channel 2 shares the amplifier, then at high input powers, G will be lower than G_2. Because, when one signal is present, input intensity in the amplifier is low, and according to (8), g will be higher i.e. total gain will be higher than the gain when two input signals are present.

When, both the channels are ON,

$$P_{1out}=G\times P_{1in}$$

$$P_{2out}=G\times P_{2in} \qquad (20)$$

When, channel 1 is OFF and channel 2 is ON,

$P_{1out}=0$, since $P_{1in}=0$

$$P_{2out}=G_2\times P_{2in} \qquad (21)$$

This gain difference will cause crosstalk, which is defined as,

$$\begin{aligned} crosstalk &= P_{2out}\,(P_{1in} = OFF) - P_{2out}\,(P_{1in} = ON) \\ &= (G_2 \times P_{2in}) - (G \times P_{2in}) \end{aligned} \qquad (22)$$

If after one span, a receiver is placed, then, crosstalk variance at receiver will be,

$$\sigma^2{}_{cross} = 2qB_e\Re P_{cross} \qquad (23)$$

where,

$P_{cross} = crosstalk$ from (22)

$B_e =$ Receiver bandwidth

$\Re =$ Responsivity of receiver

$q =$ Charge of an electron

At the receiver the signal power is P_{2out}, the mean square input photocurrent is,

$$\langle i^2_{ph} \rangle = \sigma^2_{ph} = \Re^2 P^2_{2out} \qquad (24)$$

The signal to crosstalk ratio is,

$$SCR = \frac{\sigma^2_{ph}}{\sigma^2{}_{cross}} = \frac{\Re^2 P^2_{2out}}{2qB_e\Re P_{cross}} \qquad (25)$$

Bit error rate is given by [18],

$$BER = \frac{1}{2} erfc\left[\frac{\sqrt{SCR}}{2\sqrt{2}}\right] \qquad (26)$$

When multiple spans are considered, the cumulative effect of the crosstalk is obtained by replacing P_{cross} in (23) by NP_{cross}, where N is the number of amplifiers.

(ii) For Multiple Channel

When there are multiple input signals in the amplifier, value of crosstalk depends on the random bit pattern of different input signals, but the worst case occurs between the incidents when all the channels are present simultaneously and when only the specific channel (whose crosstalk is being considered) is present. For N channel system, if crosstalk is to be measured for channel 2, then (22) will be modified as,

$$crosstalk = P_{2out}(P_{1in}, P_{3in}, P_{4in} \ldots\ldots P_{N\,in} = OFF) - P_{2out}(P_{1in}, P_{3in}, P_{4in} \ldots\ldots P_{N\,in} = ON)$$

$$= P_{2in} G_2 - P_{2in} G \qquad (27)$$

here, G_2 is the amplifier gain when only channel 2 exists, and G is the gain when all the N channels are to be amplified simultaneously. However, (27) will give the crosstalk value of the worst case.

If random bit pattern is considered, then average crosstalk can be calculated. For example, if there are three channels in a WDM system and crosstalk of channel 3 is to be measured, then channel 3 can have three different gain, depending on the bit patterns in other two channels. Fig. 2.11 illustrates the situation.

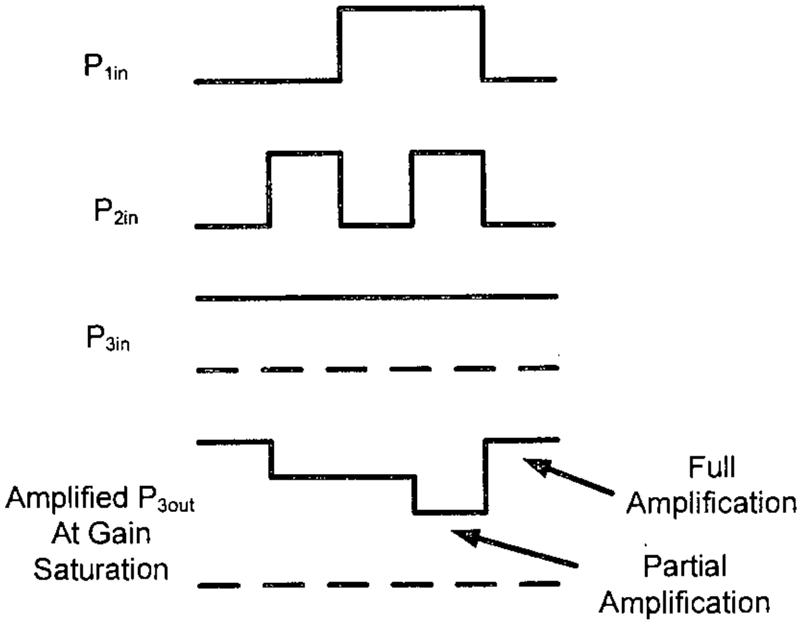


Fig. 2.11: Gain saturation effect in channel 3 due to random bit patterns in other two channels.

In channel 1 and 2, four different bit patterns can occur as 00, 01, 10 and 11. When channel 1 and 2 have 0 bits, channel 3 shares the amplifier alone and has maximum gain. A 1 bit in either of channel 1 and 2 will reduce the overall gain and cause crosstalk in channel 3. The worst condition occurs when all three channels have 1 bit. So, average crosstalk is measured considering all possible bit patterns in other channels. SCR and BER for multiple channels are same as two channels shown previously.

2.9 Analysis of Signal to 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 photodetector current i_{tot} is proportional to the square of the electric field of the optical signal,

$$i_{tot} \propto (E_s + E_{sp})^2 = E_s^2 + E_{sp}^2 + 2E_s E_{sp} \qquad (28)$$

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.

Considering ASE noise, and neglecting dark current noise, the total shot noise current is given by [2],

$$\left\langle i_{shot}^2 \right\rangle = \sigma_{shot}^2 = \sigma_{shot-s}^2 + \sigma_{shot-sp}^2 = 2qB_e(I_p + I_{sp}) \qquad (29)$$

$$I_p = \Re G P_{in}$$

$$I_{sp} = \Re P_{sp}$$

where, I_p and I_{sp} are the photocurrents equivalent of the input signal power and spontaneous emission power respectively, $\Re$ is the responsivity of the receiver, G

is the amplifier gain.

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 [10],

$$\sigma^2_{s-sp} = 4(\Re GP_{in})(\Re P_{sp}\frac{B_e}{B_o}) \tag{30}$$

In addition, since the ASE spans a wide optical frequency range, it can beat against itself giving rise to the noise current as [10],

$$\sigma^2_{sp-sp} = (\Re P_{sp})^2 B_e \frac{(2B_o - B_e)}{B_o^2} \tag{31}$$

The total mean-square receiver noise current then becomes,

$$\left\langle i^2_{totol} \right\rangle = \sigma^2_{totol} = \sigma^2_{th} + \sigma^2_{shot-s} + \sigma^2_{shot-sp} + \sigma^2_{s-sp} + \sigma^2_{sp-sp} \tag{32}$$

If the effect of crosstalk due to gain saturation is considered, (32) becomes,

$$\left\langle i^2_{totol} \right\rangle = \sigma^2_{totol} = \sigma^2_{th} + \sigma^2_{shot-s} + \sigma^2_{shot-sp} + \sigma^2_{s-sp} + \sigma^2_{sp-sp} + \sigma^2_{cross} \tag{33}$$

SNR is expressed as,

$$\frac{S}{N} = \frac{(\Re GP_{in})^2}{2qB_e\Re(GP_{in} + P_{sp} + P_{cross}) + 4(\Re GP_{in})(\Re P_{sp}\frac{B_e}{B_o}) + (\Re P_{sp})^2 B_e \frac{(2B_o - B_e)}{B_o^2} + \frac{4kTB_eF_n}{R_L}} \tag{34}$$

BER is given by [18],

$$BER = \frac{1}{2}erfc\left[\frac{\sqrt{SNR}}{2\sqrt{2}}\right] \tag{35}$$

In most cases of practical interest, thermal noise dominates receiver performance, i.e. $\sigma^2_{th} >> \sigma^2_{shot}$ [17]. Neglecting the shot noise terms in (34), SNR becomes,

$$\frac{S}{N} = \frac{(\Re GP_{in})^2}{2qB_e\Re P_{cross} + \frac{4kTB_eF_n}{R_L}} \tag{36}$$

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

$$\frac{S}{N} = \frac{(\Re GP_{in})^2}{2qB_e\Re(GP_{in} + P_{sp} + P_{cross}) + 4(\Re GP_{in})(\Re P_{sp}\frac{B_e}{B_o}) + (\Re P_{sp})^2 B_e \frac{(2B_o - B_e)}{B_o^2}} \qquad (37)$$

In a multiple span system, where N numbers of amplifiers are cascaded, the crosstalk power (P_{cross}) and the spontaneous emission power (P_{sp}) in (37) is to be replaced by NP_{cross} and NP_{sp} respectively in order to obtain cumulative effect of crosstalk and amplified spontaneous noise.

2.10 Summary

Theoretical study of semiconductor optical amplifier with gain saturation effect is given in this chapter. The crosstalk due to gain saturation effect is explained. The effect of ASE noise in the receiver is also described. An analytical expression for BER considering the statistics of the gain saturation induced crosstalk and the ASE noise due to SOA is developed.

Chapter-3

Results and Discussion

Following the theoretical analysis presented in chapter 2, the performance results of DWDM transmission system with gain saturation effect of semiconductor optical amplifier are evaluated considering the effect of crosstalk alone and also with the effect of amplified spontaneous emission noise present in SOA. The parameters used in theoretical computations for a Fabry-Perot type SOA and direct detection optical receiver are given in Table 3.1.

Table 3.1: List of Parameters

Symbol	Parameter	Value
R_1	Power reflectivity at the input facet	0.03
R_2	Power reflectivity at the output facet	0.30
L	Amplifier length	250 μm
w	Active layer width	1.5 μm
d	Active layer thickness	0.2 μm
n_g	Effective group index	4.01
λ_0	Wavelength of an unsaturated FP mode	1.4859 μm
Γ	Optical confinement factor	0.33
α_0	Waveguide loss	40 cm^{-1}
I_s	Saturation intensity	11.6 $\mathrm{mW/(\mu m)^2}$
n_{sp}	Spontaneous emission factor	1.5
--	Wavelength separation between two channels	Sufficiently large to neglect interchannel crosstalk
$\Re$	Responsivity of optical receiver	0.95
R_L	Load resistance of optical receiver	50Ω

3.1 Effect of Crosstalk due to Gain Saturation

The material gain coefficient g_0 is related to the signal intensity according to equation (8) of chapter 2. At higher power levels, the gain coefficient is reduced and the signal gain decreases. Fig. 3.1 illustrates the gain saturation effect of semiconductor optical amplifier for three different gain coefficients. As the input power is increased, the signal gain decreases gradually. Amplifier with higher gain coefficient suffers greater signal gain degradation.

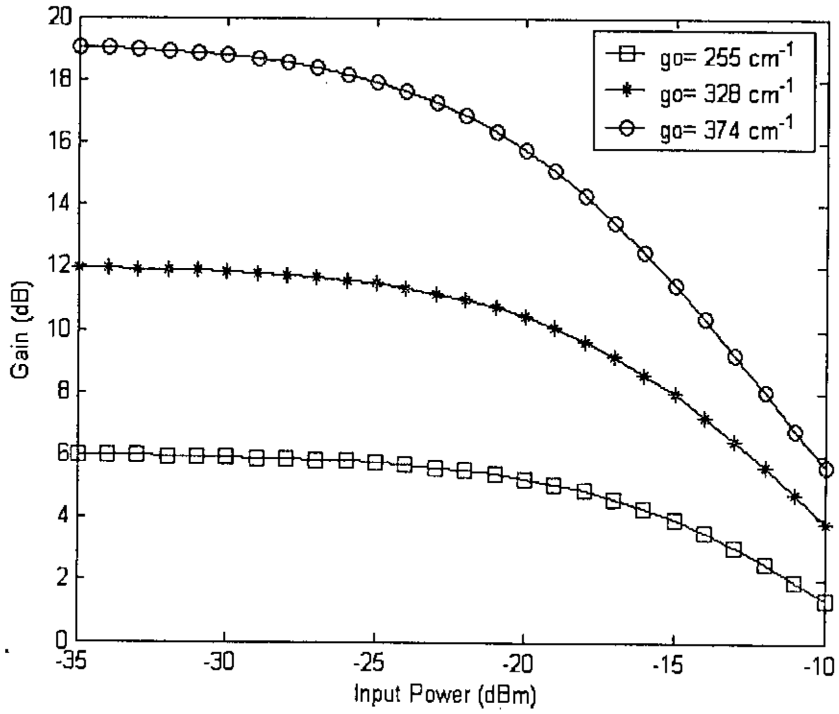


Fig. 3.1: Signal gain as a function of input power at SOA for different gain coefficients.

3.1.1 Results for two channel DWDM transmission system

At first, two signal channels are considered to be amplified simultaneously by SOA. The power level of channel 2 is kept constant at -20dBm, and power level of channel 1 is varied from -30dBm to -10dBm. Signal to crosstalk ratio (SCR) and bit error rate (BER) of channel 2 due to crosstalk is theoretically calculated for multiple span system. Fig. 3.2 shows BER performance of channel 2 against total input power at

SOA after 100 span. BER increases with the increase in total input power. This is because of increase in crosstalk due to gain saturation effect of SOA. The figure shows that greater bit rate causes greater BER. From the figure, it is seen that, total input power should not be more than -13dBm to achieve BER 10^{-9} for bit rate 10Gbps. Bit rate 20Gbps allows total input power not more than -15dBm.

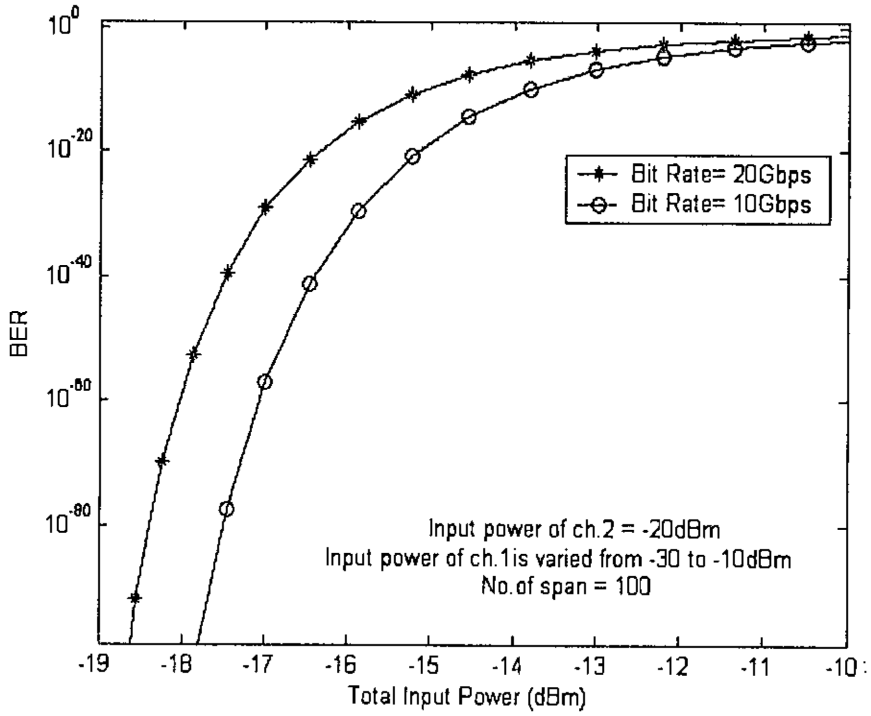


Fig. 3.2: BER performance of channel 2 as a function of total input power for two different bit rates considering the effect of crosstalk while input power of channel 1 is varied. The gain coefficient is 352 cm^{-1}.

Fig. 3.3 shows the BER performances of channel 2 for the two channel system, when input power of both channels are being varied simultaneously from -30dBm to -15dBm. Fig. 3.4 is the same plot for different bit rate.

From the figures, it can seen that when input power of each channel is small, gain saturation effect is negligible, and the signal with higher gain has lower BER, but when input power is sufficiently large to cause gain saturation, then the signal with higher gain suffers gain saturation effect greater than the signal with lower gain and has greater BER.

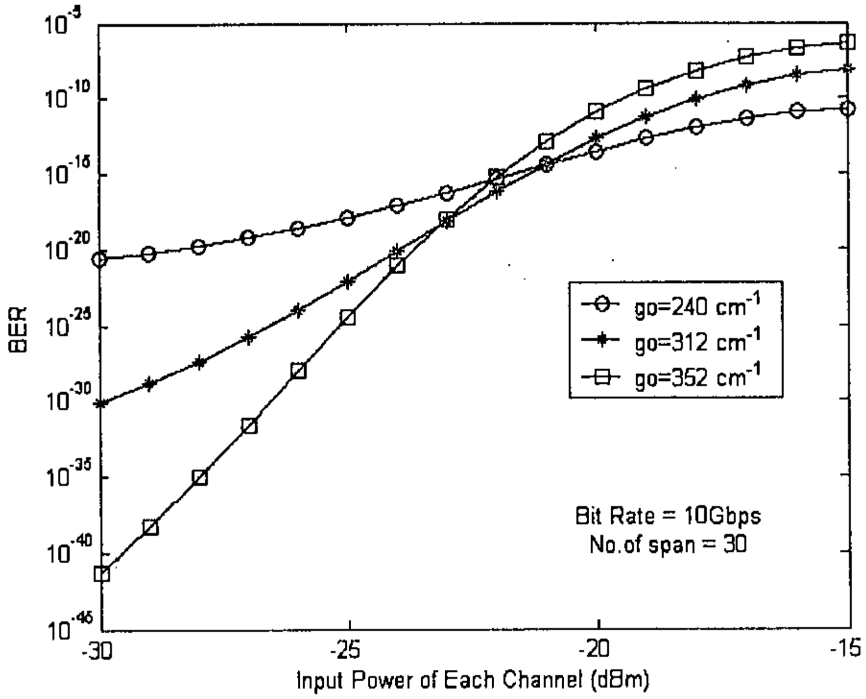


Fig. 3.3: BER performance of channel 2 as a function of input power of each channel considering the effect of crosstalk for different gain coefficients when bit rate is 10Gbps.

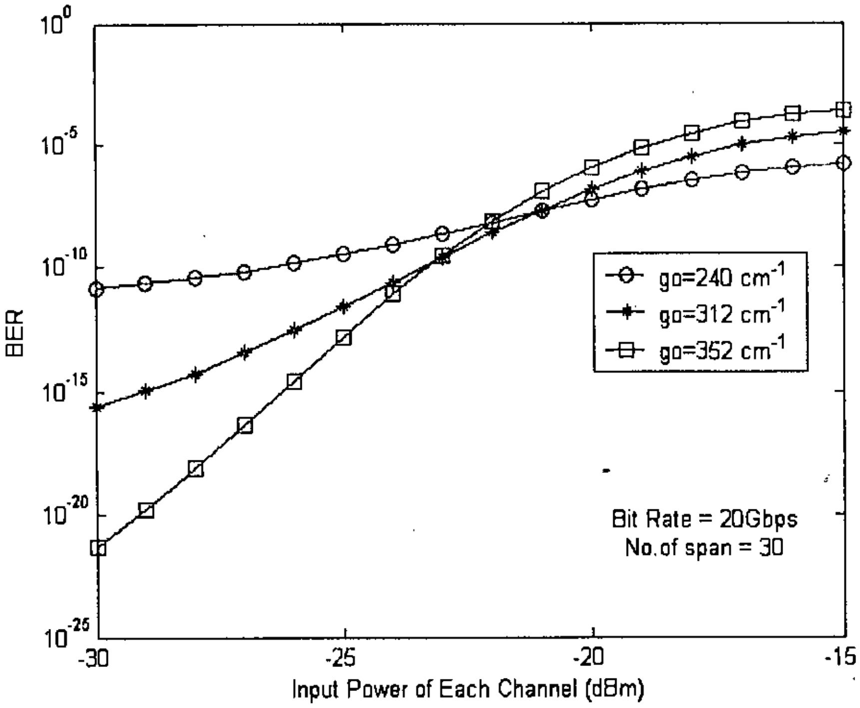


Fig. 3.4: BER performance of channel 2 as a function of input power of each channel considering the effect of crosstalk for different gain coefficients when bit rate is 20Gbps.

Again at larger bit rate, the BER increases. For example, at 10Gbps, 10^{-9} BER is achievable at -18.5dBm input power, having gain coefficient 312 cm^{-1}, but for the same input power and gain, BER increases to 10^{-6} at 20Gbps.

In these figures, it is also seen that, among three plots with different gain coefficients, the one with lower BER achieves higher BER after crossing some input power level because of gain saturation effect. For example, in Fig. 3.3, this transition occurs at about -22dBm. So, in multiple span system, the relation between signal gain and number of span depends on input power level which is illustrated in Fig. 3.5- 3.8.

From Fig. 3.5 and 3.6, maximum number of cascaded spans can be determined which will give BER 10^{-9} at the receiver end. The results obtained from the figures are summarized in Table 3.2 for two different bit rates.

Table 3.2: Maximum no. of span for different gain and bit rates considering crosstalk effect

P_{in} (dBm)	G (dB)	No. of Span (Bit Rate =10Gbps)	No. of Span (Bit Rate =20Gbps)
-25	5	125	60
	10	175	85
	15	225	114
	20	300	150
-17	2	79	40
	5	70	35
	7	55	28
	8	39	19

At input power -25dBm, lower number of spans can be cascaded with lower signal gain and higher signal gain allows greater number of span. Again, with the increase of bit rate BER increases and the number of spans decreases.

For input power -17dBm, a reverse situation occurs which is shown in Fig. 3.7 and Fig. 3.8. The results are summarized in Table 3.2. So, at input power -17dBm, the number of span decreases with the increase in gain.

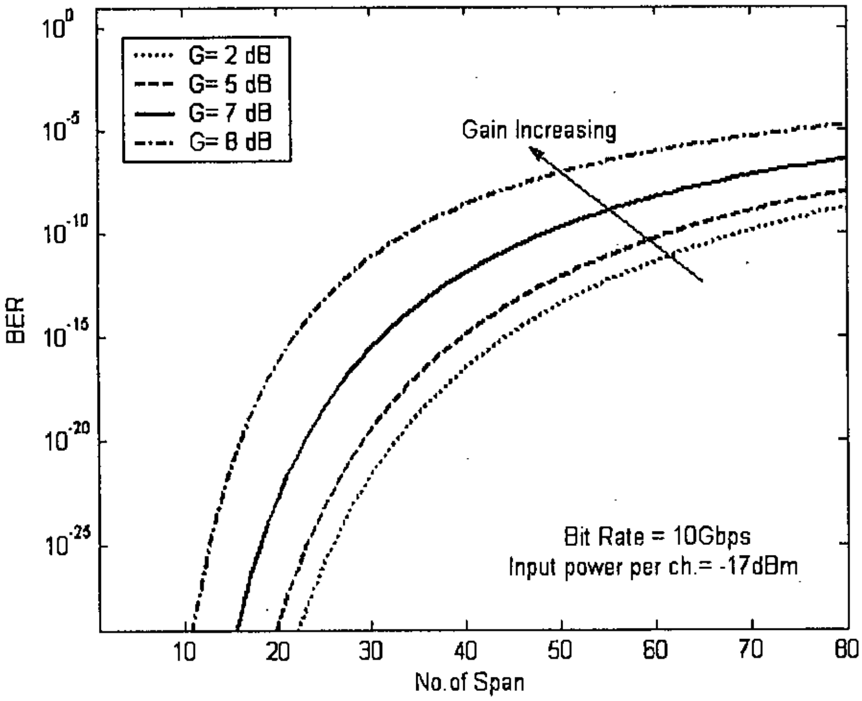


Fig. 3.7: BER versus number of span considering the effect of crosstalk when input power per channel is -17dBm and bit rate 10Gbps.

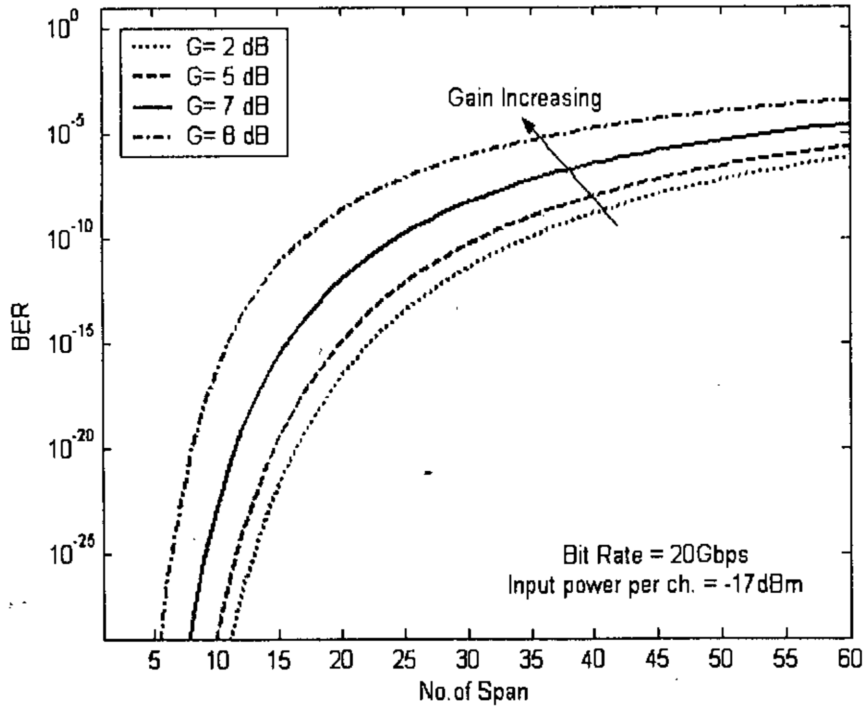


Fig. 3.8: BER versus number of span considering the effect of crosstalk when input power per channel is -17dBm and bit rate 20Gbps.

Fig. 3.9 shows the maximum number of spans for different input power in each channel which will give BER of 10^{-9} at the receiver. The figure also shows the effect of two different gain coefficients. At lower input power, there is no effect of gain saturation. With the higher amplifier gain, the number of span is also higher. For -35dBm input power per channel, about 500 spans can be cascaded with g_o= 374 cm^{-1} and about 150 spans can be cascaded with g_o= 255 cm^{-1}.

Fig. 3.10 shows the comparison between two bit rates for gain coefficient g_o= 374 cm^{-1}. Some of the results from the plot for gain coefficient g_o= 374 cm^{-1} are shown in Table 3.3. For example, an increase in bit rate from 10Gbps to 20Gbps decreases about a 100 number of spans for input power -25dBm per channel. From the statistics of the data, it can be conclude that when the bit rate doubles, the number of span approximately halves.

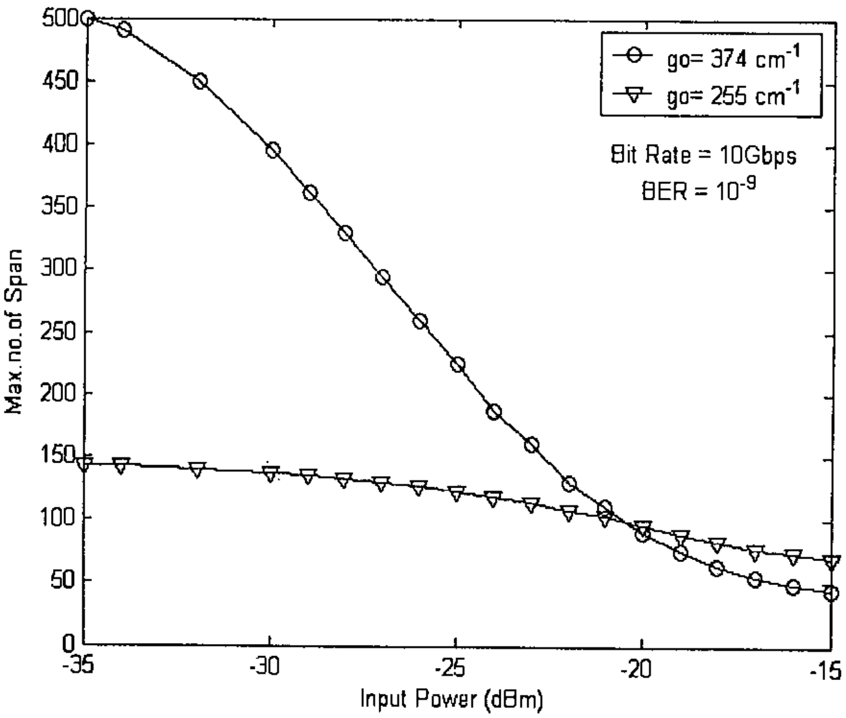


Fig. 3.9: Maximum number of span versus input power per channel considering the effect of crosstalk for two different gain coefficients.

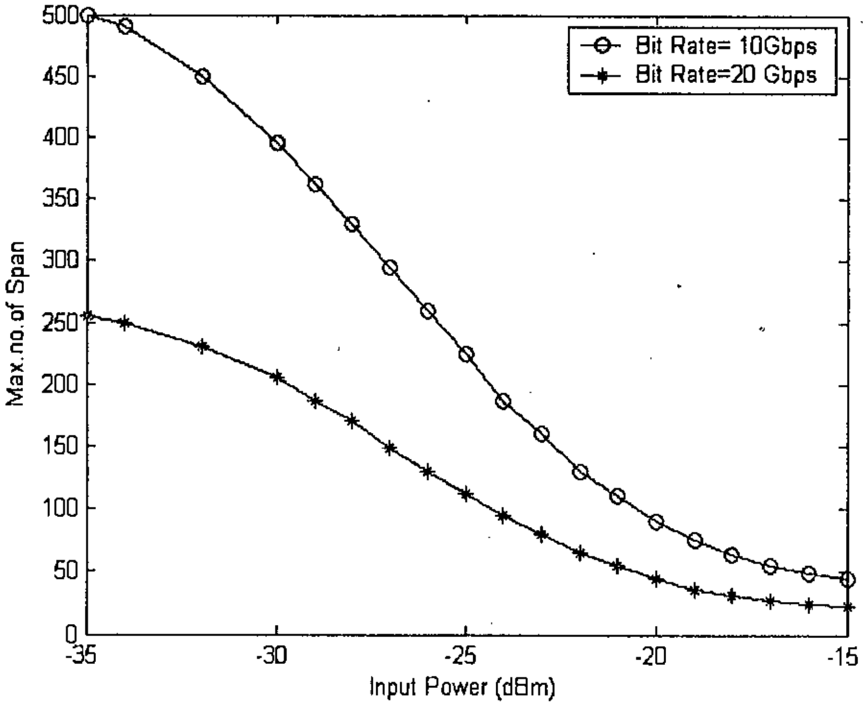


Fig. 3.10: Maximum number of span versus input power per channel considering the effect of crosstalk for two different bit rates.

Table 3.3: Maximum no. of span for different input power per channel and bit rates considering crosstalk effect

g_o (cm^{-1})	P_{in} (dBm)	No. of Span (Bit Rate =10Gbps)	No. of Span (Bit Rate =20Gbps)
374	-35	500	255
	-30	400	205
	-28	330	170
	-25	222	112
	-22	130	65
	-17	55	27
	-15	45	22

3.1.2 Results for three channel DWDM transmission system

Among three input channels, the power level of channel 3 is kept constant at -15dBm, and random bit patterns for other two channels are considered. In channel 1 and 2, four different bit patterns can occur as 00, 01, 10 and 11. The maximum crosstalk will occur when all three channels have bit 1 simultaneously. So, for three channel system, two cases are considered, the BER performance of channel 3 is plotted for the maximum crosstalk i.e. the worst case and for the average crosstalk due to four different bit patterns in other two channels.

Fig. 3.11 shows the BER performance of channel 3 and Fig. 3.12 shows the same for different bit rate. When there will be 0 bit in channel 1 and 2, channel 3 will get maximum gain, 1 bit in either of channel 1 and 2 will degrade the gain and cause crosstalk in channel 3, and when three channels will have bit 1, gain will be further decreased.

So, value of average crosstalk for four different bit patterns will be lower than the crosstalk when all three channels share the amplifier. Comparing the Fig 3.11 and 3.12, it can be seen that, number of span decreases significantly with the increase in bit rate.

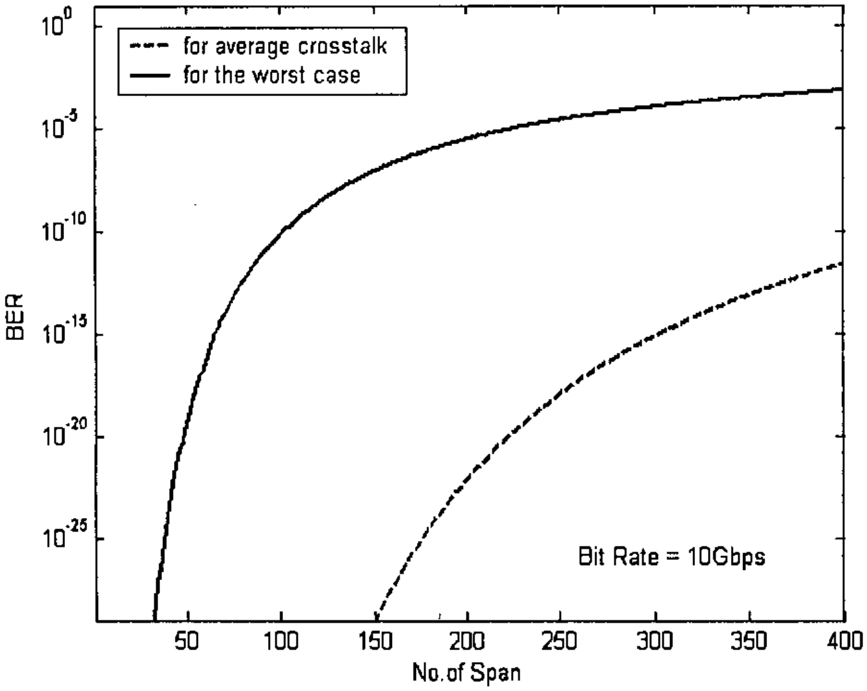


Fig. 3.11: BER performance of channel 3 against number of span considering the effect of crosstalk while bit patterns in channel 1 and 2 are varied. Bit rate = 10Gbps, and $g_0 = 328\ cm^{-1}$.

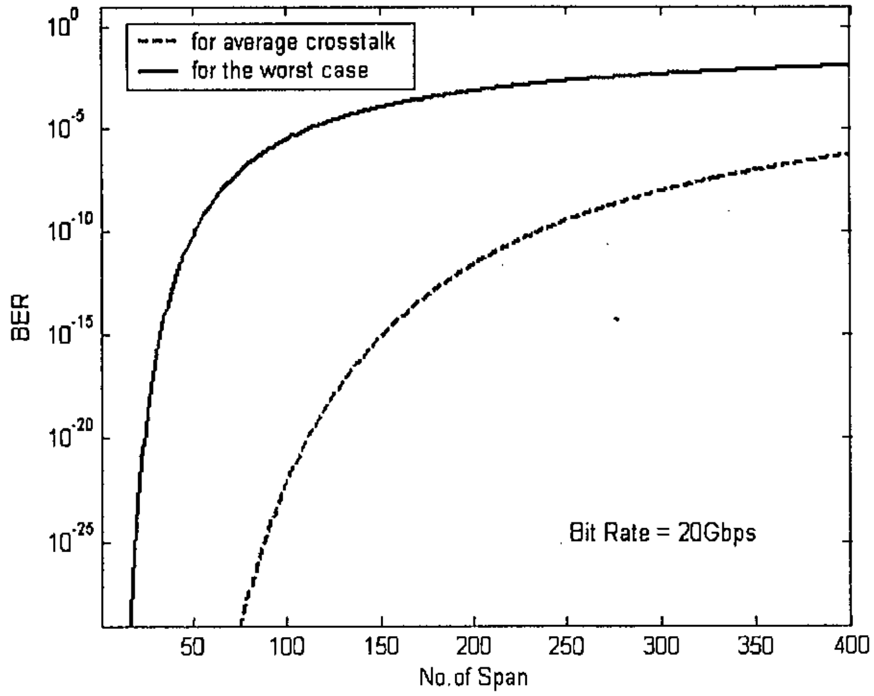


Fig. 3.12: BER performance of channel 3 against number of span considering the effect of crosstalk while bit patterns in channel 1 and 2 are varied. Bit rate = 20Gbps, and $g_0 = 328\ \text{cm}^{-1}$.

3.2 Thermal Noise Dominating

3.2.1 Results for two channel DWDM transmission system

When thermal noise is considered along with crosstalk effect, the BER performance changes, which is shown in Fig. 3.13. At lower input power level, the crosstalk effect is negligible since gain saturation does not occur, but thermal noise has a large value. With the increase in input power, the BER starts decreasing, but due to crosstalk effect at high power level, BER again increases.

From the figure, it is seen that, to have BER 10^{-9} at receiver, the power of each channel must be within the range from -36dBm to -23dBm. Fig. 3.14 and 3.15 depict BER performance with the variation of input power per channel for two different bit rates and at two different span numbers. With the increase in bit rate and span number, BER increases.

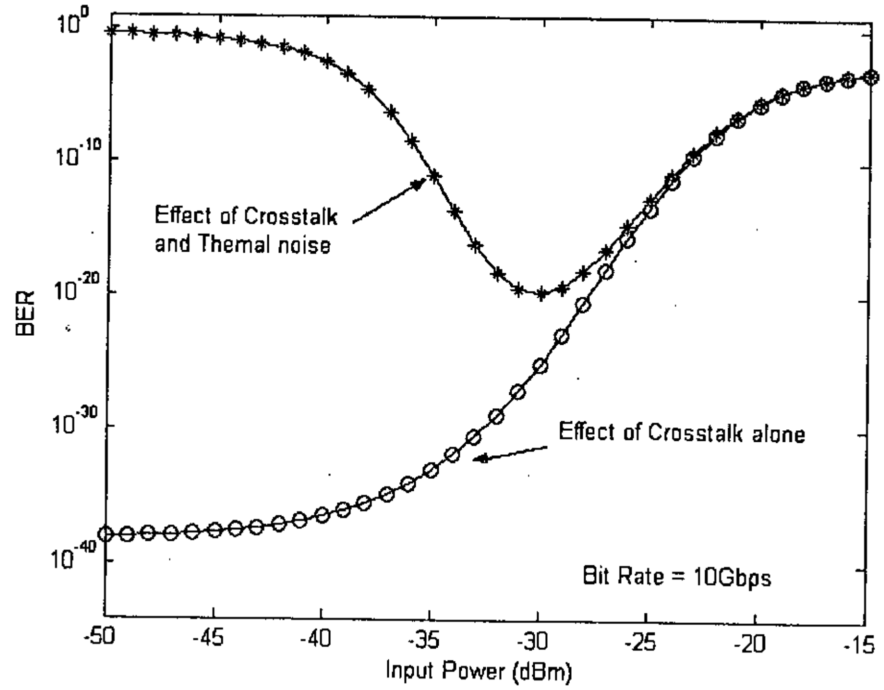


Fig. 3.13: BER performance showing crosstalk effect along with thermal noise effect as a function of input power per channel. Bit rate = 10Gbps and $g_0 = 380\text{cm}^{-1}$.

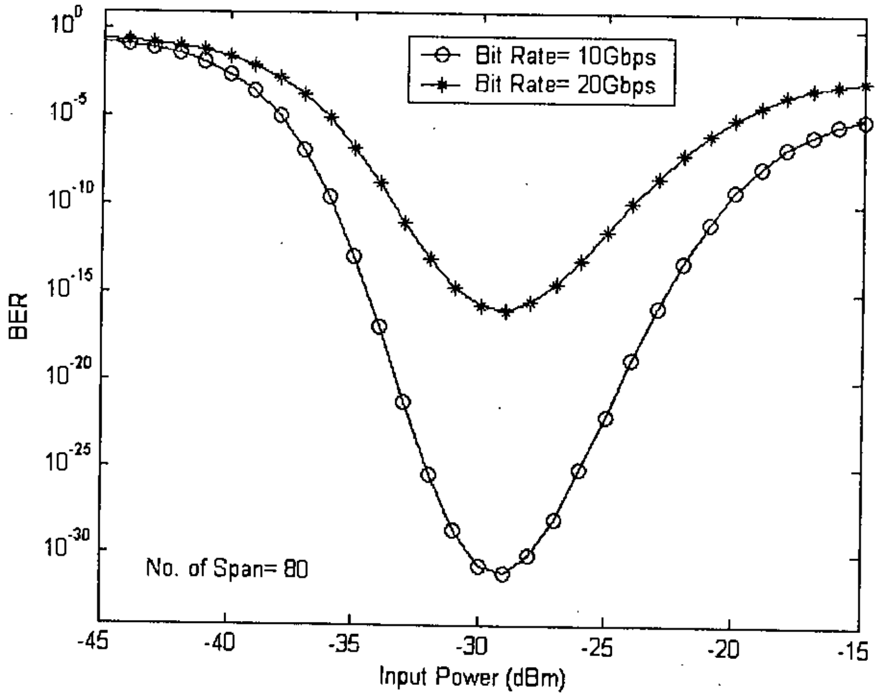


Fig. 3.14: BER performance as a function of input power per channel for a two channel system, considering the effect of crosstalk and thermal noise at span 80.

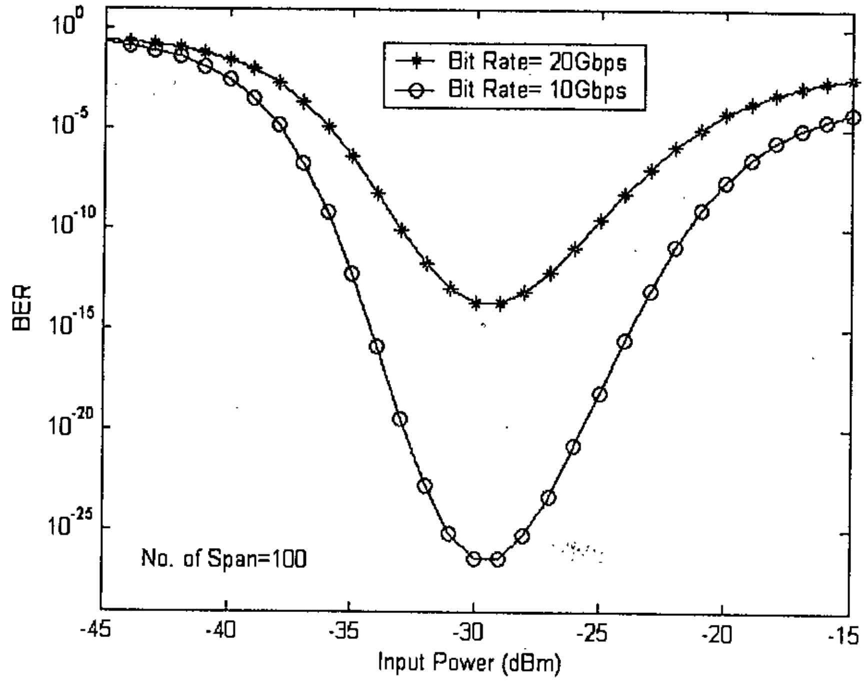


Fig. 3.15: BER performance as a function of input power per channel for a two channel system, considering the effect of crosstalk and thermal noise at span 100.

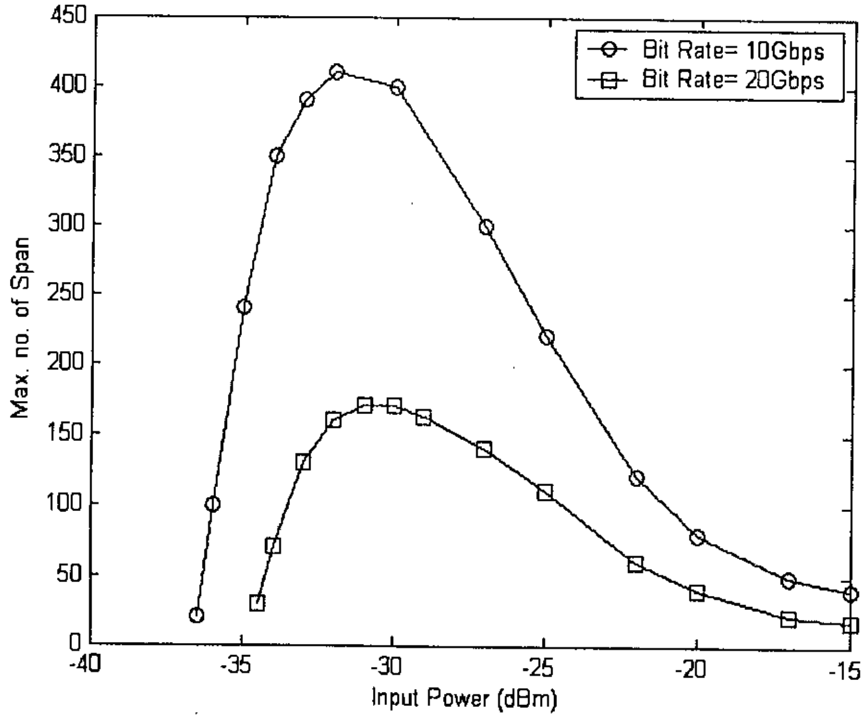


Fig. 3.16: Maximum number of span versus input power per channel for a two channel system, considering the effect of crosstalk and thermal noise for different bit rates. $g_o = 380\ cm^{-1}$.

Fig. 3.16 illustrates the maximum number of span against input power per channel and some outcomes are listed in Table 3.4. As the bit rate doubles, maximum number of span approximately halves.

Table 3.4: Maximum no. of span for different input power per channel and bit rates considering crosstalk and thermal noise effect in two channel system

g_o (cm^{-1})	P_{in} (dBm)	No. of Span (Bit Rate =10Gbps)	No. of Span (Bit Rate =20Gbps)
380	-34	350	70
	-33	390	130
	-30	400	170
	-27	300	140
	-25	220	110
	-22	120	60
	-20	80	40
	-17	50	22
	-15	40	18

3.2.2 Results for three channel DWDM transmission system

For three channel system, the following figures are plotted considering simultaneous existence of all three channels so that crosstalk effect is maximum. Fig. 3.17 is a similar plot like Fig. 3.14, but increased number of channel increases BER. Fig. 3.18 illustrates the maximum number of span against input power per channel and some results are shown in Table 3.5.

Table 3.5: Maximum no. of span for different input power per channel and bit rates considering crosstalk and thermal noise effect in three channel system

g_o (cm^{-1})	P_{in} (dBm)	No. of Span (Bit Rate =10Gbps)	No. of Span (Bit Rate =20Gbps)
380	-34	175	25
	-33	200	50
	-30	180	80
	-27	125	56
	-25	80	38
	-22	40	18
	-20	25	10
	-17	15	6

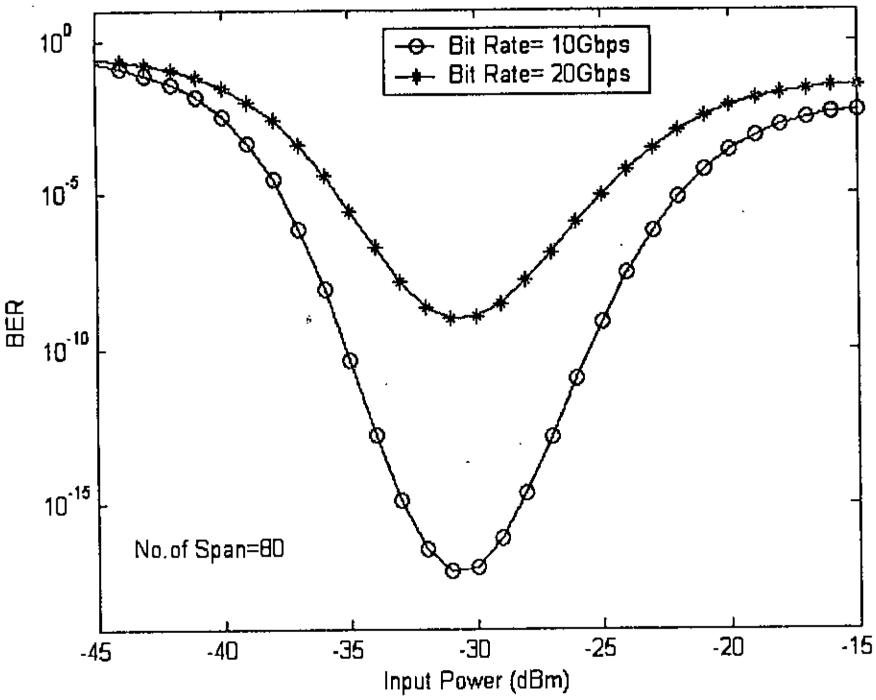


Fig. 3.17: BER performance as a function of input power per channel for a three channel system, considering the effect of crosstalk and thermal noise at span 80.

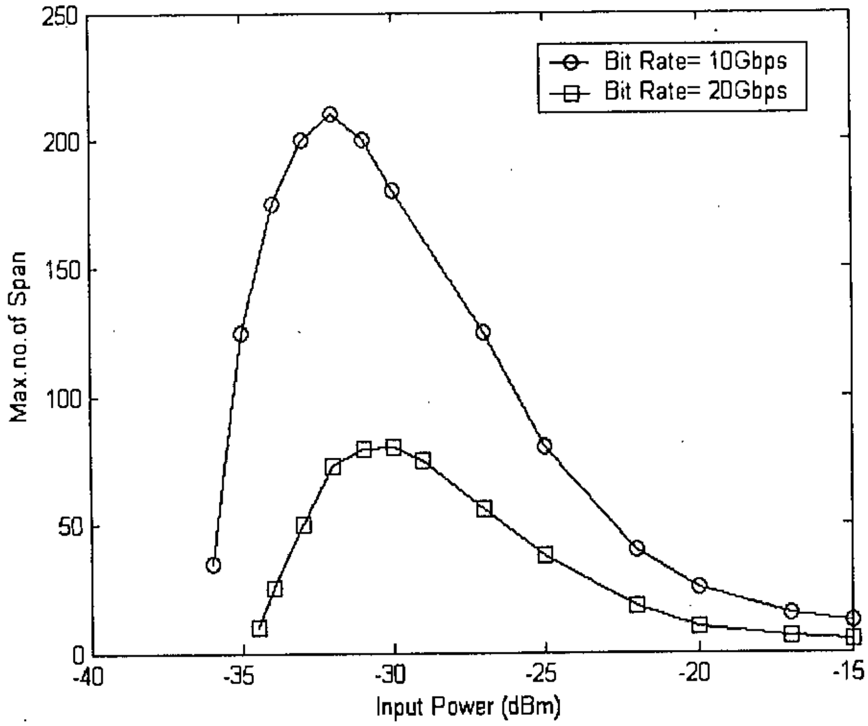


Fig. 3.18: Maximum number of span versus input power per channel for a three channel system, considering the effect of crosstalk and thermal noise for different bit rates. $g_o = 380\ \mathrm{cm}^{-1}$.

3.2.3 Comparison between two and three channel systems

Fig. 3.19 illustrates that with the increase in mode number i.e. channel number, BER increases. So, for BER 10^{-9}, the input power range for two channel is larger than three channel system which is from -36dBm to -20dBm, whereas for three channel, the range is from -35dBm to -25dBm.

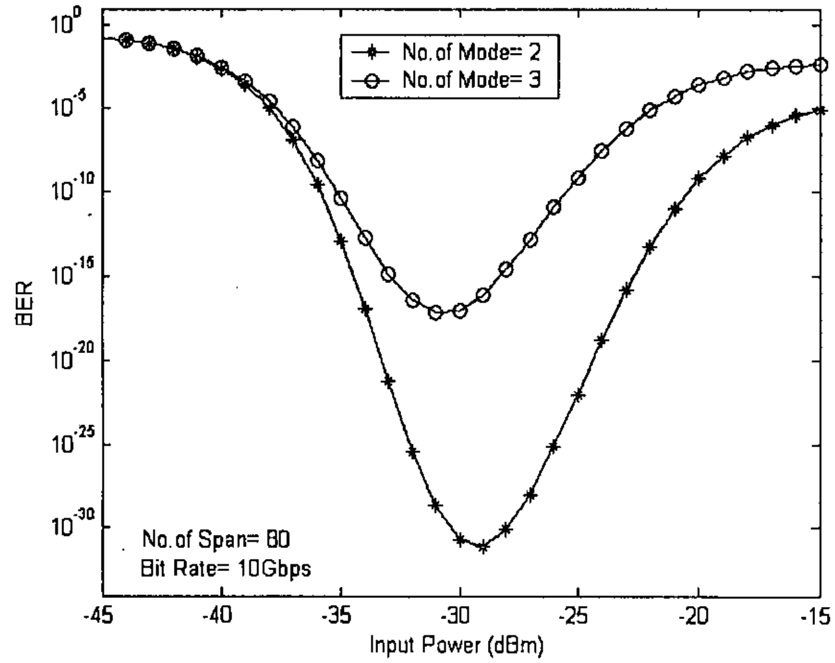


Fig. 3.19: BER performance as a function of input power per channel at span 80, showing the comparison between two and three channel systems for bit rate 10Gbps.

Table 3.6: Maximum no. of span for different input power per channel and no. of channel considering crosstalk and thermal noise effect

g_o (cm^{-1})	P_{in} (dBm)	No. of Span (Bit Rate =10Gbps)	
		Mode 2	Mode 3
380	-34	350	175
	-33	390	200
	-30	400	180
	-27	300	125
	-25	220	80
	-22	120	40
	-20	80	25
	-17	50	15

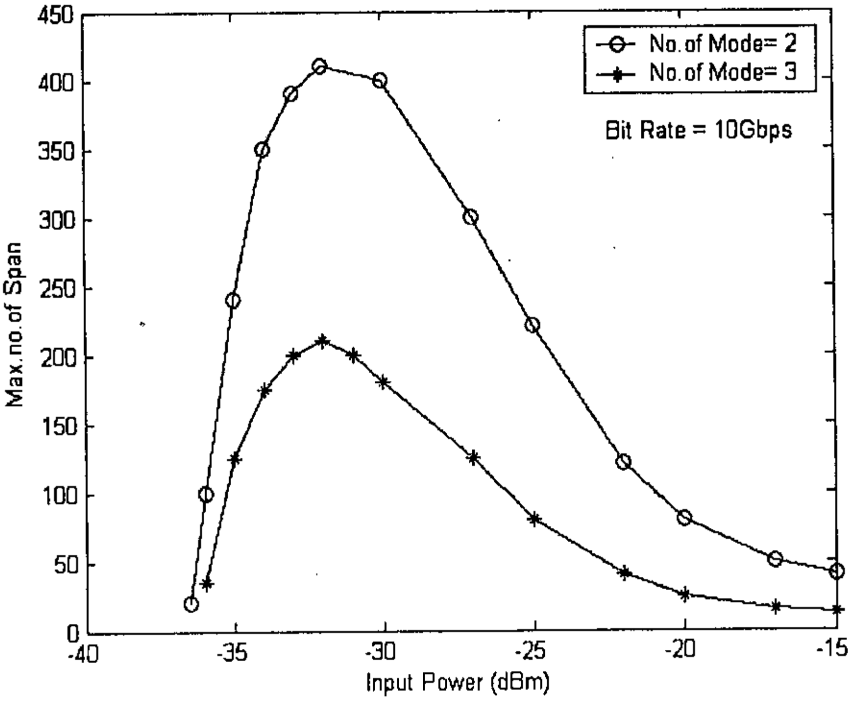


Fig. 3.20: Maximum number of span as a function of input power per channel, showing the comparison between two and three channel systems for bit rate 10Gbps.

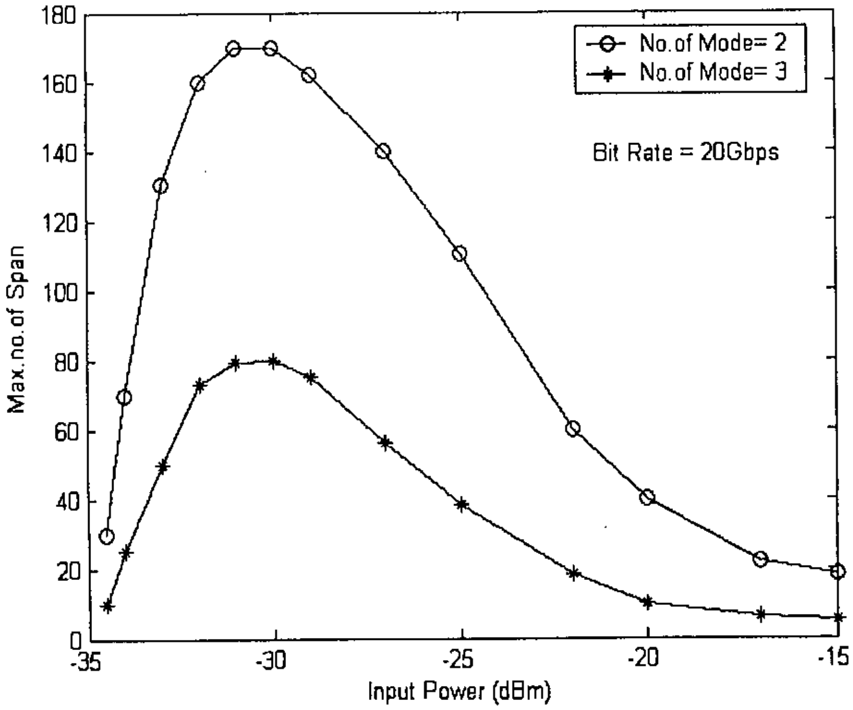


Fig. 3.21: Maximum number of span as a function of input power per channel, showing the comparison between two and three channel systems for bit rate 20Gbps.

Fig. 3.20 and 3.21 shows the difference of number of span in the system if the channel number changes from two to three. For example, at 10Gbps bit rate and -30dBm input power per channel, number of span reduces by around 200, if the channel number is made three instead of two. Similarly, for 20Gbps, the span number reduces by approximately 100 for -30dBm input power. The comparison for 10Gbps bit rate is shown in Table 3.6

3.3 Shot Noise Dominating

3.3.1 Results for two channel DWDM transmission system

In case of dominating shot noise, we consider a few cases. At first, we consider all the noise term and crosstalk effect together. Secondly, we consider all the noise term but no crosstalk effect. Thirdly, we consider no gain saturation effect i.e. constant gain of SOA.

Fig. 3.22 shows both first and second case. It is found that, incorporation of crosstalk effect degrades BER performance. Without consideration of crosstalk effect will allow input power per channel -15dBm to give BER 10^{-9}, but in actual case with crosstalk effect BER is 10^{-6} and minimum -13dBm input power is required to have BER 10^{-9}. Fig. 3.23 gives same plot for different bit rate. BER decreases with increase in bit rate.

Fig. 3.24 gives the maximum number of span for different input powers to have BER 10^{-9}. The obtained results are summarized in Table 3.7. At 10Gbps, and –14dBm input power the number of span approximately halves if crosstalk effect is considered. Fig. 3.25 is for bit rate 20Gbps.

Fig. 3.26 also includes the third case in Fig. 3.22, considering that the amplifier has constant gain i.e. no gain saturation occurs. BER performance curves for amplifier with constant gain of 10dB and 20dB are shown. The figure depicts that for higher gain, BER is higher. With the increase in input power per channel the BER decreases.

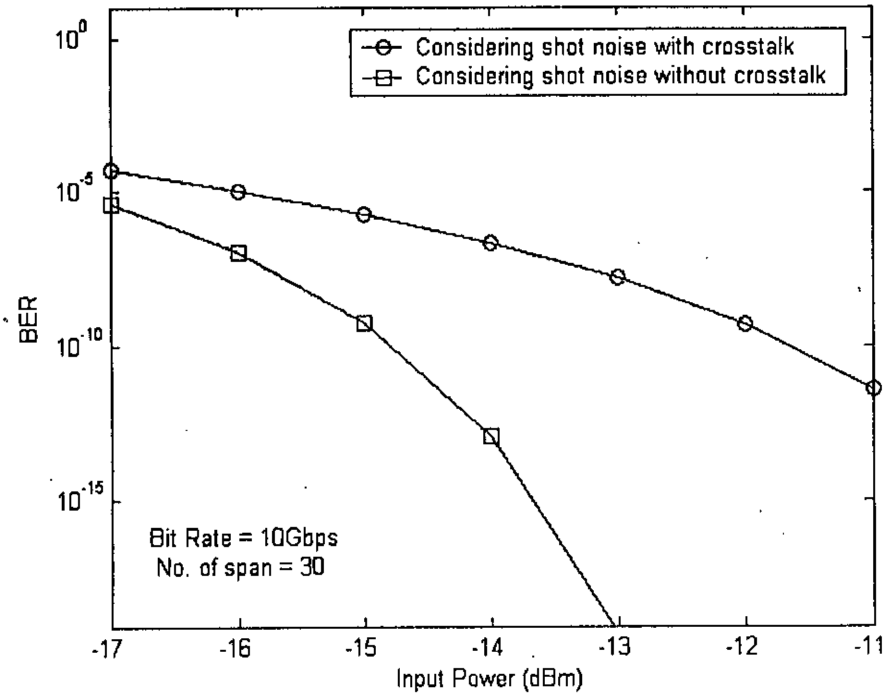


Fig. 3.22: BER performance as a function of input power per channel for a two channel system, considering the effect of shot noise with and without crosstalk after span 30. Bit rate = 10Gbps and g_o= 380 cm^{-1}.

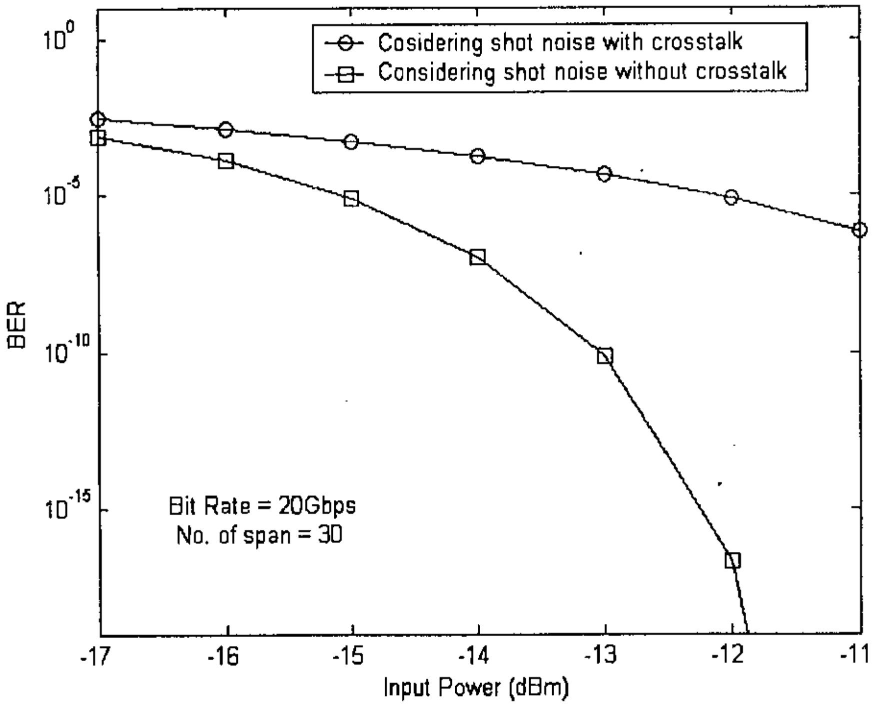


Fig. 3.23: BER performance as a function of input power per channel for a two channel system, considering the effect of shot noise with and without crosstalk after span 30. Bit rate = 20Gbps and g_o= 380 cm^{-1}.

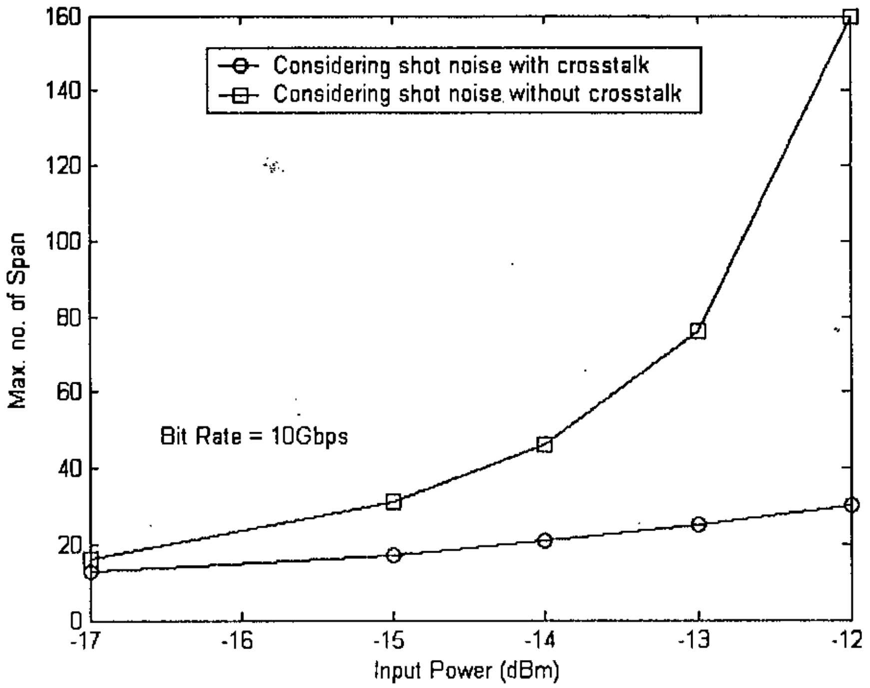


Fig. 3.24: Maximum number of span versus input power per channel for a two channel system, considering the effect of shot noise with and without crosstalk. Bit rate = 10Gbps and g_o= 380 cm^{-1}.

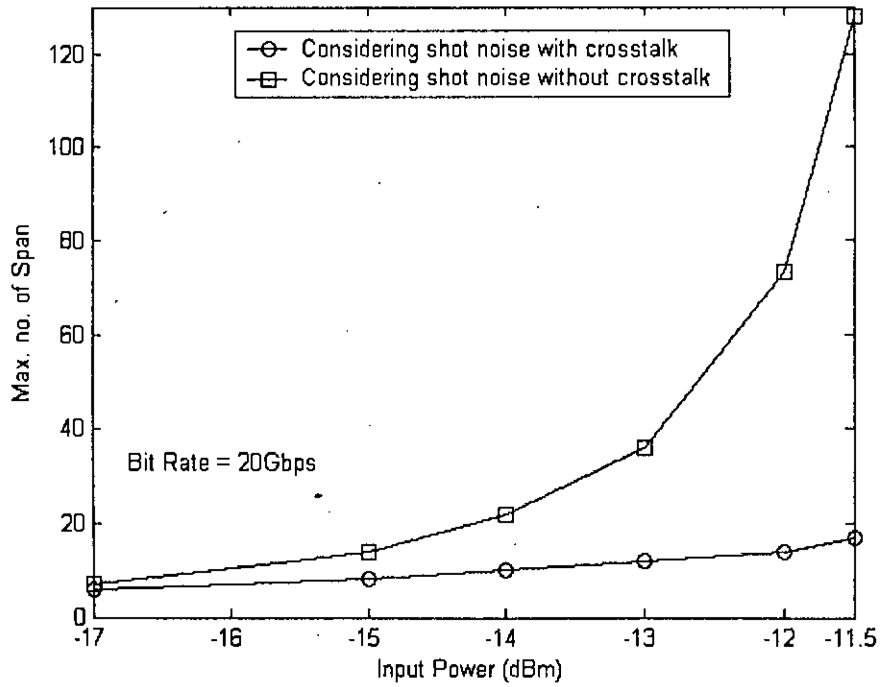


Fig. 3.25: Maximum number of span versus input power per channel for a two channel system, considering the effect of shot noise with and without crosstalk. Bit rate = 20Gbps and g_o= 380 cm^{-1}.

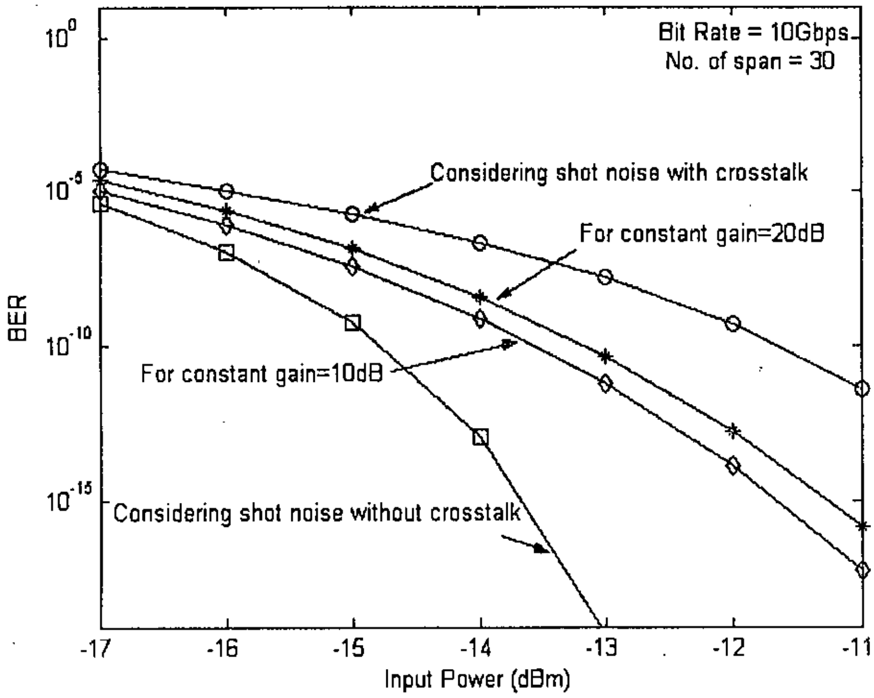


Fig. 3.26: BER performance as a function of input power per channel for a two channel system, including the plot for the amplifiers with constant signal gain of 10dB and 20dB, when bit rate is 10Gbps.

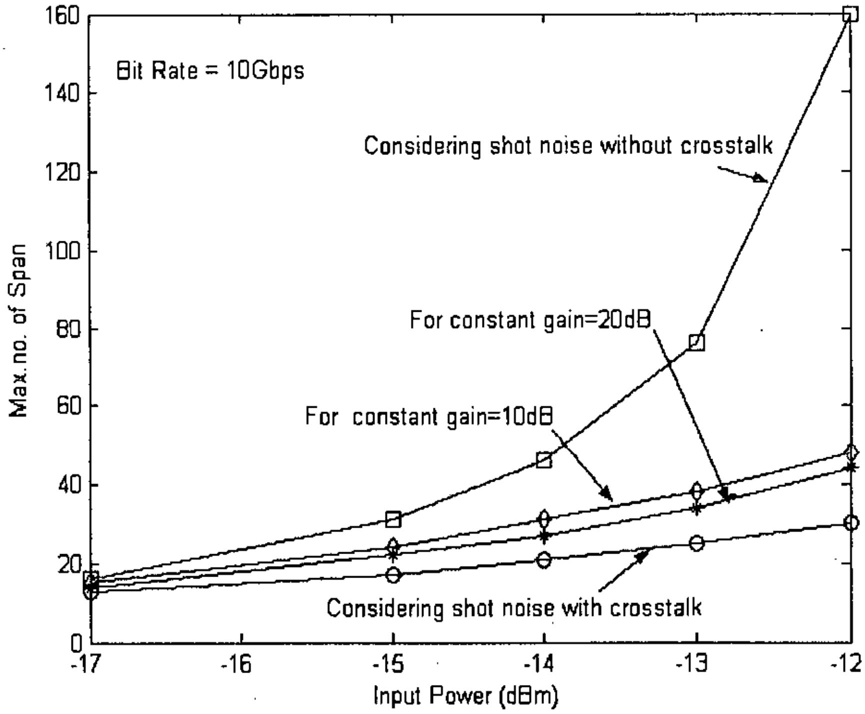


Fig. 3.27: Maximum number of span versus input power per channel for a two channel system, including the plot for the amplifiers with constant signal gain of 10dB and 20dB, when bit rate is 10Gbps.

Table 3.7: Maximum no. of span for three different cases for bit rate 10Gbps

P_{in} (dBm)	No. of Span (Bit Rate =10Gbps)			
	Considering shot noise with crosstalk	Considering constant gain of amplifier		Considering shot noise without crosstalk
		20dB	10dB	
-17	13	14	15	16
-15	17	22	24	31
-14	21	27	31	46
-13	25	34	38	76
-12	30	44	48	160
-11.5	35	50	55	270

Fig. 3.27 is similar to Fig. 3.24 which gives the maximum number of span for different input powers to have BER 10^{-9} including the case considering constant gain of amplifier. Table 3.7 lists some of the findings from the plot for bit rate 10Gbps. The variation of number of span for 10dB and 20dB is not so significant.

3.3.2 Comparison between two and three channel systems

While considering shot noise and crosstalk together, the increase in number of channels further increases the BER. Fig. 3.28 shows the input power per channel versus BER plot, from which it can be seen that for BER 10^{-9}, the input power is required -18dBm for two channel system and -15dBm for three channel system. In the two channel system, when the input power per channel is -14dBm, the BER is about 10^{-16} and in the three channel system, the BER is about 10^{-9}.

Fig. 3.29 depicts the maximum number of span that can be cascaded considering dominant shot noise for two and three channel system. Some of the findings are mentioned in Table 3.8 for bit rate 10Gbps. The number of span decreases when the mode number increases. For example, the number of span decreases from 25 to 13 at input power –13dbm when number of channel is increased from two to three.

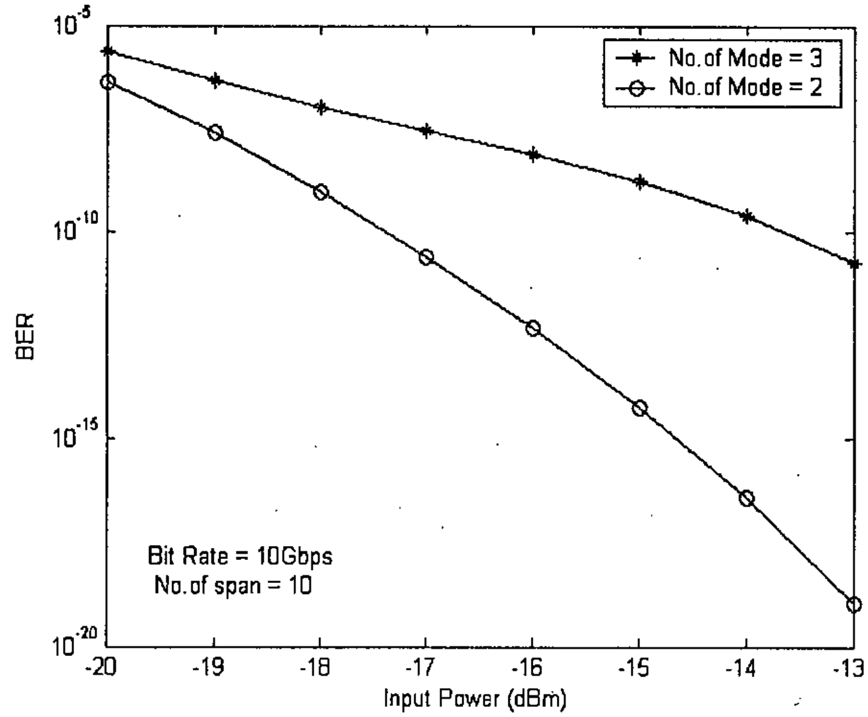


Fig. 3.28: BER performance as a function of input power per channel at span 10, showing the comparison between two and three channel systems, considering the effect of crosstalk and shot noise, when bit rate is 10Gbps.

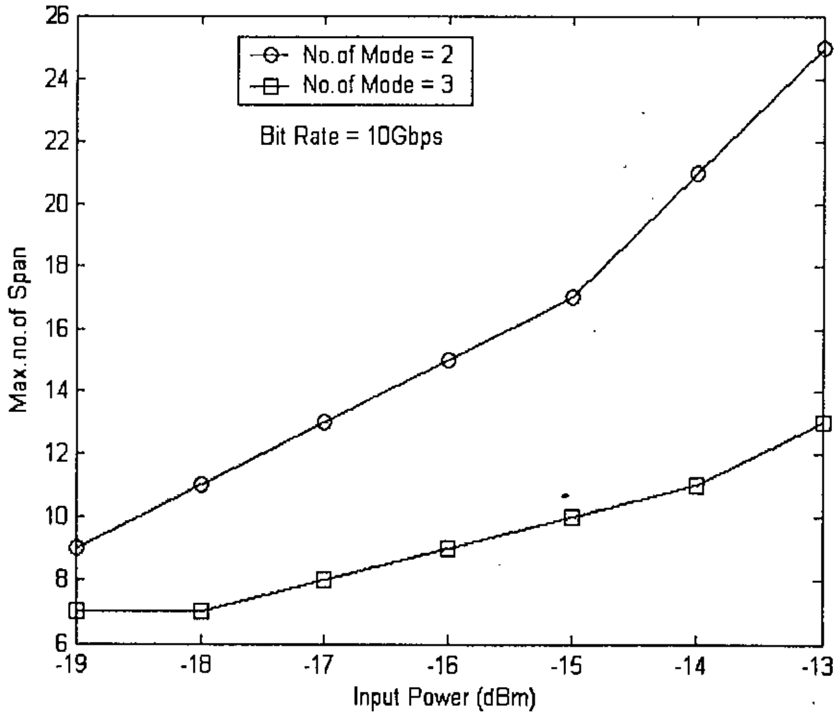


Fig. 3.29: Maximum number of span versus input power per channel, showing the comparison between two and three channel systems, considering the effect of crosstalk and shot noise when bit rate is 10Gbps.

Table 3.8: Maximum no. of span for different input power per channel and number of channel considering crosstalk and shot noise effect

g_o (cm^{-1})	P_{in} (dBm)	No. of Span (Bit Rate =10Gbps)	
		Mode 2	Mode 3
380	-19	9	7
	-17	13	8
	-16	15	9
	-15	17	10
	-14	21	11
	-13	25	13

3.4 Summary

The combined effect of gain saturation induced crosstalk and ASE noise in a WDM system with optical amplifiers in cascade is investigated in this chapter. The simulation is done based on the theoretical analysis of chapter 2. The effect of the variation of input power, gain coefficient, number of channels on BER performance and on the number of spans is discussed in this chapter.

Chapter- 4

Conclusion and Scope of Future Work

4.1 Conclusion

The effect of crosstalk due to gain saturation in semiconductor optical amplifier is theoretically analyzed for a DWDM system with optical amplifier in cascade. An analytical expression for SCR and BER due to gain saturation effect of SOA is derived for multiple span optical transmission system. The expression is modified for a multi-channel WDM system. The expression of SNR is developed with the combined effect of crosstalk and ASE noise present in SOA. The performance of WDM transmission system is investigated in terms of SNR and BER with the variation of signal power, amplifier gain, number of spans and the number of channels.

In a system with multiple spans, the crosstalk effect reduces SCR and increases BER with the increase in the number of amplifier and also with the number of WDM channels. To achieve a required BER at the receiver, the crosstalk effect ultimately limits the number of spans or amplifiers that can be cascaded in the system. In two channel system, it is found that, when both input power per channel is -25dBm and amplifier gain is 20dB, about 300 spans can be cascaded for bit rates 10Gbps. For the same system, when the input power per channel is increased to -17dBm, gain saturation occurs and amplifier gain is reduced to 8dB, which supports only 39 spans for BER 10^{-9}. When the bit rate doubles, the BER increases and the number of span approximately halves. Again, the BER increases when the number of channel is increased. For example, at the input power -30dBm, the number of span decreases from 400 to 180 when the channel number is increased from two to three.

ASE noise present in SOA degrades the system performance as the noise gets accumulated with the increase in number of cascaded amplifier. The ASE noise gives rise to different shot noise terms in the receiver, among which the signal-spontaneous beat noise is the most dominant one. Performance results are evaluated for thermal noise limited and shot noise limited receiver operations. It is noticed that for thermal noise dominating operation, the maximum allowable input power is limited to a value which is much less than that for shot noise dominant case. When signal-spontaneous beat noise dominates over thermal noise, the input power has to be sufficiently large to have large SNR and give BER 10^{-9} at the receiver. When the performance is dominated by thermal noise, a specific range of lower input power becomes sufficient to ensure BER 10^{-9}. For example, in two channel WDM system, input power from -36dBm to -23dBm allows BER 10^{-9} at receiver for bit rate 10Gbps when thermal noise is dominating, while shot noise dominating system requires input power greater than -12dBm. Again, in the same system, it is found that, with -17dBm input power per channel, 50 spans can be used when thermal noise is dominating and 13 spans at shot noise dominating.

The comparison between two and three channel system performance is also shown. The BER performance deteriorates with the increase in number of channels for both shot noise limited and thermal noise limited receiver operations. With the increase in number of channels in the amplifier, the input power level increases which causes the gain to saturate earlier, which in turn increases the crosstalk and limits the number of span. For bit rate 10Gbps and input power -27dBm per channel in two channel system, the maximum number of spans can be 300, whereas in three channel system, number of span can only be 125, when receiver performance is dominated by thermal noise. The analysis shows that thermal noise dominated receiver gives better performance at lower input power range where effect of crosstalk is lower and number of amplifiers in cascade can be increased.

4.2 Scope of Future Work

The simultaneous presence of several channels gives rise to the possibility of crosstalk between the channels. In this thesis work only the crosstalk due to gain saturation effect is considered to determine the system performance. The effect of interchannel crosstalk is not considered. The narrow wavelength separation between channels will make the interchannel crosstalk dominant. Interchannel crosstalk is essentially a four-wave mixing (FWM) effect. So, future work can include interchannel crosstalk also.

Again, in this work, the parameters used for the simulation are for Fabry-Perot type amplifier, similar analysis can be done for traveling-wave amplifier and Erbium-doped fiber amplifier (EDFA).

Similar analysis can be carried out for OTDM-WDM and wavelength hoping time spreading OCDMA system.

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