PERFORMANCE LIMITATIONS OF AN OPTICAL PSK HETERODYNE WDM SYSTEM DUE TO RAMAN AMPLIFIER INDUCED CROSSTALK

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This thesis titled "**Performance limitations of an optical PSK heterodyne WDM system due to Raman amplifier induced crosstalk**" submitted by Abdullah (201416015), Md. Ferdous Patwary (201416092), Rafid-Ur-Rahman (2014160105) has been accepted as satisfactory in partial fulfillment of the requirements of degree of Bachelor of Science in Electrical, Electronic and Communication Engineering on December 27, 2017.

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Declaration

This is to certify that the thesis work presented here under the title "**Performance limitations of an optical PSK heterodyne WDM system due to Raman amplifier induced crosstalk**" is carried out as a partial fulfillment of B.Sc. in Electrical, Electronic and Communication Engineering. The thesis is written by us based on the results found by analysis. All the sources which have been used are acknowledged by references. This thesis or any part of it has not been submitted anywhere for the award of any other Degree.

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Dedicated

to

Our beloved Parents

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Abstract

The thesis investigates the performance of an optical PSK heterodyne WDM system based on Raman amplifier induced crosstalk. The analysis is carried out to find out the performance of a WDM system in case of constant amplitude modulation. The performance analysis is carried out on the basis of bit error rate(BER). An analytical model is presented for the system. Analysis includes the effect of crosstalk due to optical amplified spontaneous emission(ASE) and receiver noise. The results are evaluated in the form of IF signal to Crosstalk plus Noise Ratio and BER for several system parameters. It is noticed that the system suffers significant amount of power penalty due to ASE induced crosstalk and penalty is high for higher transmission distance and can be reduced by increasing the local oscillator laser power. Power penalty is found to be 9.9 dB, 15.8 dB, 19.6 dB and 23.4 dB for a distance of 50 km, 80 km, 100 km and 120 km respectively for a local oscillator power of 10 mW at a BER of 10^{-10}.

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List of Abbreviations

RF	Radio Frequency
FSO	Free-Space Optical
IM	Intensity Modulation
DD	Direct Detection
WDM	Wavelength Division Multiplexing
SOA	Semiconductor Optical Amplifier
EDFA	Erbium-Doped Fiber Amplifier
FRA	Fiber Raman Amplifier
HOA	Hybrid Optical Amplifier
ASK	Amplitude Shift Keying
OOK	On-Off Keying
FSK	Frequency Shift Keying
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
BPSK	Binary Phase Shift Keying
FM	Frequency Modulation
PM	Phase Modulation
QAM	Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
EOPM	Electro-Optic Phase Modulator
EOIM	Electro-Optic Intensity Modulator
BER	Bit Error Rate
SCNR	Signal to Crosstalk plus Noise Ratio
ASE	Amplified Spontaneous Emission
DRA	Distributed Raman Amplifier
SPS	Signal-Pump-Signal
LO	Local Oscillator
RZ	Return-to-Zero
NRZ	Non-Return-to-Zero
FIR	Finite Impulse Response
DSP	Digital Signal Processing
RIN	Relative Intensity Noise

PDF	Probability Density Function
SRS	Stimulated Raman Scattering
SDM	Space Division Multiplexing
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
OTDM	Optical Time Division Multiplexing
OFDM	Optical Frequency Division Multiplexing
OFDM	Optical Code Division Multiplexing
SCM	Subcarrier Multiplexing
OCDMA	Optical Code Division Multiple Access
CWDM	Course Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
ADC	Analog to Digital Converter
GSM	Global Positioning System
VCO	Voltage-Controlled Oscillators
PMD	Polarization Mode Dispersion
AFC	Automatic Frequency Control
IF	Intermediate Frequency
SMF	Single Mode Fiber
LPF	Low Pass Filter

List of Symbols

G_{Hybrid}	Hybrid Amplifier Gain
G_{EDFA}	Erbium Doped Fiber Amplifier Gain
G_{Raman}	Raman Amplifier Gain
ϕ	Phase Shift
f_s	Signal Frequency
f_i	Subcarrier Signal Frequency
λ	Wavelength
S_{WDM}	WDM Signal
S_{pump}	Pump Source Signal
e_{WDM}	Electric field of the WDM system
$e_{s,n}$	Electric Field due to Signal
$e_{ct,n}$	Electric Field due to Crosstalk
Θ_{ct}	Phase Crosstalk Noise
e_{LO}	Local Oscillator Electric Field
g'	Raman Gain Slope
Δf	Inter Channel Frequency Spacing
Z_e	Effective Propagation Distance
α	Fiber Attenuation Coefficient
$i_{sh,n}$	Overall Shot Noise
ω	Angular Frequency
σ_{th}^2	Thermal Noise
σ_{ct}^2	Crosstalk Variance
P_{ASE}	Amplifier Spontaneous Emission(ASE) Noise Power
B_0	Optical Bandwidth
$erfc$	Complementary Error Function
A_{eff}	Effective Area of Core
Pp	Pump Power

CHAPTER 1

INTRODUCTION

1.1 Introduction to Communication System

communication system is a process of conveying information from a source to a Adestination. The components of a communication system depend on the distance and types of communication. The components of a communication system are as follows [1]:

- The *source* originates a message, such as a human voice, a television picture, a teletype message, or data. If the data is nonelectrical, it must be converted by an *input transducer* into an electrical waveform referred to as the baseband signal or message signal.
- The *transmitter* modifies the baseband signal for efficient transmission.
- The *channel* is a medium through which the transmitter output is sent.
- The *receiver* reprocesses the signal received from the channel by undoing the signal modifications made at the transmitter and the channel. The receiver output is fed to the *output transducer*, which converts the electrical signal to its original form-the message.

1.2 Types of Communication System

According to the mode of transmission, communication systems are of two types:

- Analog transmission
- Digital transmission

According to the applications, communication systems are of following types:

- Radio frequency (RF) communication

- Microwave communication
- Wireless communication
- Optical communication

1.3 Optical Communication System

Optical communication system uses light as the transmission medium. Optical communication systems differ in principle from microwave systems only in the frequency range of the carrier wave used to carry the information.

Fig. 1.1 Generic optical communication system

1.3.1 Types of Optical Communication System

Basically, there are two types of optical communication system

- Free-space optical (FSO) communication
- Optical fiber communication

1.3.1.1 Free-Space Optical (FSO) Communication

In Free Space Optical (FSO) system, propagating light is used to transmit data in free space. There is no physical connection between the transmitter and the receiver. FSO Communication system has been used in space for communication. Because of the complexity associated with phase or frequency modulation, current free-space optical communication systems typically use intensity modulation with direct detection (IM/DD). Atmospheric turbulence can degrade the performance of free-space optical links, particularly over ranges of the order of 1 km or longer. FSO communication through atmosphere turbulence is now under active research and various methods have been proposed to mitigate turbulence-induced communication signal fading [2].

1.3.1.2 Optical Fiber Communication System

Optical Fiber Communication in basic concept, is similar to any type of communication system. In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier [3].

The generic block diagram of Fig. 1.1 applies to a fiber-optic communication system, the only difference being that the communication channel is an optical fiber cable. The other two components, the optical transmitter and the optical receiver, are designed to meet the needs of such a specific communication channel [4].

Advantages of Optical Fiber Communication System

- The capacity of fibers for data transmission is huge.
- A large number of channels can be reamplified in a single fiber amplifier, if required for very large transmission distances.
- Due to the huge transmission rate achievable, the cost per transported bit can be extremely low.
- Compared with electrical cables, fiber-optic cables are very lightweight.

Limitations of Optical Fiber Communication System

- The initial cost of installation or setting up cost is very high.
- The maintenance and repairing of optical fiber system is not only difficult but also expensive.

- Optical fibers are difficult to splice, and there are losses of the light in the fiber due to scattering.
- There are various fiber losses in an optical fiber such as scattering, dispersion, attenuation and reflection.

1.4 Optical Amplifiers

The transmission distance of any fiber-optic communication system is eventually limited by fiber losses. For long-haul systems, the loss limitation has traditionally been overcome using optoelectronic repeaters in which the optical signal is first converted into an electric current and then regenerated using a transmitter. Such regenerators become quite complex and expensive for wavelength-division multiplexed (WDM) optical fiber communication systems. An alternative approach to loss management makes use of optical amplifiers, which amplify the optical signal directly without requiring its conversion to the electric domain [4]. Hence over recent years optical amplifiers have emerged as promising network elements not just for use as linear repeaters but as optical gain blocks, wavelength converters, optical receiver preamplifiers and, when used in a nonlinear mode, as optical gates, pulse shapers and routing switches [3].

1.4.1 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 [5].

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.

A preamplifier amplifies a signal immediately before it reaches the receiver. This type of optical amplifier operates with a week signal.

1.5 Types of Optical Amplifier

We will consider four different types of amplifiers here:

- Semiconductor Optical Amplifiers (SOA)
- Erbium-Doped Fiber Amplifiers (EDFA)
- Raman Amplifier
- Hybrid Optical Amplifier (HOA)

1.5.1 Semiconductor Optical Amplifiers (SOA)

Semiconductor optical amplifiers (SOA) 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, and hence optical amplification is achieved. Depending on the actual structure, SOAs are distinguished as

- Semiconductor traveling wave laser optical amplifiers
- Fabry-Perot laser amplifiers

The SOA has higher noise, lower gain, moderate polarization dependence and high nonlinearity with fast transient time. The main advantage of SOA is that all four types of nonlinear operations (cross gain modulation, cross phase modulation, wavelength conversion and four waves mixing) can be conducted. Furthermore, SOA can be run with a low power laser. SOAs have become useful building blocks for all-optical signal processing. From the early 1990s, the SOA-based structures have been developed into monolithically integrated interferometric optical gates that offer many advantages, such as signal reshaping and noise suppression [6].

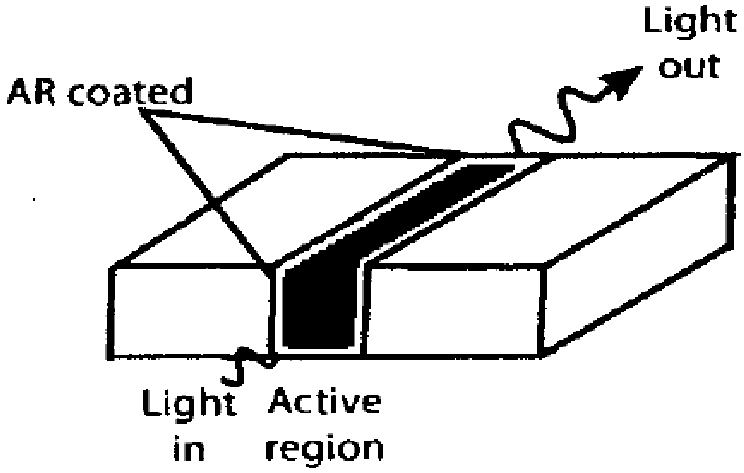

Fig. 1.2 Block Diagram of Semiconductor Optical Amplifier (SOA)

1.5.2 Erbium-Doped Fiber Amplifiers (EDFA)

An erbium-doped fiber amplifier (EDFA) is shown in Fig. 1.3. It consists of a length of silica fiber whose core is doped with ionized atoms, Er^{3+}, of the rare earth element erbium. This fiber is pumped using a pump signal from a laser, typically at a wavelength of 980 nm or 1480 nm. In order to combine the output of the pump laser with the input signal, the doped fiber is preceded by a wavelength-selective coupler. At the output another wavelength-selective coupler may be used if needed to separate the amplified signal from any remaining pump signal power. Usually, an isolator is used at the input and/or output of any amplifier to prevent reflections into the amplifier.

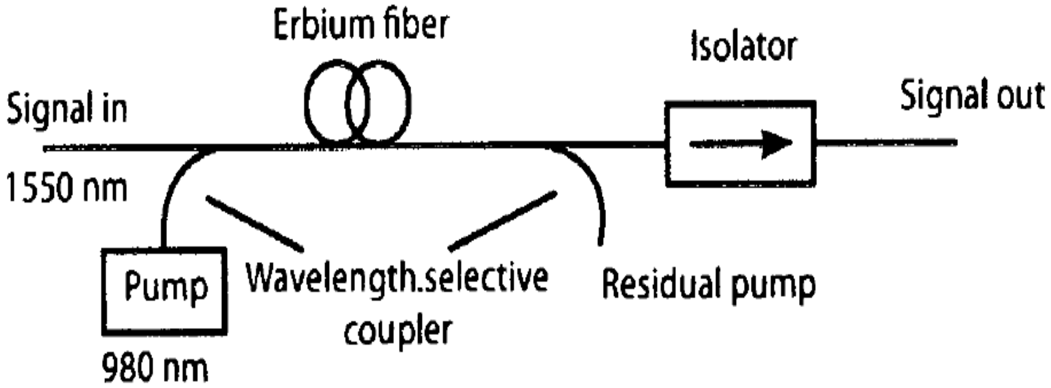

Fig. 1.3 An erbium-doped fiber amplifier (EDFA)

The gain of an EDFA depends on a large number of device parameters such as erbium ion concentration, amplifier length, core radius, and pump power. The bandwidth of EDFAs is large enough that they have proven to be the optical amplifier of choice for WDM applications [4].

1.5.3 Raman Amplifier

A Raman amplifier is an optical amplifier based on Raman gain, which results from the effect of stimulated Raman scattering. Raman amplification exhibits advantages of self-phase matching between the pump and signal together with a broad gain–bandwidth or high-speed response in comparison with the other nonlinear processes. In particular the broad gain–bandwidth associated with Raman amplification is attractive for current WDM systems [3].

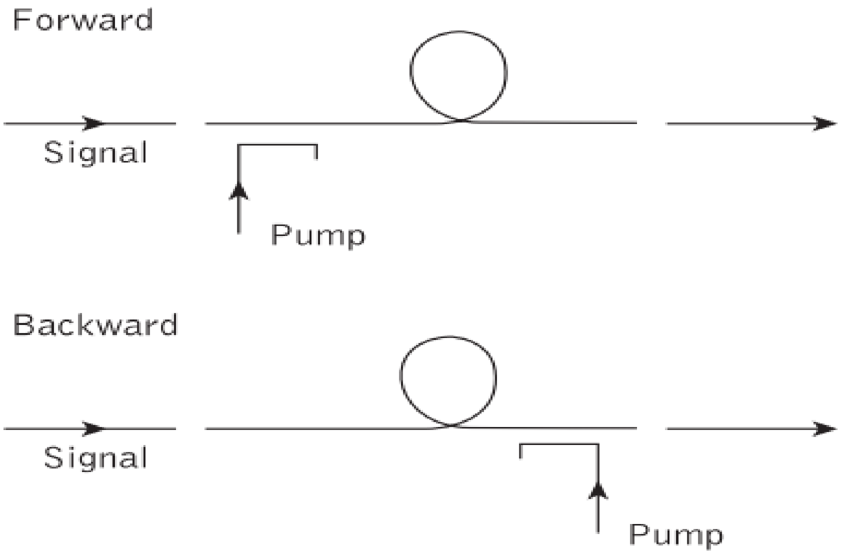

Fig. 1.4 Illustrations of the forward and backward pumping capability associated with the fiber Raman amplifier

There are three pumping schemes [7]:

- Co-pumping, or Forward-pumping, where both signal and pump are propagating in the same direction.
- Counter-pumping or Backward-pumping, where signal and pump are propagating in opposite directions.
- The bidirectional pumping which includes both the co-pumping and counter-pumping, simultaneously.

Raman fiber amplifiers can be divided into two main categories, namely discrete and distributed. Distributed Raman amplifiers improve the noise figure and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength. discrete Raman amplifiers are primarily used to increase the capacity of fiber-optic networks [8].

The major concern with Raman amplifiers is crosstalk between the WDM signals due to Raman amplification. To ensure small crosstalk, the signal gain and the injected pump power should be limited to the value well below the threshold of Raman amplification [9].

1.5.4 Hybrid Optical Amplifiers (HOA)

The combination of more than one amplifier in a configuration is called HOA. Mohammed N. Islam described that the total amplifier gain (G_{Hybrid}) is the sum of the two gains [10]:

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

However, the bandwidth of the HOA is limited by that of the EDFA or the Raman amplifier. Moreover, each of the EDFA and the Raman amplifier needs many optical components so cost is high but HOAs are cost effective. Both gain spectra of Raman and EDFA amplifiers complement each other, therefore the preparation of both amplifiers in series (cascade) can produce high wideband gain spectrum [11].

1.6 Optical Modulation Schemes

There are many benefits of using optical communication system over electric system and its main advantages are very low attenuation, noise and a large bandwidth. This strength can be further achieved utilizing the advanced modulation formats. There are several types of modulation techniques in optical communication system as discussed below.

1.6.1 Optical Amplitude Shift Keying (ASK) / On-Off Keying (OOK)

Optical ASK is a type of amplitude modulation which represents the optical power output of a source in the form of variations in the amplitude of a signal. Any modulated signal has a high frequency carrier. For the same performance, the pulse energy in optical ASK must be twice that in optical PSK. Hence, optical ASK requires 3 dB more power than optical PSK. Thus, in coherent detection, optical PSK is always preferable to optical ASK. But optical ASK can be useful in noncoherent (envelope) detection [1].

1.6.2 Optical Frequency Shift Keying (FSK)

Optical FSK is the optical modulation technique in which the frequency of the carrier signal varies according to the optical signal changes. It is used for modulating an optical signal over two carriers by using a different frequency for a “1” or a “0”. The difference between the carriers is known as the frequency shift. This type of modulation is similar to FM generation, except that the modulating signal is in optical [12]. Optical FSK has high signal-to-noise ratio (SNR) but low spectral efficiency. It was used in all early low bit-rate modems [13].

1.6.3 Optical Phase Shift Keying (PSK)

Optical PSK is a method of transmitting and receiving optical signals in which the phase of a transmitted signal is varied to convey information. For example, when encoding, the phase shift could be 0^o for encoding a “0” and $180^o$for encoding a “1,” thus making the representations for “0” and “1” apart by a total of 180^o [13].

Optical PSK has a perfect SNR but must be demodulated synchronously, which means a reference carrier signal is required to be received at the receiver to compare with the phase of the received signal, which makes the demodulation circuit complex.

1.6.4 Optical Quadrature Phase Shift Keying (QPSK)

The optical QPSK is a variation of BPSK, which sends two bits of optical information at a time. Optical QPSK takes the concept of optical PSK a step further as it assumes that the number of phase shifts is not limited to only two states. With optical QPSK, the carrier undergoes four changes in phase and can thus represent four binary bit patterns of data, effectively doubling the bandwidth of the carrier. The following are the phase shifts with the four different combinations of input bits [14].

$$\begin{array}{lcl}
\boldsymbol{\phi_{0,0}} = \mathbf{0} & & \boldsymbol{\phi_{0,0}} = \frac{\boldsymbol{\pi}}{\mathbf{4}} \\
\boldsymbol{\phi_{0,1}} = \frac{\boldsymbol{\pi}}{\mathbf{2}} & & \boldsymbol{\phi_{0,1}} = \frac{\mathbf{3}\boldsymbol{\pi}}{\mathbf{4}} \\
\boldsymbol{\phi_{1,0}} = \boldsymbol{\pi} & \textbf{or} & \boldsymbol{\phi_{1,0}} = -\frac{\mathbf{3}\boldsymbol{\pi}}{\mathbf{4}} \\
\boldsymbol{\phi_{1,1}} = \frac{\mathbf{3}\boldsymbol{\pi}}{\mathbf{2}} & & \boldsymbol{\phi_{1,1}} = -\frac{\boldsymbol{\pi}}{\mathbf{4}}
\end{array}$$

1.6.5 Electro-Optic Phase Modulator (EOPM)

A light wave can be phase modulated, without change in polarization or intensity, using an electro-optic crystal and an input polarizer in the proper configuration. The simplest type of electro-optic modulator is a phase modulator known as EOPM, containing only a Pockels cell, where an electric field (applied to the crystal via electrodes) changes the phase delay of a laser beam sent through the crystal. The polarization of the input beam often has to be aligned with one of the optical axes of the crystal, so that the polarization state is not changed [15].

1.6.6 Electro-Optic Intensity Modulator (EOIM)

Combined with other optical elements, in particular with polarizers, Pockels cells can be used for other kinds of modulation. In particular, an amplitude modulator is based on a Pockels cell for modifying the polarization state and a polarizer for subsequently converting this into a change in transmitted optical amplitude and power [15].

The intensity (optical energy) of a light wave can be modulated in several ways. Some possibilities include using (1) a dynamic retarder configuration with a crossed polarizer at the output, (2) a dynamic retarder configuration with a parallel polarizer at the output, (3) a phase modulator configuration in a branch of a Mach-Zehnder interferometer, or (4) a dynamic retarder with push-pull electrodes.

1.7 Bit Error Rate (BER)

The BER is the number of bit errors per unit time. The bit error ratio (also BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. BER is a unitless performance measure, often expressed as percentage. The bit error ratio can be considered as an approximate estimate of the bit error probability.

1.7.1 Factors Affecting BER

BER can be affected by a number of factors. By manipulating the variables that can be controlled it is possible to optimize a system to provide the performance levels that are required. Some factors are interference, increased transmitter power, lower order modulation, reduced bandwidth. It is necessary to balance all the available factors to achieve a satisfactory bit error rate. Normally it is not possible to achieve all the requirements and some trade-offs are required.

1.8 Signal to Crosstalk Plus Noise Ratio (SCNR)

SCNR is defined as the ratio of signal power to the crosstalk plus noise power which measures the original signal corruption. The better ratio of SCNR causes the better signal stand out, makes the better quality of original signal or transmitted information signals.

1.9 Challenges of Raman Amplifier

Raman amplifiers turned out to be technically very attractive in all the aspects of capacity, reach, and bit rate. Even though Raman amplifiers are actually being deployed into systems in commercial service, the practical issues such as cost, reliability, noise, crosstalk, safety, are yet to be further discussed. The challenges of the Raman technologies in early stages had been the high-power output of pump lasers [16].

1.9.1 Amplified Spontaneous Emission (ASE) Noise

Optical amplification is an intrinsic source of noise due to the amplified spontaneous emission (ASE). The noise has direct and multiple implications on the performance of optical communication systems: it degrades the signal-to-noise ratio and induces timing jitter and frequency fluctuations. Therefore, an accurate description of the ASE noise is crucial to assess optical fiber communication systems [17].

Amplified Spontaneous Emission (ASE) noise influences the performance of various optical fiber amplifiers. This noise introduces bit errors into the received signal. The ASE noise may be measured in terms of the average probability of symbol error [18].

A saturated Fiber Raman Amplifier (FRA) exhibits a unique behavior under saturation in that its ASE noise component at the signal frequency f_S propagating in the direction of the pump (the direction of increasing gain) compresses faster than the gain (at f_S) whereas the ASE noise compresses slower than the gain in the opposite direction of the pump propagation [19].

1.9.2 Stimulated Raman Crosstalk

The most important issue in the design of WDM networks is the crosstalk. Crosstalk is the general term given to the effect of other signals on the desired signal. The launched power into the system is limited because of these Raman crosstalk effects.

It is found that backward pumped distributed Raman amplifier (DRA) suffers minimum crosstalk among the three pumping schemes i.e. forward, backward and bidirectional.

With the increase in inter-channel separation, keeping wavelength range fixed, crosstalk suffered by the signals decreases. With the increase in input power of the system, crosstalk increases. With the increase in bit rate of the system, crosstalk decreases [20].

Inter-Band Crosstalk

Inter-band crosstalk is the crosstalk situated in wavelengths outside the channel slot This crosstalk can be removed with narrow-band filters. In a WDM networks, inter-band crosstalk appears from channels of different wavelengths.

Intra-Band Crosstalk

The crosstalk within the same wavelength slot is called intra-band crosstalk. Intra-band crosstalk occurs when the signal and the interferer have the closely valued wavelengths.

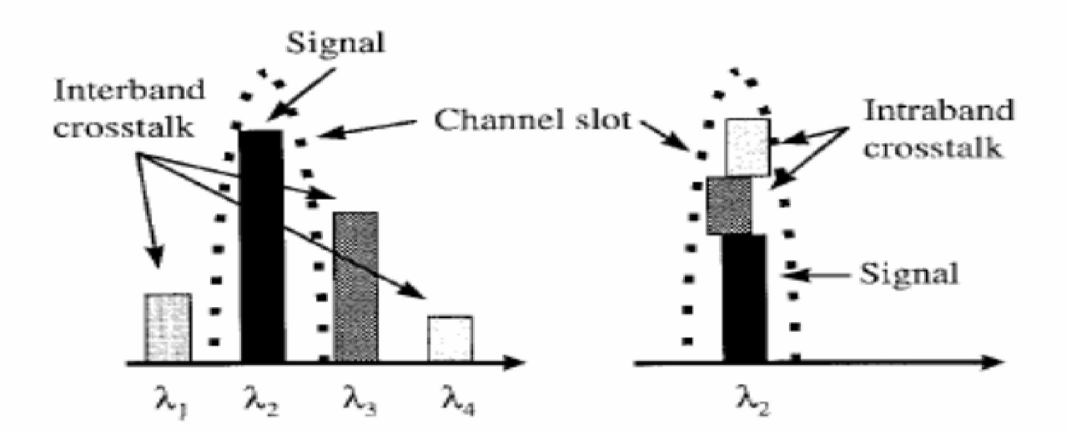

Fig. 1.5 Inter-band and Intra-band crosstalk

Pump-Signal Crosstalk

Because of the very short response time, any fluctuations in pump power slower than the response time can cause gain fluctuations if the pump and signal are propagating in the same direction. This results in additional noise on the signal. If, on the other hand, the pump and signal are counterpropagating, the signal passes the pump that propagates in the opposite direction. This introduces a strong averaging of the accumulated gain and hence reduces the effect of pump-signal cross talk [21].

Signal-Pump-Signal Crosstalk

In the Raman process, the amplitude modulation of the encoded signals is impressed upon the pump. Thus, even a perfectly fictive noise free pump, that is, no fluctuations in wavelength or amplitude, will become noisy during the Raman amplification process. Thereby, induced noise on the pump may be transferred to other signals through the Raman process, in the following denoted as signal-pump-signal (SPS) cross talk [21].

1.9.3 Local Oscillator(LO) Noise

LO noise consists of quantum noise and excess noise. Quantum noise in optical heterodyning and homodyning is usually analyzed under the assumption that the photodetector output is conditionally Poisson (conditioned on the input signal). This quantum noise is frequently supposed to arise from LO shot noise. Excess noise from the local oscillator always affects homodyning and, when it is broadband, also heterodyning [22].

Local Oscillator(LO) Phase Noise

The LO phase noise will limit the ultimate signal-to-noise ratio which can be achieved when listening to a frequency modulated (FM) or phase-modulated (PM) signal. The performance of some types of amplitude modulation detectors may be degraded by the LO phase noise. When the receiver is used to monitor phase-shift keyed (PSK) or frequency-shift keyed (FSK) signals, the phase noise may limit the maximum bit error rate which the system can achieve. The LO phase noise will affect the overall performance that can be achieved in a receiving system [23].

1.10 Literature Review

Raman amplifier is a recently advanced technology in the field of internet trafficking and network communication developed by WDM technique. A significant amount of works has been carried out in this field to minimize Raman induced crosstalk. The performance of an optical communication system is defined by the optical connectors, fibers, amplifiers, couplers, transmitters and receivers. The study of the BER and SCNR is of great interest in WDM links of optical fiber communication system.

M. N. Islam [8] reviewed some of the technical reasons behind the wide-spread acceptance of Raman technology. Distributed Raman amplifiers improve the noise figure and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength. Lumped or discrete Raman amplifiers are primarily used to increase the capacity of fiber-optic networks, opening up new wavelength windows for wavelength-division multiplexing. Raman amplifiers provide a simple single platform for long-haul and ultralong-haul amplifier needs.

Vinod Kumar et al. [9] investigated the crosstalk between WDM channels with external Raman amplification including second-order dispersion terms. The higher-order dispersion severely degrades the performance of optical communication systems. To ensure small crosstalk, the signal gain and the injected pump power should be limited to the value well below the threshold of Raman amplification.

Akhmad Hambali et al. [11] summarized the performance of hybrid optical amplifier in long-haul ultra-dense wavelength division multiplexing system. the U-DWDM long haul system with hybrid amplifier configuration (Raman-EDFA) arranged in series with the specifications listed in this research is only effective at a maximum distance of 205 km. Both gain spectra of Raman and EDFA amplifiers complement each other, therefore the preparation of both amplifiers in series (cascade) can produce high wideband gain spectrum.

Ezra Ip et al. [24] reviewed the principles of coherent detection in optical communications, and described digital techniques for compensating channel impairments. For a given modulation format, using coherent detection, they offer fundamentally the same spectral and power efficiency, but may differ in practice, because of different impairments and implementation details.

Payal et al. [25] experimentally analyzed that EDFA-EDFA hybrid optical amplifier produces better Q-factor than EDFA–SOA hybrid optical amplifier. Moreover, Q-factor of hybrid optical amplifier using RZ format is more as compared to NRZ format and long-distance communication is achieved using RZ modulation format.

Apoorva Apoorva et al. [26] experimentally analyzed that at 80 km EDFA-Praseodymium (Pr) hybrid amplifier gives the best performance parameters like quality factor, bit error rate, eye height and channel power, whereas at 120 km EDFA-Ytterbium (Yb) hybrid amplifier is better than the rest of the hybrid configurations studied such as Raman-EDFA, EDFA-Yb, Raman-Yb, EDFA-Pr and Raman-Pr. In case of minimum BER with respect to the length of the fiber, BER values increase as the length of fiber increases.

Md. Asraful Sekh et al. [27] proposed that using gain flattened EDFA for a 32 channels WDM system in the wavelength range of 1546 to 1560 nm with channel spacing of 0.4 nm for data rate of 10 Gb/s the gains are flattened within 43.6 ± 0.8 dB with noise figure about 7.38 dB at pump power of 600 mW and input power of -34 dBm using optimized erbium doped fiber of 6.2 m length.

Dipika D. Pradhan et al. [28] presented that the performance of equal multi-pump signal frequency spacing is better than un-equal and semi-equal spacing. The quality factor is better than other type of spacing. As the transmission distance increases the output power decreases.

Anu Sheetal et al. [29] analyzed that the Raman-EDFA outpower YDFA-EDFA in terms Q-factor at higher channel spacing. The maximum repeaterless transmission distance for the worst-case scenario at 25 GHz channel spacing is 120 km and 100 km for Raman-EDFA and YDFA-EDFA respectively. It has been observed that as the channel spacing reduces, the performance of the system degrades drastically.

S. Shameem et al. [30] presented that the bidirectional pumping offers better noise performance when compared to forward only and backward only pumping schemes. It has been found that Raman gain is produced where there is an optical fiber in the light wave communication system, and thus, it is said that Raman amplification is flexible. Thus, the system performance is increased at a lower cost.

Kazuro Kikuchi [31] reviewed research activities and developments concerning coherent optical communications and presented the principle of coherent detection, including its quantum-noise characteristics. Digital signal processing plays an important role in the newly developed digital coherent receiver, with special focus on finite-impulse-response (FIR)-filter-based adaptive equalization. The combination of coherent detection and DSP provides with new capabilities that were not possible without the detection of the phase of the optical signal.

Jianjun Yu et al. [32] reviewed the recent progress on high-speed optical transmission with coherent detection based on DSPs. The trend for bit rate per channel is from 100 G to 400 G and even higher. 100 G per channel is widely deployed, and 400 G or 1 T is a hot research topic. Using advanced DSPs can greatly improve the signal performance and spectral efficiency, and reduce the time consumption for signal procession.

Yoshihisa Yamamoto et al. [33] investigated the feasibility and potential application of the coherent optical fiber transmission systems by considering constituent devices and system performance. The long-distance transmission system and the undersea transmission system across a strait are promising applications of the coherent optical fiber transmission system which covers a 220-240 km repeater spacing.

Abu Jahid et al. [34] investigated the effects of optical amplifiers and optical receiver in the presence of crosstalk on the overall performance; in particular, Signal-to-Noise Ratio (SNR) and Bit-Error-Rate (BER) performance of a DWDM system. The system suffers from a power penalty which increases with the decrement in channel spacing and with the increment of optical amplifiers, and number of hops. The system performance can be substantially improved by using optimum number of optical amplifiers with higher gain and optimum receiver gain having moderate bandwidth.

Jake Bromage [35] highlighted novel Raman pumping schemes that have recently been developed. Raman amplification is flexible in the sense that gain can be produced wherever there is optical fiber within a light-wave system. Furthermore, gain can be produced at any wavelength given the appropriate pumps. This flexibility enables system designers to pursue a number of options to get higher system performance at a lower cost.

F. H. Tithi et al. [36] analyzed that the WDM system with optical on off-keying (OOK) and heterodyne envelope detection suffers power penalty at a given BER, due to stimulated Raman scattering which increases with the number of WDM channel, channel separation, pump power and transmission distance.

F. H. Tithi et al. [37] presented an analytical approach to evaluate the impact of Raman amplifier induced crosstalk on the bit error rate performance of a WDM transmission system with optical on off-keying (OOK) and heterodyne envelope detection. BER is highly degraded due to combined influence of crosstalk beat noise components of signal and crosstalk and local oscillator power.

Abd El–Naser A. Mohamed et al. [38] studied an analytical model for optical distributed Raman amplifiers (DRAs) in the transmission signal power and pump power within Raman amplification technique in co-pumped, counter-pumped, and bi-directional pumping direction configurations through different types of fiber cable media. They have deeply investigated multiplexing/demultiplexing based Distributed optical fiber Raman amplifier over wide range of the affecting parameters**.**

C. R. S. Fludger et al. [39] presented an analytical model and measurements of the pump to signal relative intensity noise (RIN) transfer characteristics of co-pumped and counter-pumped Raman amplifiers. The resulting RIN on the signal channels can be worse than the RIN on the pump lasers. In a counter-pumped Raman amplifier, the different direction of propagation causes the noise to be low-pass filtered. In a co-pumped Raman amplifier, chromatic dispersion will average the noise transfer. Non-dispersion-shifted fibers and other fibers with high dispersion between the signal and pump wavelengths give a greater potential for use in co-pumped Raman amplified systems.

S. J. B. Yoo [40] demonstrated various wavelength conversion techniques, discusses the advantages and shortcomings of each technique, and addresses their implications for transparent networks.

N. Anders Olsson [41] investigated theoretically and experimentally the performance of optical amplifiers in fiber optic communication systems. The noise and BER characteristics of optical networks with optical amplifiers are calculated and the dependence of system performance on amplifier characteristics is shown.

Keang-Po Ho [42] presented that the probability density function (pdf) of stimulated Raman crosstalk is a lognormal distribution (Gaussian distribution in decibel scale). When constant gain or loss is equalized, crosstalk ratio, power penalty, and power limit depend only on the crosstalk variance. The crosstalk standard deviation must be less than 0.4 dB for a power penalty less than 1dB.

H. Kim et al. [43] reported on the effect of stimulated Raman scattering (SRS) on the hybrid wavelength-division-multiplexing (WDM) system. They estimated the maximum number of WDM digital channels that a hybrid WDM system could support.

Peter Winzer et al. [44] studied how the robustness to in-band crosstalk of QAM signals is reduced as the number of levels in the QAM format increases through simulations and experiments at 21.4 G Baud. They demonstrated the effect of in-band crosstalk on several advanced optical modulation formats at 21.4 G Baud, showing a 1-dB penalty at a bit-error ratio of 1×10-3 from a crosstalk of –18 dB, –24 dB, and –32 dB for QPSK, 16-QAM, and 64-QAM, respectively.

M. A. Iqbal et al. [45] demonstrated the overall noise performance improvement and noise figure tilt reduction of a broadband distributed Raman amplifier using bidirectional amplification with dual order co-pumping seeded by a first order pump without deteriorating the signal relative intensity noise (RIN) performance. They have also investigated the impact of 1st order co-pump seed power and RIN level on the trade-off between noise figure improvement and net transmission performance.

Milad I. Akhlaghi et al. [46] demonstrated a reduction of coherent stochastic noise using the intrinsic coherence properties of the field with single-shot heterodyne detection and quantified the efficiency in low-SNR conditions.

1.11 Objectives of The Thesis

The objectives of the thesis work are:

- To develop an optical PSK modulated WDM system model with heterodyne detection for continuous output and to find out the effect of crosstalk in the WDM system.
- To develop an analytical approach to find the expression for crosstalk induced by fiber Raman amplification considering a WDM input signal.
- To find out signal to crosstalk plus noise ratio for the developed system.
- To find out the bit error rate of the WDM system and to find the performance results in terms of BER and SCNR.
- To find out an optimum number of channel and signal power to minimize the noise induced by crosstalk and ASE noise.
- To find out the power penalty suffered by a WDM system due to Raman amplifier induced crosstalk for different parameters and to find out the optimum system parameters like number of channels, maximum allowable input power etc. at a given BER .

1.12 Organization of The Thesis

The thesis includes four chapters.

At the beginning of the **chapter 1,** an introduction on communication system is presented. After that, types of communication system and optical fiber communication system along with advantages and limitations are described. Different Multiplexing techniques and optical amplifiers and a brief discussion on Raman amplifier is given. Finally, previous works and objectives of the thesis are presented.

Chapter 2 provides a short description on WDM system, coherent detection and heterodyne detection. A system model is presented for PSK modulation with heterodyne detection. Analytical representation in terms of SCNR and BER are also shown in this chapter.

Chapter 3 shows the results and discussion on the basis of the model. Results are evaluated by changing different parameters. Numerically power penalty for the system also found.

In **chapter 4** conclusion and discussion and suggestion on future scope of the work are presented.

CHAPTER 2

WDM SYSTEM MODEL

2.1 Multiplexing Technique for Optical Communication

Multiplexing is the process in which multiple data streams, coming from different sources, are combined and transmitted over a single data channel or data stream. Multiplexing is the ability of a number of devices to share a transmission facility. If each device needs the facility only a fraction of time, then the sharing arrangement allows the cost of the facility to be spread over many users. A multiplexing technique which does not involve the application of several message signals onto a single fiber is known as space division multiplexing (SDM). In SDM, each signal channel is carried on a separate fiber within a fiber bundle or multifiber cable form [3].

2.1.1 Necessity of Multiplexing

Multiplexing technique is designed to reduce the number of electrical connections or leads in the display matrix. Besides reducing the number of individually independent interconnections, multiplexing also simplifies the drive electronics, reduces the cost and provides direct interface with the microprocessors. To utilize the system capacity fully, it is necessary to transmit many channels simultaneously through multiplexing. This can be accomplished through time-division multiplexing (TDM) or frequency-division multiplexing (FDM) [4]. The aim of multiplexing is to share an expensive resource. For example, in electronics, multiplexing allows several analog signals to be processed by one analog-to-digital converter (ADC), and in telecommunications, several phone calls may be transferred using one wire. In communications, the multiplexed signal is transmitted over a communication channel, which may be a physical transmission medium [32].

2.1.2 Applications of Multiplexing

A multiplexer is used in numerous applications like, where multiple data can be transmitted using a single line. Some applications are:

- Communication system
- Computer memory
- Telephone network
- Telegraphy
- Digital and analog broadcasting
- Video processing

2.2 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.

2.2.1 Optical Time Division Multiplexing (OTDM)

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 [3]. Pulses from the individual channels are interleaved and transmitted sequentially, thus enhancing the bandwidth utilization of a single fiber link. A strategy for increasing the bit rate of digital optical fiber systems beyond the bandwidth capabilities of the drive electronics is known as optical time division multiplexing (OTDM). A block schematic of an OTDM system which has demonstrated 160 Gbit s^{-1} transmission over 100 km is shown in Fig. 2.1. The principle of this technique is to extend electrical time division multiplexing (ETDM) by optically combining a number of lower speed electronic baseband digital channels. In the case illustrated in Fig. 2.1, the optical multiplexing and demultiplexing ratio is 1:4, with a baseband channel rate of 40 Gbit s^{-1}. Hence the system can be referred to as a four-channel OTDM system.

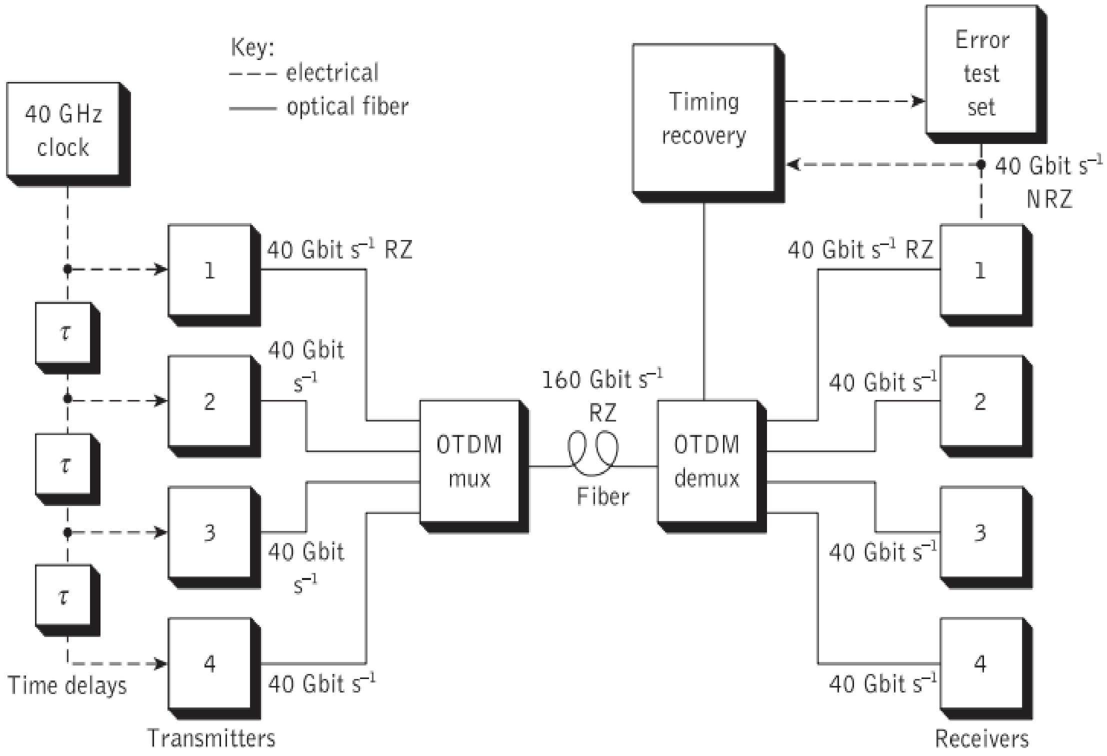

Fig. 2.1 Four-channel OTDM fiber system

2.2.2 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission technique which is based on frequency division multiplexing (FDM) [3]. 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 [24]. In the upper spectral diagram as illustrated in Fig. 2.2 ,10 non-overlapping subcarrier frequency signals arranged in parallel depicting conventional FDM, each being separated by a finite guard band. OFDM is displayed in the bottom spectral diagram where the peak of one signal coincides with the trough of another signal [3].

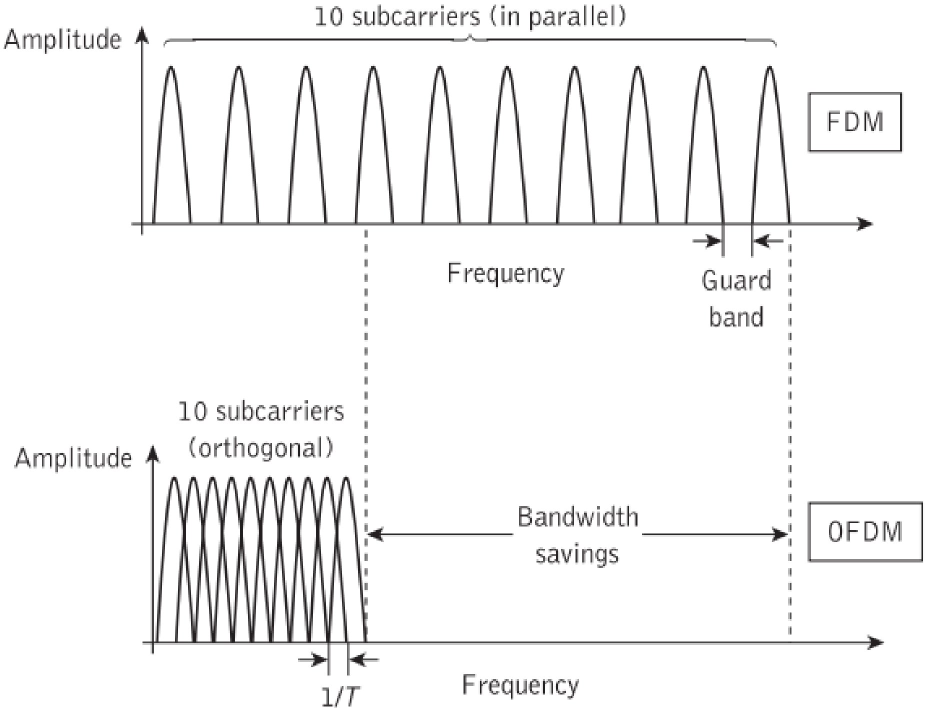

Fig. 2.2 Orthogonal frequency division multiplexing (OFDM) compared with conventional frequency division multiplexing (FDM)

2.2.3 Optical Code Division Multiple Access (OCDMA)

Optical code division multiplexing (OCDM), sometimes termed optical code division multiple access (OCDMA) is a digital technique where, instead of each channel occupying a given wavelength, frequency or time slot, the information is transmitted using a coded sequence of pulses. Each channel employs a specific code to transmit and recover the original signal. It utilizes the basic principle of spread spectrum transmission where all users share the fiber channel bandwidth simultaneously [3].

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.

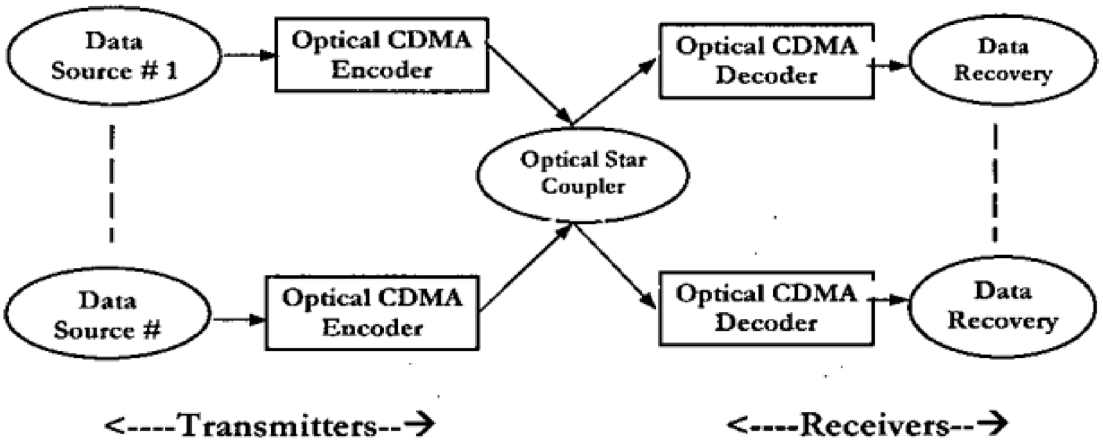

Fig. 2.3 Optical CDMA network

OCDMA techniques are used as a channel access scheme e.g. for mobile phone service and in wireless networks, with the advantage of spreading intercell interference among many users. Another important application of CDMA is the Global Positioning System (GSM).

2.2.4 Subcarrier Multiplexing(SCM)

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 [3].

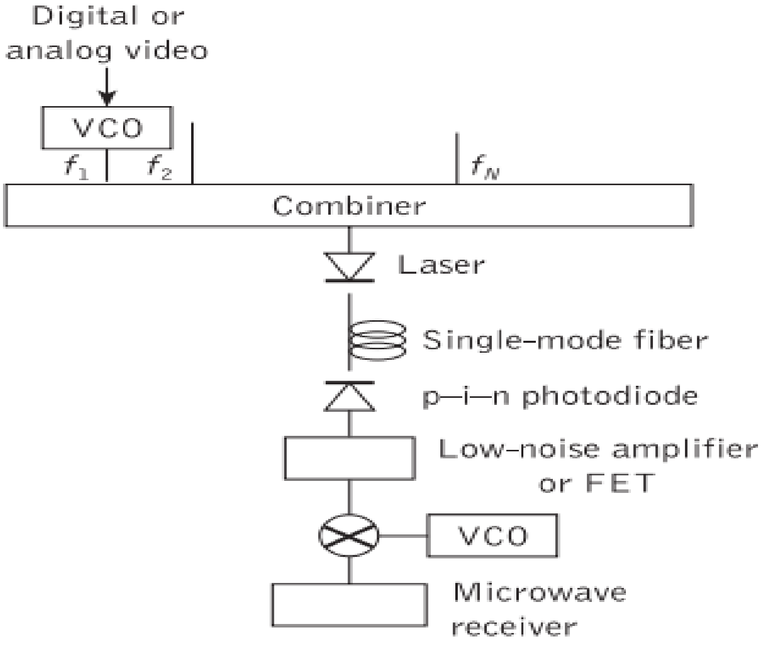

Fig. 2.4 Basic subcarrier multiplexing (SCM) fiber system [3]

A block schematic of a basic SCM system is shown in Fig. 2.4. The modulated microwave subcarrier signals are obtained by frequency up-conversion from the baseband using voltage-controlled oscillators (VCOs). These subcarrier signals f_i are then summed in a microwave power combiner prior to the application of the composite signal to an injection laser which is d.c. biased at around 5 mW in order to produce the desired intensity modulation. The IM optical signal is then transmitted over single-mode fiber and directly detected using a wideband photodiode before demultiplexing and demodulation using a conventional microwave receiver.

2.2.5 Hybrid Multiplexing

When two (or more) different multiplexing techniques are combined to allow optical signal multiplexing for several optical signals, the resultant is referred to as hybrid multiplexing. It should be noted that different multiplexing strategies exhibit their own advantages and drawbacks and therefore the combination of different multiplexing techniques can be used to overcome the problems associated with a specific technique. A hybrid multiplexing system can comprise either optical or electrical domain multiplexing, or combination of both signal types. Common examples of optical hybrid multiplexing are WDM being combined with OTDM, OCDM or SCM [3].

2.2.6 Wavelength Division Multiplexing (WDM) System

Wavelength division multiplexing (WDM) is a technique modulating various data streams, i.e. optical carrier signals of varying wavelengths in terms of colors of laser light onto a single optical fiber. WDM is similar to frequency-division multiplexing (FDM) but referencing the wavelength of light to the frequency of light.

This technique permits bidirectional communications over one strand of fiber, as well as multiplication of capacity. A WDM system uses a multiplexer at the transmitter end and a de-multiplexer at the receiver end to split the channels apart. The advances in this technique has opened up diverse paths for all-optical devices that provide loss compensation at the time of regenerating the signal with low cost [25].

2.2.6.1 Evolution of WDM Technology

Until the late 1980s, optical fiber communications were 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.

The first WDM system only combined two signals, one channel is at 1330 nm and the other is at 1550 nm. 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. The WDM technique is illustrated in Fig. 2.5 where a conventional (i.e. single nominal wavelength) optical fiber communication system is shown together with a duplex (i.e. two different nominal wave-length optical signals traveling in opposite directions providing bidirectional transmission), and also a multiplex (i.e. two or more different nominal wavelength optical signals transmitted in the same direction) fiber communication system. It is the latter WDM operation which has generated particular interest within telecommunications.

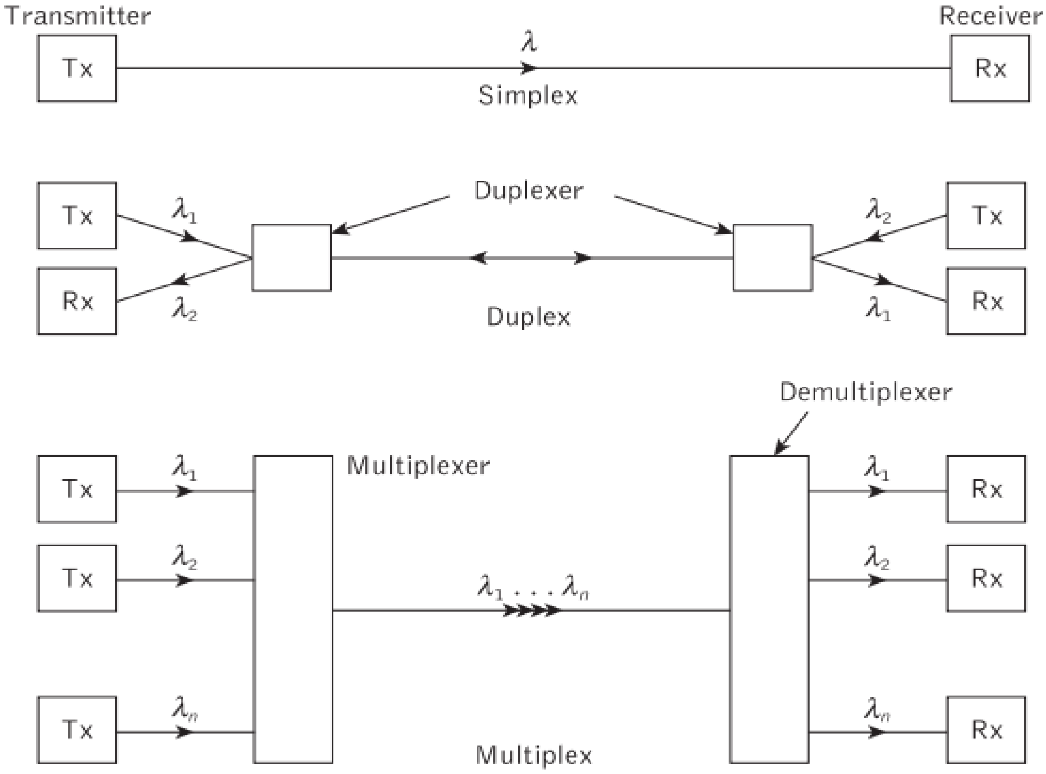

Fig. 2.5 Optical fiber system operating modes illustrating WDM system [3]

2.2.6.2 Merits of Wavelength Division Multiplexing (WDM) System

- A single fiber optic cable can handle dozens of channels, instead of using 12 channels only use 1 channel.
- Multiply the effective bandwidth of a fiber optic communications system.
- Reduces the cost and increases the capacity of the cable to carry data.
- Faster access to new channels and easy system expansion.

2.2.6.3 Limitations of Wavelength Division Multiplexing (WDM) System

- Complex transmitters and receivers.
- They must be wide-band, which means they are more expensive and possibly less reliable.

2.2.6.4 Types of Wavelength Division Multiplexing (WDM) System

WDM systems are divided according to wavelength categories, generally course WDM (CWDM) and dense WDM (DWDM).

Course Wavelength Division Multiplexing (CWDM)

CWDM is a method of combining multiple signals on laser beams at various wavelengths for transmission along fiber optic cables, such that the number of channels is fewer than in dense wavelength division multiplexing (DWDM) but more than in standard wavelength division multiplexing (WDM). Fig. 2.6 shows the CWDM wavelengths. There are 18 center wavelengths of 20 nm spacing from 1270 nm~1610 nm, covering the O-, E-, S-, C- and L-band.

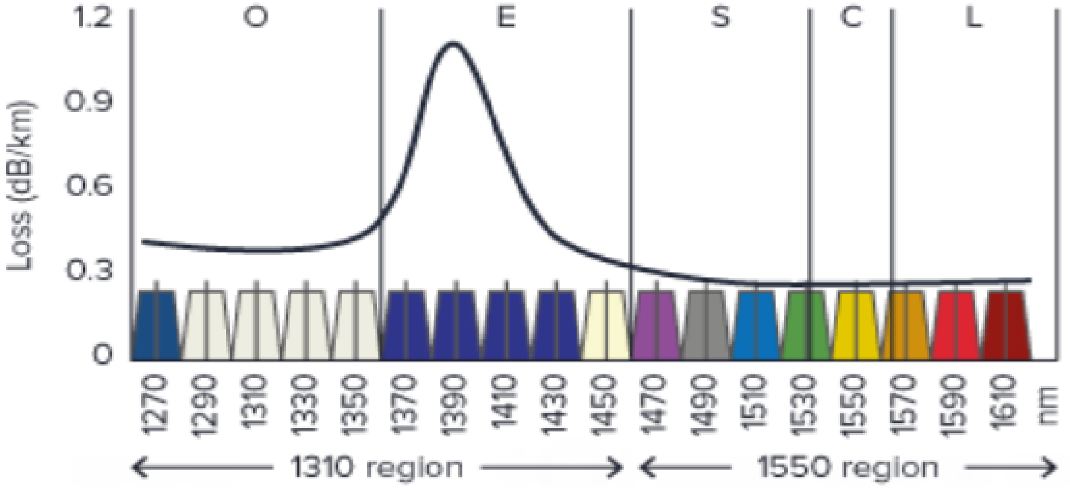

Fig. 2.6 Optical wavelength channel allocation for CWDM system

Dense Wavelength Division Multiplexing (DWDM)

DWDM is a technology that allows multiple signals simultaneously that are to be transmitted on a single fiber at different wavelengths and it is also an optical multiplexing technology used to increase bandwidth over existing fiber networks. This technology offers excellent performance characteristics including narrow channel separation and wide channel bandpass in the range of frequencies which are passed through a filter.

Fig. 2.7 shows a block schematic for a DWDM system where a large number of channels N, each utilizing a single wavelength (i.e. from λ_1 to λ_N), are multiplexed onto a single-fiber transmission medium. Both the deployment of EDFAs and dispersion compensation are required for long-haul DWDM systems to offset any optical signal power losses caused by optical wavelength multiplexers and other passive optical devices [47].

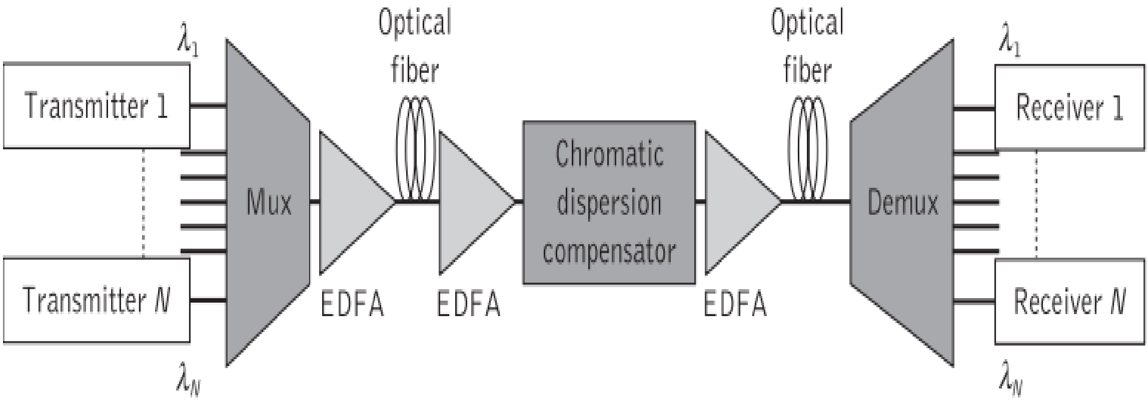

Fig. 2.7 Block schematic of a dense wavelength division multiplexed system

2.3 Coherent Detection

A “coherent” optical transmission system is characterized by its capability to do “coherent detection”, which means that an optical receiver can track the phase of an optical transmitter (and hence “phase coherence”) so as to extract any phase and frequency information carried by a transmitted signal. For a given modulation format, using coherent detection, they offer fundamentally the same spectral efficiency and power efficiency, but may differ in practice, because of different impairments and implementation details [24].

The coherent detection offers several important advantages compared to direct detection (1) improved receiver sensitivity, (2) better frequency selectivity, (3) possibility of using constant amplitude modulation formats (FSK, PSK), (4) tunable optical receivers similar to RF receivers are possible, and (5) with coherent detection the chromatic dispersion and Polarization Mode Dispersion (PMD) can easier be mitigated [48].

2.3.1 Coherent Detection Principle

In this section, we describe the basic concepts of coherent detection. Especially, local oscillator, homodyne detection, heterodyne detection [48].

2.3.1.1 Local Oscillator

The basic idea behind coherent detection consists of combining the optical signal coherently with a continuous-wave(CW) optical field before it falls on the photodetector, as illustrated in Fig. 2.8. Coherent detection is well known in wireless communication systems. In those wireless systems, a radio frequency (RF) local oscillator (LO) is tuned to “heterodyne” with a received signal through an RF mixer, so that both the amplitude and phase information contained in an RF carrier can be recovered in the following digital signal processor (DSP). On the other hand, for an optical coherent system, a narrow-linewidth tunable laser, serving as an LO, tunes its frequency to “intradyne” with a received signal frequency through an optical coherent mixer, and thereby recovers both the amplitude and phase information contained in a particular optical carrier.

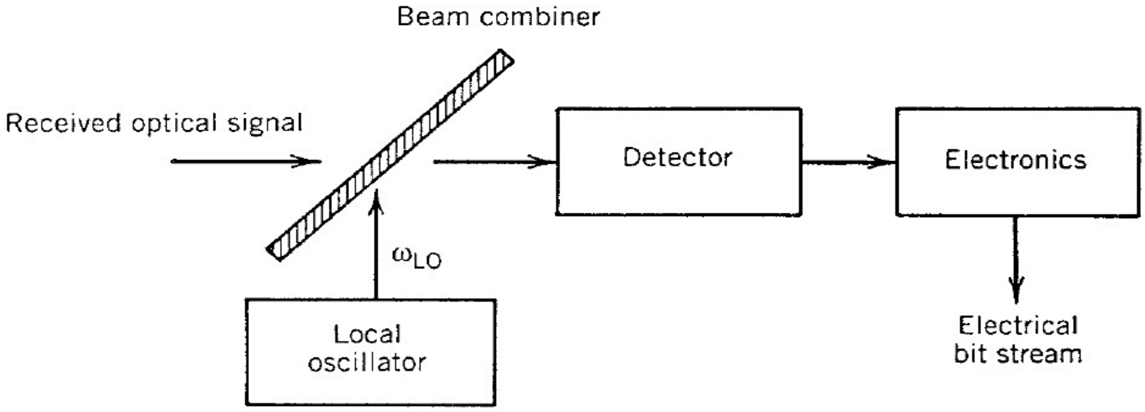

Fig. 2.8 Schematic illustration of a coherent detection scheme [4]

2.3.1.2 Homodyne Detection

When the optical frequencies (or wavelengths) of the incoming signal and the local oscillator laser output are identical, then the receiver operates in a homodyne mode and the electrical signal is recovered directly in the baseband [3]. In the homodyne detection, the phase of the local oscillator signal is locked to the incoming signal, then, by definition, a synchronous detection scheme must be employed. Moreover, the result of the mixing process in the optical detector produces an information signal which is in the baseband and thus requires no further demodulation [3]. An Automatic Frequency Control (AFC) loop is also shown within the homodyne receiver configuration of Fig. 2.9 to provide the necessary frequency stabilization between the two signals. Hence any variant detection schemes based on homodyne detection, but in which the local oscillator laser is not phase locked to the incoming signal such as phase diversity or multiport detection, could be considered as a form of heterodyne rather than homodyne detection [49].

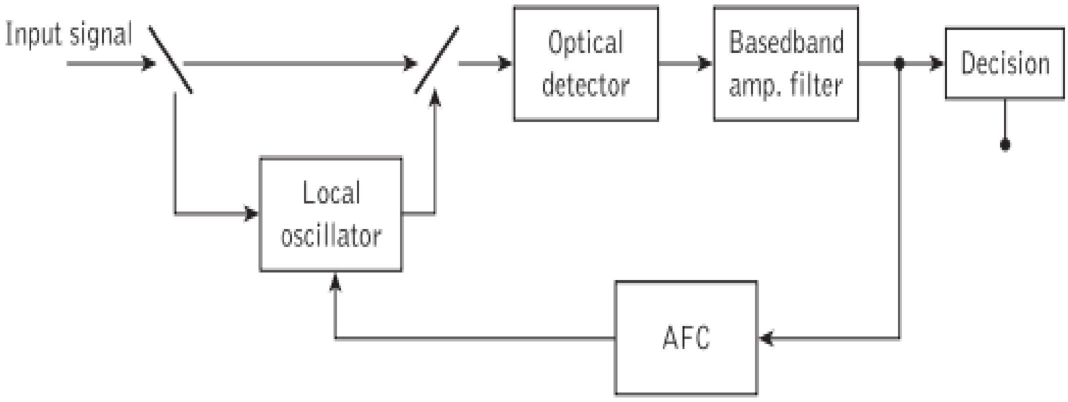

Fig. 2.9 optical homodyne receiver illustrating the phase locking between the local oscillator and incoming signals [3]

signal such as phase diversity or multiport detection, could be considered as a form of heterodyne rather than homodyne detection [49].

2.3.1.3 Heterodyne Detection

In heterodyne detection, the local oscillator frequency is offset from the incoming signal frequency and therefore the electrical spectrum from the output of the detector is centered on an intermediate frequency (IF) which is dependent on the offset and is chosen according to the information transmission rate and the modulation characteristics. This IF, which is a difference signal (or difference frequency), contains the information signal and can be demodulated using standard electrical techniques [50]. Optical heterodyne detection involves optical signal and local oscillator waves, whereas the mixing product is an electrical signal. The mixing product is not obtained by mixing the signal and local oscillator wave in a nonlinear crystal, but rather simply by detecting the linearly superimposed waves with a square-law photodetector, typically a photodiode [4].

2.4 WDM System Scheme

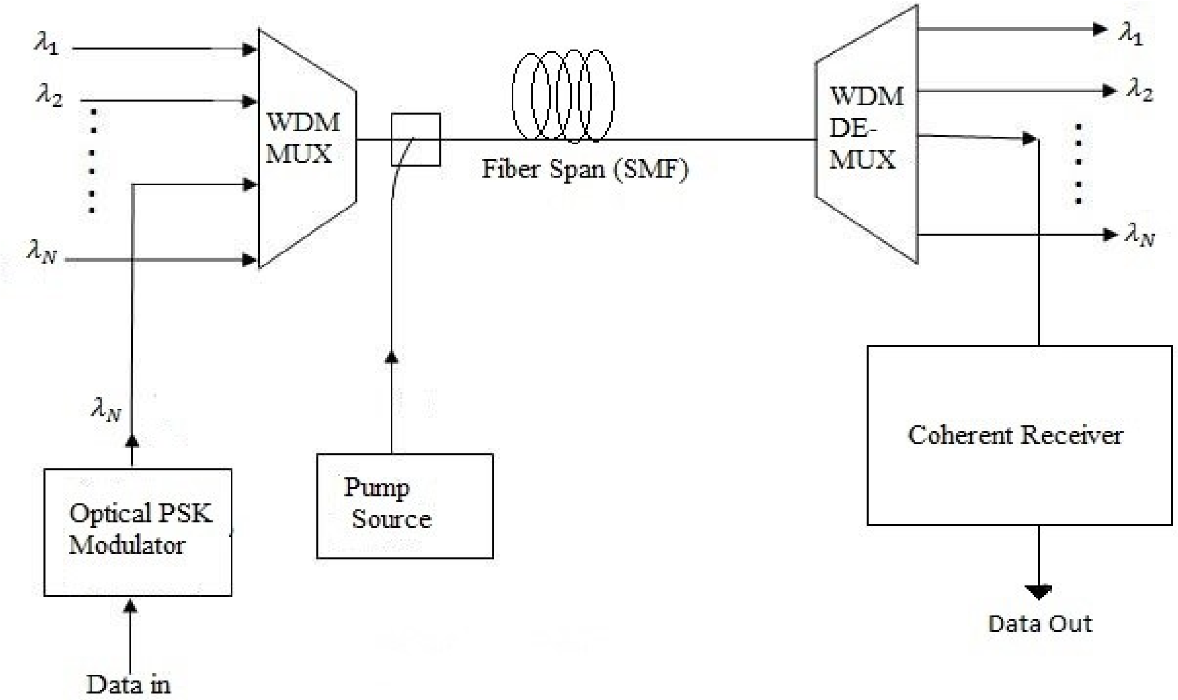

Fig. 2.10 System model of an N channel WDM system with Raman amplifier

The block diagram of a WDM system with optical PSK modulation and distributed Raman amplifier is shown in Fig. 2.10. At first electrical signals were converted into optical signal through a drive circuit. The optical signal is then modulated by a PSK modulator. N data channels are used to modulate N laser source of wavelength λ_1 to λ_N using phase shift keying modulation and are multiplexed by a Wavelength division multiplexer (WDM). N channel input signal are then converted into single output. The output of the multiplexer is fed into a fiber Raman amplifier. The WDM signal then passes through the fiber along with pump signal. As the signal passes through the fiber the signal power decreases. A pump signal is used to increase the signal power so that it became easy for the detector to detect the signal at a distant place. The signal then transmits through optical fiber. At the receiving end the output of the amplifier is demultiplexed and converted into signal through different detection system.

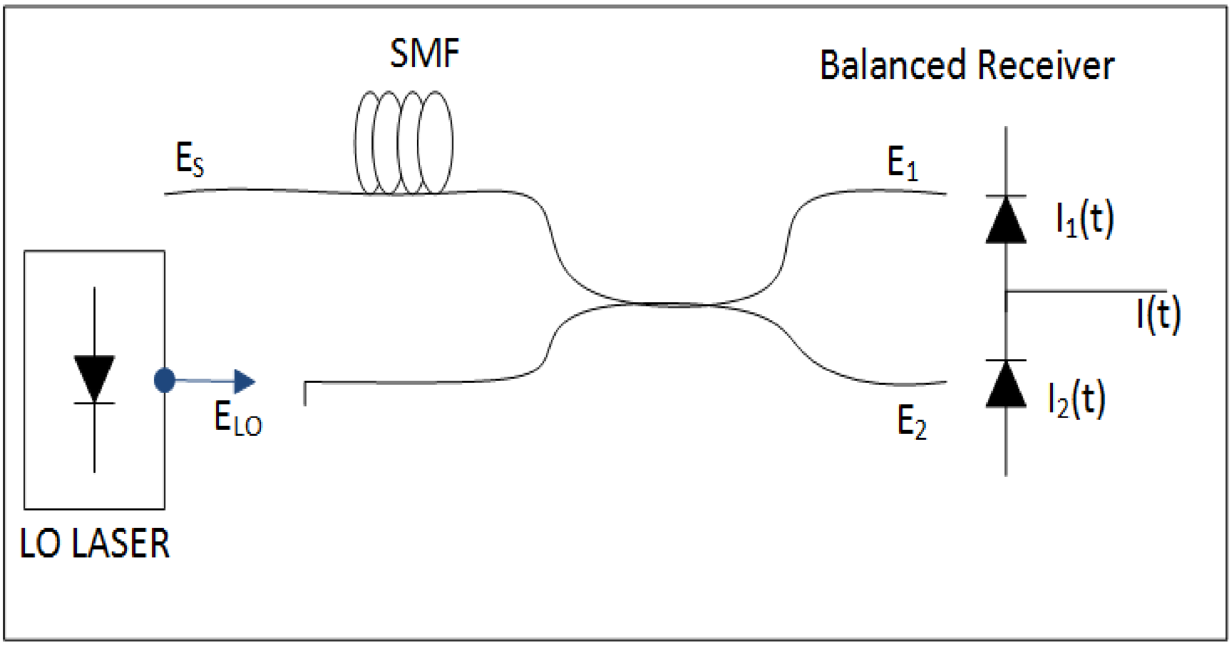

Fig. 2.11 Coherent optical receiver for phase shift keying(PSK) modulation

The signal at the output of the demultiplexer is received through a coherent heterodyne system. In PSK there are two components of the current. The summand component is passed through a pre-amplifier. A local oscillator power is multiplexed with the signal power in heterodyne system to make it easier detecting the signal. The multiplexed signal being passed through a low pass filter and sampler finally emerges as an output data.

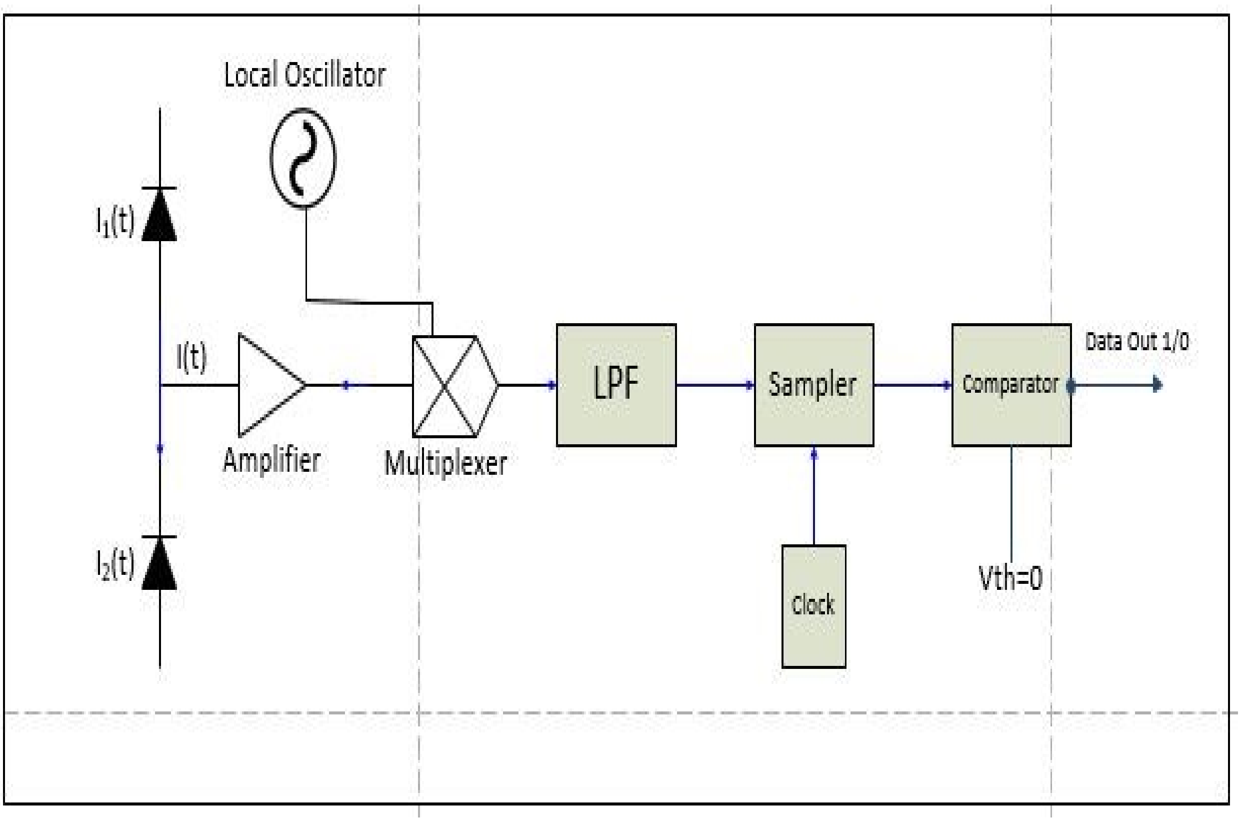

Fig. 2.12 Block diagram of data detection of heterodyne PSK receiver

2.5 System Analysis

We consider a WDM system with N number of equally spaced channels in which signals propagate at the same speed through the fiber. Let us consider that all the channels lie within the linear portion of the Raman gain profile and are equally separated in spectral domain. Let us employ the triangular approximation to the Raman gain curve [51]. The signals are modulated with a phase shift keying (PSK) modulator. We evaluate a simplified equation of output current for the system to find out bit error rate(BER) performance.

The WDM signal with N number of channel with PSK modulation is [37]

$$S_{WDM} = \sum_{k=0}^{\infty} \sum_{n=1}^{N} \sqrt{2P_{s,n}(0)}\, a_k^n \, \cos\left[\frac{2\pi c}{\lambda_n} t\right] \tag{2.1}$$

and the signal from the pump source is

$$S_{pump} = \sqrt{2P_0(0)} \, \cos\left[\frac{2\pi c}{\lambda_p} t\right] \tag{2.2}$$

Electric field of the WDM system at a distance z is found to

$$e_{WDM}(t,z) = \sum_{n=1}^{N} e_{s,n}(t,z) \, + e_{ct,n}(t,z) \tag{2.3}$$

where, electric field due to signal

$$e_{s,n}(t,z) = \sum_{n=1}^{N} \sqrt{2P_{s,n}(z)} \cos\left[\frac{2\pi c}{\lambda_n} t - \beta . z\right] \tag{2.4}$$

and the electric field due to crosstalk is expressed as

$$e_{ct,n}(t,z) = \sqrt{2P_{ct}(z)} \cos\left[\frac{2\pi c}{\lambda_n} t + \Theta_{ct}(t,z)\right] \tag{2.5}$$

where, $\Theta_{ct}(t,z)$ denotes the random phase crosstalk noise.

The local oscillator has the electric field as

$$e_{LO}(t) = \sqrt{2P_{LO}(t)} \cos\left[\frac{2\pi c}{\lambda_n} t\right] \tag{2.6}$$

The signal power of a WDM system decreases as it travels through the fibre. The signal power at a distance z is [52]

$$\mathrm{P_{s,n}(z) = P_{n0} J_0 \, e^{-\alpha z} \exp[G J_0 (n-1) Z_e]} \left[\sum_{\mathrm{m=1}}^{\mathrm{N}} \mathrm{P_{m0} e^{G J_0 (m-1) Z_e}}\right]^{-1} \tag{2.7}$$

where,

$$\mathrm{G} = \frac{\mathrm{g'}\Delta \mathrm{f}}{2\mathrm{A}}$$

$$\mathrm{Z_e} = \frac{1 - \mathrm{e}^{-\alpha \mathrm{z}}}{\alpha}$$

$$\mathrm{J_0} = \sum_{\mathrm{m=1}}^{\mathrm{N}} \mathrm{P_{m0}}$$

g' denotes the Raman gain slope, Δf indicates the interchannel frequency spacing, Z_e is the effective propagation distance and α is the fiber attenuation coefficient. Equation (2.7) is still applicable for significant pump depletion and unequal channel loading.

In case of equal channel launch, power the signal power can be written as, [52]

$$P_{s,n}(z) = NP_p e^{-\alpha z} exp\left[\left(\frac{GJ_0Z_e}{2}\right)(2n - N - 1)\right]\left[\frac{\sinh\left(\frac{GJ_0Z_e}{2}\right)}{\sinh\left(\frac{NGJ_0Z_e}{2}\right)}\right] \tag{2.8}$$

Crosstalk of a system increases as we go along the distance. At a distance z the crosstalk power of the WDM system can be expressed by,

$$P_{ct}(z) = \left[1 - Nexp\left[-GNP_0Z_e\frac{(N-1)}{2}\right]\left[\frac{\sinh\left(\frac{NP_0GZ_e}{2}\right)}{\sinh\left(\frac{N^2P_0GZ_e}{2}\right)}\right]P_0e^{-\alpha z}\right] \tag{2.9}$$

In case of small crosstalk when $P_0GZ_e \ll 1$ [52]

$$P_{ct}(z) = \frac{N}{2}(N-1)\, P_0GZ_e \tag{2.10}$$

We have considered Coherent PSK detection. In case of PSK detection the coupler shifts either of the signal field to 180^0.The electric field on the upper and lower photodiodes are [31]

$$E_1 = \frac{1}{\sqrt{2}}(E_S + E_{LO}) \tag{2.11}$$

$$E_2 = \frac{1}{\sqrt{2}}(E_S - E_{LO}) \tag{2.12}$$

$$E_1 = \frac{1}{\sqrt{2}}\left(\sqrt{2P_S}\cos\frac{2\pi C}{\lambda_S}(t) + \sqrt{2P_{LO}}\cos\frac{2\pi C}{\lambda_{LO}}(t)\right) \tag{2.13}$$

$$E_2 = \frac{1}{\sqrt{2}}\left(\sqrt{2P_S}\cos\frac{2\pi C}{\lambda_S}(t) - \sqrt{2P_{LO}}\cos\frac{2\pi C}{\lambda_{LO}}(t)\right) \tag{2.14}$$

The output photocurrents at the receiver end are, [53]

$$I_1 = R|E_1|^2 \tag{2.15}$$

$$I_2 = R|E_2|^2 \tag{2.16}$$

$$I_1(t) = \frac{R}{2}\left[Re\left\{\frac{\sqrt{2P_S}\cos\frac{2\pi C}{\lambda_S}(t) + \sqrt{2P_{LO}}\cos\frac{2\pi C}{\lambda_{LO}}(t)}{\sqrt{2}}\right\}\right]^{ms} \tag{2.17}$$

$$I_1(t) = \frac{R}{2}[P_S + P_{LO} + 2\sqrt{P_S P_{LO}}\ \cos\{\omega_{IF}(t) + \theta_{sig}(t) - \theta_{LO}(t)\}] \tag{2.18}$$

$$I_2(t) = \frac{R}{2}\left[Re\left\{\frac{\sqrt{2P_S}\cos\frac{2\pi C}{\lambda_S}(t) - \sqrt{2P_{LO}}\cos\frac{2\pi C}{\lambda_{LO}}(t)}{\sqrt{2}}\right\}\right]^{ms} \tag{2.19}$$

$$I_2(t) = \frac{R}{2}[P_S + P_{LO} - 2\sqrt{P_S P_{LO}}\ \cos\{\omega_{IF}(t) + \theta_{sig}(t) - \theta_{LO}(t)\}] \tag{2.20}$$

where, $\theta_{LO} = \frac{2\pi C}{\lambda_{LO}} t$

$$\omega_{IF} = \omega_S - \omega_{LO}$$

The summing content of the output current is considered as zero as it will exceed the bandwidth of the photodiode. So, the output current at the receiving end will be,

$$I(t) = I_1(t) - I_2(t) + i_{sh,n} \tag{2.21}$$

$$I(t) = 2R\sqrt{P_S(t)P_{LO}}\ \cos\{\omega_{IF}(t) + \theta_{sig}(t) - \theta_{LO}(t)\} + i_{sh,n} \tag{2.22}$$

where, the overall shot noise

$$i_{sh,n} = i_{sh,1} - i_{sh,2}$$

Considering heterodyne detection, the angular frequency

$$\omega_{IF} = \frac{\omega_b}{2};$$

where, ω_b denotes the modulation bandwidth.

For PSK signal the signal power P_S is constant and the signal phase is

$$\Theta_{sig}(t) = \Theta_s(t) + \Theta_{sn}(t) \tag{2.23}$$

where, $\Theta_{sn}(t)$ is the phase noise and $\Theta_s(t)$ is the phase modulation. So, [31]

$$I(t) = 2R\sqrt{P_S(t)P_{LO}}\ \cos\{\omega_{IF}(t) + \Theta_s(t) + \Theta_{sn}(t) - \Theta_{LO}(t)\} + i_{sh,n} \tag{2.24}$$

Total phase noise of the receiver is denoted by

$$\Theta_n(t) = \Theta_{sn}(t) - \Theta_{LO}(t) \tag{2.25}$$

Now we can write the receiver output current as

$$I(t) = 2R\sqrt{P_S(t)P_{LO}}\ \cos\{\omega_{IF}(t) + \Theta_s(t) + \Theta_n(t)\} + i_{sh,n} \tag{2.26}$$

Considering Heterodyne coherent detection, the IF signal power at the receiver is

$$P_{sig,IF} = \frac{\left(2R\sqrt{P_S P_{LO}}\right)^2}{2} \tag{2.27}$$

$$P_{sig,IF} = 2R^2 P_s P_{LO} \tag{2.28}$$

Thermal noise of the receiver is

$$\sigma_{th}^2 = \frac{4ktB}{R} \tag{2.29}$$

The crosstalk variance at the output of receiver is

$$\sigma_{ct}^2 = (RP_{ct})^2 \tag{2.30}$$

The amplifier spontaneous emission(ASE) noise power is [37]

$$P_{ASE} = h\nu\eta B_0 T\left[G_0 - 1 + \frac{G_0\alpha}{GP_0}\left(e^{\alpha z} - \frac{1}{G_0}\right)\right] \tag{2.31}$$

where, Gain $G_0 = \exp(GZ_eP_0)$, $h\nu = 6.63 \times 10^{-34} J$ is the photon energy, ηT is the thermal equilibrium photon number and B_0 is the optical bandwidth.

So, the ASE noise variance is

$$\sigma_{ASE}^2 = (RP_{ASE})^2 \tag{2.32}$$

The shot noise at the output of receiver due to signal, Crosstalk and Local Oscillator power is given by,

$$\sigma_{shot}^2 = 2eBR_d(P_s + P_{ct}) \qquad (2.33)$$

The IF signal to crosstalk plus noise ratio is

$$(SCNR)_{IF} = \frac{P_{SIG,IF}}{\sigma_{ct}^2+\sigma_{ASE}^2+\sigma_{th}^2+\sigma_{shot}^2} \qquad (2.33)$$

Bit Error Rate (BER) of the heterodyne phase shift keying (PSK) coherent receiver is,

$$BER = \frac{1}{2}erfc\left(\sqrt{(SCNR)_{IF}}\right) \qquad (2.34)$$

CHAPTER 3

RESULTS AND DISCUSSION

The analytical approach presented in the previous section, has been evaluated in this chapter at a bit rate of 10 Gbps including all the crosstalk and noise for a phase shift keying (PSK) modulation. Parameters those we assumed are shown in the Table below:

Table 3.1 Table of values of constants and parameters used for analysis

Parameter	***Value***
Effective area of core, A_{eff}	$50\mu m^2$
Raman gain slope, g'	4.9×10^{-18} m/(W GHz)
Channel spacing, Δf	10 ~100 GHz
Fiber attenuation constant, α	0.046 km^{-1}
Operating wavelength, λ_{eff}	1550 nm
Pump power, P_p	2 ~ 10 mW
Local Oscillator power, P_{LO}	2-30 mW
IF BPF Bandwidth, B_{IF}	10 GHz

3.1 Results on ASE Noise Variance

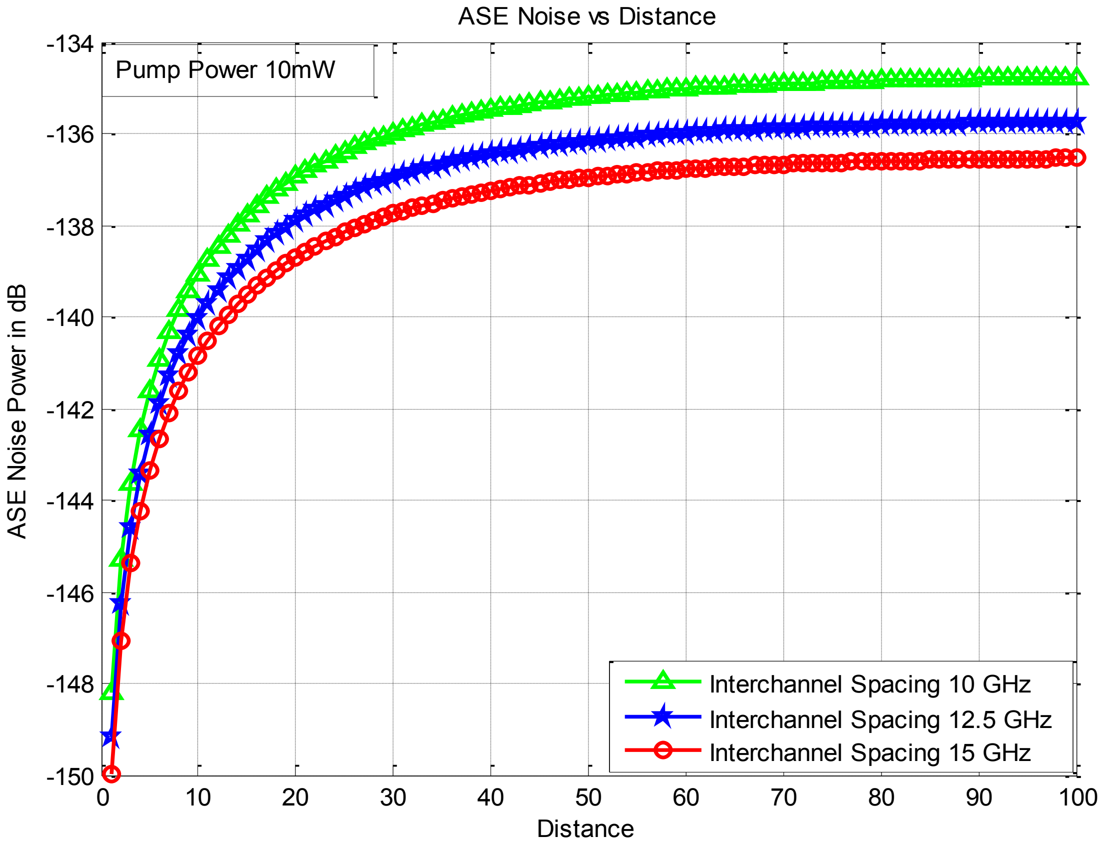

Fig. 3.1 Plots of ASE noise power versus Distance for different channel spacing at a certain pump power

The plots of amplified spontaneous emission(ASE) noise as a function of distance are shown in Fig. 3.1 with channel spacing 10 GHz, 12.5 GHz, 15 GHz at a pump power 10 mw. It is noticed that ASE noise power increases significantly with the increase in distance travelled by the signal due to amplified spontaneous emission. The effect of ASE noise is high at a smaller distance as observed that the ASE noise power increases from -150 dB to -136 dB for distance of 50 km. It is further noticed that the ASE noise power can be reduced if channel spacing is increased.

3.2 Results on IF Signal to Crosstalk plus Noise

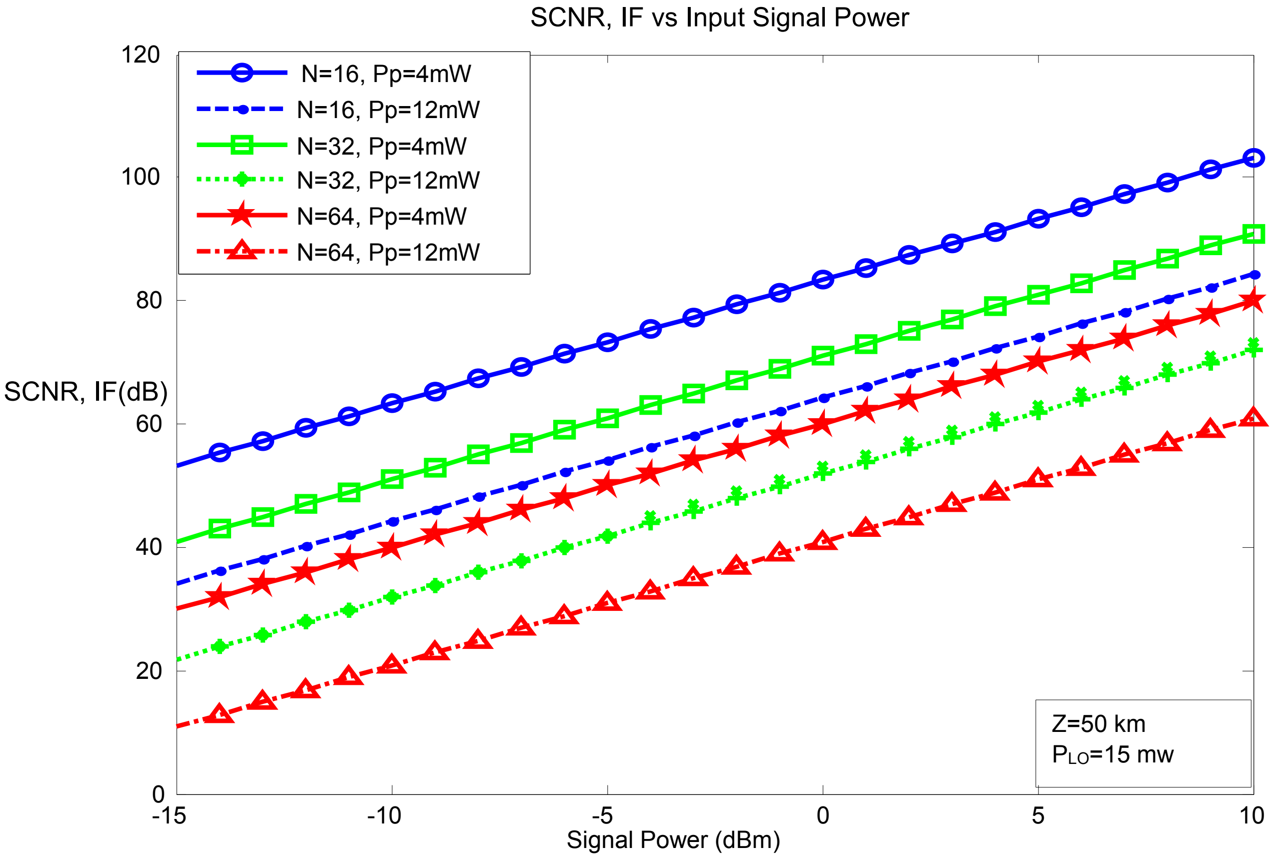

Fig. 3.2 Plots of IF signal to crosstalk plus noise ratio versus input signal power at a distance of 50km

Plots of IF SCNR versus input signal power for different number of channel and pump power are shown in Fig. 3.2 at a distance of 50 km with local oscillator power of 15 mW for number of channel 16, 32 and 64 and pump power 4 and 12 mW. The IF SCNR improves as the signal power increases due to increase in signal strength. If the number of channel increases then signal to noise plus crosstalk reduced due to higher crosstalk induced by ASE. There is a further reduction of IF SCNR with the increase in pump power due to high value of induced crosstalk. So increasing pump power needs to be under consideration in WDM system.

3.3 Effect of Transmission Distance on SCNR

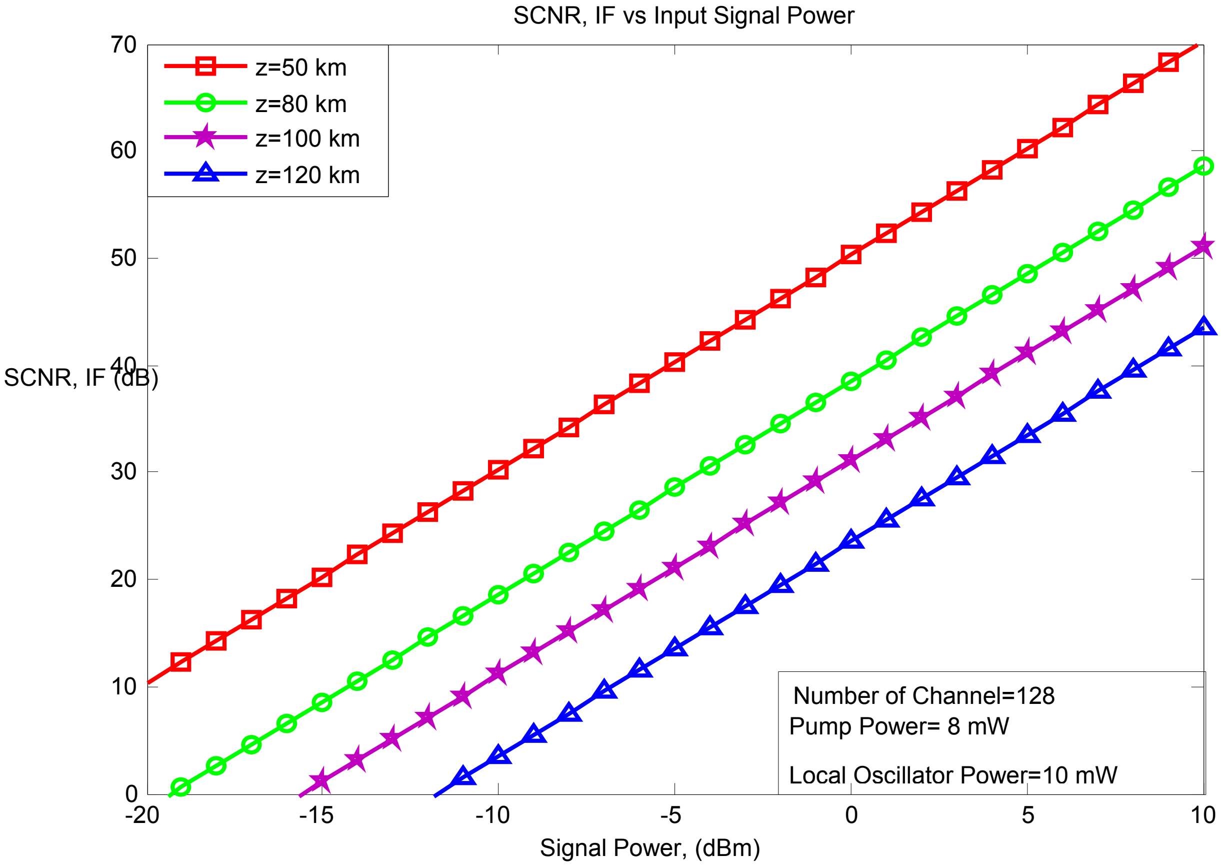

Fig. 3.3 Plots of SCNR, IF vs input signal power at different distance for 128 channels

Plots of IF signal to crosstalk plus noise ratio versus Input signal power for 128 channels with pump power 8 mW at a distance of 50 km, 80 km, 100 km and 120 km are shown in Fig. 3.3. It is seen that for a fixed Local Oscillator power 10 mW the IF SCNR decreases as the distance travelled by a signal is increased due to high ASE induced crosstalk.

3.4 Results on Power Penalty Due to Number of Channels

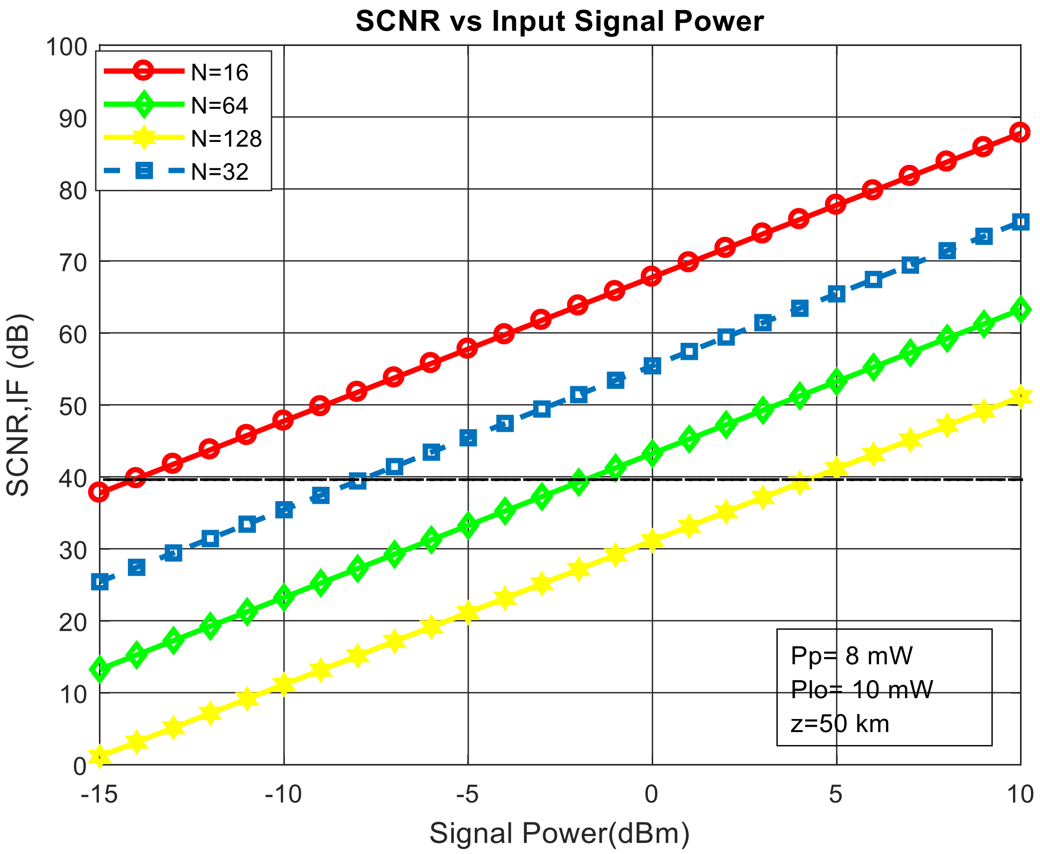

Fig. 3.4 Plots of IF SCNR vs signal power at a distance of 50 km for various channels

In order to calculate the amount of power penalty the system suffers due to increase in number of channel at a certain SCNR plots of SCNR vs signal power at a distance of 50 km with 16, 32, 64, 128 channels are shown in Fig 3.4. It is seen that the SCNR decreases significantly as the number of channels is increased due to increase in induced crosstalk. For example, at a signal power of -15 dBm the amount of SCNR for 16 channels is 38 dB, for 32 channels is 25 dB, for 64 channels is 12 dB, for 128 channels is 1 dB.

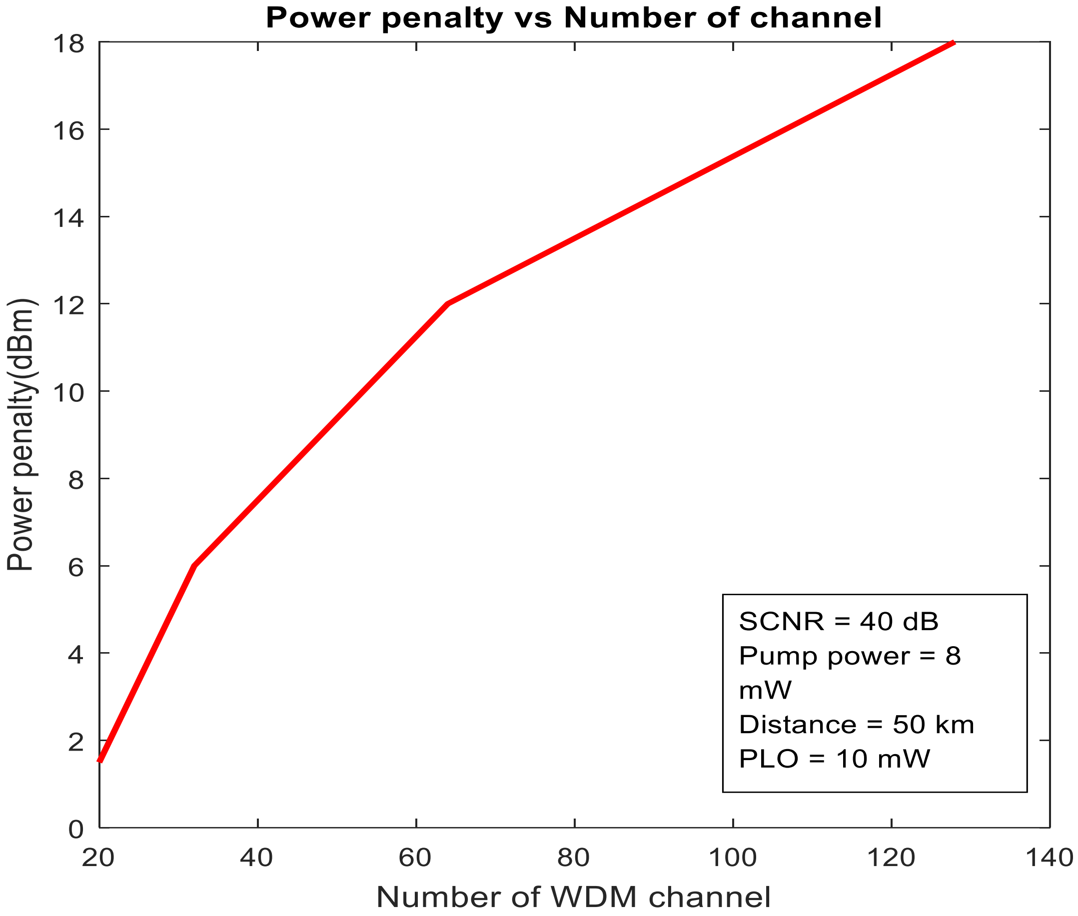

Fig. 3.5 Plot of power penalty vs number of channel at a SCNR of 40 dB

Plots of power penalty for number of channel at a SCNR of 40 dB are shown in Fig. 3.5. It is seen that the power penalty increases with the increase in number of channel. The power penalty become 6 dB if number of channels is increased from 16 to 32 dB. The power penalty increases up to 18 dB with the increase of channel from 16 to 128.

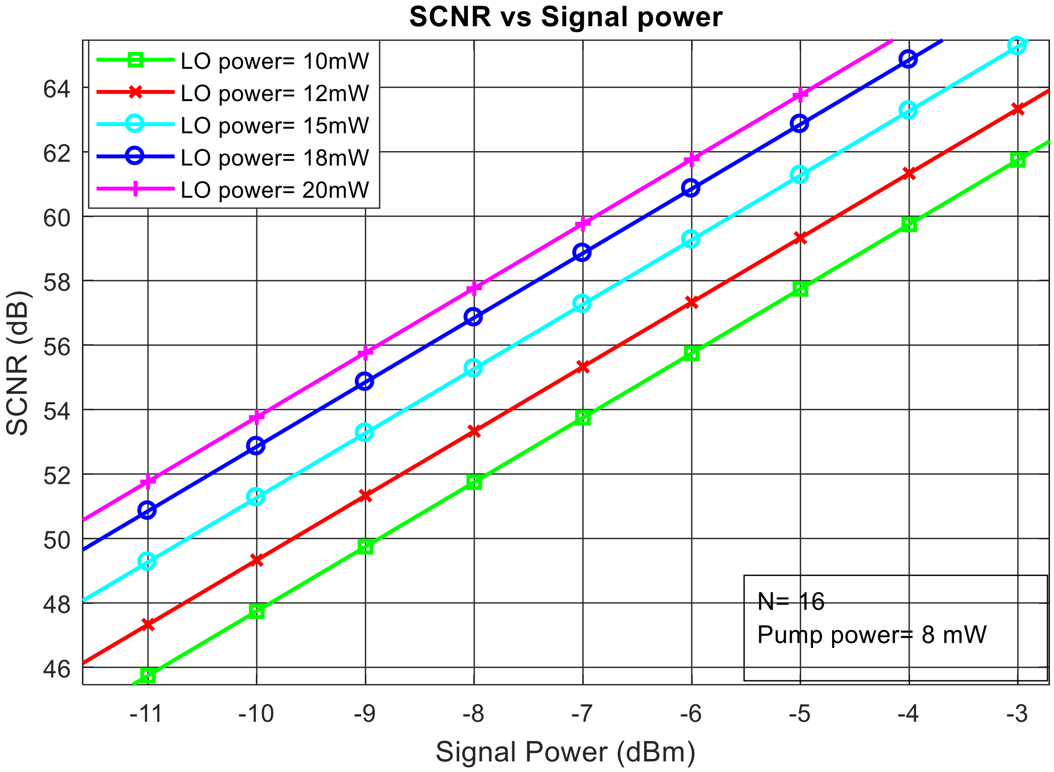

Fig. 3.6 Plots of IF signal to crosstalk plus noise ratio vs signal power for various local oscillator power

The plots of IF signal to crosstalk plus noise ratio versus signal power for 16 channels with pump power 8 mW for local oscillator power of 10 mW, 12 mW, 15 mW, 18 mW and 20 mW are shown in Fig. 3.6. It is seen that the IF SCNR improves with the increasing in signal power. At a signal power of -10 dBm the SCNR was 48 dB whereas it increases to 62 dB for signal power of -3 dBm. There is a further improvement of IF SCNR with the increment of local oscillator power as it is easy for the receiver to receive signal with higher strength of signal. For example, at a signal power of -10 dBm the SCNR is 48 dB for local oscillator power 10 mW. But for local oscillator power 20 mW the SCNR increased to 54 dB.

3.5 Results on Bit Error Rate

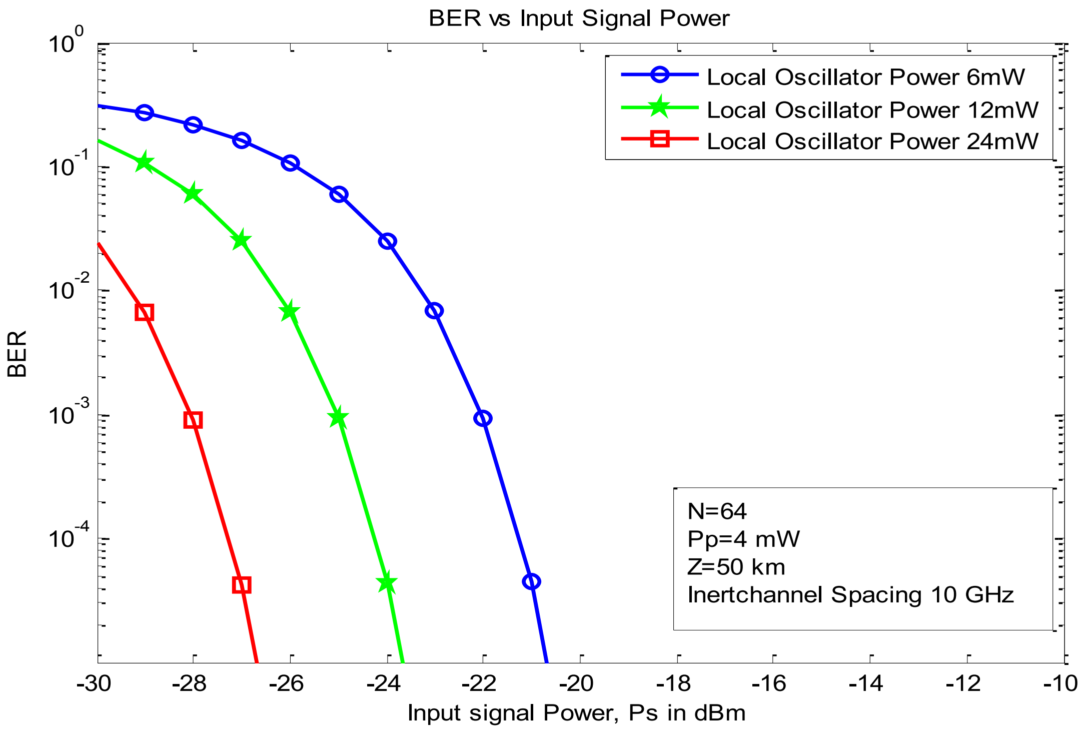

Fig. 3.7 Plots of BER vs signal power for different local oscillator power

Plots of BER versus signal power at a distance of 50 km for 64 channels with pump power 4 mW and local oscillator power 6mW, 12 mW and 24 mW are shown in Fig. 3.7. It is seen from the results that the BER performance improves with the increase in signal power due to increase in SCNR. For example, for local oscillator power 6 mW at a signal power of -26 dBm the BER was 10^{-1} whereas it decreases to 10^{-4} for signal power of -21 dBm. It is also depicted that increasing the local oscillator power the BER performance can further be improved. From the results it is seen that at a signal power of -28 dBm the BER is $10^{-0.6}$ for local oscillator power 6 mW whereas the BER improves to 10^{-3} for local oscillator power of 24 mW. So, by changing local oscillator power the BER performance of a WDM system with heterodyne detection can be improved.

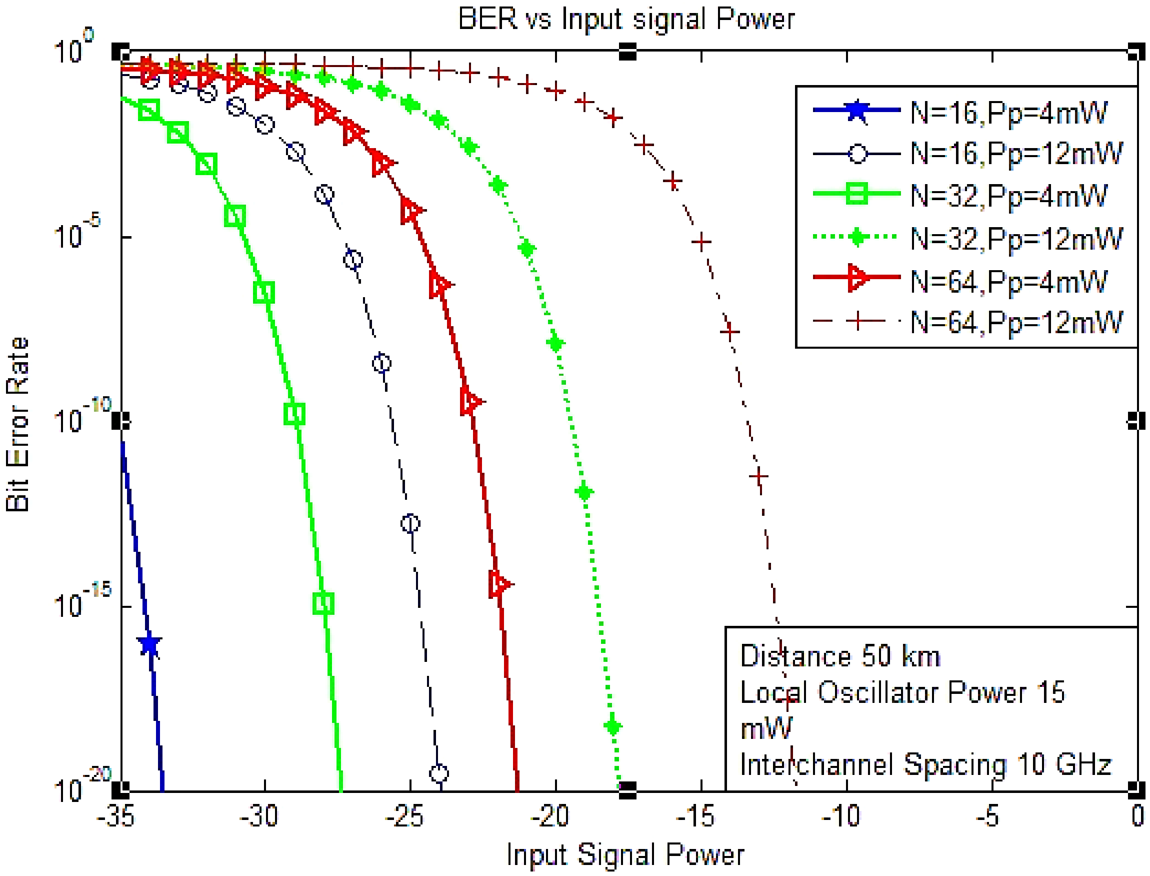

Fig. 3.8 Plots of BER vs signal power at a distance of 50 km for various parameters

Plots of BER versus signal power at a distance of 50 km for 16, 32 and 64 channels with pump power 4 mw and 12 mw are shown in Fig. 3.8. The BER performance deteriorates with the increase in number of channel due to induced crosstalk. For example, at a BER of 10^{-10} the signal power required for 16 channels is -35 dBm but required signal power for 64 channels is -23 dBm. There is a further degradation in BER performance with the increase in pump power due to amplifier spontaneous emission.

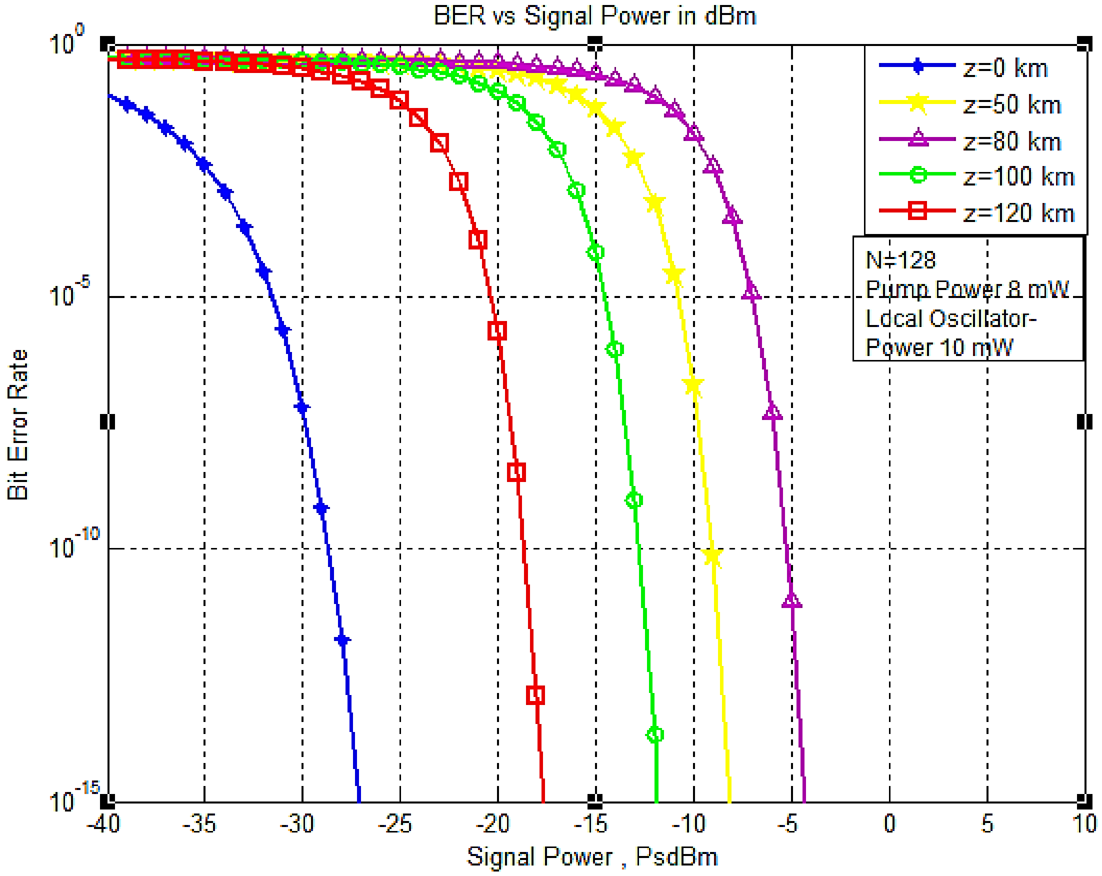

Fig. 3.9 Plots of BER vs signal power for 128 channels at a distance of 50 km, 80 km, 100km and 120 km.

Plots of BER vs signal power for 128 channels at a distance of 50 km, 80 km, 100 km, 120 km with local oscillator power 10 mW. It is found that the BER deteriorates with the increase in distance travelled by signal due to amplifier spontaneous emission. The system suffers power penalty at a given BER.

Table 3.2 Calculation of power penalty at various distance

Distance (km)	0	50	80	100	120
Power Penalty (dB)	0	9.9	15.8	19.6	23.4

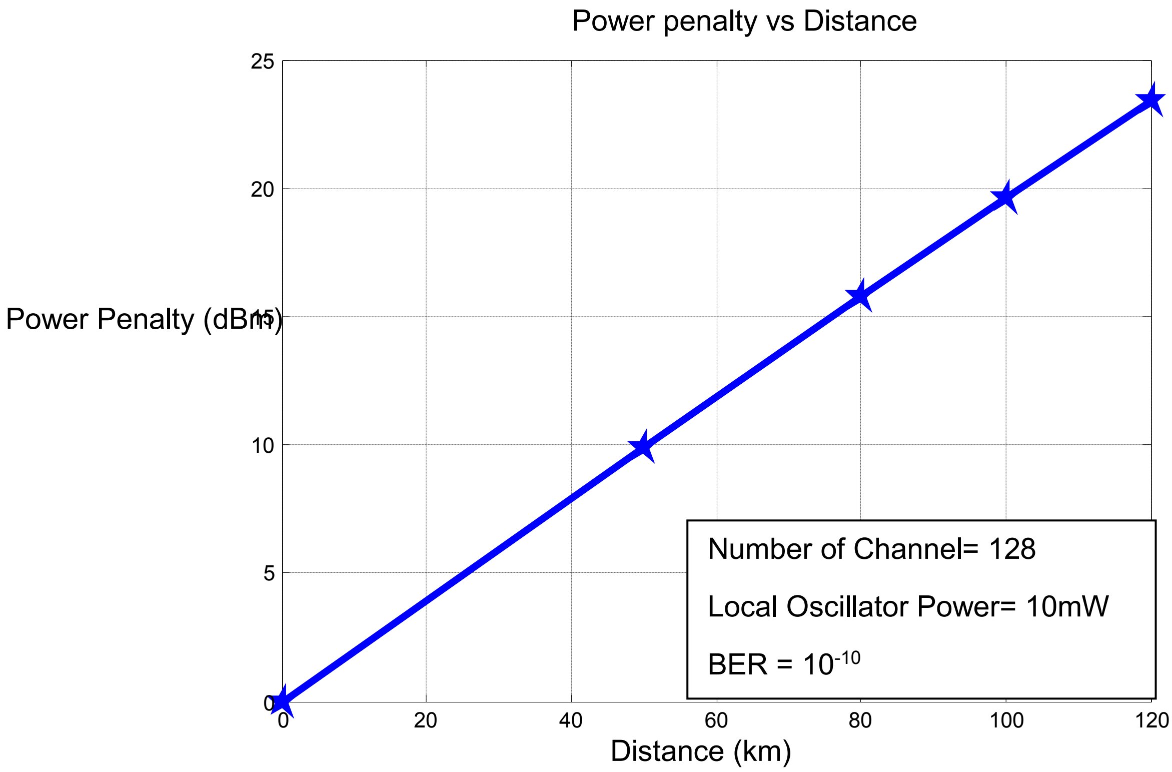

Fig. 3.10 Plot of power penalty versus distance at a BER of 10^{-10} for a WDM link with N=128

Plots of power penalty vs distance at a BER of 10^{-10} for 128 channels are shown in Fig. 3.10. with local oscillator power of 10 mW. It is seen that the power penalty increases linearly with the increase in distance. It is seen that the power penalty for 50 km is 9.9 dBm, 80 km is 15.8 dBm, 100 km is 19.6 dBm and 120 km is 23.4 dBm.

3.6 Effects of Local Oscillator Power on BER

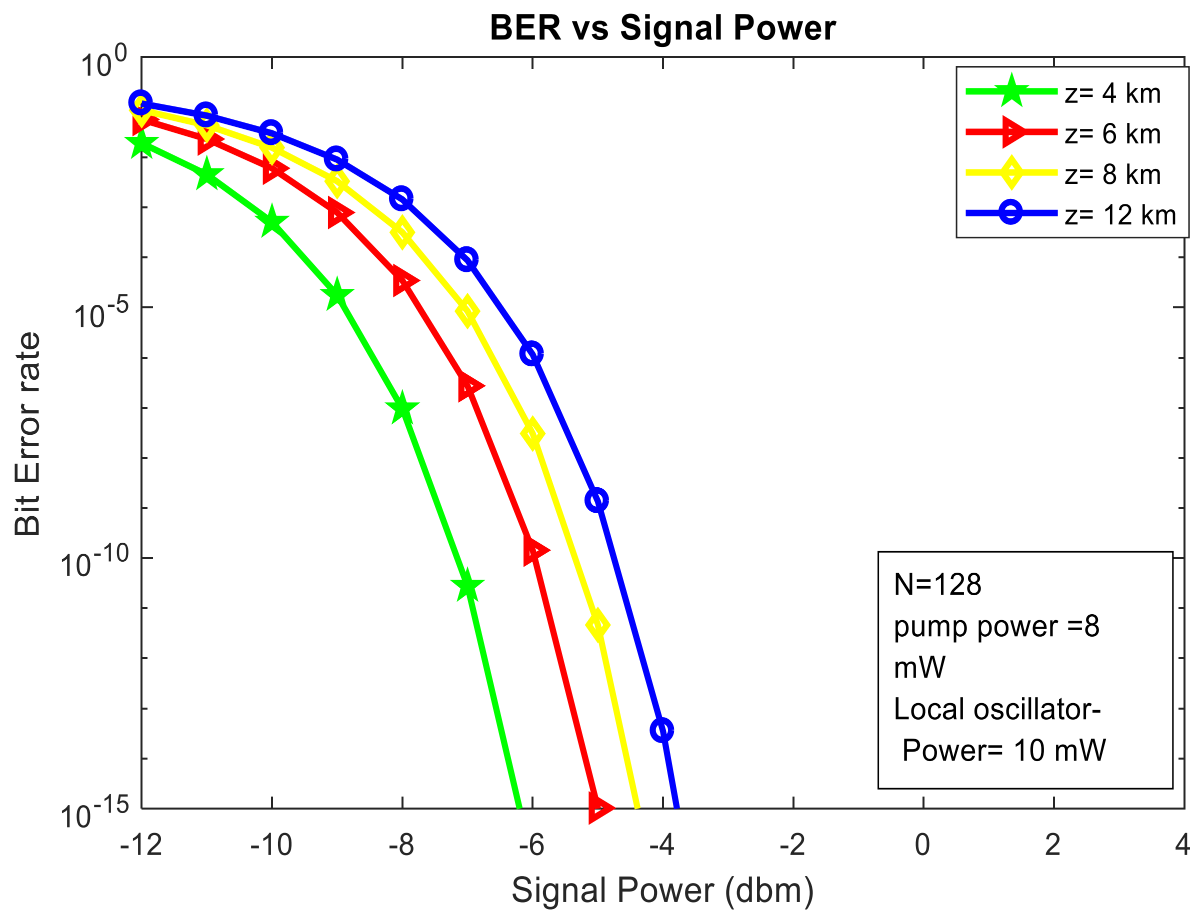

Fig. 3.11 Plots of BER vs signal power for 128 channels at various distances with local oscillator power 10 mW

Plots of BER versus signal power for 128 channels at a distance of 4 km, 6 km, 8 km and 12 km with pump power 8 mW and local oscillator power 10 mW are shown in Fig. 3.11. It is seen from the results that the BER performance improves with the increase in signal power due to increase in SCNR. But, BER performance deteriorates with the increase in distance. For example, at a certain BER of 10^{-10} the signal power required is -7 dBm at a distance of 4 km which increases to -4.5 dBm for distance of 12 km.

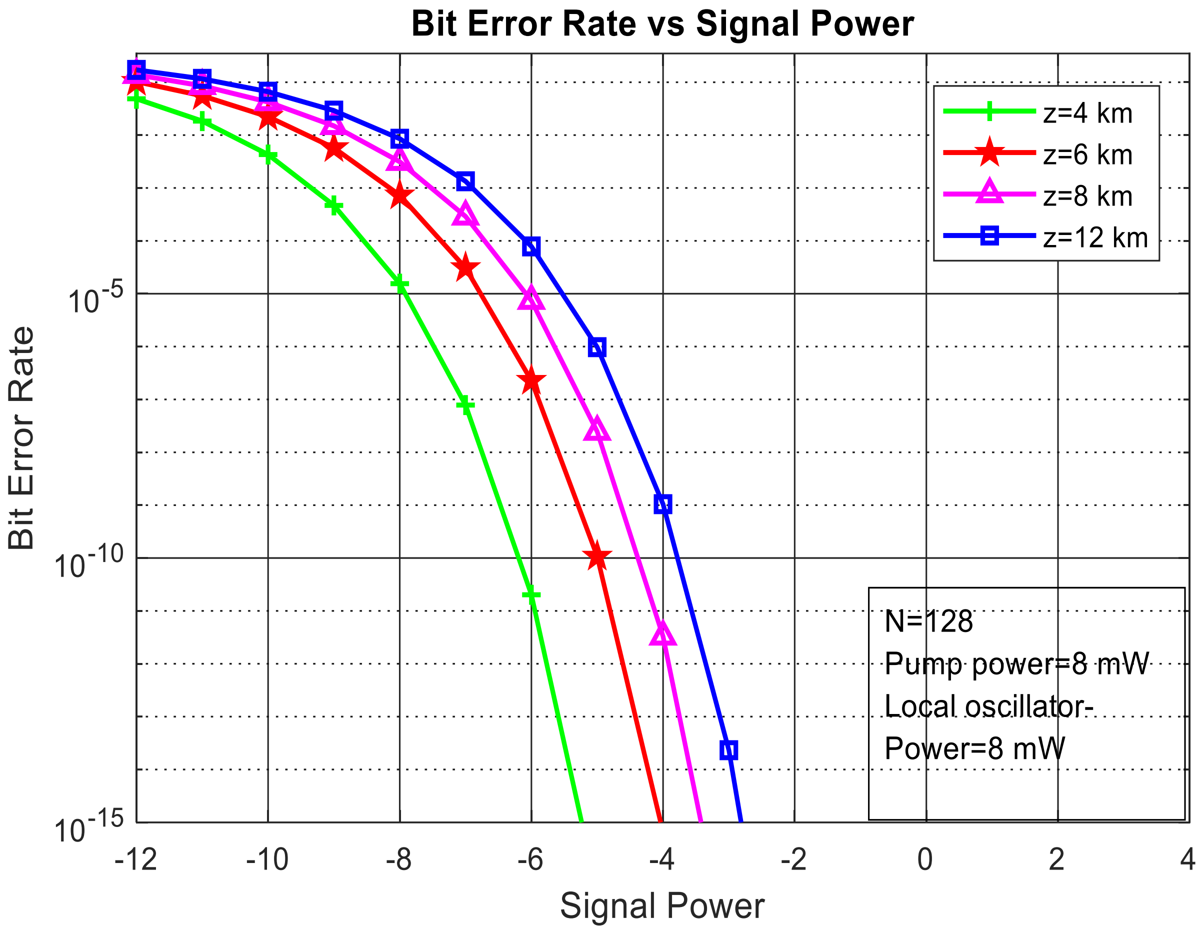

Fig. 3.12 Plots of BER vs signal power at various distance with local oscillator power of 8 mW for 128 channels

Similar plots of BER vs sgnal power at distance of 4 km, 6 km, 8 km and 12 km for 128 channels with local oscillator power 8 mW are shown in Fig. 3.12. It is noticed that the BER performance deteriorates with the decrease in local oscillator power as compared to Fig. 3.11.

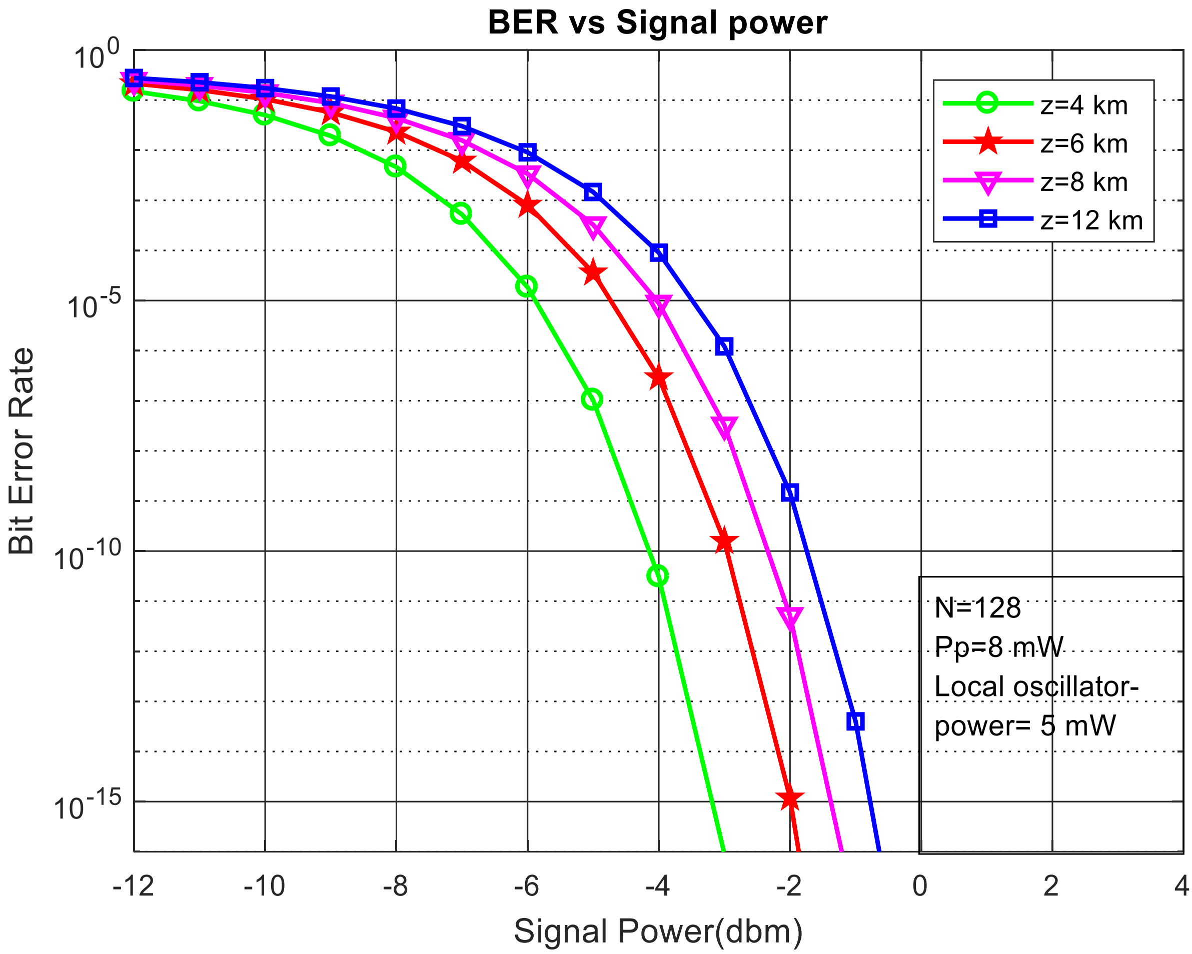

Fig. 3.13 Plots of BER vs input signal power at various distance with local oscillator power 5 mW

Similar plots of BER versus input signal power with local oscillator power 5 mW at a distance of 4 km, 6 km, 8 km and 12 km are shown in Fig. 3.13. The BER performance further deteriorates with the decreasing in local oscillator power.

3.7 Results on Power Penalty at a Certain BER

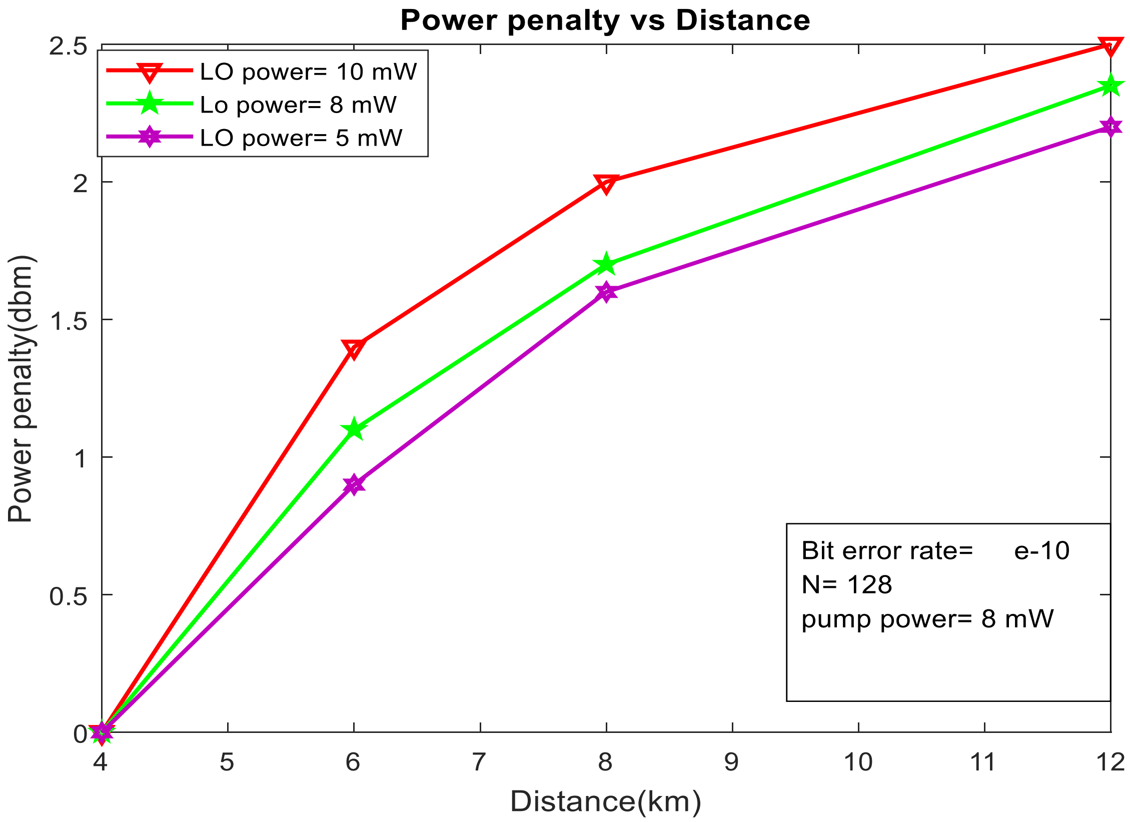

Fig. 3.14 Plots of power penalty of a WDM system at a BER of 10^{-10} for 128 channels

Plots of power penalty versus distance transmitted by a signal in a WDM system with heterodyne coherent detection at a certain BER of 10^{-10} are shown in Fig. 3.14. It is seen from the results that the power penalty increases with the increase in distance due to induced crosstalk. For example, with local oscillator power 5 mW at a distance of 6 km the power penalty is 0.9 dBm which increased to 2.2 dBm at a distance of 12 km. There is a further increment of power penalty with the increase in local oscillator power. For example, at a distance of 12 km the power penalty for local oscillator power 5 mW is 2.2 dBm, 8 mW is 2.35 dBm and 10 mW is 2.5 dBm.

CHAPTER 4

CONCLUSION AND FUTURE SCOPE

4.1 Conclusion

n analytical approach is presented to evaluate the bit error rate(BER) performance of a AWDM transmission system with Raman amplifier considering PSK modulation and optical heterodyne receiver. Analysis is done to evaluate the amount of crosstalk due to Raman amplifier induced crosstalk. It is found that BER degrades severely with distance due to crosstalk and system suffers considerable power penalty at a given BER.

We have first theoretically analyzed the effect of crosstalk in a WDM system for constant amplitude modulation. An analytical derivation of signal to crosstalk plus noise ratio and bit error rate is presented. The expression of SCNR and BER is developed considering crosstalk, Local Oscillator power and Amplifier Spontaneous Emission Noise.

The numerical results are evaluated in terms of amount of crosstalk with heterodyne coherent detection at a BER of 10^{-10}. It is found that the system induced ASE crosstalk increase with the increase in channel separation. There is a further increase in ASE noise with the increase in number of WDM channels. The system SCNR degrades severely with the increase in number of channels. Maximum allowable number of channels for a given power penalty is also calculated.

The performance of the WDM system are evaluated in terms of BER and it is found that the BER deteriorates with the increase in distance of transmission. There is a significant amount of power penalty suffered by a signal at a given BER and can be solved by increasing the local oscillator power. The amount of power penalty for a distance of 50 km is 9.9 dB and for 100 km the power penalty is 19.6 dB. The maximum allowable transmission distance at a given power penalty is also evaluated.

The analysis presented here will find its application considering the limitations of crosstalk in a WDM transmission link.

4.2 Future Scope of The Work

Future work can be carried out on the gain saturation effect of Raman amplifier in case of optical communication. An analytical approach can be developed to find the effect of gain saturation over the system performance.

Hybrid optical amplifier is a hot topic for the upcoming communication system. Hybrid amplifier has a potential in this field. An analytical model can be presented based on hybrid amplifier with WDM system. The performance of EDFA-Raman is better than SOA-Raman hybrid amplifier. Analytical approach can be presented and the performance of the system.

Work can be initiated to validate the results by a simulation work in future.

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