Study of Fiber Nonlinearities and Effect of Phase, Input Power and Chirping Factor on Received Power

A Thesis

Submitted in the partial fulfillment of requirement for the award of the degree of

Master of Engineering
In
Electronics and Communication
by

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CERTIFICATE

This is to certify that the Thesis report entitled “Study of Fiber Nonlinearities and Effect of Phase, Input Power and Chirping Factor on Received Power”, which is being submitted herewith by Ms. Manju Bala (Regd. No. 8024112) towards the partial fulfillment or the award of the degree of Master of Engineering in Electronics & Communication of Thapar Institute of Engineering & Technology (Deemed University), Patiala is a bonafide work carried by her under my supervision and guidance.

It is further certified that the research work embodied in this thesis has not been submitted to any other University/Institute for the award of any degree/diploma.

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(MANJU BALA)

ABSTRACT

Optical fibers are not only used in telecommunication links but also used in the Internet and local area networks (LAN) to achieve high signaling rates**.** In this dissertation, fiber nonlinearities have been studied, and analyze the effect of various parameters on the received power. Optical amplifiers like EDFAs simply amplify the optical signal by several orders of magnitude without being limited by electronic speed. Transmission impairments, which are general not significant in a regenerative system, accumulate along the transmission link when amplifiers are used, so that they can not be simply ignored, and this puts a new challenge to transmission design engineers. The nonlinearities in optical fibers fall into two categories. One is ***stimulated scattering*** (Raman and Brillouin), and the other is the ***optical Kerr effect*** due to changes in the refractive index with optical power. Phase modulation due to intensity dependent refractive index induces various nonlinear effects, namely, self-phase modulation (SPM), cross-phase modulation (CPM), and four-wave mixing (FWM). For an understanding of nonlinear phenomena in optical fibers it is necessary to understand the ***Nonlinear Schrödinger*** equation, which describe the propagation of wave in nonlinear medium. It is required to solve the nonlinear Schrödinger equation to understand various impairments occurring during signal transmission. The ***split-step Fourier method*** is one of the most popular algorithms because of its good accuracy and relatively modest computing cost. Nonlinear equations are simulates in using split step Fourier transform to study the effect of various parameters.

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LIST OF ABBREVIATIONS

ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
BPF	Band-Pass Filter
CPM	Cross-Phase Modulation
DSF	Dispersion-Shifted Fiber
DWDM	Dense-WDM
FWM	Four-Wave Mixing
GVD	Group Velocity Dispersion
ICI	Inter-Channel Interference
ISI	Inter-Symbol Interference
LD	Laser Diode
LED	Light Emitting Diode
NBER	Nonlinear Bandwidth Expansion Receiver
NLSE	Non-Linear Schrödinger Equation
NPR	Noise Power Ratio
NRZ	Non-Return to Zero
NSD	Normalized Square Deviation
PRBS	Pseudo-Random Bit Sequence
RF-FDM	Radio-Frequency Frequency Division Multiplexing
RMS	Root Mean Square
RZ	Return to Zero
SBS	Stimulated Brillouin Scattering
SNR	Signal to Noise Ratio
SPM	Self-Phase Modulation
SRP	Sinusoidal Response Penalty
SRS	Stimulated Raman Scattering
SS-	WDM Spectrum-Sliced WDM
WDM	Wavelength Division Multiplexing

LIST OF SYMBOLS

$A(z, t)$	Slowly varying envelope of optical field
A_{eff}	Effective core area of fiber
B_o	Optical filter bandwidth
B_t	Channel bandwidth
C_T	Total transmission capacity
$C(t)$	Auto-covariance
D	Dispersion parameter
G	Optical amplifier gain
L_D	Dispersion distance,
L_N	Nonlinear distance,
$M(\%)$	Normalized intensity interference
N	Nonlinearity parameter,
P_o	Peak power of optical signal
P_{avg}	Path-averaged power of optical signal, *dz e P*
P_α	Output power of the BPF *without* the notch filter at the input
P_β	Output power of the BPF *with* the notch filter at the input
R_b	Bit rate
T_b	Bit period
T_c	Full-width of auto-covariance at 1/*e* maximum value
T_o	An arbitrary temporal characteristic value of the initial pulse
T_r	Rise time of the pulse
$A(z,t)$	Normalized slowly varying envelope
d	Walk-off parameter
m	Transmission parameter of a SS-WDM system, $m = B_t/R_b$
t	Local time, $t = t' - z/v_g$ (t' = physical time)

t_o	Initial pulse width (half-width at 1/*e* intensity)
V_g	Group velocity
z	Fiber length, Propagation distance
Z_a	Amplifier spacing
Z_c	Critical distance (the distance at which NSD =10-3)
Δf	Channel spacing in frequency
$\Delta\lambda$	Channel spacing in wavelength
α	Fiber loss
β_2	Second order group-velocity dispersion parameter
β_3	Third order group-velocity dispersion parameter
γ	Fiber nonlinear coefficient
λ	Wavelength
λ_0	Center wavelength
λ_{ZD}	Zero dispersion wavelength
σ_{min}	Minimum output RMS pulse width
σ_o	RMS pulse width of input signal
σ_{opt}	Optimum input RMS pulse width
ω	Angular frequency
ω_p	Fundamental angular frequency of a periodic signal

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CHAPTER 1

INTRODUCTION

Twenty first century is the era of 'Information technology'. There is no doubt that information technology has had an exponential growth through the modern telecommunication systems. Particularly, optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Today, optical fibers are not only used in telecommunication links but also used in the Internet and local area networks (LAN) to achieve high signaling rates. In the recent years, the advent of erbium-doped fiber amplifier (EDFAs) is one of the most notable breakthroughs in the fiber optical communication technology[2]. Before the emergence of EDFAs, the standard method of compensating fiber loss was to space electronic generators periodically along the transmission link. A regenerator consists of photo-detectors, electronic processing and amplification block, and a transmitter. Functionally, it performs optical to electronic conversion, electronic processing and electrical to optical conversion, and retransmission of the regenerated signal. The advantages of regenerative systems is that transmission impairments such as noise, dispersion, and nonlinearties do not accumulate, which makes it easy to design transmission links. However electronic blocks in regenerators prevent exploitation of the huge bandwidth of the fiber. Electronics components are normally designed for the specific bit rate and modulation format, it is necessary to replace all the regenerative repeaters along the link when the system capacity must be increased. On the other hand, optical amplifiers like EDFAs simply amplify the optical signal by several orders of magnitude without being limited by electronic speed. In addition amplification is bit rate and modulation format independent, which implies that optically amplified links can be upgraded by replacing terminal equipment alone. The optically amplified transmission lines can be considered as a transmission pipe, which is transparent to data rate and signal modulation format.

However, transmission impairments, which are general not significant in a regenerative system, accumulate along the transmission link when amplifiers are used, so that they can not be simply ignored, and this puts a new challenge to transmission design engineers. Among those impairments, dispersion, fiber nonlinearties and noise accumulation from the optical amplifiers are the key limited factors. Dispersion a linear phenomenon is relatively well understood, and various effective dispersion compensation techniques have been devised to cope with dispersion induced performance degradation. Fiber nonlinearties, on the other hand, have not been fully analyzed and understood especially when other impairments like dispersion are also present.

1.1 Historical Perspective Of Optical Communication

The use of light for transmitting information from one place to another place is a very old technique. In 800 BC., the Greeks used fire and smoke signals for sending information like victory in a war, alerting against enemy, call for help, etc. Mostly only one type of signal was conveyed. During the second century B.C. optical signals were encoded using signaling lamps so that any message could be sent. There was no development in optical communication till the end of the 18th century. The speed of the optical communication link was limited due to the requirement of line of sight transmission paths, the human eye as the receiver and unreliable nature of transmission paths affected by atmospheric effects such as fog and rain. In 1791, Chappe from France developed the semaphore for telecommunication on land. But that was also with limited information transfer[6] . In 1835, Samuel Morse invented the telegraph and the era of electrical communications started throughout the world. The use of wire cables for the transmission of Morse coded signals was implemented in 1844. In 1872, Alexander Graham Bell proposed the photophone with a diaphragm giving speech transmission over a distance of 200 m. But within four years, Graham Bell had changed the photophone into telephone using electrical current for transmission of speech signals. In 1878, the first telephone exchange was installed at New Haven. Meanwhile, Hertz discovered radio waves in 1887. Marconi demonstrated radio communication without using wires in 1895. Using modulation techniques, the signals were transmitted over a long distance using radio waves and microwaves as the carrier. During the middle of the twentieth century, it was realized that an increase of several orders of magnitude of bit rate distance product would be possible if optical waves were used as the carrier . Table 1 shows the different communication systems and their bit rate distance product. Here the repeater spacing is mentioned as distance [1]. In the old optical communication system, the bit rate distance product is only about 1 (bit/s)-km due to enormous transmission loss (105 to 107 dB/km). The information carrying capacity of telegraphy is about hundred times lesser than telephony. Even though the high-speed coaxial systems were evaluated during 1975, they had smaller repeater spacing. Microwaves are used in modern communication systems with the increased bit rate distance product. However, a coherent optical carrier like laser will have more information carrying capacity. So the communication engineers were interested in optical communication using lasers in an effective manner from 1960 onwards. A new era in optical communication started after the invention of laser in 1960 by Maiman. The light waves from the laser, a coherent source of light waves having high intensity, high monochromaticity and high directionality with less divergence, are used as carrier waves capable of carrying large amount of information compared with radio waves and microwaves.

1.2 Unguided Optical Communication

The optical communication systems are different from microwave communication systems in many aspects. In the case of optical systems, the carrier frequency is about 100 THz and the bit rate is about 1T bit/s. Further the spreading of optical beams is always in the forward direction due to the short wavelengths. Even though it is not suitable for broadcasting applications, it may be suitable for free space communications above the earth’s atmosphere like intersatellite communications. For the terrestrial applications, unguided optical communications are not suitable because of the scattering within the atmosphere, atmospheric turbulence, fog and rain. The unguided optical communication systems played

Table 1.1 Bit rate distance product.

System	Bit rate distance product (bit/s) /km
Old optical communication	1
Telegraph	10
Telephone	103
Coaxial cables	105
Microwaves	106
Laser light in open air	109

an important role in the research between 1960 and 1970. For longer range unguided optical communication systems the neodymium laser (1.06 nm) and the carbon dioxide laser (10.6 nm) were the most favorable sources. Using narrow bandgap compound semiconductors like indium sulphide (for neodymium laser) and cadmium mercury telluride (for CO_2 laser) one can have better detection using heterodyne detection techniques.

1.3 The Birth Of Fiber Optic Systems

To guide light in a wave-guide, initially metallic and non-metallic wave-guides were fabricated. But they have enormous losses. So they were not suitable for telecommunication. Tyndall discovered that through optical fibers, light could be transmitted by the phenomenon of total internal reflection. During 1950s, the optical fibers with large diameters of about 1 or 2 millimeters were used in endoscopes to see the inner parts of the human body. Optical fibers can provide a much more reliable and versatile optical channel than the atmosphere; Kao and Hockham published a paper about the optical fiber communication system in 1966. But the fibers produced an enormous loss of 1000 dB/km. But in the atmosphere, there is a loss of few dB/km. Immediately Kao and his fellow workers realized that these high losses were a result of impurities in the fiber material. Using a pure silica fiber these losses were reduced to 20 dB/km in 1970 by Kapron, Keck and Maurer. At this attenuation loss, repeater spacing for optical fiber links become comparable to those of copper cable systems. Thus the optical fiber communication system became an engineering reality.

1.4 Basic Optical Fiber Communication System

Figure 1 shows the basic components in the optical fiber communication system. The input electrical signal modulates the intensity of light from the optical source. The optical carrier can be modulated internally or externally using an electro-optic modulator (or) acousto-optic modulator. Nowadays electro-optic modulators (KDP, $LiNbO_3$ or beta barium borate) are widely used as external modulators, which modulate the light by changing its refractive index through the given input electrical signal. In the digital optical fiber communication system, the input electrical signal is in the form of coded digital pulses from the encoder and these electric pulses modulate the intensity of the light from the laser diode or LED and convert them into optical pulses. In the receiver stage, the photo detector likes avalanche photodiode (APD) or positive-intrinsic-negative (PIN) diode converts the optical pulses into electrical pulses. A decoder converts the electrical pulses into the original electric signal.

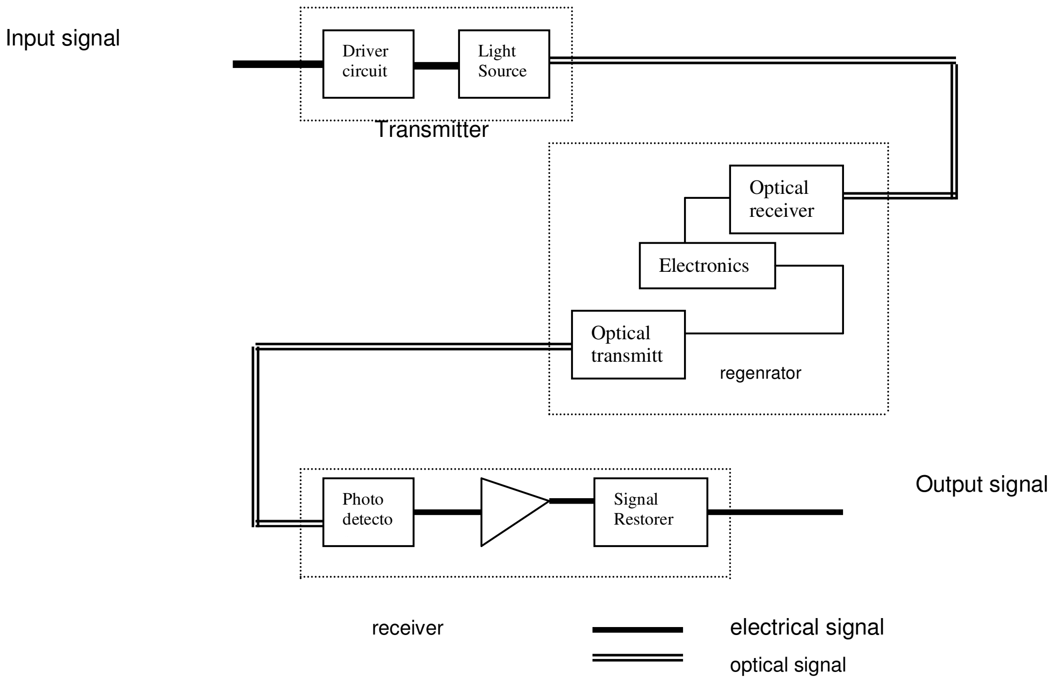


Figure 1.1 Major elements of the basic optical communication

Table 1. 2 Different generations of optical fiber communication systems

Generation	Wavelength of source (μm)	Bit rate Mb/s	Repeater spacing (km)	Loss dB/km	Existed up to
I	0.8	4.5	10	1	1980
II	1.3	1.7×10^2	50	<1	1987
III	1.55	1.0×10^4	70	<0.2	1990
IV	1.55	1.0×10^5	100	<0.02	2000
V	1.55	$> 1.0 \times 10^9$	>100	<0.002	

1.5 Multiplexers

The transmission of multiple optical signals (channels) over the same fiber is a simple way to increase the transmission capacity of the fiber against the fiber dispersion, fiber nonlinearity and speed of electronic components, which limit the bit rate. So multiplexing techniques are followed. *Multiplexing* means many signals at a given time [7]. Suppose for each channel the bit rate is 100 Gb/s and by accommodating 100 channels through multiplexing technique the total bit rate through a single fiber can be increased to 10 Tb/s (1 Tera = 10^{12}): ***Thus the information carrying capacity of a fiber is increased by the multiplexing technique***.

There are three types of multiplexing techniques:

(i) TDM – Time division multiplexing
(ii) FDM – Frequency division multiplexing
(iii) WDM – Wavelength division multiplexing

(i) Time division multiplexing (TDM): In time division multiplexing, different communication links shares the same channel on the basis of time. In TDM high bit rate data stream is constructed directly by time multiplexing several lower bit rate optical streams. Similarly, at the receiver end of the system, the very high bit rate signal is demultiplexed to several lower bit rate signals before detection. Each specific link is assigned specific time slots during which it is allowed to send its data from end to other end and during this slot no other link is allowed to send data. TDM works best when it is dealing with links all of the same type and all given permanents assigned time slots of equal time interval.

(ii) Frequency Division Multiplexing (FDM): FDM is possible when the useful bandwidth of the transmission medium exceeds the required bandwidth of signals to be transmitted. In the frequency division multiplexing increases transmission capacity and flexibility by utilizing the very large bandwidth potential of the radio frequency. In FDM, a number of frequency channels can be placed adjacent to each other to provide a large capacity of transmitted signals. Several messages can be simultaneously along the channel. To prevent interference, the channels are separated by guard bands, which are unused portion of the spectrum.

TDM and FDM techniques are operated in the electrical domain and are widely used in the conventional radio wave communication. WDM technique is very useful in the optical domain and by WDM the bit rate can be increased beyond 10 Tb/s in the optical fiber communication.

(iii) Wavelength division multiplexing (WDM): With wavelength division multiplexing different communication links share the same fiber on the basis of wavelength. Information associated with each link first goes through a modulation process. The result is the generation of light modulated by the information [7]. The light from the links can be coupled into a single fiber optic and then transmitted together down the fiber. At the receiving end different links can be separated on the basis of wavelength using demultiplexing operation. The resulting received information is then directed to the appropriate data device destination.

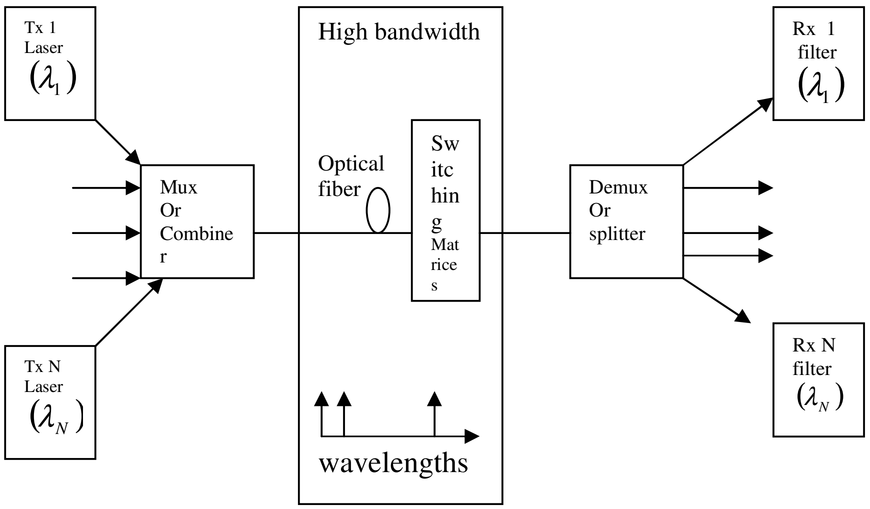


Figure 1.2 shows the basic principle of WDM technique.

In the figure1.2 different wavelengths carrying separate signals are multiplexed by the multiplexer and then they are transmitted through a single fiber. At the receiver end, the separate signals at different wavelengths are demultiplexed by the demultiplexer and are given to separate receivers. From the receiver side also the signals can be transmitted in the same manner through the same fiber. Thus instead of handling a single channel with single wavelength and limited bit rate (10 Gb/s), the bit rate is raised to about 10 Tb/s, hence the information capacity of the fiber is increased by WDM technique. In principle any optical wavelength demultiplexer can be also used as a multiplexer. Thus for simplicity the word ‘multiplexer’ is often used as a general term to refer to both multiplexers and demultiplexers, except when it is necessary to distinguish the two devices or functions. There are two types of wavelength division multiplexers:

1. Angularly dispensive devices such as **prisms** or **gratings.**
2. Interference filter based devices such as **multilayer thin film interference filters** or single mode integrated optical devices [1].

(i) Grating as a multiplexer: A plane diffraction grating can be taken as a wavelength division multiplexer. Taking θ as the angle of diffracted beam, the dispersive power of the grating is given by

$$\frac{d\theta}{d\lambda} = 2\frac{\tan\theta}{\lambda}$$

The combination of different wavelengths (multiplexing) or separation of different wavelengths (demultiplexing) is directly proportional to the dispersive power of grating i.e. directly proportional to tanθ and inversely proportional to λ. The different signals carried by different wavelengths λ1, λ2, λ3, are collimated by a convex lens and then are incident on a reflection grating. The reflected light is a composite light or multiplexed light. The same grating multiplexer can also act as demultiplexer if we change the direction of the light beam.

(ii) Interference filter as a multiplexer: There are reflection interference filter type and absorption interference filter type multiplexers. Among these, absorption filter type is not used widely due to their higher absorption of signals. In the reflection type filter, there is a flat glass substrate upon which multiple layers of different dielectric films are deposited for wavelength sensitivity. These filters can be used in series to separate additional wavelength channels.

1.5.1 Soliton based optical fiber communication

Solitons are very narrow laser pulses of pulse width 10^{11} second with high peak powers more than 100 mW. Solitons are mainly used to increase the bit rate or transmission capacity of the fiber by reducing the losses and dispersion effects. Soliton propagation means the propagation of laser pulses through the optical fiber without undergoing any loss or dispersion. That is the pulses are transmitted without change in their shape as they travel down the fiber. Today soliton fiber lasers are available. Soliton type propagation is achieved by the nonlinear property of the silica fiber when the intensity of the light pulses is more than 15 mW. In the case of single mode silica fiber, when the power level of optical pulses is more than 15 mW, then its refractive index is dependent on intensity such that $n = n_0 + n_2 I$. If the effective area of the fiber mode is about 50 $(\mathrm{nm})^2$ and the power of the optical pulse is about 100 milliwatt, then n_2 = -6.4×10^{11} for silica fiber. So inside the optical fiber, the high intensity portion of the pulse will propagate in a high refractive region of the fiber compared with the lower intensity portion of the pulse. This intensity dependent refractive index leads to a phenomenon called self phase modulation (SPM). Due to this phenomenon the distance traveled by the optical pulse inside the fiber is continuously increased due to lower speed of the high intensity portion of the pulse. Thus there is a generation of additional frequencies and hence the broadening of the spectrum of the pulse while keeping the temporal shape unaltered. Further SPM leads to a chirping of the pulse with lower frequencies in the leading edge and high frequencies in the trailing edge of the pulse. So one can conclude that even though the distance traveled by the high intensity optical pulse is greater than the distance traveled by the low intensity optical pulse inside the fiber having negative nonlinearity, the optical pulse travels down the fiber without any dispersion. When the operating wavelength is about 1.3 nm there is zero dispersion. But when the operating wavelength is greater than 1.3 nm, then the fiber has positive group velocity dispersion. So the low frequency components of the pulse will travel at a lower speed than the high frequency components of the pulse. But in the case of self phase modulation, we get the opposite effect. That is due to SPM the low frequency components of the pulse will travel faster than the high frequency components. Thus the broadening of the spectrum by SPM is properly compensated by the compressions of the spectrum by group velocity spectrum, and then the pulse will propagate without change in the temperate shape and without broadening of the spectrum of the pulse. Even though there is no dispersion effect, still there is some loss in the fiber due to scattering and absorptions. To compensate this small loss in the transmissions link, for every 100 km or 150 km length, an optical fiber laser amplifier of length 10 m is connected. Due to sufficient amplification at the receiver end one can get the signal without loss of power. Thus during the propagation of the optical pulse through the fiber, there is no change in pulse shape and height and width. Such propagation is called *soliton propagation*. At present there are many optical fiber communication links throughout the world without using optical solitons. When we introduce optical solitons as light pulses through the fibers, we can achieve high quality telecommunication at a lower cost. We can expect a great revolution in optical fiber communication within a few years by means of solitons.

1.6 Objective The Dissertation

In optical communication systems, the input signal to the fiber is usually a composite optical signal modulated with information bit streams. When all the input signal frequencies interact due to fiber nonlinearities, the output bit stream may behave in a complicated way giving adverse effects on system performance. Fiber nonlinearities represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optic fiber. **The key objective of this dissertation is to develop analytical models to analyze the effects of various variables on the received power at the receiver end.** First the theoretical background is discussed on how the fiber nonlinearties affect system performance of an optical fiber communication system, also discussed the affects of nonlinearties on wavelength division multiplexing system.

Then the numerical study of variation of power with variation in various parameters is done. There are the various variables such as nonlinear coefficient 'γ', variation of received power with phase, and variation with distance etc. Simulation is done by simulating various nonlinear equations in MATLAB using Split Step Fourier Transform.

1.7 Outline of Dissertation

One of the most important changes in the optical fiber communication systems brought about by EDFAs is the expansion of regenerator spacing up to transoceanic distances. However a new problem has arisen, that is, the accumulation of fiber nonlinearties along the links. The high optical power levels available from the EDFAs makes system performance more vulnerable to various nonlinear effects. In a multi-channel system, the effect of fiber nonlinearties should be addressed more properly to understand interchannel effects. While the other two conventional limiting factors in designing optical communication systems, namely, fiber loss and dispersion, compensation, fiber nolinearties have not been fully analyzed and understood despite a rich collection of literature dealing with fiber nonlinearties and their effects on fiber-optic communication systems. When all the input signal frequencies interact due to fiber nonlinearties, the output bit stream may behave in a complicated way giving adverse effects on the system performance. **This chapter** includes the introduction to the optical communication, history of the optical communication. In this various multiplexing techniques such as **Time Division** M**ultiplexing**, **Frequency Division Multiplexing,** and **Wavelength Division multiplexing** are discussed in brief. These techniques are used to increase the capacity of the system. Also discuss the generation and various developments done the field of optical communication system. **Second chapter** contains the literature survey of effects of nonlinearties on optical communication. In this, experimental and analytical study of nonlinearties, which is done by various authors, is discussed. **Third chapter** contains the theory of nonlinearties origin of nonlinearties, types of nonlinearties, types of nonlinearities. **Chapter four** include the Nonlinear Schrödinger equation, generalized nonlinear Schrödinger equation, and also explain the various methods to study the effect of nonlinearities. In this dissertation split step Fourier method because of its accuracy and easy analysis power when both nonlinearities and dispersion are present in the system. **Chapter five** explains the various applications of the nonlinearities as well as adverse effects of the nonlinearities. And at last, **Chapter six** contains the simulation parts and study of various parameters such as phase shift, nonlinear refractive index, input power, etc. Simulation is done using MATLAB software in which split step Fourier transform is simulated with nonlinear equation. In this dissertation effect of various parameters on the received power at the receiver end is studied.

CHAPTER 2

LITERATURE SURVEY

M. Arumugam, Department of Physics, Anna University, Chennai in his paper **"Optical fiber communication —An overview" gives the views about the fiber optic communication.** This paper deals with the historical development of optical communication systems and their failures initially. Then the different generations in optical fiber communication along with their features are discussed. Some aspects of total internal reflection, different types of fibers along with their size and refractive index profile, dispersion and loss mechanisms are also mentioned. Finally the general system of optical fiber communication is briefly mentioned along with its advantages and limitations. Future soliton based optical fiber communication is also highlighted. In this paper they explain how can we achieve high quality telecommunication at a lower cost using solitons.

In the paper "**Theoretical Investigations for Intensity Fluctuations in Self Phase Modulation and Cross Phase Modulation in Multispan WDM Optical Fiber Systems with Second Order Dispersion**" **Dr. Kaler** theoretically analyze the effects of cross phase modulation and self phase modulation. In this they analyze the Intensity fluctuations for self phase modulation (SPM) and cross phase modulation (XPM) in multispan intensity modulation direct detection (IM-DD) optical systems including second order dispersion term. The expression for intensity fluctuation in multispan WDM optical fiber system has been derived. The plots for power transfer function for single and two span systems with non-zero dispersion shifted fiber and ordinary single mode fiber have been plotted. It is found that the second order dispersion term has no impact on intensity fluctuations in multispan WDM system but if the first order dispersion term is zero then there is certainly some impact of second order dispersion term. The spectral characteristics have been found to be strongly dependent on channel spacing and dispersion of the fiber. Further it is also observed that for multispan systems, the first order dispersion term induces oscillatory spectral response and this response increases with increase in modulation frequency.

Osamu Aso, Masateru Tadakuma and Shu Namiki explain in various application and theory of FWM in their paper" **Four-Wave Mixing in Optical Fibers and Its Applications".** In this paper they did the comparison of simultaneously measured values of nonlinear coefficient n_2/ Aeff with those by crossphase modulation. Authors have examined techniques for achieving broadband all-optical simultaneous wavelength conversion by taking advantage of four-wave mixing (FWM) occurring in the fiber, together with techniques for the simultaneous measurement of the nonlinear coefficient and chromatic dispersion. This paper discusses the theory of FWM, and then introduces one of its applications --a broadband all-optical simultaneous wavelength converter developed using a high nonlinearity dispersion fiber (HNL-DSF) that efficiently produces FWM. As a further application, a novel technique is introduced for measuring the nonlinear coefficient of optical fibers by evaluating FWM generating efficiency. With this technique it is now possible to effect simultaneous measurement of the chromatic dispersion and nonlinear coefficient of fiber.

In the next paper i.e. "**A Report on Four-Wave Mixing in Optical Fiber and its Metrological Applications**" by **D H Nettleton** gives the idea about the non-linear optical effect known as four-wave mixing (FWM) and its implications in optical fibers. The metrological applications are discussed with particular reference to the requirements of the telecommunications industry, which represents the main driver for research in this field. This industry in particular will benefit from a detailed study of FWM in fibers because the effect can be both detrimental to systems already installed and used as the basis for new devices that will complement the ultra high-speed networks of the future. This paper gives a brief overview of four-wave mixing and highlights the relevant fiber parameters. The physical mechanisms behind the effect, including the requirements for phase matching, are covered in detail.

In the book **"Nonlinear Fiber Optics"** by **G. P. Aggrawal** provide the background material and the mathematical tools needed for understanding the various nonlinear effects. Starting from the Maxwell's equation, the wave equation in a nonlinear dispersive medium is used to discuss the fiber modes and to obtain the basic propagation equation. The main effect of GVD and dispersion induced broadening is also explained in detail. This book also explains the nonlinear phenomenon of SPM occurring as a result of intensity dependence of the refractive index. Study of higher optical solitons is introduced together with the inverse scattering method used to solve the nonlinear Schrödinger equation. Also focus other nonlinear effects such as XPM, SRS, and SBS. During the description of theory SBS Dr.Aggarwal describes the important features such as the brillouin threshold, pump depletion, and gain saturation. This book also explains the application of nonlinearities in industry and in telecommunications.

In the paper **"Implementation of the Split-step Fourier Method for solving nonlinear Schrödinger Systems"** written By Scott Zoldi, Victor Ruban, Alexandre Zenchuk, and Sergey Burtsev explain the important of split step Fourier transform. They also explain usefulness of split step Fourier transform. Large-scale simulations of the nonlinear Schrödinger equation (NLSE) are required in the solution of many problems in fiber optics, among them accurate modeling of wavelength division multiplexed transmission systems. The split-step Fourier (SSF) method, commonly used in the numerical solution of the NLSE, often proves too slow in serial versions, even on the fastest workstations. In this article, we present a SSF algorithm that is appropriate for multiprocessors. The SSF method is used to integrate many types of nonlinear partial differential equations. Because it is often more efficient than finite differences for the simulation of nonlinear Schrödinger (NLS) systems, the SSF method is the more commonly used.

"Four-wave mixing in wavelength–division multiplexed soliton systems: ideal fibers" written by **M. J. Ablowitz and G. Biondini** according to them Analytic expressions for four-wave-mixing terms in an ideal, loss less wavelength–division-multiplexed soliton system are derived with an asymptotic expansion of the *N*-soliton solution of the Nonlinear Schrödinger equation. The four-wave contributions are shown to grow from a vanishing background and then to decay. Their importance becomes evident in real, nonideal fibers, where they grow by an order of magnitude and equilibrate to a stable value as an effect of periodic amplification.

Authers Arne John Glenstrup, Villy bae**k** Iversen **write in their paper "Exact Evaluation of Blocking in WDM Networks"** about the routing and blocking of the packets of information. They have shown that it is possible to re-use the existing blocking calculation tools for calculating blocking probabilities in WDM networks. This is done by generalizing the link/route tables to constraint/route tables, which include restrictions for enforcing the wavelength continuity constraint. We have shown how this can be achieved using a two-step algorithm: first building a link exclusion table, and then calling a recursive function, to construct the rows of the constraint/route table. The results from running the blocking calculation programs on constraint/route tables for two small WDM networks show that direct (one-hop) paths experience lower blocking in WDM networks, at the cost of paths with 2 or 3 hops experiencing higher blocking.

Eriv hu, Kenneth K. Y.Wong, Scott Yam in the paper **"Fiber Nonlinearities"** they have written that Wavelength-division multiplexing (WDM) is rapidly evolving as a key technology for future optical networks ranging from local area networks (LANs) to wide-area networks (WANs). Fiber nonlinearities (self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), Stimulated Brillouin Scattering (SBS), and Stimulated Raman Scattering) set limits on the capacity of WDM networks. They also explain various effects of fiber nonlinearities on the performance and limitation of WDM networks. They developed models to predict the XPM effect as a function of modulation frequency, wavelength separations, dispersion, and optical amplifier locations. This model will be extended to include effects from other third-order fiber nonlinearities, namely SPM and FWM. We are also studying the impact of fiber nonlinearities on analog optical links, both signal channel and WDM. The focus on signal channel analog links includes the impact of SBS, SBS suppression techniques, and the impact of SBS suppression on link linearity. In WDM analog links, the focus is mainly on SRS induced crosstalk, which is the dominant source of crosstalk in 1.55 mm system transmitting over non-dispersion-shifted fiber (NDSF).

CHAPTER 3

FIBER NONLINEATIES

3.1 Introduction

The rapid expansion fiber optic communication systems and technologies can be credited, in part, to the deployment of wavelength division multiplexing systems, allowing multiple independent data channels per fiber. In addition, the cutting costs via the use of longer amplifier span, more channels per fiber, higher signal power levels may allow further expansion. As transmission distance and number of channels increases, signals become more vulnerable to a number of debilitating fiber nonlinear effect. To combat this, network operators routinely ensure that signal power levels remain below a “safe” threshold, where the degradation induced by the nonlinearties is negligible. However as the optical and networking technologies expand, some recent work has envisioned the “intelligent”, reconfigurable, dynamic optical network, where channels may be routed optically, and channels/wavelengths are added and dropped routinely at network nodes. Since the power of each channel at the output of a saturated EDFA depends on the number of input channels, a rapid change in the number of channels may results in large increase in nonlinear effects as the signal travels down the amplifier chain. The key nonlinear effects in such systems are self phase modulation, cross phase modulation and four wave mixing. SPM is an intra channel effect and is present even in single channel systems while XPM and FWM are present only in multi channel systems. These effects can be dynamic and will change as the power and wavelength makeup the channels changes. A key point here is that the knowledge of the general nonlinear characteristics of a link is not enough information to fully characterize these effects of nonlinearties on a systems, due to the following:(i) chromatic dispersion variation with temperature changes the nonlinearties effects and (ii) periodic repair and maintenance of the fiber plant can alter the properties of the link itself, both resulting in changes the power penalty. Fiber nonlinearties present a new obstacle that must be overcome. These factors impose a requirement for monitoring the nonlinear properties in WDM system.

3.2 The Origins of Non-linearity

When radiation is incident upon a medium, the oscillating electromagnetic field interacts with electric dipoles in the molecules of the medium and causes them to oscillate. The result is a time-varying local electric polarization in the medium. This oscillating electric field then re-radiates the electromagnetic field and the incident wave is considered to propagate through the medium via a series of such absorption and re-radiation processes. The polarization vector **P**, induced by an electric field with amplitude vector **E** can be expressed as a general series expansion of the form [4]

$$P = \varepsilon_0 \left(\chi \cdot E + \chi_2 : EE + \chi_3 \vdots EEE + ... \right)$$

ε_0 is the electric permittivity of a vacuum,

χ is the linear susceptibility tensor of the medium and

χ_2 and χ_3 are second and third order susceptibility tensors terms.

If the induced polarization has a purely linear dependence on the applied electric field then the re-radiated electric field will be identical to the incident field. However, when second or higher-order susceptibility terms are non-zero, harmonics begin to appear in the radiated field that was not present in the incident field. For materials that have a symmetrical molecular structure, the polarisation induced by an incident electric field is symmetrical, as illustrated in figure 3.1. The susceptibility of these materials contains only odd expansion terms, as opposed to anti-symmetric molecules for which even terms such as may be non-zero.

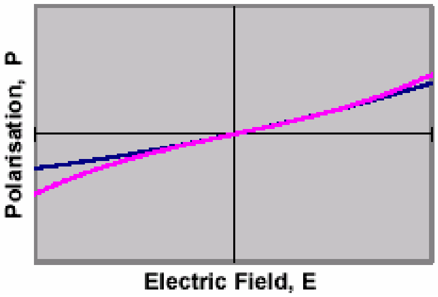


Figure 3.1 Electric polarisation versus electric field for materials with inversion symmetry (broken line) and with asymmetric molecular structure (solid dark line).

The dominant susceptibility term is the linear term, χ, which determines the linear refractive index of the medium, *n,* and the absorption attenuation coefficient, α. The orders of the non-zero expansion terms determine the type of non-linearity to which the medium is susceptible. In materials, which lack a center of symmetry, such as quartz, KDP and ADP, the second order susceptibility is responsible for *second harmonic generation [9],* in which an intense wave at angular frequency ω_1 generates another wave at twice this frequency, $2\omega_1$. Another effect which is possible in these materials is *sum-frequency generation*, in which two waves at ω_1 and ω_2 interact to produce waves at $\omega_1 + \omega_2$, $2\omega_1 + \omega_2$, and $2\omega_2 + \omega_1$.

Silica (SiO_2), the basic constituent of optical fibers is a symmetric molecule and consequently, vanishes and second-order non-linear effects are not normally observed. Rather, it is the third-order term in equation 3.1 that is responsible for non-linear behavior, which includes *self-phase modulation* (SPM) and *cross-phase modulation* (XPM) as well as four-wave mixing. SPM and XPM can be viewed as processes that result from the refractive index of the fiber material being a function of the intensity of the electromagnetic field. These effects will occur under fairly broad ranging conditions provided that the intensity of the optical field is high enough, whereas FWM requires the satisfaction of a stringent condition know as *phase matching* in order to occur efficiently. It is the degree of phase matching that is the crucial parameter when considering both the beneficial and detrimental effects of four wave mixing in an optical fiber system.

3.3 Types of Fiber Nonlineaties

The nonlinearities in optical fibers fall into two categories. One is **stimulated scattering** (Raman and Brillouin), and the other is the **optical Kerr effect** due to changes in the refractive index with optical power. While stimulated scatterings are responsible for intensity dependent gain or loss, the nonlinear refractive index is responsible for intensity dependent phase shift of the optical signal. One major difference between scattering effects and the Kerr effect is that stimulated scatterings have threshold power levels at which the nonlinear effects manifest themselves while the Kerr effect doesn't have such a threshold.

3.3.1 Optical Kerr Effect

The refractive index of silica fiber for communication is weakly dependent on optical intensity, and is given by [8],

$$n = n_0 + n_2 I(t)$$

$n_0 = 1.5$, $n_2 = 2.6 \times 10^{-20}\ m^2/W$, $I(t)$ = Optical intensity

Although the refractive index is a very weak function of signal power, the higher power from optical amplifiers and long transmission distances make it no longer negligible in modern optical communication systems. In fact, phase modulation due to intensity dependent refractive index induces various nonlinear effects, namely, self-phase modulation (SPM), cross-phase modulation (CPM), and four-wave mixing (FWM).

3.3.2 Self-Phase Modulation (SPM)

The dependence of the refractive index on optical intensity causes a nonlinear phase shift while propagating through an optical fiber. The nonlinear phase shift is given by

$$\phi_{NL} = \frac{2\pi}{\lambda} n_2 I(t)$$

where λ is the wavelength of the optical wave, and *z* is the propagation distance.

Since the nonlinear phase shift is dependent on its own pulse shape, it is called *self-phase modulation (SPM).* When the optical signal is time varying, such as an intensity modulated signal, the time-varying nonlinear phase shift results in a broadened spectrum of the optical signal. If the spectrum broadening is significant, it may cause cross talk between neighboring channels in a *dense wavelength division multiplexing* (DWDM) system. Even in a single channel system, the broadened spectrum could cause a significant temporal broadening of optical pulses in the presence of chromatic dispersion. However, under some circumstances SPM and chromatic dispersion can be beneficial. One extreme example is the *soliton*, which is known to be stable and dispersion-free. Even with *non-return-to-zero* (NRZ) pulses, it is known that pulse compression could be achieved partially in the anomalous dispersion region[1]where the linear chirp induced by chromatic dispersion and the nonlinear one due to SPM have opposite signs. When a transmission system is designed to achieve the optimum compensation of the linear chirp and the nonlinear chirp, it is often called a *nonlinear assisted transmission system.*

3.3.3 Cross-Phase Modulation (CPM)

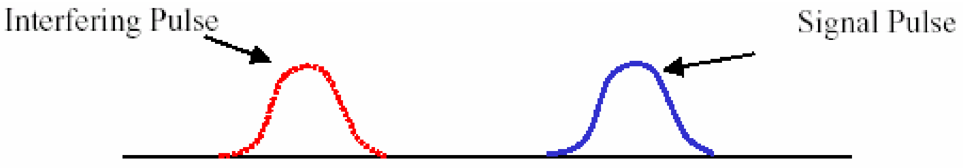
Another nonlinear phase shift originating from the Kerr effect is *cross-phase modulation (CPM)*. While SPM is the effect of a pulse on it own phase, CPM is a nonlinear phase effect due to optical pulses in other channels. Therefore, CPM occurs only in multi-channel systems. In a multi-channel system, the nonlinear phase shift of the signal at the center wavelength λ_i is described by

$$\phi_{NL} = \frac{2\pi}{\lambda_i} n_2 z \left[I_i(t) + 2\sum_{i \neq j} I_j(t) \right]$$

The first term is responsible for SPM, and the second term is for CPM. above equation might lead to a speculation that the effect of CPM could be at least twice as significant as that of SPM. However, CPM is effective only when pulses in the other channels are synchronized with the signal of interest. When pulses in each channel travel at different group velocities due to dispersion, the pulses slide past each other while propagating. Figure 3-2 illustrates how two isolated pulses in different channels collide with each other. When the faster traveling pulse has completely walked through the slower traveling pulse, the CPM effect becomes negligible. The relative transmission distance for two pulses in different channels to collide with each other is called the *walk-off distance*, L_w [11].

$$L_w = \frac{T_0}{\left| v_g^{-1}(\lambda_1) - v_g^{-1}(\lambda_2) \right|} \approx \frac{T_0}{D\Delta\lambda}$$

where T_o is the pulse width, v_g is the group velocity, and λ_1, λ_2 are the center wavelength of the two channels. D is the dispersion coefficient, and $\Delta\lambda = |\lambda_1 - \lambda_2|$.



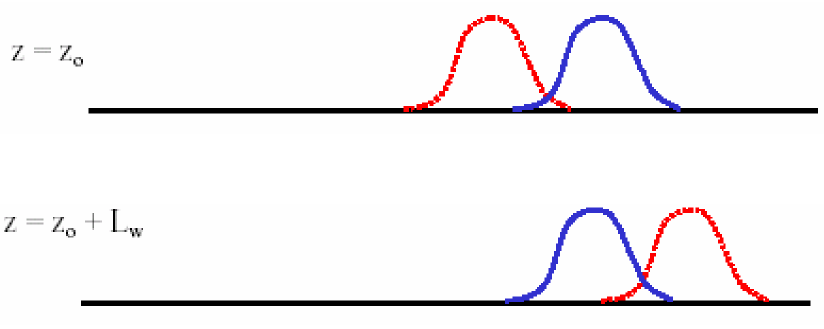
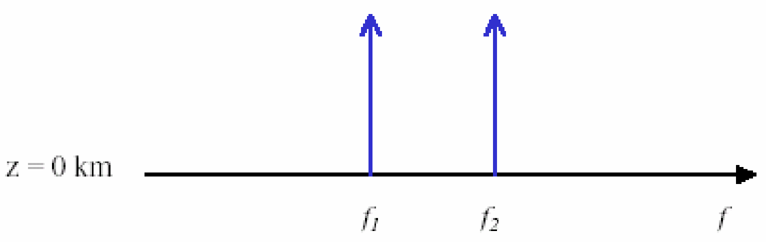


Figure 3.2 Illustration of walk-off distance

When dispersion is significant, the walk-off distance is relatively short, and the interaction between the pulses will not be significant, which leads to a reduced effect of CPM. However, the spectrum broadened due to CPM will induce more significant distortion of temporal shape of the pulse when large dispersion is present, which makes the effect of dispersion on CPM complicated.

3.3.4 Four-Wave Mixing (FWM)

Four-wave mixing (FWM), also known as *four-photon mixing*, is a parametric interaction among optical waves, which is analogous to intermodulation distortion in electrical systems. In a multi-channel system, the beating between two or more channels causes generation of one or more new frequencies at the expense of power depletion of the original channels. When three waves at frequencies f_i, f_j, and f_k are put into a fiber, new frequency components are generated at $f_{FWM}=f_i+f_j-f_k$ [19]. In a simpler case where two continuous waves (cw) at the frequencies f_1 and f_2 are put into the fiber, the generation of side bands due to FWM is illustrated in Figure 3-3



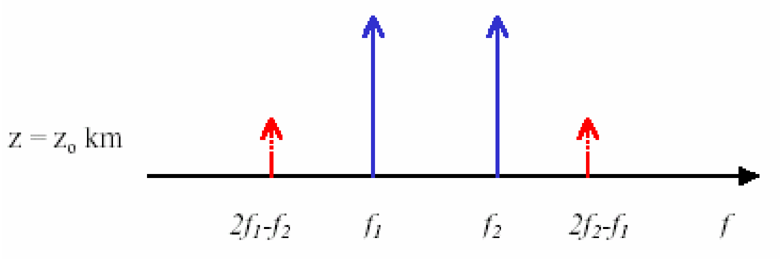


Figure 3-3 Illustration of side-bands generation due to FWM in two-channel system (straight line shows original frequency and dotted line shows new frequencies)

The number of side bands due to FWM increases geometrically, and is given by ,

$$M = \frac{1}{2}\left(N_{CH}^{3} - N_{CH}^{2}\right)$$

where N_{ch} is the number of channels, and M is the number of newly generated sidebands. For example, eight channels can produce 224 side bands. Since these mixing products can fall directly on signal channels, proper FWM suppression is required to avoid significant interference between signal channels and FWM frequency components.

When all channels have the same input power, the FWM efficiency, h, can be expressed as the ratio of the FWM power to the output power per channel, and is proportional to

$$\eta \; \alpha \left[\frac{n_2}{A_{eff} D(\Delta\lambda)^2}\right]^2$$

where *Aeff* is the effective area of fiber.

This equation indicates that FWM of a fiber can be suppressed either by increasing channel spacing or by increasing dispersion. Large dispersion can cause unacceptable power penalties especially in high bit rate systems. However, careful design of the dispersion map (often called *dispersion management*) which allows large local dispersion but limits the total average dispersion to be below a certain level is found to be very effective to combat both dispersion and FWM induced degradations.

3.3.5 Stimulated Scattering

When light is incident on material it undergoes various scattering process. Most of the scattering is elastic, and the scattered wave has the same frequency as the incident wave. However, this scattered light is, in general, at some arbitrary angle to the forward direction of propagation. Hence, if one measures the transmitted light in the forward direction, there is a reduction in intensity as a result of the scattering into other directions. This loss is known as Rayleigh scattering loss.

In addition to the elastically scattered component, a small fraction (about 1 to 10^6) of the incident photons undergo inelastic scattering. The scattered photon emerges with a frequency shifted below or above the incident photon frequency. The difference in energy between the incident and scattered photons is deposited in, or extracted from, the scattering medium. The frequency shifts* can be small (approximately 1 cm^{-1}) or large (greater than 100 cm^{-1}). When the frequency shift is small, the process is known as Brillouin scattering. The larger frequency shifts characterize the regime of Raman scattering.

3.3.5.1Stimulated Brillouin Scattering (SBS)

Optical waves and acoustic waves in a fiber can interact to cause stimulated Brillouin scattering. In stimulated Brillouin scattering, a strong optical wave traveling in one direction (forward) provides narrow band gain for light propagating in the opposite direction (backward). Some of the forward-propagating signal is redirected to backward, resulting in power loss at the receiver. If the SBS threshold is defined as the input power at which the scattered power increases as large as the input power in the undepleted pump approximation, the SBS threshold power is proportional to

$$P_B^{th} \approx \frac{1}{g_B}\left(1+\frac{\Delta v_s}{\Delta v_B}\right)$$

where g_B is the Brillouin gain coefficient, Δv_S is the linewidth of the source, and Δv_B is the Brillouin linewidth.

Eq. indicates that the threshold power will be increased as the linewidth of the source increases. For optical fibers at 1550nm, the Brillouin linewidth is about 20MHz, so optical signals modulated at higher bit rates will experience lesser effects of SBS. From a system point of view, the relatively narrow gain spectrum of SBS prevents interactions among channels in a WDM system, which makes SBS independent of channel number. Only each individual channel signal needs to be below the threshold power [11]. Another characteristics of SBS which make it less troublesome compared to other nonlinear effects is that the threshold of SBS does not decrease in a long amplified system because practical optical amplifiers have one or more optical isolators. The optical isolators prevent accumulations of the backscattered light from SBS. Therefore, although SBS could be a detrimental nonlinear effect in an optical communication system, system limitations are usually set by other nonlinear effects.

3.3.5.2 Stimulated Raman Scattering (SRS)

SRS is due to the interaction of photons with a fiber's molecular vibrations. Unlike SBS, SRS scatters light waves in both directions, forward and backward. However, the backward-propagating light can be eliminated by using optical isolators. Therefore, the forward scattered light is of more concern. The Raman gain coefficient is about three orders of magnitude smaller than the Brillouin gain coefficient, and the SRS threshold is known to be around 1W for a single-channel system . In a single-channel system, the large threshold power makes SRS a negligible effect. However, the gain bandwidth of SRS is of the order of 12THz, which is about 6 orders of magnitude greater than that of SBS. The large gain bandwidth of SRS enables it to couple different channels in a WDM system, which can cause performance degradation through cross talk. Chraplyvy and Tkach estimated the worst case of signal-to-noise ratio (SNR) degradation in an amplified system due to SRS [16]. According to the estimate, the requirement to ensure a SNR degradation of less than 0.5 dB in the worst channel is that the product of total power, total bandwidth, and the total effective length of the system should be less than 10 THz-mW-Mm. Although it was assumed in their estimate that all the channels are transmitting mark states simultaneously, the probability of which is very low in a multi-channel system, it indicates that SRS may impose a fundamental limit on the capacity of future optical communication systems. However, the SRS threshold is high enough such that other nonlinear effects caused by nonlinear refractive index are more limiting factors in contemporary communication networks.

CHAPTER 4

ANALYSIS OF FIBER NONLINEARITIES BY NONLINEAR SCHRÖDINGER EQUATION

For an understanding of nonlinear phenomena in optical fibers, it is necessary to consider the theory of electromagnetic wave propagation in dispersive nonlinear media.

4.1 Nonlinear Schrödinger Equation

The propagation of optical waves in a single mode fiber is governed by Maxwell's equations, which lead to the wave equation

$$\Delta \times \Delta \times E = -\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 P}{\partial t^2} \qquad 4.1$$

Where 'c' is the speed of light in vacuum and relation $\mu_0\varepsilon_0 = \frac{1}{c^2}$ is used. E is the electric vector, μ_0 is the vacuum permeability, P is the polarization density field. To complete the description, a relation between the induced polarization P and the electric field E is needed. To account fiber nonlinearties, the induced polarization consists of two parts such that

$$P(r,t) = P_L(r,t) + P_{NL}(r,t) \qquad 4.2$$

where the linear part P_L and nonlinear part P_{NL} are related to electric field by general relation [5]

$$P_L(r,t) = \varepsilon_0 \int_{-\infty}^{\infty} \chi^1(t-t^{'}) \cdot E(r,t^{'})dt^{'} \ , \qquad 4.3$$

$$P_{NL} = \varepsilon_0 \iint \int_{-\infty}^{\infty} \chi^3(t-t_1, t-t_2, t-t_3) \vdots E(r,t_1)E(r,t_2)E(r,t_3)dt_1 dt_2 dt_3 \qquad 4.4$$

The third order susceptibility, $\chi^{(3)}$, is a fourth rank tensor, and could have 81 different terms. However, in isotropic media like a single mode fiber operating far from any resonance, the number of independent terms in the third order susceptibility is reduced to one. Eq. (4.2) to (4.4) can be used in Eq. (4.1) to derive the propagation equation in nonlinear dispersive fibers. However, a few simplifying assumptions are generally made to solve Eq. (4.1). First, P_{NL} is treated as a small perturbation of P_L, and the field polarization is maintained along the fiber. Another assumption is that the index difference between core and cladding is very small (so called *weakly guiding approximation*), and the center frequency of the wave is assumed to be much greater than the spectral width of the wave (so called *quasi-monochromatic assumption*). The quasi-monochromatic assumption is analogous to low-pass equivalent modeling of bandpass electrical systems, and is equivalent to the *slowly varying envelope approximation* in the time domain. Finally, the propagation constant, $\beta(\omega)$, is approximated by a few first terms of a Taylor series expansion about the carrier frequency, ω_0, that is,

$$\beta(\omega) = \beta_0 + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2 \beta_2 + \frac{1}{2}(\omega - \omega_0)^3 \beta_3 + ... \quad 4.5$$

$$\text{where} \quad \beta_m = \left(\frac{d^m \beta}{d\omega^m}\right)_{\omega=\omega_0} \qquad \text{m= 1,2...........} \quad 4.6$$

The second order propagation constant β_2 [ps^2/km], accounts for the dispersion effects in fiber-optic communication systems. Depending on the sign β_2, the dispersion region can be classified into two regions, normal (β_2>0) and anomalous (β_2< 0). Qualitatively, in the normal-dispersion region, the higher frequency components of an optical signal travel slower than the lower frequency components. In the anomalous dispersion region, the opposite occurs. Fiber dispersion is often expressed by another parameter, D [ps/(nm/km)], which is called the dispersion parameter. D is defined as

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) \quad 4.7$$

and the relationship between β_2 and D is given by [7]

$$\beta_2 = \left(\frac{\lambda^2}{2\pi c}\right)D \quad 4.8$$

where λ is the wavelength and v_g is the group velocity.

The cubic and higher-order terms in Eq.(4.5) are generally negligible as long as the spectral width $\Delta\omega << \omega_0$ assumption holds. However, when the center wavelength of an optical signal is near the zero-dispersion wavelength (that is $\beta_2 \approx 0$), the β_3 term should be included.

If the input electric field is assumed to propagate in the +z direction and is in the x direction the Eq.(4.5) becomes

$$
\begin{aligned}
\frac{\partial}{\partial z}A(z,t) &= -\frac{\alpha}{2}A(z,t) && \text{(linear attenuation)}\\
&+ j\frac{\beta_2}{2}\frac{\partial^2}{\partial^2 t}A(z,t) && \text{(second order dispersion)}\\
&+ \frac{\beta_3}{6}\frac{\partial^3}{\partial^3 t}A(z,t) && \text{(third order dispersion)}\\
&- j\gamma\left|A(z,t)\right|^2 A(z,t) && \text{(Kerr effect)}\\
&+ j\gamma T_R\frac{\partial}{\partial t}\left|A(z,t)\right|^2 A(z,t) && \text{(SRS)}\\
&- \frac{\gamma}{\omega_0}\frac{\partial}{\partial t}\left|A(z,t)\right|^2 A(z,t) && \text{4.9 (self steepening effect)}
\end{aligned}
$$

where

A(z,t) = the slowly varying envelope of the electric field

z = propagation distance

t = *t'-z/vg* (*t'*= physical time, v*g* = the group velocity at the center wavelength)

α= the fiber loss coefficient ([1/km])

β*2* = the second order propagation constant ([ps^2/km])

β*3* = the third order propagation constant ([ps^3/km])

γ= the nonlinear coefficient = $\frac{2\pi n_2}{\lambda_0 A_{eff}}$

n_2 = the nonlinear index coefficient

A_{eff} = the effective core area of fiber

λ_0 = the center wavelength

ω_0 = the center angular frequency

T_R = the slope of the Raman gain (~5fs)

Eq.(4.9) is often called the *generalized nonlinear Schrödinger equation*. and is known to be applicable for propagation of pulses as short as ~50fs. This corresponds to a spectral width of ~20THz. When the pulse width is greater than 1ps, Eq.(4.9) can be considerably simplified (as indicated below) because the Raman effect term and the self steepening effect term are negligible compared to the Kerr effect term [5].

$$\frac{\partial A}{\partial z} = -\frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} - \frac{\alpha}{2}A + i\gamma|A|^2 A \qquad 4.10$$

In Eq.(4.10), the third order dispersion term is also ignored, because this is negligible compared to the second order dispersion term unless operation is near the zero-dispersion wavelength.

4.2 Normalized Nonlinear Schrödinger Equation

For pulse width $T_o \geq 1$ps, Eq.(4.9) can be used as a propagation equation instead of the generalized NLSE (Eq.(4.9)) because of negligible effects of higher-order nonlinearities - the stimulated Raman scattering (SRS) and the self-steepening. Eq.(4,10) describes the propagation of an optical pulse in single-mode fibers under the effects of loss, group velocity dispersion (GVD), and the nonlinear Kerr effect which are the most important transmission effects in contemporary optical communication systems. Since Eq.(4.10) involves various physical parameters, it is often convenient to convert to normalized units by defining two length scales L_D(dispersion distance) and L_N (nonlinear distance). These two distances are defined as

$$L_D = \frac{T_0^2}{|\beta_2|} \qquad 4.11$$

$$L_N = \frac{1}{\gamma P_0} \qquad 4.12$$

where β_2 is the second order propagation constant, γ is the nonlinear coefficient, and P_o is the peak power of the slowly varying envelope, *A(z, t)*. The parameter T_0 is an arbitrary temporal characteristic value of the initial pulse. T_o is often defined as either full width half maximum (the pulse 3dB width) or the rise time of the pulse, T_r[12].

When the slowly varying envelope, *A (z, t),* is normalized by its peak value such that *A (z, t) =*$\sqrt{P_0}$ A(z,t) , Eq.(4.10) can be expressed in terms of *LD* and *LN* as below,

$$i\frac{\partial U}{\partial z}=\frac{\operatorname{sgn}(\beta_2)}{2L_D}\frac{\partial^2 U}{\partial \tau^2}-\frac{\exp(-\alpha z)}{L_N}|U|^2U \qquad 4.13$$

where $\operatorname{sgn}(\beta_2)$= +1 when β_2 > 0, and $\operatorname{sgn}(\beta_2)$ = -1 when β_2 < 0. τ represents a normalized time unit such that t *=τ /To*.

In an amplified optical transmission system, signal power fluctuates periodically along the link, and Eq. (4.13) can be further simplified by defining average power along the link. When optical amplifiers are placed uniformly along the transmission link with amplifier spacing *za*, the average power is expressed by

$$P_{avg}=\frac{1}{z_a}\int_0^{z_a}P_0e^{-\alpha z}dz=\frac{P_0}{\alpha z_a}\left(1-e^{-\alpha z_a}\right) \qquad 4.14$$

In the evaluation of Eq. (4.14), it is assumed the physical length of the amplifier is negligible compared to transmission distance, which is a good approximation in real systems. Now Eq. (4.13) can be expressed without a loss term by approximating the power fluctuation as a constant value of *Pavg.*

$$i\frac{\partial U}{\partial z}=\frac{\operatorname{sgn}(\beta_2)}{2L_D}\frac{\partial^2 U}{\partial \tau^2}-\frac{1}{L_N}|U|^2U \qquad 4.15$$

and

$$\bar{L}_N=\frac{1}{\gamma P_{avg}} \qquad 4.16$$

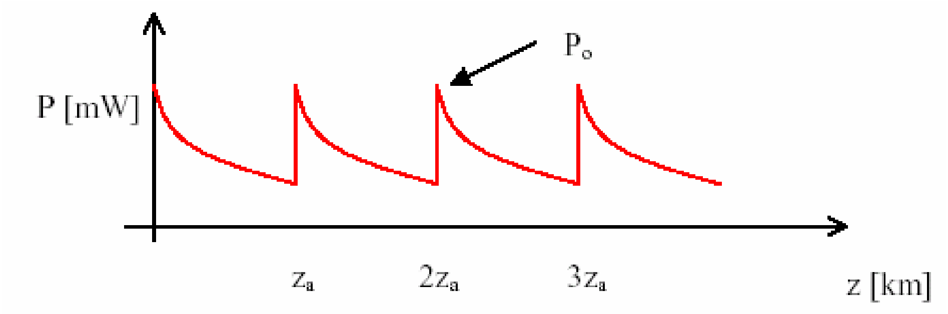
Eq. (4.16) is equivalent to Eq. (4.13) without a loss term, but with a constant optical power, *Pavg*, and its validity will be justified subsequently. Figure 4-1 illustrates an optically amplified system and its equivalent loss less system.

A lossless system modeling with average power is a good approximation, and from now on, it is assumed that signal power is its averaged value along the transmission link and $\bar{L}_N$ will be denoted as L_N unless it is necessary to distinguish these. If we normalize distance by the dispersion distance, L_D, such that $\xi = z/L_D$, Eq. (4.16) can be further simplified as below.

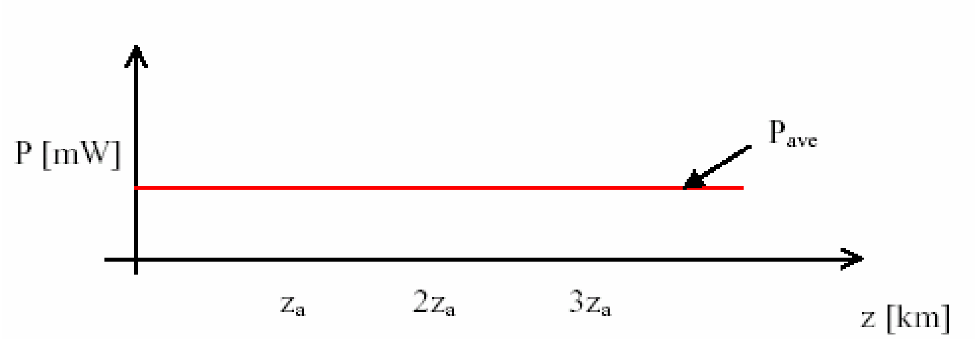
$$\frac{\partial U}{\partial \xi} = -\frac{1}{2} i \cdot \mathrm{sgn}(\beta_2) \frac{\partial^2 U}{\partial \tau^2} + iN^2 |U|^2 U \qquad 4.17$$

where $$N^2 = \frac{L_N}{L_D} = \frac{\gamma P_{avg} T_0^2}{|\beta_2|}$$

The resulting Eq. (4.17) is called ***the normalized NLSE***. It has some advantages over Eq. (4.10) since it involves only a single dimensionless parameter N, which makes the equation easier to deal with and might give better physical insight.



(a) Power fluctuation in an optically amplified system



(b) its equivalent model

Figure 4-1 (a) Power fluctuation in an optically amplified system (Eq. (4.13) (b) its equivalent model (Eq.(4.16))

4.3 Analysis Using Numerical Methods

The NLS equation is a nonlinear partial differential equation that does not generally lend itself to analytic solution except for some specific cases in which that inverse scattering method can be employed. A numerical approach is therefore often necessary for an understanding of nonlinear effects in optical fiber. Recently, K. V. Peddanarappagari and M. Brandt-Pearce solved the nonlinear Schrödinger equation by the Volterra series transfer function approach. Because this approach gives a closed-form solution, it can be a useful design tool for a nonlinear equalizer at the output of the fiber. However, its complicated analytical form not only makes it hard to get physical insight, but also in many cases makes it less attractive in computational time compared to the split-step Fourier method [12]. Additionally, its range of validity, that is, the valid range of the various physical parameters involved to assure accuracy within an allowable tolerance, has not been fully studied. A large number of numerical methods can be used for this purpose. These can be classified into two broad categories known as

1. The finite-difference methods
2. The pseudospectral methods
3. Volterra series transfer function
4. split step Fourier transform

Generally speaking, pseudospectral methods are faster by up to an order of magnitude to achieve the same accuracy.

4.4 Split Step Fourier Transform

It is required to solve the nonlinear Schrödinger equation to understand various impairments occurring during signal transmission. However, it is not possible to solve it analytically when both the nonlinearity and the dispersion effect are present, except in the very special case of soliton transmission. Therefore, numerous numerical algorithms have been developed to solve Eq.(4.9) or Eq.(4.10). The s*plit-step Fourier method* is one of these, and is the most popular algorithm because of its good accuracy and relatively modest computing cost.

The implementation of split step Fourier method is relatively straightforward.

As shown in the figure(4.2), the fiber is divided in to large number of segments that need not be spaced equally. The optical pulse is propagated from segment to segment using the prescription of Eq.(4.21). More specifically, the optical field A(z,t) is first propagated for a distance h/2 with dispersion only using the FFT algorithm. At the midplane z+h/2,the field is multiplied by a nonlinear term that represnts the effect of nonlinearty over the whole segmentlength h. finally, the field is propagated remaining distance h/2 with dispersion only to obtain A(z+h,t).

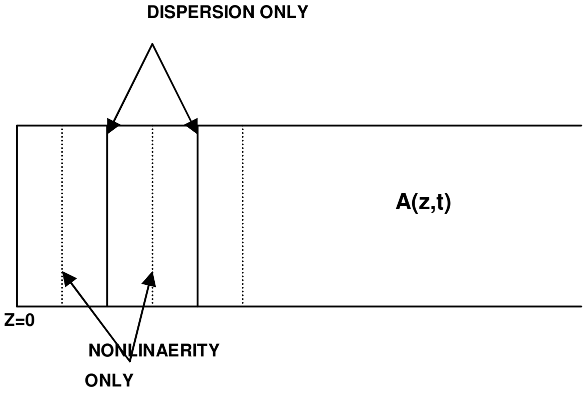


Figure 4-2 Diagram illustrate split step Fourier method adopting for numerical simulations. Fiber length is divided into a large number of segments of width h. within a segment, the effect of nonlinearity is included at midplane shown by a dashed line[5].

The algorithm is briefly discussed in the following. Eq. (4.10) can be expressed as

$$\frac{\partial A(z,t)}{\partial z} = \left(\hat{L} + \hat{N}\right)A(z,t) \qquad 4.18$$

where the linear operator, $\hat{L} = -\frac{\alpha}{2} - \frac{j}{2}\beta_2\frac{\partial^2}{\partial t^2}$, and nonlinear operator, $\hat{N} = j\gamma|A(z,t)|^2$. When the electric field envelope, *A(z,t),* has propagated from z to z+h, the analytical solution of Eq.(4.18) will have a form of

$$A(z+h,t) = \exp\left(hz\left(\hat{L} + \hat{N}\right)\right)A(z,t) \qquad 4.19$$

In general, dispersion and nonlinearities act together along the length of fiber. The step split Fourier transform method obtains an approximate solution by assuming that in propagating the optical field over a small distance h, the dispersive and nonlinear effects can be pretended to act independently. More specifically, the propagation from z to z+h is carried out in two steps. In the first step, the nonlinearity acts alone, and dispersion $\hat{L}$ is zero. In the second step, dispersion acts alone, and nonlineaties $\hat{N}$ is zero.

In the split-step Fourier method, it is assumed that the two operators commute with each other. That is,

$$A(z+h,t)=\exp\left(h\hat{L}\right)\exp\left(h\hat{N}\right)A(z,t) \qquad 4.20$$

Eq.(4.20) suggests that *A(z+*h*, t)* can be estimated by applying the two operators independently. If h is sufficiently small, Eq.(4.20) can give a fairly good result. Δz is usually chosen such that the maximum phase shift($\phi_{\max} = \gamma|A_P|^2 h$) , A_P = peak value of A(z,t) due to the nonlinear operator is below a certain value. It has been reported that when $\phi_{\max}$ is below 0.05 rad, the split-step Fourier method gives a good result for simulation of most contemporary optical communication systems [12].

The accuracy of the Split Fourier method can be improved by adopting a different procedure to propagate the optical pulse over one segment from z to z+h. in this procedure Eq.4.20 is replaced by

$$A(z,t)=\exp\left(\frac{h}{2}\hat{D}\right)\exp\left(\int_{z}^{z+h}\hat{N}\left(z'\right)dz'\right)\exp\left(\frac{h}{2}\hat{D}\right)A(z,t) \qquad 4.21$$

the main difference is that the effect of nonlinearity is included in the middle of the segment rather than at the segment boundary. Because of the symmetric form of the exponential operators in Eq.(4.21), this scheme is known as the symmterized split step Fourier method.

CHAPTER 5

APPLICATIONS AND ADVERSE EFFECTS OF NONLINEARITIES

5.1 FOUR WAVE MIXING

5.1.1 Adverse Effects of Four-Wave Mixing

FWM in optical fibers can be both harmful and important depending on the application. It can induce crosstalk in WDM communication systems and limit the performance of such systems. However, FWM can be avoided using unequal channel spacing or using fibers with large enough GVD that the FWM process is not phase matched over long fiber lengths.

1. Multichannel Communication System

Wavelength Division Multiplexed systems greatly increase the total bandwidth of each optical fiber by using a number of closely spaced channels at wavelengths within the typical 1530nm to 1565nm gain spectrum of erbium doped fiber amplifiers (EDFAs). Any interaction between these channels will lead to a degradation of the bit error rate (BER) of the system The most detrimental cross modulation between channels in a WDM communication system occurs for closely-spaced frequencies with uniform frequency separation near the fiber dispersion zero λ_0. This occurs for two reasons:

1. The phase matching between the signals is more easily achieved in this region.
2. The reduced chromatic dispersion slows the walk-off between neighbouring signals and reduces any averaging of the cross-modulation that would otherwise occur. This will be particularly serious in NRZ systems where trains of 1's and 0's in neighbouring channels may be modulated by each other and become fragmented.

2. Crosstalk

Crosstalk is defined as the ratio of FWM power to signal power in the worst affected channel; the results confirmed that it increases as the average channel wavelength approaches λ_0. It was also demonstrated that crosstalk increased with decreasing channel separation, as expected. Crosstalk measurements were also performed by starting with a 3-channel system centered on λ_0 and adding groups of four channels. Although the actual number of four-wave mixing products increased when more channels were added, it was found that crosstalk increased to a maximum at 19 channels and did not increase any further when four more were added. This effect was attributed to the increasing separation between the newly added channels and the center of the channel spectrum at λ_0. This increased separation had two effects: firstly, the efficiency of the FWM was lower and secondly the products from the additional channel were not extending to the worst affected channels at the center of the comb.

In summary, WDM system degradation due to four-wave mixing can be minimized by

1. Using non-uniform frequency spacing between channels in dispersion-shifted fiber.
2. Increasing the channel separations
3. Operating away from the zero dispersion wavelength of the fiber by using nonzero dispersion-shifted fiber.
4. Using optical differential phase shift keying (DPSK) with direct detection rather than intensity modulation.

5.1.2 Applications of Four-wave Mixing

1. High-Speed Optical Multiplexing/Demultiplexing

In order to make the most efficient use of the available bandwidth of optical fibers, data streams at bit rates well below the rate that can be supported by a single fiber are combined by interleaving them in time. Increasing the capacity of OTDM systems requires that the bit rate of the multiplexed signal be increased - reducing the time interval allocated to each bit. Currently, multiplexing and demultiplexing are required at speeds in the region of 2.4 Gb/s to 10 Gb/s and may be performed electronically. However, to increase the channel capacity by using higher bit-rates of 100 Gb/s or more requires faster optical techniques for interleaving and selectively extracting optical pulses. Four-wave mixing has been successfully used to multiplex and demultiplex data at these ultrahigh-speeds and provides a 10 dB SNR improvement over the alternative Nonlinear Loop Mirror (NOLM) demultiplexer[10].

It is anticipated that these systems will become more significant in the very near future. WDM systems use of OTDM to maximize the bandwidth of each individual channel. Therefore, although four-wave mixing acts to limit the maximum number of channels, it may also be used to help maximize system bandwidth through allowing higher demultiplexing rates in each one. FWM is therefore a significant effect for maximizing the bandwidth of existing OTDM and future WDM fiber systems with large markets[18].

2. Wavelength Conversion

Future all-optical networks based on WDM and optical routing will need wavelength converters to allow maximum flexibility when multiplexing and allocating channels. Wavelength conversion based on fourwave mixing has the advantage over other methods such as cross-gain modulation and optoelectronic methods that conversion is coherent and maintains the phase of the wave. FWM-based wavelength converters are therefore suitable for coherent systems based on phase-shift keying (PSK) as well as intensity modulation schemes.

Conversion efficiency in optical fibers may be limited by the effect of stimulated Brillouin scattering (SBS), which acts to limit the maximum forward propagating optical power in the fiber. Once the forward propagating optical power has exceeded a threshold value, SBS causes any increase in power to be transferred to a backscattered wave. SBS has been demonstrated to truncate the increase in FWM power for incident powers above 10 dBm in a 10 km length of DSF. However, specialized fiber manufacturing techniques have been shown to raise the SBS threshold by varying the dopant concentration along the fiber core[13], allowing the FWM power to continue increasing for pump powers up to 15 dBm.

3. Dispersion Compensation

Four-wave mixing has been suggested as a possible technique for compensation of chromatic dispersion in long-haul optical fiber systems. The dispersion that occurs along an initial length of fiber is corrected by reversing the chirp on an optical pulse using FWM in an *optical phase conjugator* (OPC) to perform *mid-span spectral inversion*. The chromatic dispersion of the following fiber then brings the pulse back to its original shape. The FWM effect is known as phase conjugation and is essentially a form of wavelength conversion. A pump at the zero dispersion wavelength of the OPC fiber is used to generate a conjugate signal on the opposite side of λ_0 to the initial signal, reflecting its power spectrum into the region of opposite chromatic dispersion. Providing the resulting dispersion after the OPC is of equal magnitude to that before, zero net dispersion results. The conversion efficiency from the signal to the conjugate wave in the OPC is maximized under the same conditions as FWM - namely phase matching, small signal-pump wavelength separation and low dispersion. Phase matching is satisfied by using a pump signal at λ_0 but the small signal-pump separation requires that the signal should be propagating near the zero dispersion wavelength of the fiber. This means that WDM systems, which tend to use non-zero dispersion shifted fiber, are unlikely to benefit from this dispersion management technique but it can be used on conventional OTDM systems. Another important point is that mid span spectral inversion cannot correct for third-order chromatic dispersion, which can be problematic for very high bit rate systems. Polarization sensitivity must also be considered when using this technique if the conversion efficiency is to be independent of the signal polarization. Using two pump waves with orthogonal polarization and different wavelengths, it has been shown that polarization sensitivity can be reduced.

5.2 Cross Phase Modulation

The nonlinear phenomenon of XPM is both beneficial and harmful. Its most direct impact is on the design of WDM lightwave systems where XPM often limits the system performance.[14]

5.2.1. Adverse effects of Cross Phase Modulation

1. Effect on transmission distance

Multiwavelength transmission systems with increasing number of channels and longer interamplifier spans require necessarily higher powers per channel to maintain acceptable signal-to-noise ratios (SNR's). In these systems, the transmission distances will be limited mainly by fiber nonlinearities including cross-phase modulation (XPM) and self-phase modulation (SPM). The high fiber dispersion converts the induced nonlinear SPM/XPM into amplitude modulation, and results in signal distortion, which increases with bit rate broadening. New results explaining the nature of transmission penalty in 50-GHz spaced WDM transmission over standard fiber, pre- and postcompensated with DCF at 10 Gb/s[12]. In particular, at power levels of 4–8 dBm/channel, precompensation allows significantly longer transmission distance. This can be explained by the pulse compression, rather than pulse broadening, which occurs with postcompensation.

However, precompensation is also accompanied by spectral broadening and jitter, which eventually limit the transmission distance. Accurate measurements and simulations of the optical spectra have shown that coherent crosstalk at the receiver, due to XPM- and SPM-induced spectral broadening, can be a main source of penalty in precompensated DWDM transmission. The increased coherent crosstalk between spectral components of neighboring channels, broadened by fiber nonlinearity, is the dominant mechanism explaining the increase in the penalties measured in the multichannel experiments.

2. Intensity distortion

In dispersion compensated systems, the intensity distortion induced by the interplay between cross-phase modulation and fiber chromatic dispersion can be a primary cause of transmission degradation. Dispersion compensation in long-distance high-speed wavelength-division-multiplexing (WDM) transmission systems should ideally suppress the linear distortion due to group velocity dispersion (GVD) while strongly reducing fourwave-mixing effects. However, self-phase modulation (SPM) and cross-phase modulation (XPM), interacting with GVD, and still be primary causes of transmission degradation. Phase-to intensity (PM/IM) conversion induced through GVD by a phase modulation present at the input of the fiber can be perfectly undone by a compensating fiber, the one induced by XPM components generated away from the input cannot be perfectly compensated, and the resulting residual intensity distortion impairs the performance of intensity modulated, direct detected systems. Such intensity distortion has been mostly studied by means of computer simulations, because the nonlinear Schr¨odinger equation is not analytically solvable for general pulses when both the nonlinear and the dispersive terms are present. Simulations involving XPM are almost prohibitively time consuming, because they require the propagation of all the WDM channels. polarization. *Probe* channel is CW, while *pump* channel is intensity modulated, being the Fourier transform of its power at the beginning of the fiber. Let and be the group velocities of the two channels, and let be the walkoff parameter, with the fiber dispersion at the probe wavelength and the channel spacing. The pump power at coordinate along the fiber, in the assumption of undistorted pump, has Fourier transform (with respect to a time frame moving with the probe group velocity)[15].

5.2.2 Applications of Cross Phase Modulation

1. XPM- induced pulse compression

XPM induced pulse compression is that, in which, XPM can compress weak input pulse. However, the XPM-induced chirp is affected by pulse walk-off and depends critically on the initial relative pump-signal delay. As a result, the practical use of XPM induced pulse compression requires a careful control of pump pulse parameters such as its width, peak power, wavelength and initial delay relative to the signal pulse [5].

2. XPM- Induced Optical Switching

The induced phase shift can also be used for optical switching. Several interferometric schemes have been used to take advantages of the XPM –induced phase shift for ultra fast optical switching .The physics behind the XPM –induced switching can be understood by considering a generic interferometer designed such that a weak signal pulse, divided equally into two arms and is transmitted through constructive interference. If the pump pulse at a different wavelength is injected into one of the arms of the interferometer, it would change the signal phase through XPM in that arm. If the XPM-induced phase shift is large enough (close to π), the signal pulse will not be transmitted because of the destructive interference occurring at the output. Thus, an output pump pulse can switch the signal pulse through the XPM-induced phase shift[20].

The XPM-induced phase shift depends not only on the width and shape of the pump pulse but also on the group velocity mismatch. In the case in which both the pump and signal beams are pulsed, the phase shift also depends on the initial relative time delay between the pump and signal pulses. In fact, the magnitude and the duration of XPM-induced phase shift can be controlled through the initial delay. The main point to note is that phase shift can be quite uniform over most of the signal pulse when the two pulses are allowed to completely pass through each other, resulting in complete switching of the signal pulse. The pump power required to produce π phase shift is generally quite large because of the group velocity mismatch [5].

3.XPM-Induced Nonreciprocity

XPM also occurs when two beams having the same (or different) wavelengths are propagated in opposite direction inside a fiber such that the counter propagating waves interact with each other through XPM. Such an interaction can lead to new qualitative features, manifested through optical bistability and other instability when the fiber is used to construct a nonlinear ring resonator. Of particular interest is the XPM induced nonrecprocity that can affect the performance of fiber gyroscope.

XPM-induced nonreciprocity can be detrimental for high precision fiber gyroscope used to measure rotation rates as small as 0.01 degree per hour. the XPM interaction between two counter propagating optical pulses is generally quite weak and can be neglected in the case of ultrashort pulses. This is just because of that the XPM induced phase decrease even for copropagating pulses as the relative group velocity difference increases. For counterpropagating pulses the group velocity mismatch is so large that the two pulses have little time to interact with each other [5].

5.3 Self Phase Modulation

5.3.1 Adverse Effect of Self Phase Modulation

1. Effect on Transmission

With the fiber loss being compensated by the erbium doped fiber amplifier (EDFA), group velocity dispersion (GVD) and nonlinearities have become major factors in limiting the bandwidth length product of the ultrashort pulse transmission link. The bandwidth length product of the transmission link is no longer limited by the GVD but by higher order dispersion and nonlinear effects. The dominant nonlinear effect in the TDMA and CDMA optical fiber systems is the self-phase modulation effect (SPM), which is caused by the nonlinear dependence of the refractive index on pulse intensity. Since high-speed data transmission systems require greater received power for error-free detection, the performance of ultrashort pulse dispersion compensated link is eventually limited by the interaction of SPM and the fiber dispersion[16]. Hence, it becomes necessary to investigate the nonlinear effects on a dispersion compensated link for a complete understanding of the limitation of the DCF compensating technique in a fs-pulse transmission system. Previously, the SPM effects on the dispersion compensated link with DCF were studied only in the sub-10 to 100 ps range. As the pulse width of the transmission link is continuously decreased into fs regime, the pulse broadening and recompression factor will be drastically increased. The cubic phase will also be significantly increased.

5.3.2 Application of Self Phase Modulation

1. Pulse restoration

Optical communication systems that use the return to zero (RZ) data format and operate at 40 Gb/s and beyond require new techniques to combat transmission effects that lead to pulse broadening distortion like polarization mode dispersion (PMD) and higher order chromatic dispersion. Techniques exist to correct for PMD. The main problem with these methods is that PMD in a transmission fiber varies over time and, thus, they rely on instantaneous information about the actual PMD value as well as orientation of the principal states of polarization (PSP). Restoration of distorted optical pulses is achieved using nonlinear fiber self-phase spectral broadening and subsequent optical band-pass filtering of a single sideband. The advantage with this approach is that, to a certain degree, pulse distortion can be restored using optical nonlinearities and thus no measured information about actual PMD or PSP is required[17].

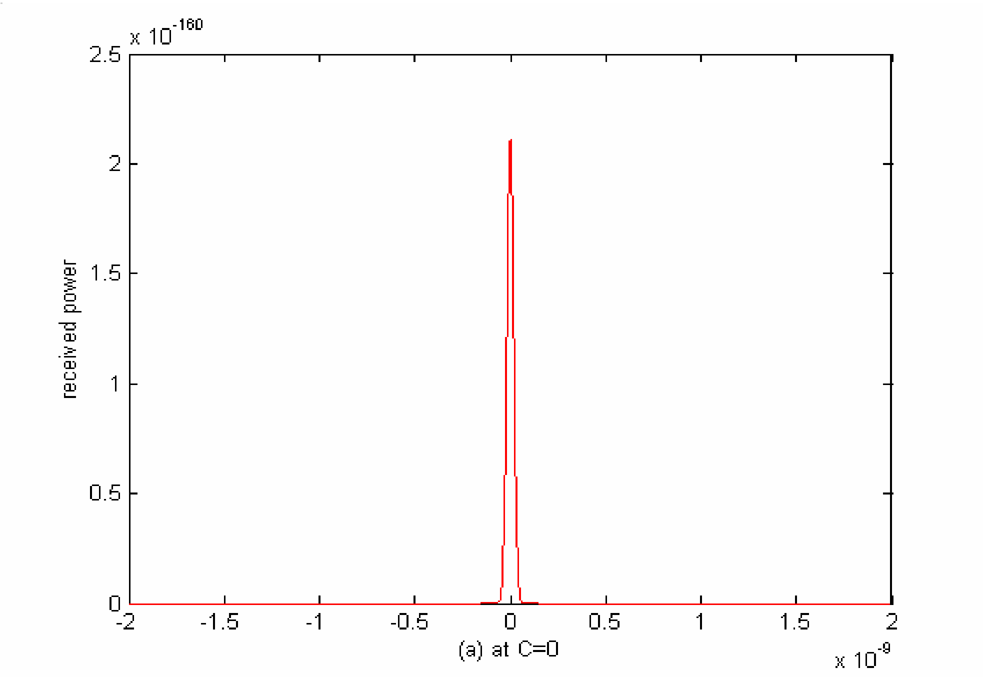
The basic idea is to substantially broaden the spectrum using SPM, and subsequently slice the spectrum with an optical band-pass filter. This filter determines the output pulse-width in the same manner as with a super-continuum source. The filter has to be slightly offset from the original center wavelength to select one of the two generated side bands [15]. The long and short wavelength side bands are originated from the leading and trailing edge of the input pulse, respectively, which allows a shorter pulse at the output than at the input. Thus, the spectral broadening depends on the slopes of the input pulse rather than the actual input pulsewidth. This feature is especially useful to combat pulse-splitting effects like PMD, where at least in the case of moderate first order PMD the pulse slopes. Slicing of a broadened optical spectrum may result in a severe degradation of the SNR if only a very small noise component is present at the input bandwidth. The transferred amount however is different for each channel as it determined by the amount of Raman gain corresponding to the relative wavelength spacing[2].

CHAPTER 6

SIMULATION AND RESULTS

6.1 variation in the received power due to chirp

Figure 6.1(a) - (h) shows the variation of received power Vs time for the chirping factor C = 0 to 7. Figure 6.2 shows the variation of received power and chirping factor.



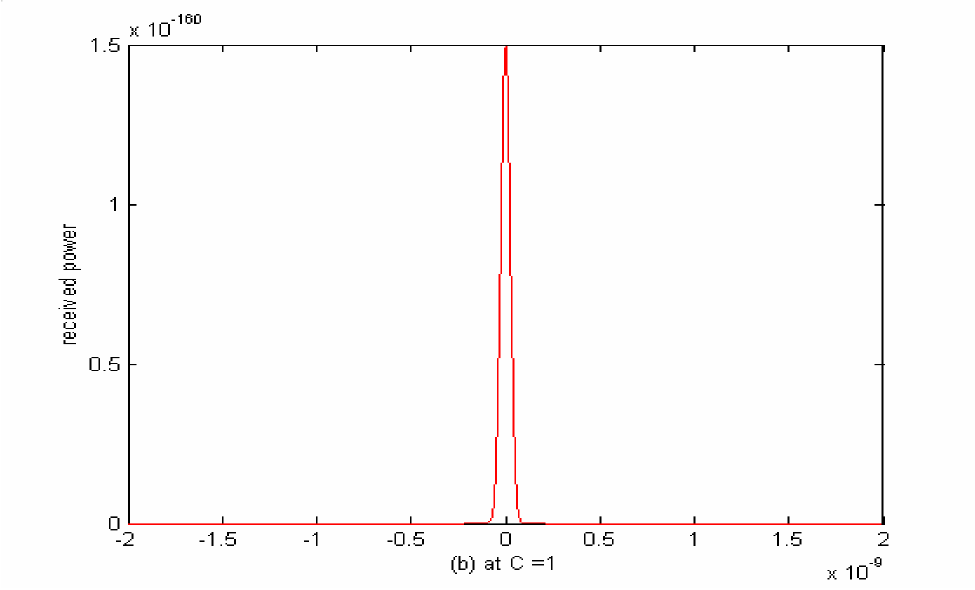
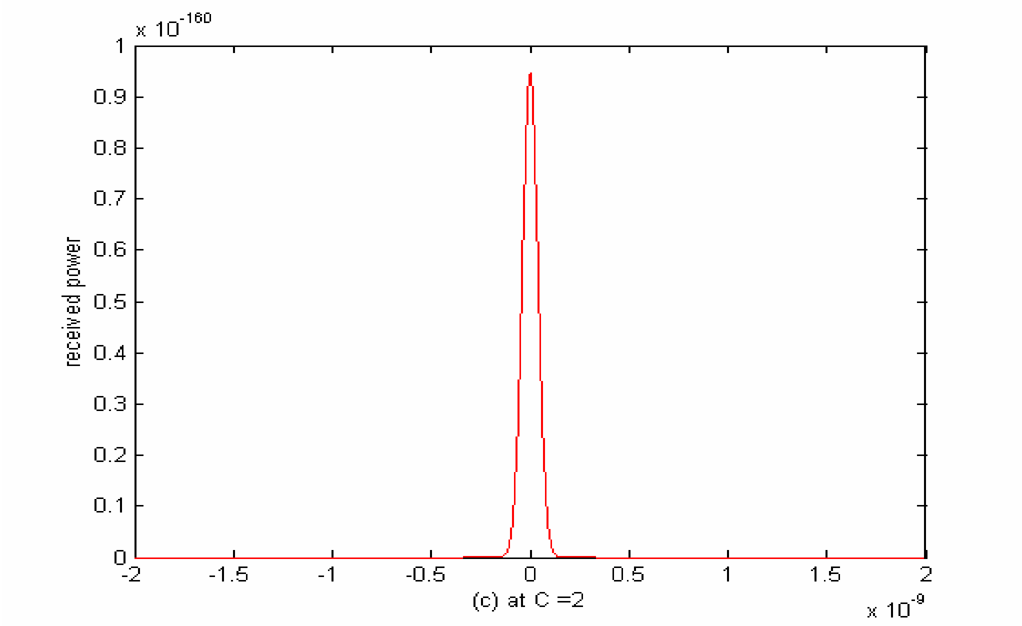
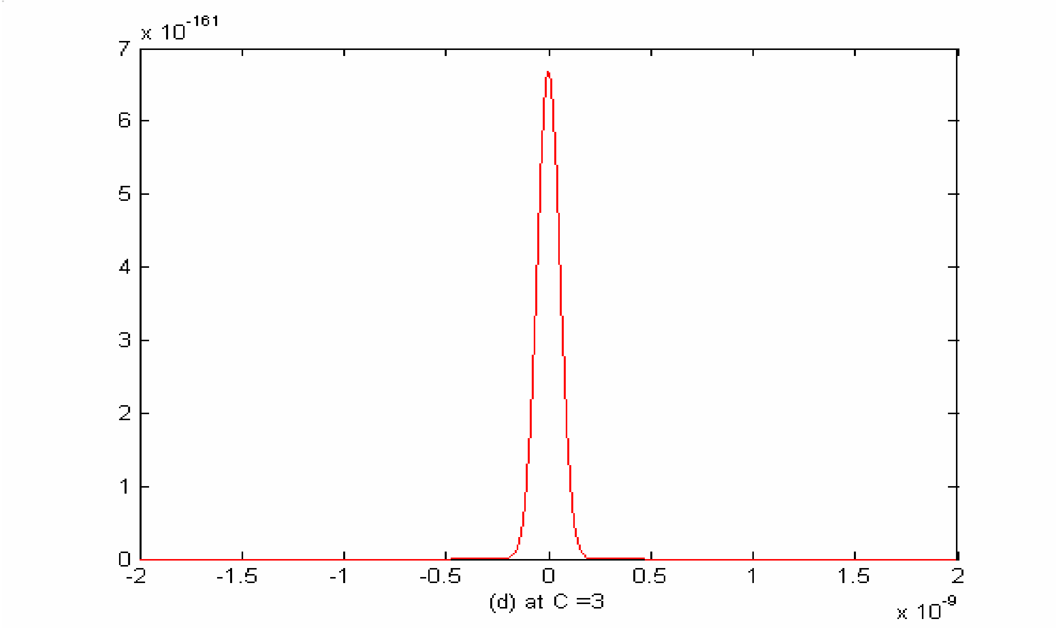


Figure 6.1 Variation of received power VS time for (a) C = 0 , (b) C=1.

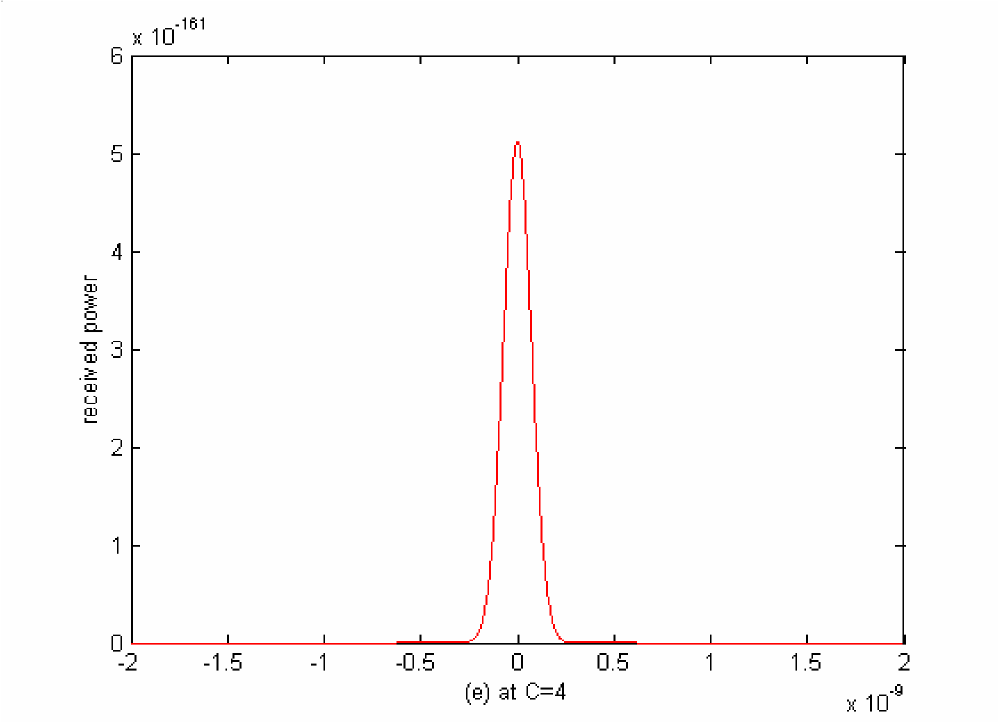


(c) at C =2



(d) at C =3

Figure 6.1 Variation of received power VS time for (c) C = 2 , (d) C=3.



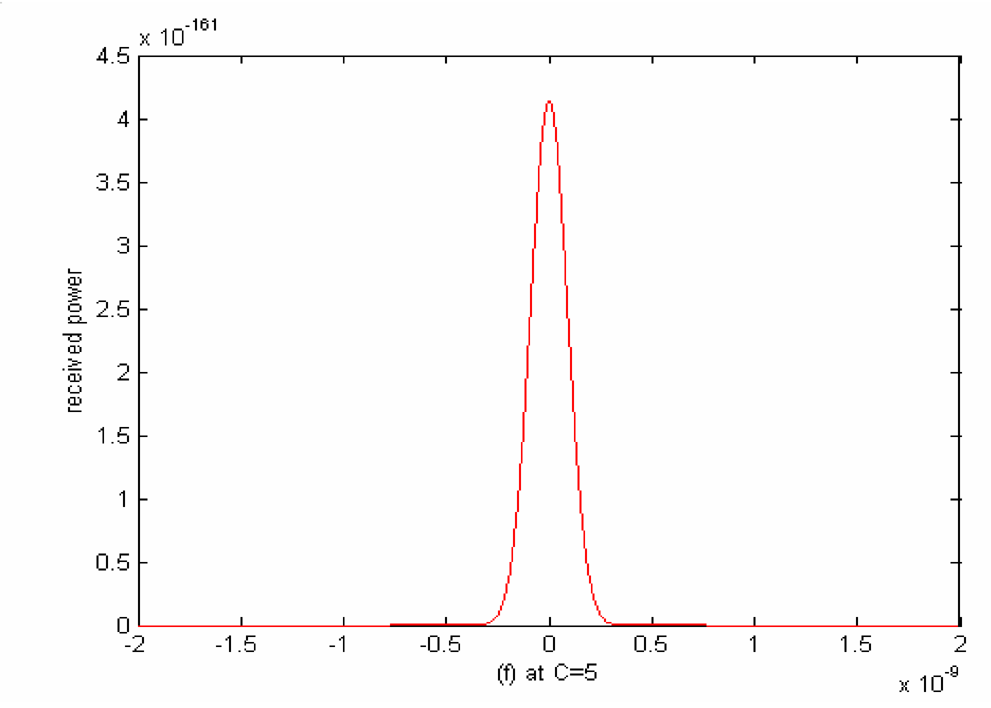
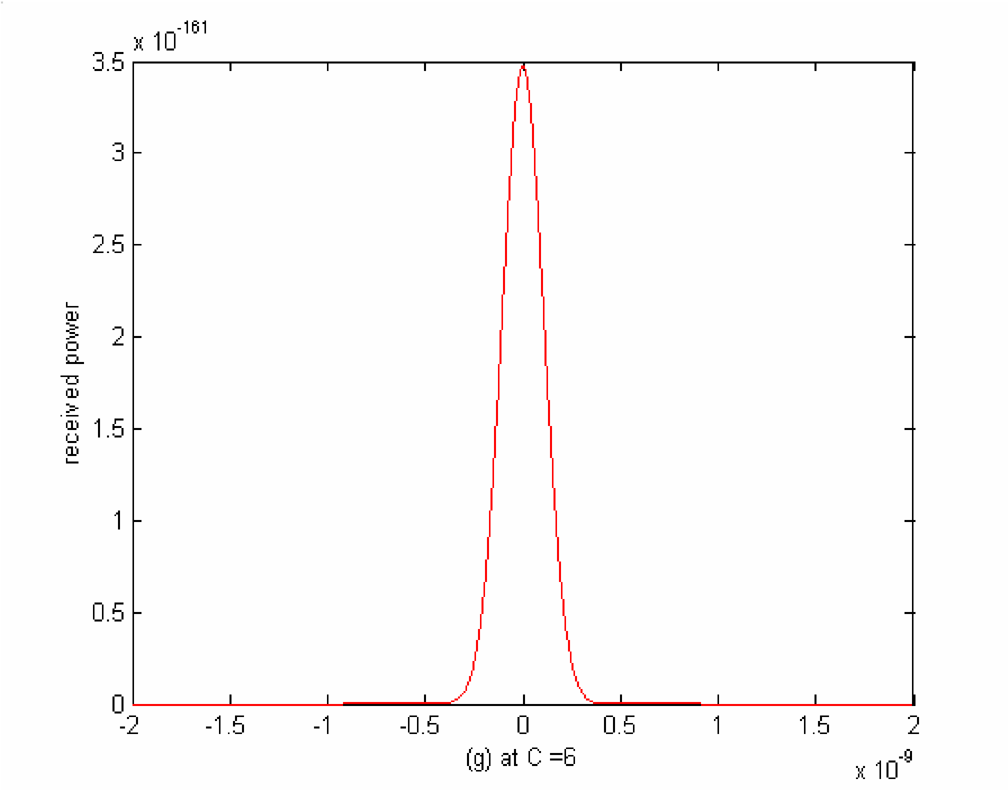


Figure 6.1 Variation of received power VS time for (e) C = 4 , (f) C=5.



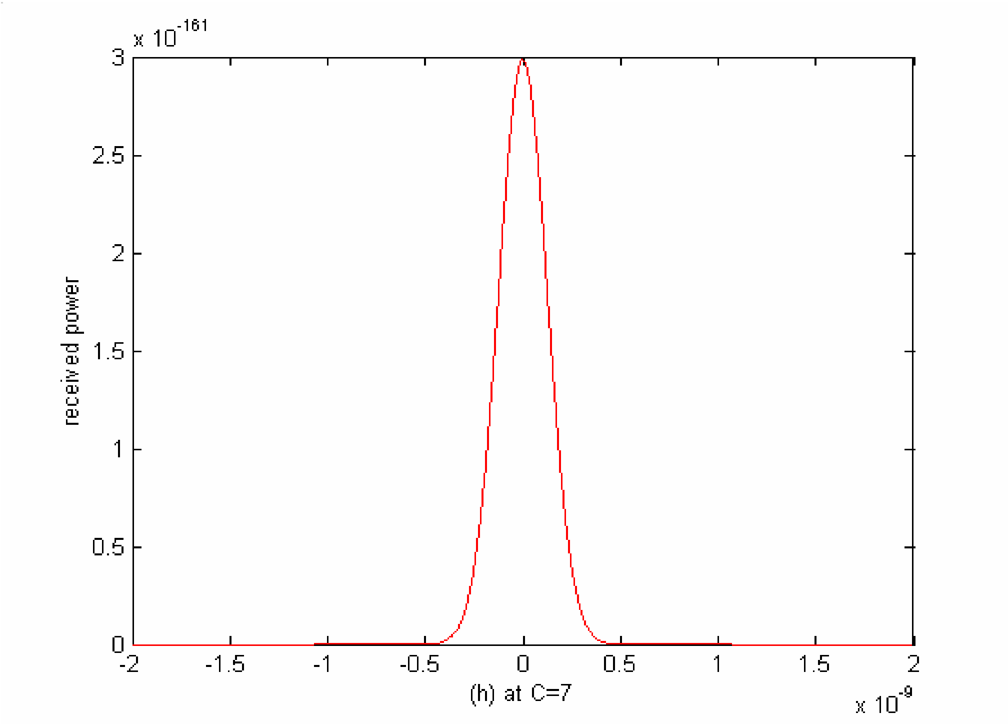


Figure 6.1 Variation of received power VS time for (g) C = 6 , (h) C=7.

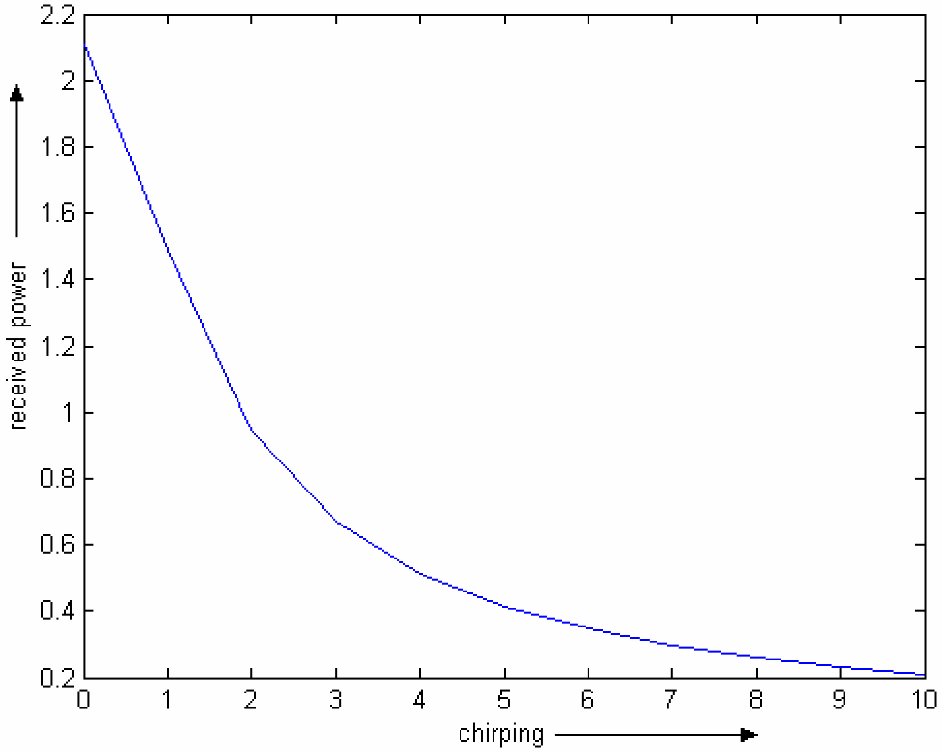
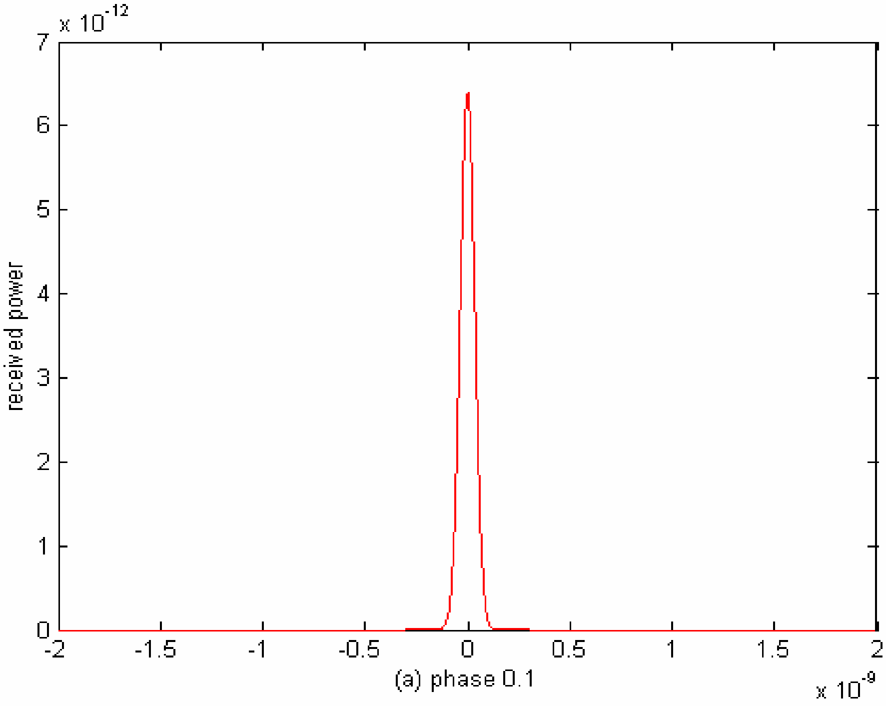


Figure 6.2 Variation of received power VS Chirping factor (C)

6. 2 Variation in the Received Power due to Phase Shift

Figure 6.3(a) - (f) shows the variation of received power Vs time for the variation in phase from (0.1 to 0.05) rad. Figure 6.4 shows the variation of received power and phase.



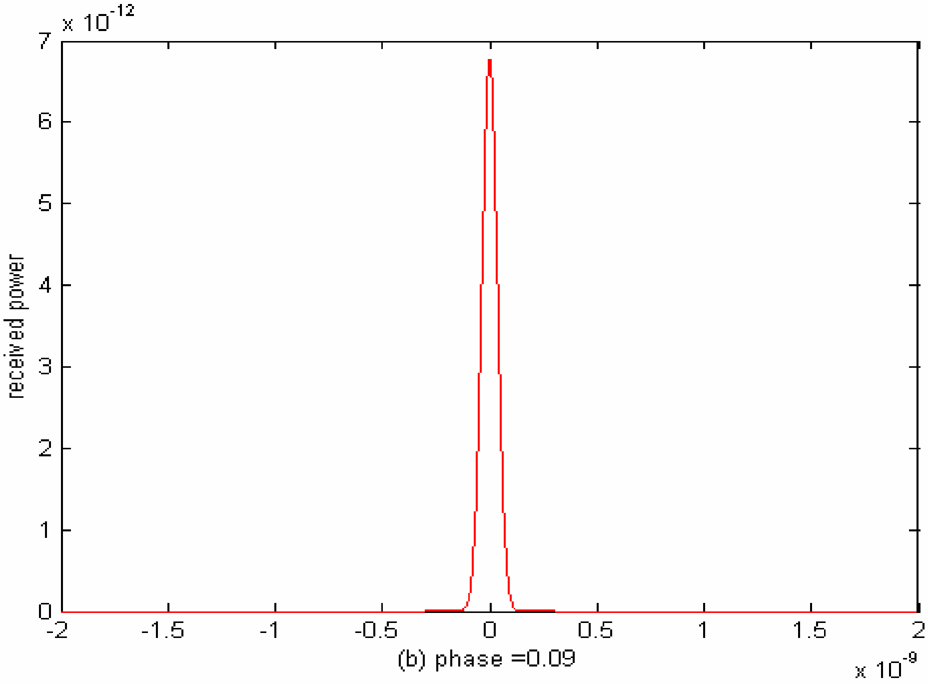
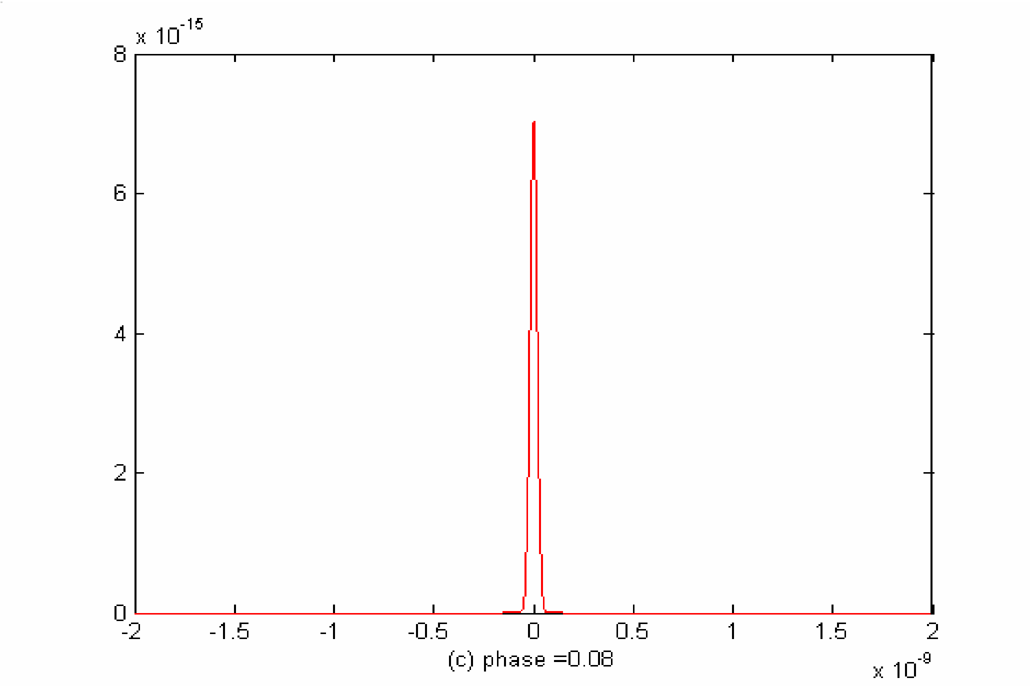
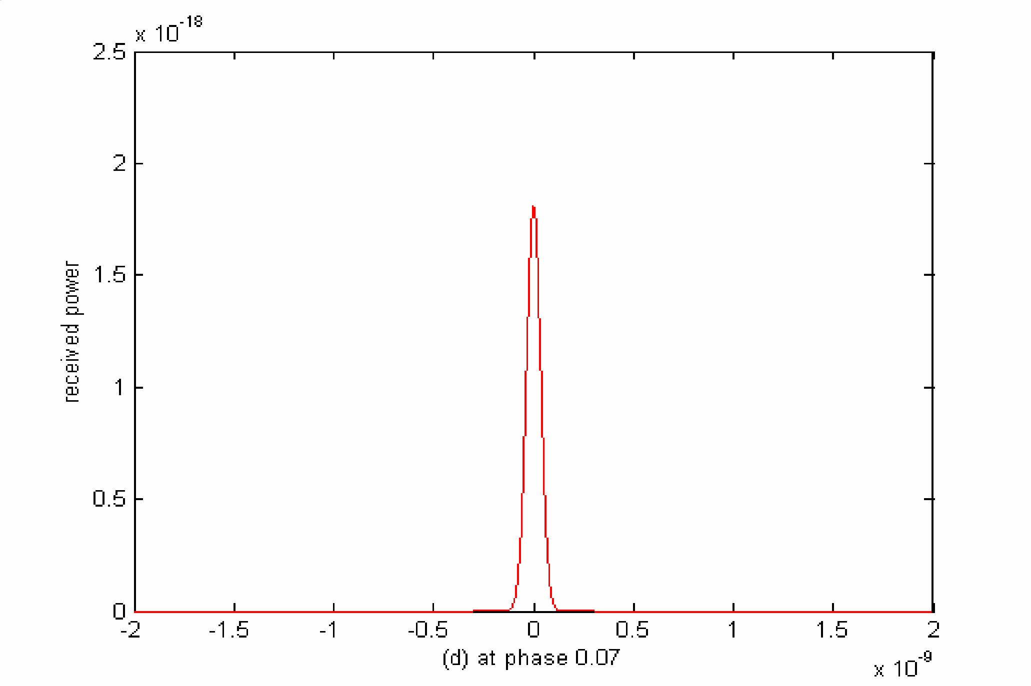


Figure 6.3 Variation of received power Vs time for (a) phase=0.1 rad. (b) phase=0.09 rad.

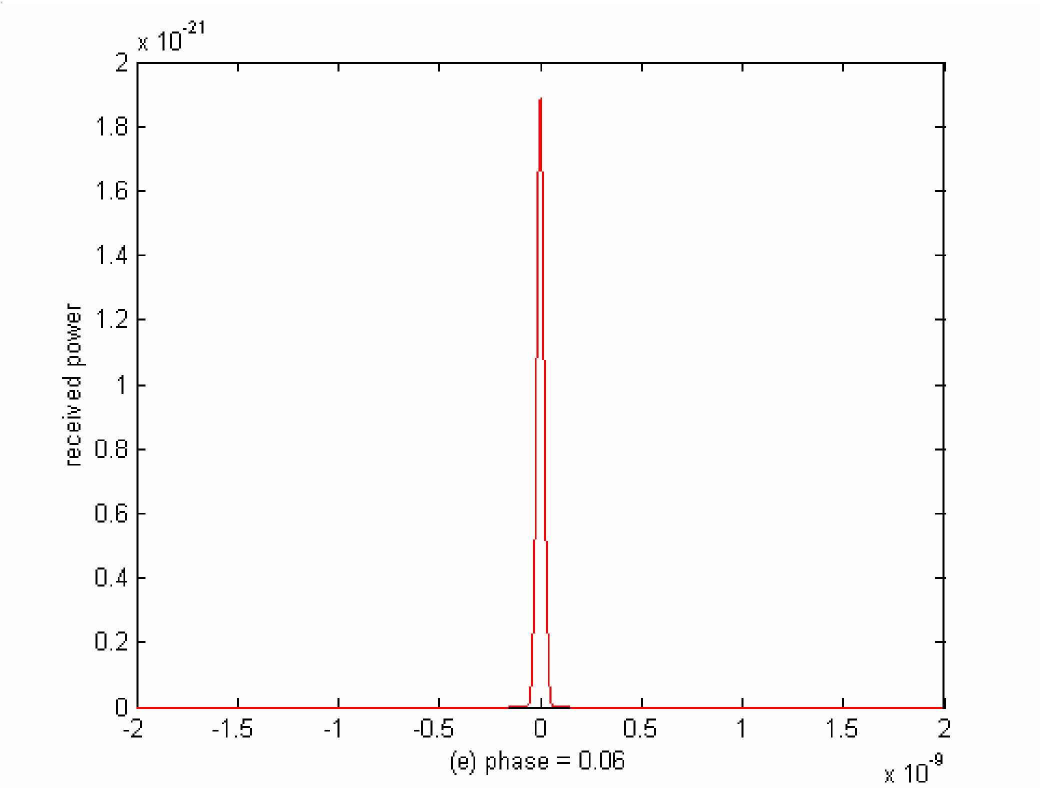


(c) phase =0.08



(d) at phase 0.07

Figure 6.3 Variation of received power Vs time for (c) phase=0.08 rad. (d) phase=0.07 rad.



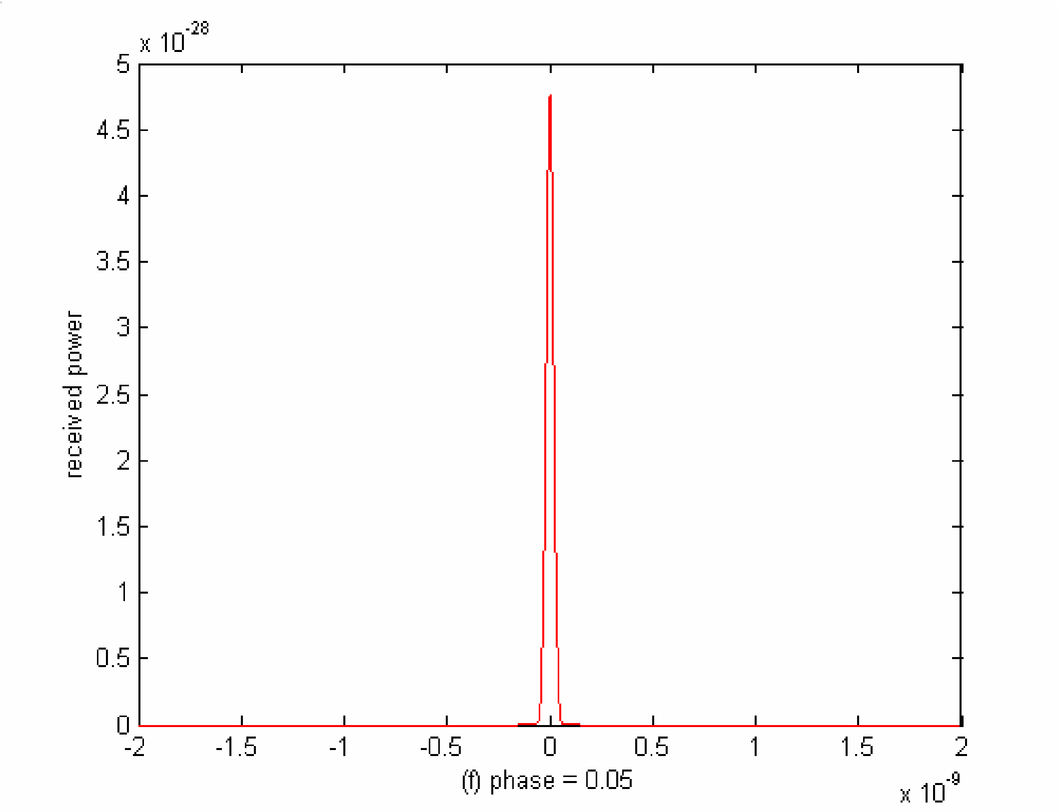


Figure 6.3 Variation of received power Vs time for (e) phase=0.06 rad. (f) phase=0.05 rad.

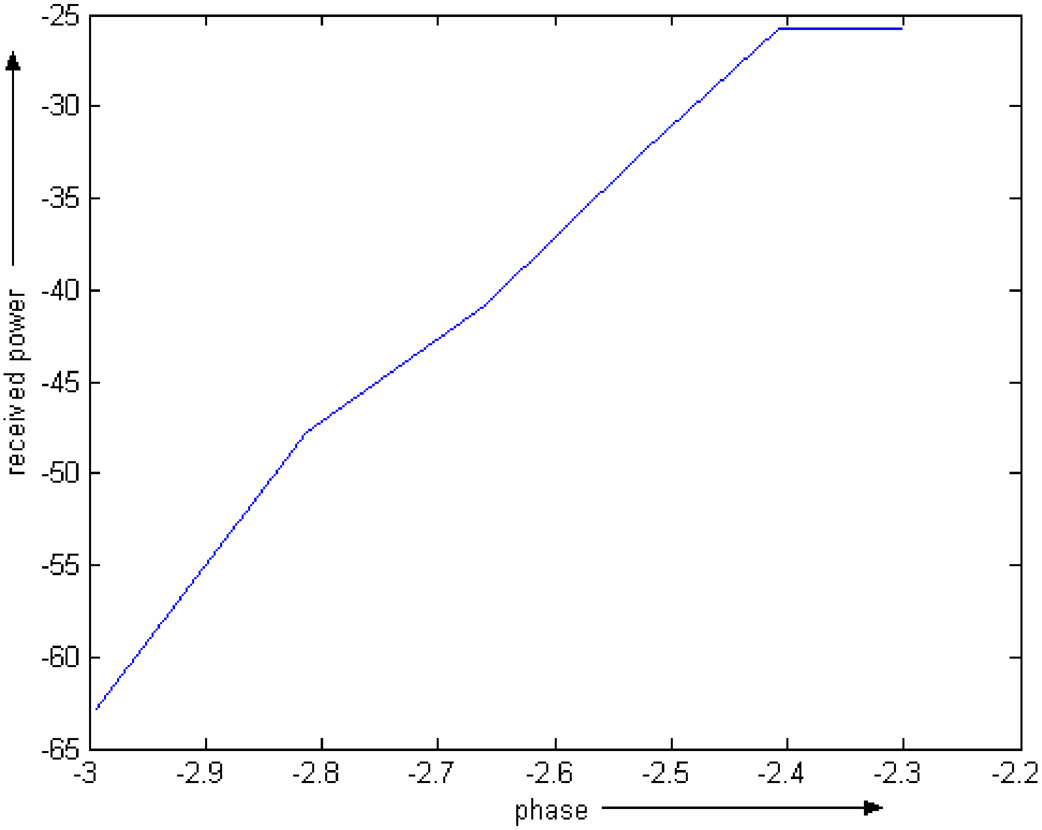
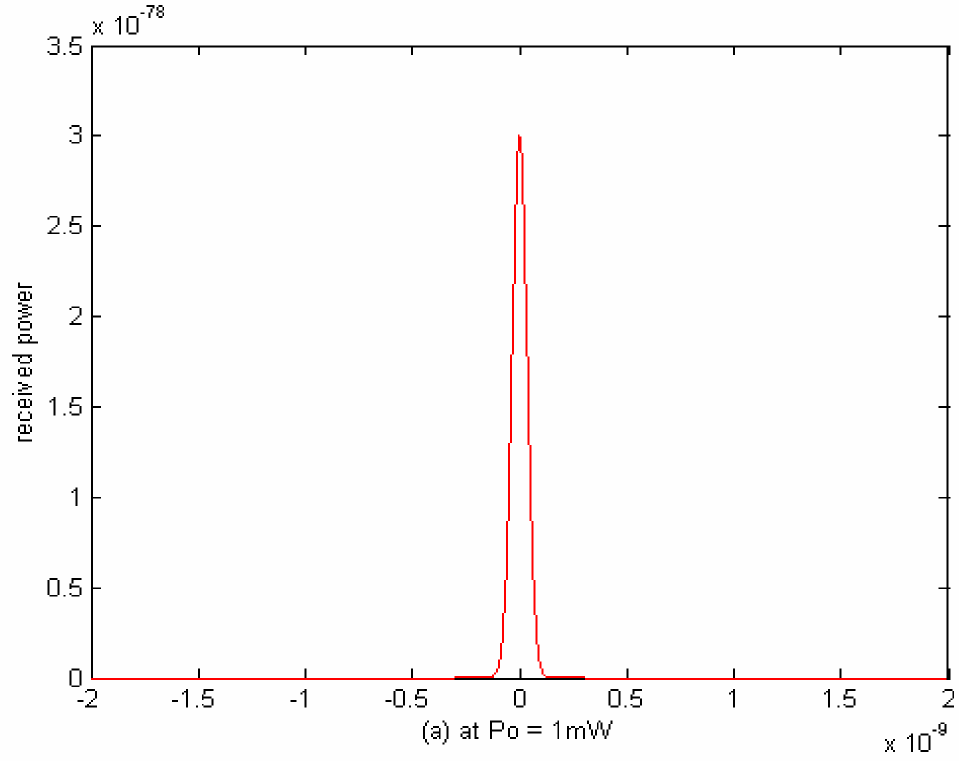
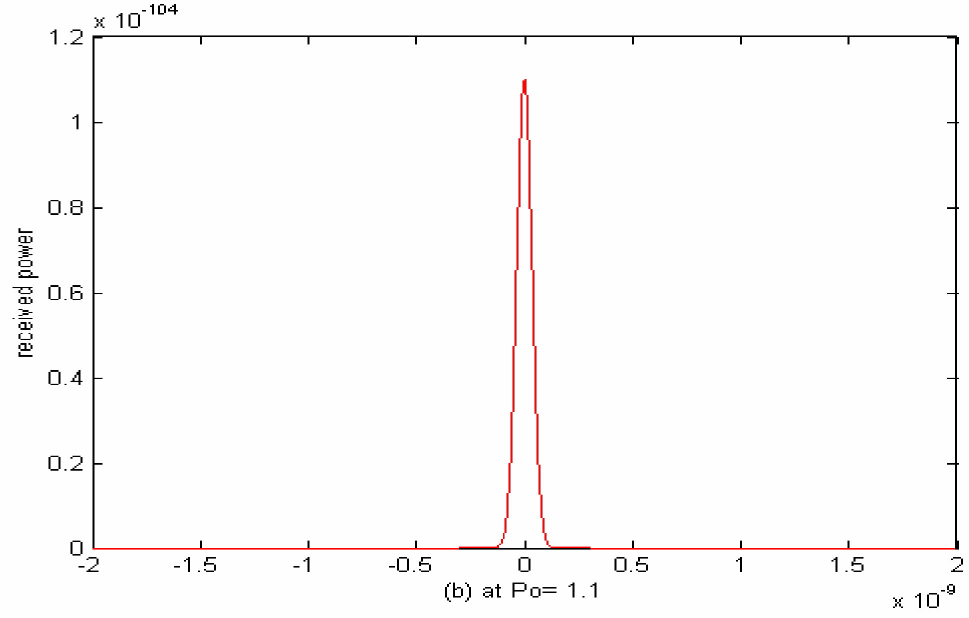


Figure 6.4 Variation of received power Vs log of phase

6.3 Variations in the received power due to input power

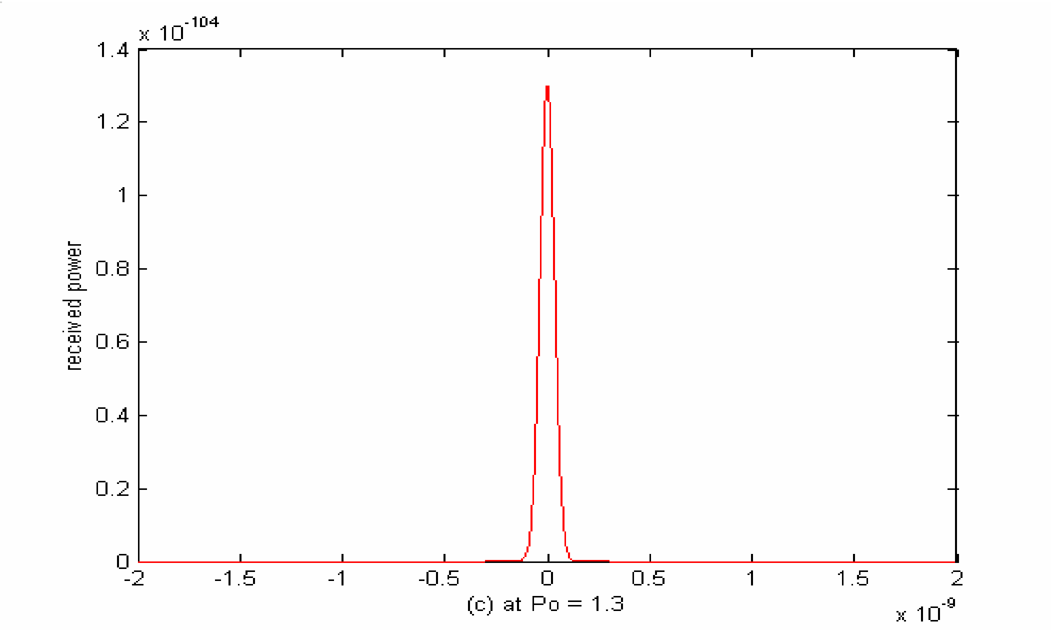


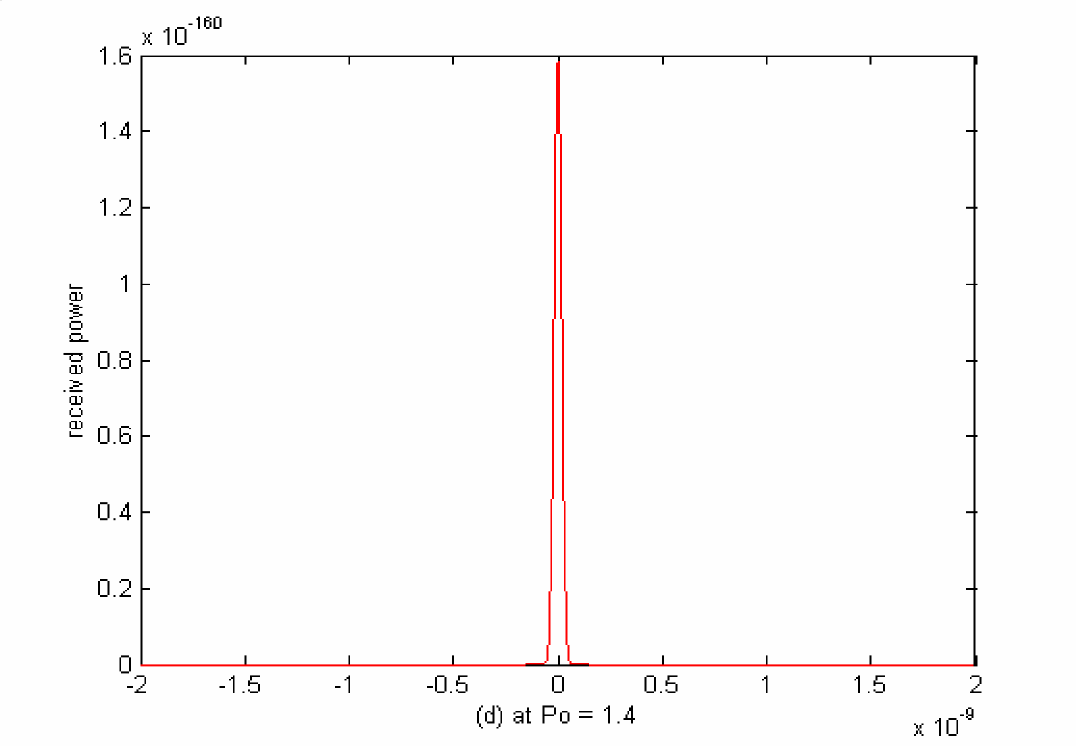
(a) at Po = 1mW



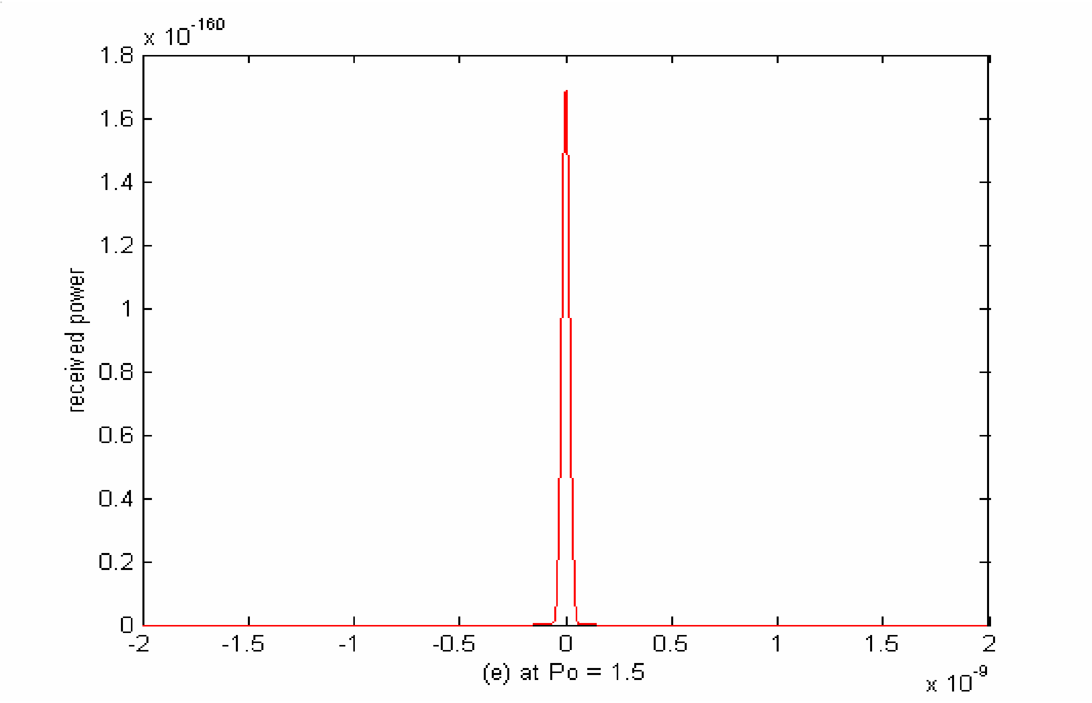
(b) at Po= 1.1

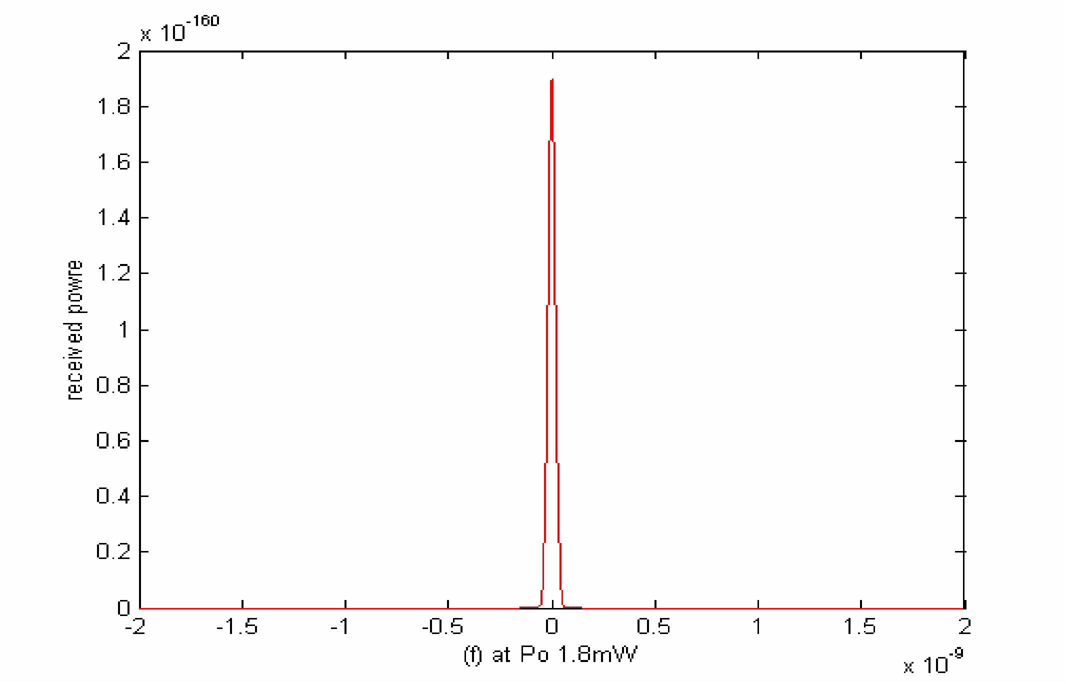
6.5 Variations of received power Vs time for (a) input power =1 mW (b) input power =1.1 mW



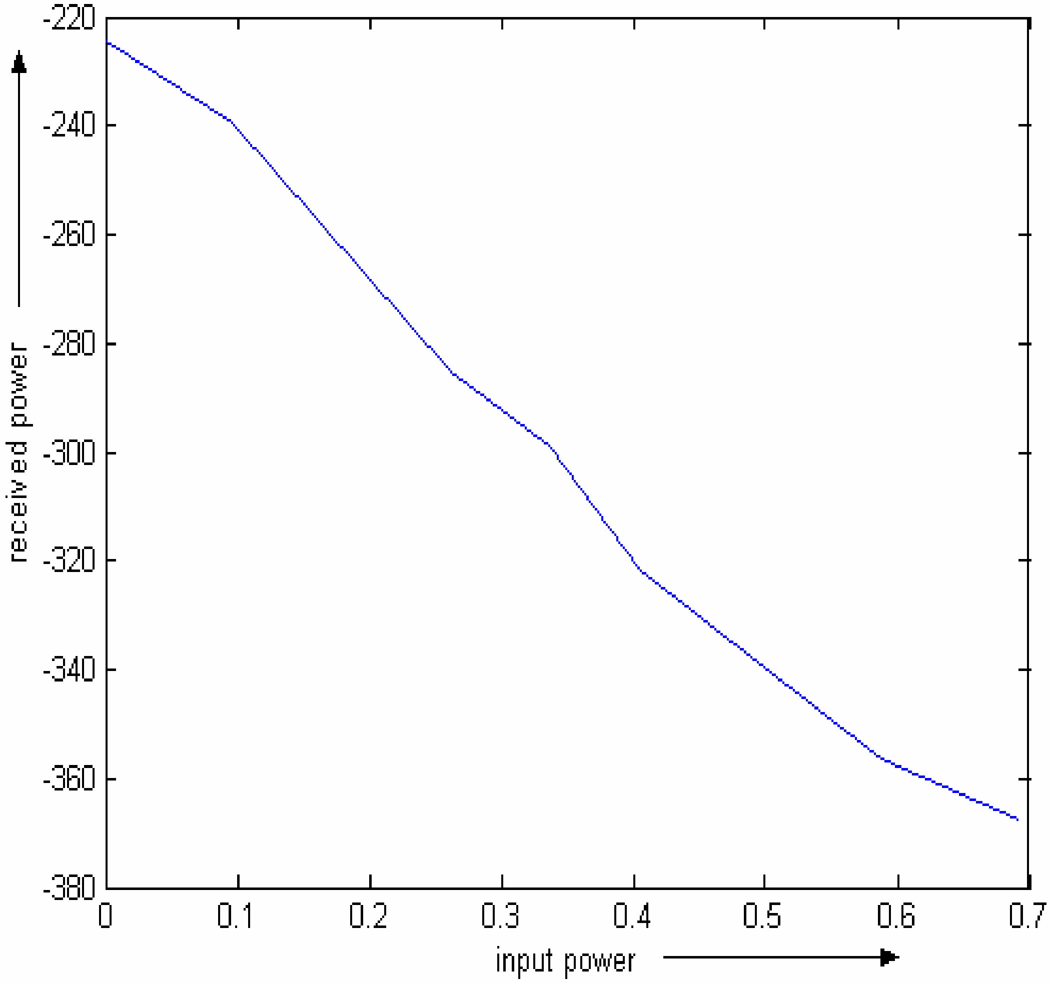


6.5 Variations of received power Vs time for (c) input power =1.3 mW (d) input power =1.4 mW





6.5 Variations of received power Vs time for (e) input power =1.5 mW (f) input power =1.6 mW



6.6 Variations of received power Vs input power

6.4 CONCLUSIONS

The main motivation of this work is to analyze the various parameters. Fiber nonlinearities have become one of most significant limiting factors of system performance since the advent of erbium-doped fiber amplifiers (EDFAs) because input power is increasing and the effects of fiber nonlinearities are accumulating with the use of EDFAs. In wavelength-division-multiplexing (WDM) systems, inter- channel Interference due to fiber nonlinearities may limit the system performance significantly. Therefore, understanding of fiber nonlinearities is crucial to optimize system performance of optical fiber transmission. In this dissertation, effects of fiber nonlinearities on fiber optic communication systems have been studied. The results obtained from simulation are the variation of power with input power, chirping factor, and phase. From 6.1 (a) to (h) & figure 6.2 it can be concluded that chirping factors should be small. For good communication it should be 1. If we consider the case of phase as shown in figure 6.3 (a) to (f) & 6.4 it is clear that with increase in the phase received power decreases So, the phase should be as small as possible. The figures 6.5 (a) to (f) shows the variation in the received power at the receiver end Vs time due to variation in the value of input power. The figure 6.6 show that with increase in the input power, received power decreases because of nonlinearities.. These results show the variation of received power with different parameters like phase , input power and chirping factor.

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