TECHNIQUES TO OPTIMISE DATA TRANSMISSION IN OPTICAL FIBER

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by

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DECLARATION

I, Antone Betrano Omondi Mubinya, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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Signed **Date**

ABSTRACT

Due to the tremendous growth in data traffic and development in optical fiber transmission technologies, the limits of the transmission capacity available with the conventional and modulation techniques have been surpassed. The present work aims at pointing out in-terms of data transmission that Solitons can effectively be a waveguide of choice in transoceanic optical fiber communication systems.

In this thesis Soliton has been identified as the ideal technique for data transmission in long transmission distance. Techniques which have been used in long haul single mode optical fibers to transmit data are discussed and their characteristics mentioned.

Solitons which constitutes a balance between chromatic dispersion and SPM is a transmission technique that adapts to instantaneous channel characteristics and significantly improves optical fiber transmission performance.

Optical fiber transmission is a technology that has been driven by the demands for streaming data and is increasingly used worldwide in the modern days.In the standard single mode fiber, Chromatic dispersion is the linear phenomenon whose effect limits maximum transmissions distance. Chromatic dispersion and SPM act simultaneously in optical fiber to generate a solitary pulse wave used in lightwave.

Dispersion and nonlinearity of the optical fiber are experimentally studied simulations and a comparison result discussed. Matlab simulation code has been used to compare experimental data for soliton and non soliton transmission systems. The parameters of the two techniques were maintained during simulation for the purpose of accuracy of the simulation results.

Practical application of solitons has realised a transmission distance of 70km without regenerators.

Finally, at a transmission length of 100km, solitons simulations showed higher optical level in comparison to non solitons. This practicality proved that with solitons technique, optimisation is achieved when long transmission span can be sustained with the data level not falling below 0.5mW.

ACKNOWLEDGEMENTS

> "The most important and urgent problems of today's Technology
> are no longer the satisfactions of the archetypal wishes,
> but the reparation of evils and damages due to
> the Technology of yesterday".
>
> **(Dennis Gabor, 1900 -1979)**

Understanding research work and its components cannot be the outcome efforts of an individual and knowingly that research work for this thesis has mainly been carried out at the Centre for Distributed Power and Electronics during the years 2010-2011.

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DEDICATION

This research work is dedicated to my family (Cathy, Betty, Val and Mose) and everyone else who helped me along the way to fruitful completion of my studies at CPUT. More so, The Kenya Polytechnic University College, who in July 2009, found it necessary that time was right to join Kaapstad for MTech after serving for eight years as examination co-ordinator in the office of teaching assistant.

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GLOSSARY

ASE	Amplified Spontaneous Emission
CD	Chromatic Dispersion
CFBG	Chirped Fiber Bragg Grating
D	Dispersion parameter
DCF	Dispersion Compensated Fiber
DDF	Dispersion Decreasing Fiber
DSF	Dispersion Shifted Fiber
D_{PDM}	Polarization dispersion coefficient
EDFA	Erbium Doped Fiber Amplifier
EMI	Electro Magnetic Interference
FBG	Fiber Bragg Grating
FIR	Finite Impulse Response
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FWM	Four Wave Mixing
FWHM	Full Width at Half Maximum
GVD	Group Velocity Dispersion
ISI	Inter Symbol Interference
ITU	International Telecommunications Union
LAN	Local Area Network
MATLAB	Matrix Laboratory (modeling software package)

N.A.	Numerical Aperture
ns	nanosecond
NSE	Nonlinear Schrodinger Equation
QPSK	Quadrature Phase Shift Keying
P_{in}	input Power
P_o	output Power
PMD	Polarization Mode Dispersion
RZ	Return to Zero
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SI	Step Index
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SSFM	Split step Fourier Method
SSMF	Standard Single Mode Fiber
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
XPM	Cross-phase modulation

LIST OF SYMBOLS

A_{eff}	effective core
b	normalised propagation constant
B_j	oscillator strength
c	speed of light
g_R	peak value of Raman gain
n_0	linear refractive index
n_1	respective core refractive index
n_2	respective cladding refractive index
$D(\lambda)$	Chromatic dispersion
I	field intensity
FN	linear ratio of noise figure.
fs	femtosecond
G	linear gain ratio
g_m	silica electro optical coefficient
h	Planck's constant
L	optical fiber length
L_D	dispersion length
L_{eff}	effective interval length
L_{NL}	nonlinear length
M	induced electric polarization

ps	picoseconds
P	induced magnetic polarization
r_0	wavelength dependent field radius
t	pulse movement measured time
t_0	solitons width.
T_0	pulse width
V	normalised frequency
v	photon frequency
z_{eff}	effective transmission distance
z	pulse propagation distance
α	attenuation constant
α	optical fiber loss
α_{dB}	loss dependent on wavelength
β_2	dispersion parameter
β	propagation constant
γ	nonlinear coefficient of the optical fiber
λ	operating optical wavelength
λ_j	resonance wavelength at which electrons oscillate
λ_C	cut off wavelength
$\Delta\lambda$	signal spectral width
μ_0	vacuum permeability

u	measure of electric field envelope
φ_{NL}	nonlinear phase change
ϕ	initial phasechange
Δt	pulse spread
ω	frequency
ω_0	pulse carrier frequency
ε_0	vacuum permittivity
τ	pulse's dimensionless delay time.
ξ	solitons length

CHAPTER ONE

1 INTRODUCTION TO THE RESEARCH

1.1. INTRODUCTION

The aim of the first chapter is to set the work of the thesis by highlighting some problems associated with data transmission in optical fiber. The chapter introduces historical overview, motivation and objectives, the thesis outline and the other chapters cover optical fiber communication technology.

1.2. HISTORICAL OVERVIEW

Optical fiber transmission is a technology that has been driven by the demands for streaming data and is increasingly used worldwide in the modern days.The explosion of information traffic coupled with the increase of internet use has led to a high demand for communication services. The unprecedented amount of information being transferred over the internet and the streaming data makes the world to change every second due to optical fiber communication network around the world.

The analogue devices that convey information along copper cables using electronic devices have great difficulty in responding to huge demand for information. This is mainly due to the fact that these devices are too slow and noisy compared to optical fiber cable. Digital optical systems attain much higher bit rates than electronic devices.

Long haul optical fiber systems can transmit voluminous data using a single channel but Gaussian pulses that propagate through an optical fiber suffer from both dispersion and nonlinear effects.

Modern communication techniques rely on optical fiber which is commonly used as central information superhighway. Optical fiber has been deployed by Banks, Universities and Telecom operators for streaming media over the Internet due to data security and reliability. Coupled with advantages listed below, high information carrying capacity of optical fiber has proved to be a solution to ever increasing real time systems.

- a single optical fiber can replace thousands telephone channels with full capacity,
- low transmission loss minimises the need for amplification of signal for many kilometres, and
- safety and economical, no risk of spark and cost per transported bit is very low.

Although above advantages makes it attractive, some obstacles associated with using optical fiber technology must be overcome. The transmission capacity of an optical fiber depends on the transmission length, (Paschotta, 2011).

However, the potential cannot be fully utilized due to optical fiber dispersion that emanates from optical fiber design parameters, mainly material and waveguide.

1.3. BACKGROUND OF STUDY

An optical fiber is glass or plastic fiber consisting of three layers, core, cladding and jacket and has the ability to guide lightwave along its axis. The receiver converts the received optical signal into a photocurrent. The current drives electronic amplifier and a circuit for receiving the information transmitted. Signal fluctuations add impairments to the data being transmitted thereby changing their properties.

In this thesis, the two main impairments to be discussed are the dispersion and nonlinear effects, (Rashed, 2011. Joindot & Gosselin, 2008).

Several optical soliton phenomena have been studied extensively in the area of nonlinear optical systems. They include spatial and vortex solitons in photorefractive material, waveguides and cavity solitons in resonators and the nonlinear Schrodinger solitons in dispersive optical fibers, (Kivshar & Agrawal, 2003).

In single mode fiber, nonlinear effects are constituted by Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing, (Joindot & Gosselin, 2008).

1.3.1. OPTICAL FIBER CHARACTERISTICS

The need for communication is the necessity of all human beings and optical fiber is a channel among many other channels for communication. Dispersion phenomenon is a problem for high bit rate and long haul optical communication systems. The alternative solution to this problem is soliton,a pulse that preserve its shape over long distances. Solitonstechnique has experimentally been tested and found to be capable of transmitting data over long distances.

1.3.2. THEORETICAL STUDY OF SOLITONS

James Scott Russell first discovered solitons in 1834 when a mass of water in a canal propagated undistorted over a long distance and he called this mass solitary wave, (Russell, 1834). Later, Kivshar & Agrawal, (2003) reported development during the 60's of inverse scattering model, a mathematical method used to explain the properties of the solitary waves.

The term soliton was coined in 1965 to reflect the particle like nature of a solitary wave that maintains its original shape even after collisions. In nonlinear optics, solitons are classified as either temporal or spatial soliton depending on whether light confinement occurs in time or space during wave propagation, (Rashed, 2011. Mohammed& Rashed Z. 2010.www.cse.saford).

In 1973, Hasegawa and Tappert of AT & T Bell Labs were the first to suggest that solitons could exist in optical fiber due to a balance between SPM and anomalous dispersion. In the same year, Bullough made the first mathematical report of the existence of optical solitons and proposed the idea of a solitons transmission system to increase performance of optical fiber in telecommunication, (Gedalin, et al. 1997. Aitchison, et al. 1992.Barthelemy, et al. 1985).

Mollenauer et al. (1980), succeeded in observing optical solitons in optical fiber. During the 90's, spatiotemporal solitons and quadratic solitons were discovered, (Kivshar & Agrawal, 2003).

The first demonstration of solitons pulse transmission that attained over 4,000km was realized by using Raman Effect, (Mollenauer et al. 1988).

Bell Labs,(1991) research team transmitted solitarypulse at 2.5Gb/s over 14,000km using ErbiumDoped optical Fiber Amplifiers (EDFA) and pump lasers, coupled to the optical amplifiers that energized the lightwave pulses.

Nakazawa, (1995) transmitted 20Gb/s error free soliton over a distance of 2 000km in Tokyo, (Beeckman, et al. 2004. Gedalin, et al. 1997).

Knox, et al. (1996) setup an experiment which used a combination of both solitons and dispersion compensation to increase the data rate of existing systems. They demonstrated that soliton can transmit data at 10Gbit/s over 842.5km on standard optical fiber using dispersion compensation in each amplifier.

Georges et al. (1998) in France Telecom R&D Centre combined solitons of different wavelengths (wavelength division multiplexing) and demonstrated a data transmission at 1Tb/s.

Practical use of solitons became a reality in 2001, when Algety Telecom in France deployed submarine telecommunications equipment in Europe. Using John Scott Russell's solitary wave theory, the shortest solitons pulse of approximately 15.6fs was developed, (Chakraborty, 2008. Igarashi, 2004).

Solitons concept has penetrated into almost all branches of science where scientific phenomena are described by nonlinear partial differential equations. In optical fibers,Solitonsrefer to a situation where light beam propagates through a nonlinear optical medium without any change in its shape and velocity, (Ganapathy et al. 2008).

1.4. RESEARCH QUESTION

Deregulation of telecommunication markets and global expansion of internet has increased the demand for high capacity system thereby creating the problem of optimising data transmission.

Optimization in optical fiber context refers to controlling of data impairments in an optical fiber network. Whenever changes occur in communication network, necessary control action is required for data reliability. In this thesis we concentrated on optimising data by controlling nonlinear effect of transmitted data.

Kubota et al. (1993) explained that solitons are information carriers for long haul and high bit rate systems because the pulse has short duration and high stability. The need to identify a data transmission technique, establish its performance then set improvement modality for telecommunication industry, (Kumar, et al. 2007).

It is appropriate to establish a technique that compromises impairments and the research question that links the possibility of application is stated below;

Can the solitons technique improve the optical fiber cable data transmission length?

1.5. OBJECTIVES OF THE RESEARCH

Several techniques have been used to transmit data globally but some of which introduce draw backs like attenuation, noise, jitter, pulse broadening and nonlinear effects. In order to establish a technique which can minimise the data loss, different techniques are evaluated. The major challenges for optical fiber propagation are the optical fiber nonlinearity and dispersion. This fact motivated the choice of optical fiber in data transmission systems and the problem is stated as;

To suggest a technique to optimise data transmission in optical fiber cable without compromising data quality by;

- simulating a single channel optical fiber cable using solitons system,
- demonstrating solitons efficiency on optical fiber, and
- determining the maximum optical fiber length for data transmission.

1.6. SCOPE AND LIMITATIONS OF THE PROJECT

The cost involved in experimental study is colossal hence it is not possible to carry out a practical experiment. Simulation using appropriate software can provide a replica solution to practical situations. The cost of equipment required for the practical demonstration is not attainable by an institution or small industry.

- The research emphasis is on determining the minimum optical fiber length suitable for long haul data transmission,
- Other nonlinear parameters will be assumed and the research that will cover both single mode optical fibers, and
- Finally, simulation will summarize the objective of the research.

Optimisation of transmission in optical fiber is governed by optical fiber nonlinearity, dispersion, signal intensity and optical fiber length. The research is to determine the optical fiber length at which minimum intensity can be detected.

1.7. SIGNIFICANCE OF THE RESEARCH

Upon gaining independence, the lack of an adequate telecommunication infrastructure impeded national growth in many African states. Optical fiber network has created an opportunity for Africa to link up with international telecommunication operators and utilize the network to bridge the digital divide which includes urban and rural areas. The wide band connectivity ensures fast delivery of video, data for e-commerce, e-learning and government among others.

Above all, it reduces the cost of social services across the continent through telemedicine, e-learning and outsourcing ventures. Network improvement will provide opportunities for international companies to venture into business like mobile phone and other interactive digital software industries.

According to Jansen et al. (2005), impairments of data transmitted in optical fiber should to be addressed and a technique to improve them be identified. The significance can be stated as;

The project work could open new technical contributions in the Southern Africa and in particular, African nation's telecommunication industries.

1.8. THESIS OUTLINE

The thesis starts with introduction to optical fiber and its impairments but the emphasis is on SSMF and soliton technique. The following chapters chronologically describe the main topics of this project.

Chapter 2:	Types of optical fibers, their characteristics and data transmission techniques. Description of the fundamental properties of optical fibers and various techniques that have been deployed to convey data using optical fibers are discussed.
Chapter 3:	Linear optical fibers. Introduction to linear optical fibers, description and fundamental properties and the existence of optical fiber losses and optical windows and are discussed.
Chapter 4:	Nonlinear optical fibers. Introduction and the issue of optical fiber nonlinearities are discussed in general form.
Chapter 5:	The relation between Maxwell's equations and lightwave propagations with regards to data transmission in optical fiber systems is analysed.
Chapter 6:	Simulations non soliton and solitons wave and data transmission in optical fiber systems. Various lengths are simulated and a comparative results on the same drawn.
Chapter 7:	Finally, conclusion regarding solitons practicality in long haul transmission systems and a recommendation in relation to the findings of simulations is drawn.

1.9. OPTICAL FIBER CONTRIBUTIONS

Efficient pulse propagation in optical fiber is important in telecommunication industry. In this research, discussions on optical solitons and simulations are done to further increase the understanding of optical fibers' impairments that data transmitted endure during propagation.

Research on solitons is primarily for transmission over long uninterrupted paths, such as in undersea cables.

Seacom, a telecommunication player using optical fibers owns an optical fiber link along the East-Coast, linking Southern region to East and Central Africa, Middle East and India but employ WDM to transmit data using soliton technique. Transmission uses EDFA in a bunch of optical fibers to cover several transmission distances.

CHAPTER TWO

2. LITERATURE SURVEY

Present research work provides increase attention to optical fiber communication where dispersion and nonlinearity effects are limitations. In this Master thesis the attention is focused in solitons communication and chapter II discusses some of the techniques being used in optical fiber to optimise data transmission.

2.1. INTRODUCTION

The following are the techniques that could be used to optimise data transmission in an optical fiber.

- a bunch of optical fiber cables that requires a large housing facility can be deployed but the technique is expensive and is heavily affected by optical fiber impairments,
- the use of forward and return path to limit cross-talk interference, but the design is prone to optical fiber impairments and requires a rack space in the housing facility. This may reduce the cost in comparison to the first technique, and
- other techniques are covered in the next sections

2.1.1 REVIEW OF OPTICAL FIBER

Optical fiber offers a small, light weight, flexible and secure means of distributing data globally while suffers a loss of less than 0.2dB/km. Light weight, small size, flexibility, minimal attenuation and immunity to Electromagnetic interference (EMI) are all characteristics that make an optical fiber attractive data distribution waveguide globally. Transmitted data includes, voice, video, and other applications, making them the backbone of the Internet and telecommunication industry infrastructure, (Witcher, 2005).

According to Tyndall in 1870 as cited by Goff, (2002), experiment of a beam of light with water showed that water's internal reflection enables light to follow a defined path. Ten years later, optical telephone device (photo-phone) was patented by Alexander Graham Bell (1880) and it could only carry detectable light a few meters in a free space.

Photo-phone was the greatest invention then since it allowed sound signals to be encoded into a beam of light with intensity for different tones, transmitted then decoded to sound. Photo-phone did not last long since it required a visible line of sight between the emitter and receiver. Later, research on light reflection and refraction phenomena the problem of sound transmission.

O'Brien and Kapany, (1950) introduced a high loss first practical optical device, the fiberscope and coined it optical fiber in 1956. Semi conductor laser technology revolutionized optical communication systems by reducing the optical loss and glass impurities that limited data transmission distance.

The innovation process was driven by technological competition among firms in the U.S., Great Britain, Japan, and Holland. Chicago became the first city to use an optical fiber telephone system after the U.S. military started using optical fiber technology for communications and other applications in the 1970's. Due to the advancement in single mode fiber splicing technology, GTE and AT&T soon followed by a single strand replacing several copper cables.

High bandwidth single mode fibers have been used more than multimode fibers since it became the waveguide of choice for long haul systems in 1984.However, chromatic dispersion is the limiting performance parameter in the optical fiber. It originates from the wavelength dependence of the propagation constant and contributes to different propagation velocities at different wavelengths, (Li& Nolan, 2008).

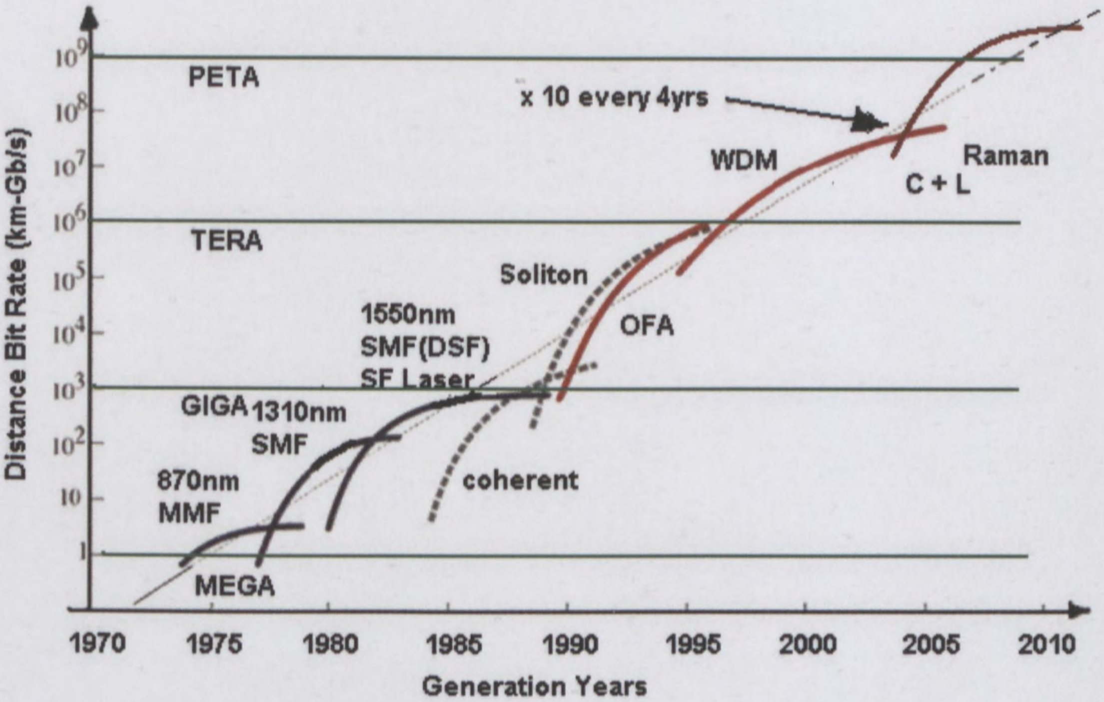


Figure 2.1: Generations of Optical fiber

(Adapted from Desurvire, 2006.Witcher, 2005)

The generations of optical fiber (Giga, Mega, Tera, Peta) illustrates is illustrated in Figure 2.1 from which 1970 was the initiation year and LED was used as the lightwave source. The first three generations of optical fiber were based on progress in optical fiber technology and semiconductor laser sources at 1310m then 1550nm. Capacity-distance product which is an indicator of optical transmission network's ability to transmit data, has increased tenfold every four years for the past three decades. The performance then was due to optical fiber attenuation and modal dispersion.

Single mode fiber (SMF) at 1300nm is limited by optical fiber attenuation where as dispersion in this region is low. At 1550nm wavelength optical fiber performance is limited by material dispersion. Transmission systems using dispersion shifted fibers are employed in the 1550nm window to reduce jitter and soliton interactions without decreasing the signal power.

The fourth generation appeared as a move to enhance the photon receiver sensitivity and transmission distances. In the fifth generation, laser diode pumped EDFA has enabled several complementary technologies, (Desurvire, 2006).

2.2 OPTICAL FIBERS AND SIGNAL DEGRADATION

Data transmission in optical fiber depends on the nature of light and optical fiber structure because optical fiber has a large information carrying capacity. Lightwave The method uses the concepts of reflection and refraction mode theory that treats lightwave as electromagnetic waves, (Bergano, & Davidson, 1996).

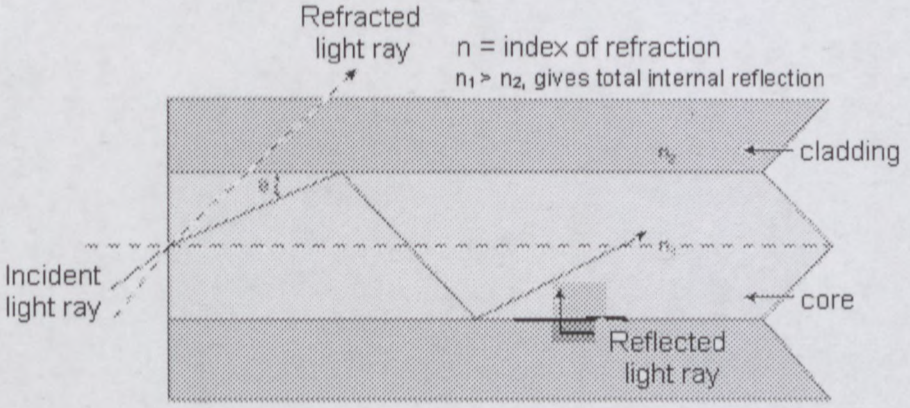


Figure 2.2: Total internal reflection

(Adapted from Kartalopoulos, 1999)

Total internal reflection necessary to confine the light to the core is achieved when refractive index of the cladding is about 1% less than the core. It occurs when a beam of light strikes the surface at an angle less than the critical angle as shown in Figure 2.2. The requirements of critical angle is met by controlling the angle at which light is injected into the optical fiber but second beam which does not meet the critical angle requirement is refracted, (Kartalopoulos,1999).

The total internal reflection occur when light is totally reflected in the optical fiber core due to refractive index of the core and cladding as depicted in eq.(2.1) derived from Fig 2.2.

$$\theta_c \geq \sin^{-} \frac{n_1}{n_2} \tag{2.1}$$

2.2.1 TYPES OF OPTICAL FIBER DEPLOYABLE

The main types of optical fiber deployed in telecommunication industry are step index multi mode and step index single mode. Step index is the abrupt change in refractive index between the core and cladding materials.

In optical fiber, light launched at the input is propagated within the core either by total internal reflection or refracted into cladding. The maximum launched and propagation angles are mathematically related to numerical aperture (N.A.), the number that expresses the light gathering power of an optical fiber.

$$\text{N.A.} = \left(n_1^2 - n_2^2\right) \tag{2.2}$$

When electromagnetic waves propagate in an optical fiber, the mode number, M of the wave which can propagate is related to the wavelength of light by,

$$M = 0.5\left(\frac{\pi d N.A.}{\lambda}\right)^2 \tag{2.3}$$

where d is the optical fiber core diameter.

Eq. (2.3) shows that M is directly proportional to core diameter and when it approaches wavelength of light, a single mode will propagate. Single mode fiber offers wide bandwidth at low losses, (Tugul & Tugul, 1989).

Telecommunication industries use two types of optical fibers which are characterized by their structure and practicalities in transmission. The modes are Single Mode Fibers (SMF) and Multimode Fibers (MMF) and the only difference arise in the core size.

2.2.1.1 SINGLE MODE FIBER (SMF)

Singlemode fiber exhibits low attenuation that enables non regenerated communication networks to cover long transmission distances. Attenuation is a limiting factor for long transmission distance but its deployment eliminates modal dispersion, the main effect of bandwidth limitation in multimode fiber.

Single mode fibers propagate one mode with a core diameter, typically $6\ to\ 8\mu m$ since the core allows fundamental propagation in the second attenuation window. The core size approaches the operational wavelength, (1300nm). When operating at wavelengths larger than the cut-off wavelength SMF looses more power at optical fiber bends because light radiates into the cladding, (Kartalopoulos, 1999. Vasil'ev, 1995).

Figure 2.3: Lightwave confined in a cladded single mode fiber

It can be seen in Figure 2.3that transmitted lightwave maintains its amplitude but there is the element of received lightwave spreading.

Core size of SMF is related to normalized frequency parameter (V) by propagation mode and given by equation 2.4 according to Snyder, 1983,

$$V \leq 2.405 \tag{2.4}$$

When V in eq. (2.4) is less than 2.405, propagation down the optical fiber core is the fundamental mode, while high order modes are lost in the cladding. The value of V should be maintained near the 2.405 level. (details about frequency parameter, V is analysed in section 2.1.1.3)

For low values of V, most of the power is propagated in the cladding material. Optical fiber bends allow transmitted lightwave to be refracted by cladding. Fundamental mode of lightwave provides signal fidelity over a long distance with minimal modal dispersion. Large information carrying capacity and low loss optical fiber networks use single mode fibers, (Chernikov, et al. 1995).

Table 2.1: comparison between SFM and MMF

PARAMETERS	SMF	MMF
Loss	low	high
BW	high	low
Data rate	- 1 Gb/s + w/ DWDM	low
dispersion	low	high
source	Laser	LED
cost	-Higher installation cost -Lower fiber cost -Higher cost connectors - Higher system cost	-Low installation cost - Higher fiber cost -Low cost connectors - Lower system cost
size	small	large
coverage	up to 60 km+	up to 2 km
NA	low	higher
Application	WAN, MAN, Access	LAN, SAN,Data centres

Table 2.1 provides a summary of the comparison between SMF and MMF. The low loss and dispersion are due to the deployment of laser in SMF but its high data rates and BW are related to optical fiber structure and operating wavelength. Dispersion which is the spreading of light as light propagates along a fiber discussed in more detail in this chapter 3.

2.2.1.2 MULTIMODE FIBERS

Multimode fiber transmits light to the receiver with high efficiency using low cost light emitting diodes (LEDs). The modal dispersion that severely limits its usable bandwidth and high loss characteristics has limited its application in high data rate transmission systems.

Multimode fiber can propagates more than 100 modes with the number of modes being propagated pegged on the core size and numerical aperture (NA). Optical fiber connection is easier with a large core size and high NA. Typical values of fiber core size and NA are quoted as 50 to 100μm and 0.20 to 0.29 respectively.

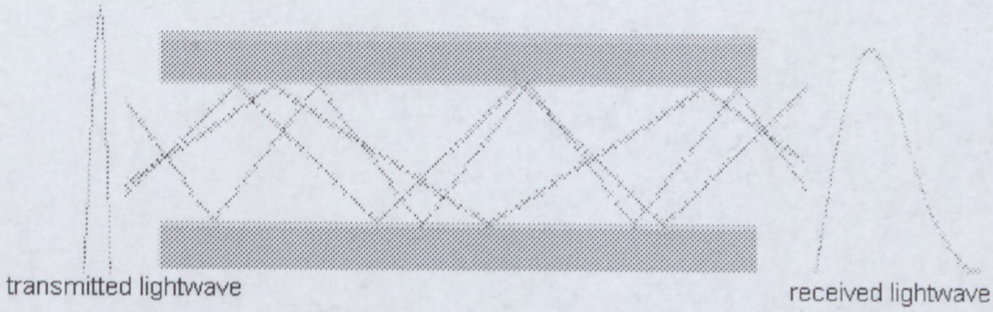


Figure 2.4: Total internal reflection for multimode fiber

As the number of modes increases in MMF the effect of modal dispersion increases. Different modes arrive at the optical fiber end at slightly different times and the time difference causes the light pulse to spread. Figure 2.4 show steps in the refractive index where the core and cladding interface for a lightwave transmitted in a medium with uniform index of refraction. The high loss and dispersion associated with this mode are due to modal dispersion.

The three modes shown above covers different distances to arrive at their destinations and the disparity between light rays arrival time is called modal dispersion. At the receiver, pulse amplitude reduces as the pulse spreads. Multimode fiber is not preferred for wide area network applications because its phenomenon affects signal quality thereby limiting transmission distance, (Kartalopoulos, 1999).

2.2.1.3 DESIGN OF OPTICAL FIBER

Optic fiber consists of a glass silica or plastic core covered with a cladding material with a refractive index of slightly less than that of the core and light is guided through it. Since the core and the cladding are made from either silica glass or plastic, connecting them is through either fusion splicing or mechanical splicing. Optical fiber requires less maintenance once installed but special skills are required to align the cores due to the microscopic precision.

Advantages of Multimode optical fiber core

- cheap transmitters, receivers and connectors can be used for connection

Disadvantages:

- high limitation of bandwidth and transmission length,
- expensive, and

- high attenuation.

Advantages of Single mode fiber core

- long high performance network.

Disadvantages:

- expensive components and interconnection methods are required.

According to Agrawal, (1992) adequate power confinement within the core and a high normalised frequency V is desired for a single mode fiber. The parameter V that combines the index difference, the core radius a, and the operating wavelength λ is defined by;

$$V = \frac{2\pi a}{\lambda}\sqrt{\left(n_1^2 - n_2^2\right)} \approx 2.405 \qquad (2.5)$$

Large V is necessary to reduce power leakage into the cladding, due to the variation of the spot size r_0 with V. The spot size is approximated to 1% accuracy of the fundamental mode of Gaussian distribution to given by;

$$\frac{r_0}{a}(V) = 0.65 + 1.619V^{3/2} + 2.876V^{-6} \qquad (2.6)$$

and $$1.2 \le V \le 3 \qquad (2.7)$$

where r_0 is the wavelength dependent field radius or spot size,

a is the core radius.

$$\frac{r_0}{a}(\lambda) = 0.65 + 0.434\left(\frac{\lambda}{\lambda_c}\right) + 0.0149\left(\frac{\lambda}{\lambda_c}\right) \qquad (2.8)$$

and wavelength ratio in equation 2.8 lies between 1.8 and 2.0

$$1.8 \le \frac{\lambda}{\lambda_c} \le 2.0 \qquad (2.9)$$

where λ_C is the cut off wavelength above which a fiber supports only one mode.

Normalised frequency V and λ_C are related with the expression;

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c} \tag{2.10}$$

where V_C = is the cut off value below which only the fundamental mode is supported.

Theoretically, V_C is 2.405 but it should be 3.0 and but upper limit on V in eq. (2.7) is therefore to restricts the optical fiber to guide only fundamental mode and reject all higher order modes data while the lower limit defines the range of curve fitting. Eq. (2.5) shows that a large refractive index variation is required for design and catering for the power will pay for a higher index difference (Jnr. Jones, 1988).

With an increase in waveguide parameter, the normalized spot size $\left({r_o}/{a} \right)$ also increases, implying that some fraction of mode field penetrates into the fiber cladding. The fraction of mode power confined in the core can be determined by eq. (2.11).

$$\frac{P_{core}}{P_{total}} = \left(1 - e^{\left(-2a^2/V^2 \right)} \right) \tag{2.11}$$

When V increases, the core diameter decreases according to eq. (2.5), it causes more loss of mode power in the cladding, and eventually an upper limit of dispersion value realizable will be reached beyond which the core diameter will be too small for light guiding or V will be too large to be realized.

Single mode fibers used in high bit-rate long-haul require the condition for the normalized frequency to conform to eq. (2.4) so that the value.

$V = 1.62$when $\lambda = 1550nm$ and $\sqrt{\left(n_1^2 - n_2^2\right)} \approx 0.1$ are substituted to eq. (2.4)

The concern is with two main parameters in the design of an optical fiber, the core radius a, and the refractive index difference at a window of a wavelength range. The cut-off wavelength constitutes the frequency above which the optical fiber is single mode (SMF).

$$i.e.\ \lambda_c = \frac{2\pi a}{2.405} \sqrt{\left(n_1^2 - n_2^2\right)} \tag{2.12}$$

2.3 OPTICAL FIBER ATTENUATION PERFORMANCE

Light transmission in optical fiber is not entirely efficient due to of absorption by the core and cladding. When a light is reflected by either the cladding or core interface, it travels for a short distance within the cladding before being reflected back. This leads to signal attenuation of approximately 0.15dB/km for a multimode optical fiber.

Attenuation in any optical fiber is governed by the wavelength and the discussion on the same is reported in the next chapter.

Optical fiber technologies have enabled today's high speed long haul telecommunication capabilities with a lot of hurdles that include attenuation and chromatic dispersion but optical fiber manufacturing methods has not eliminated deformities either.

Maximum optical fiber length L is shown as a function of bit rate in Figure 2.5 for attenuation limited conditions of an optical fiber operating at wavelengths windows 880, 1310 and 1550nm assuming fiber attenuation coefficients, 2.5, 0.35, and 0.16dB/km, respectively. In the three operating wavelength windows, transmission length reduces with the increase of bit rate at a logarithmic rate, (Saleh, & Teich, 1991).

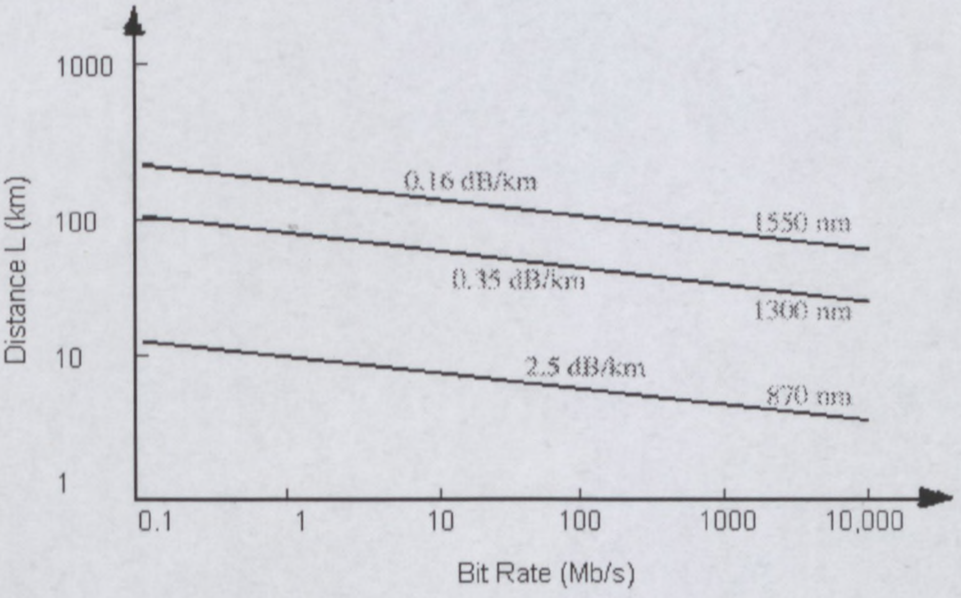


Figure 2.5: Attenuation as a function of bit rates

(Adapted from Saleh, & Teich, 1991)

Propagated pulse width depends on originally transmitted pulse width, transmitter and optical fiber response time and the receiver response time. When propagated pulse width exceeds the bit time interval, performance deteriorates due to intersymbol interference. The transmission distance is then limited by the bit rates and wavelength of operation and as illustrated in Figure 2.6.

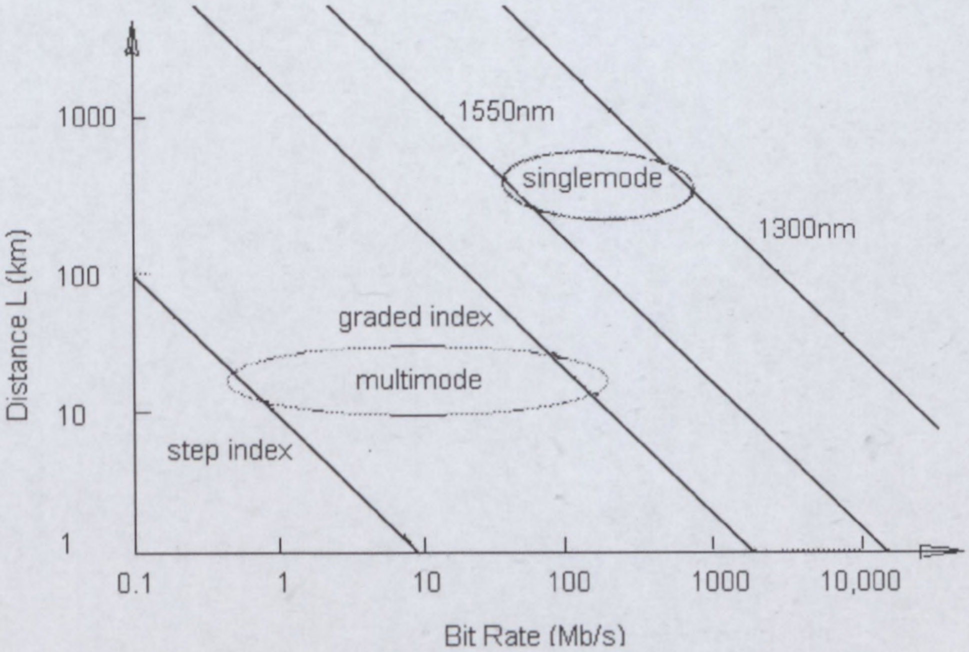


Figure 2.6: Dispersion effects on optical fiber

(Adapted from Saleh, & Teich, 1991)

Effects of attenuation and dispersion simultaneous limits the maximum transmission distance in relation to the bit rates as depicted in Figure 2.7. The curves represent maximum transmission distance at each bit rate for both attenuation and dispersion which is an indication of the order of magnitude of the relative performance of the different types of optical fibers

At low bit rates optical fiber length logarithmically reduces with bit rates maximizing attenuation. Dispersion dominates high bit rates but transmission distance is inversely proportional to bit rates. Optical fiber offers a small, light weight, flexible and secure means of distributing data globally while suffers a loss of less than 0.2dB/km, (Alhabsi & Bourdoucen, 2009).

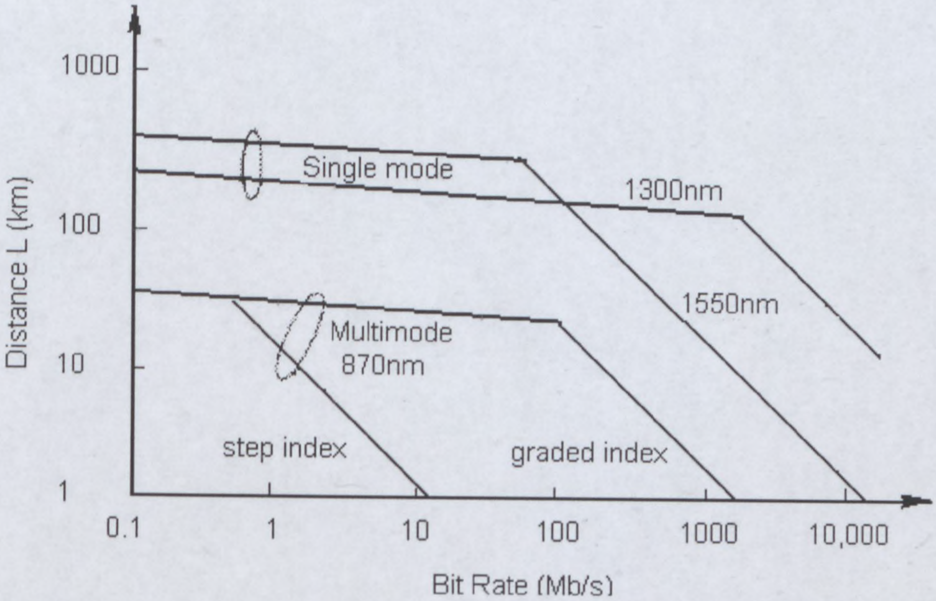


Figure 2.7: Effects of Dispersion and attenuation on bit rates

(Adapted from Saleh, & Teich, 1991)

2.3.1 FIBER ATTENUATION

The attenuation imposes an upper limit to the distance over which light can be transmitted. Total power loss in optical fiber is determined by considering power source (Ps), then summing all power losses. The power loss within an optical fiber are safety margin power(Pm), optical fiber loss in dB/km$(\alpha)$for the maximum optical fiber length (L) splicing and coupling loss(Pc) and the total power delivered to the receiver(Pr), (Rashed, 2011. Saleh, & Teich, 1991).

$$P_r = P_i - (P_i \wedge (-\alpha L) + P_c + P_m) dBm \tag{2.13}$$

Optical fiber power loss is the most significant loss according to eq. (2.13). Since both the connector and optical fiber power loss are determined by the manufacturer, the number of connectors for any network is first determined prior to network design. The maximum transmission length written in terms of distance L is then determined by the transmitter power.

$$L = \frac{\ln}{\alpha P_i}(P_i + P_r + P_c + P_m) km \tag{2.14}$$

2.4 TECHNIQUES TO OVERCOME SIGNAL DEGRADATION

The following sections summarises data transmission techniques already in use in optical fiber data transmission where objective is to receive interference free data at a minimum time. Dispersion has been identified as the main impairment in long haul transmission systems.

Dispersion management (DM) in solitons transmission systems involve periodical alternating spans of anomalous and normal dispersion optical fiber in which dispersion at the wavelength of the transmission channel is anomalous. The degree within which optical fiber impairments are compensated determines the transmission capacity of any optical fiber system.

2.4.1 DISPERSION COMPENSATED FIBER (DCF)

Dispersion compensation fiber (DCF) is an optical fiber which has opposite dispersion characteristics to the transmission network. Single mode optical fiber (SMF) has positive dispersion in the C-band operation window and has about 18ps/ (nm-km) dispersion at 1550nm wavelength, (Chen et al.2009).

Optical fibers are designed to have opposite dispersion parameters from those of SMF where second and third order dispersions are compensated. DCF will cause distortion even if the pulse width is very small but the solution lies on the design of the optical fiber with special characteristics for a particular network, (Rashed, 2011. Jiang, et al. 2005).

According to Agrawal, (2002) dispersion compensating fibers (DCF) which were originally designed for long-haul optical fiber communications networks have large negative values of dispersion in standard single mode fiber (SSMF). System using DCF must accurately be matched since DCF provides a fixed compensation over the entire network.

Besides signal delay, optical fiber loss and lack of adaptability are the main problem. High cost in manufacturing DCF and the physical size makes the technique not viable for commercial application, (Watts, et al. 2005. Izadpanah, et al. 1992).

Kumar & Sharma, (2008) explained that non zero anomalous fiber dispersion can be maintained by inserting DCF at the beginning, middle and at the end of the optical fiber network. The result showed that mid-compensated soliton transmission technique result in a better pulse evolution than the pre- and post- compensated schemes because of differential time delay between input and output soliton after a transmission.

DCF and are mainly used for compensating accumulated dispersion and this has enabled transmission distance of 18,000km to be realised. Pulse evolution in the DCF network is affected by the interplay between dispersion, nonlinearity and power. Long optical fiber length generates high attenuation and nonlinear parameter making DCF in-appropriate for existing communication network.

Accumulated positive dispersion is large after a long transmission distance and this reduces signal to noise ratio (SNR), increases the bit error rate and deteriorate system performances. The design of DCF which must compensate the accumulated positive dispersion has negative dispersion.

2.4.1.1 OPTICAL COMPENSATORS

Chirped fiber Bragg grating (CFBG) compensator is a section of a standard single mode fiber (SSMF) with a periodically modulated core refractive index used to compensate single wavelength channel. It creates dispersion opposite to the one offered by SSMF by reflecting longer wavelengths before the shorter ones. This emanates from the fact that CFBG has maximum reflection when grating period is half wavelength, (Ngo, 2009).

Mechanical strain and temperature are required to tune dispersion so that the centre wavelength is changed. Large numbers of optical compensators are required to compensate long haul network since compensators have limited tuning range of a few hundred ps/nm. Besides, optical compensators tend to have the same disadvantages as DCF in terms of cost, physical size and optical losses. Complex control schemes involving the use of temperature and strain are required to overcome dispersion, (Ngo, 2009. Pan, 2002).

According to Madsen, (2004) and Bohn, (2004) optical finite impulse response (FIR) fabricated as planar in lightwave circuits can be used to compensate both dispersion and optical fiber nonlinearity. The sixth order FIR filter suitable for 40Gb/s has been fabricated using the same method.

2.4.2 DISPERSION SUPPORTED FIBER (DSF)

In dispersion supported transmission optical fiber converts frequency modulated signal to amplitude modulated for transmission. Interference effects occur when two signals with different optical frequencies overlap.

In transmission with residual amplitude modulation, transmitter output is composed of both frequency and amplitude modulation. The output signal generates four-level optical signal which can be recovered by a low pass filter and dual threshold detection.

Introduction of dispersion shifted fibers (DSF) allowed the zero dispersion wavelengths to coincide with the least attenuation wavelength of 1550nm, and to reduce the number of repeaters. The dopants used in the DSF gave rise to strong Kerr nonlinear effects. This resulted in generation of four wave mixing (FWM) effects due to kerr effect leading to WDM crosstalk, (Agrawal, 2008, Hasegawa, 2006).

Forysiak, et al. (1994) proposed a stepwise dispersion profile optical fiber to match the exponential decay of the soliton energy by reducing amplifier span. This resulted in 40Gb/s data being transmitted successfully for over 400km.

Suzuki, et al. (2003) in their proposal achieved successful 20Gb/s transmissions for 9000km by use of periodic inserted dispersion compensation link with inline optical filters which reduced non solitons components.

Dispersion shifted fibers have enabled operation at wavelength 1550nm possible by reducing chromatic dispersion making the optical window a superior wavelength to 1300nm.

2.4.3 CHIRPING TECHNOLOGY

The transmission of intensity modulated light pulse through an anomalous dispersion optical fiber results in broadening of pulse envelope. Since this technique is based on pre-distortion technique, high frequency power components in the pulse are pushed to the leading pulse edge. This culminates into the generation of inter-symbol interference (ISI).

If the same waveform is transmitted through an anomalous dispersion optical fiber, pulses become narrower and after long transmission distance high frequency components are pushed to the trailing edge. This leads to systems' instability since ISI is introduced with the consequent of power penalty, (Agrawal, 2002. Henmi, 1994).

In pre chirping, a light wave is set to have low-frequency power component at the leading edge and high frequency components at the trailing edge. When ideal modulated waveform is transmitted through the normal dispersion optical fiber, high frequency components are pushed to the trailing edge.

2.4.3.1 CHIRPED TRANSMISSION

Transmitting high powers into an optical fiber induces self phase modulation but variation of frequency within a pulse can be used to mitigate chromatic dispersion according to eq. (2.15), (Agrawal, 2002. Loh et al. (1996).

$$\Delta f = -\frac{d\phi}{dt} = -\gamma \frac{dP}{dt} L \qquad (2.15)$$

The leading edge of the pulse has a lower frequency relative to the trailing edge, which has a negative (*dP/dt*) and it constitutes the basis of soliton systems and cancels dispersion thereby effecting transmission.

The attenuation associated by optical fiber has serious effect on chirp transmission system hence limits 10Gb/s solitons with acceptable amplifier spacing to 200km over SSMF, (Menyuk, 2002. Doran,1983).

2.4.3.2 DIRECTLY MODULATED LASER (DML)

DML can be generated by a laser modulated by changing the laser drive current. This is achieved by heating and cooling of the laser as it is switched on and off making ones and zeros to generate different frequencies.

The main drawback of DML for high bit rate transmission is the optical spectrum that impedes channel packing leading to increased signal distortions due to laser chirp broadening. The wrong phase of DML which is negatively proportional to applied power, results in pulse broadening thus making DML unsuitable for compensation of dispersion in SSMF. The negative dispersion optical fiber limits 10Gb/s transmission distances to 20km, (Winzer & Essiambre, 2006. Agrawal, 2002).

Chirp managed laser (CML) which consists of a combination DML and a narrow band optical band pass filter, has a better performance over SSMF. The filter introduces chirp, increases extinction ratio and reduce the spectral width. CML realized 10Gb/s transmission over 250km SSMF without any dispersion compensation, (Mahgerefteh, 2006)

2.4.4 OPTICAL PHASE CONJUGATION (OPC)

Optical phase conjugation (OPC) is a technique used to compensate chromatic dispersion, a deterministic impairment in optical fiber transmission systems generated by the Kerr effect. It uses a single nonlinear optical element to invert the signal spectrum such that chromatic dispersion of the second half of the network reverses the effect of the first half. Besides, it takes the complex conjugate from the phase response of the signal without changing the amplitude response and it does not compensate for polarization mode dispersion (PMD), (Jansen et al. 2007. Gnauck, 1997).

OPC compensate both GVD and SPM under certain conditions of figure of merit bandwidth-length (B-L) in transmission systems when fiber has zero. Conjugation is performed by four-waves-mixing in an optically pumped nonlinear element such as dispersion shifted fiber or semiconductor amplifier.

Although OPC can achieve long transmission distance at a single wavelength, the need to place the compensator in an exact location along the network is difficult to achieve in the field. Besides, individual wavelengths cannot easily be added or dropped at intermediate points along the network. Phase conjugation transmission distance of 10Gb/s is over 10,200km on SSMF using the RZ-QPSK format transmission, (Jansen 2005).

This OPC suffers from two problems that limit their use in the long haul optical fiber links. The insertion loss typically of 5dBcan be compensated by increasing the amplifier gain but only at the expense of enhanced amplified ASE noise. A relatively small effective mode diameter area enhances the nonlinear effects considerably, (Proakis, 2001).

2.4.5 SUPER-GAUSSIAN FILTER (SGF)

He, et al. (2009) proposed the use of super-Gaussian filters and nonlinear gains as a technique to stabilize short pulse and eliminate phase jitters. The filter in holographic fiber gratings overcame both solitons interactions and jitters. Simultaneous use of SGF and nonlinear gain stabilized propagation of solitons in an optical fiber for a distance of 5150km.

This method may not work quite well with the optical fibers already installed as it requires application to new installation which may need capital funding.

2.4.6 FORWARD ERROR CORRECTION (FEC)

Originally used in submarine systems, FEC is now common in standard long haul systems to compensate for errors introduced by excessive PMD when high transmission rates are deployed. FEC allows transmission distances to be extended since the extra errors created are corrected at the receiver, (Yardley, et al.2011).

FEC technique is used when bit error rates lower than 10^{-15} are to be maintained with a maximum of 40Gb/s. It adds extra bits to the data being transmitted and the same bits are used to correct received bit errors, but the technique limits the high bit rates systems, (Andre & Pinto, 2005).

Since extra bits are required for transmission and correction, the available bandwidth will not adequately be utilised as a result of redundant bits. The technique may not optimise data transmission as a condition for the research objective.

2.4.7 DISPERSION MANAGEMENT

Even though C-band is the optical low power loss window, optical fibers with dispersion decreasing fiber (DDF) are not used in telecommunication industry because of limited transmission length (20 - 40km).In this operating window, dispersion changes by a factor of 10 and this may reduce the practical transmission length below 10km, (Bhaskar et al. 2011).

The optical fiber cable (ITU-G652) used for long haul short pulses has high level of chromatic dispersion prompting periodic dispersion compensation to be utilised. The optical fiber is deployed in C band window whose range is 1530 – 1563nm, (Andre & Pinto, 2005).

2.4.8 NONLINEAR OPTICAL TRANSMISSION

Optical pulses have no special shape because of the existence of non linearity in the optical fiber. The pulse has self re-shaping capability that enables it to distribute power during reshaping. After re-shaping, formation of solitons may not be possible since the peak power is not sufficient to generate fundamental pulse, (N=1). Pulse disperses when initial pulse power is adjusted to get N > 1 but after re-shaping, pulse gains enough power to form fundamental solitons.

Solitons collide with each other, fall into bound states and interact in other ways like particles but still preserve their original shape. Their ability to propagate stably without broadening is a feature of greatest interest in the optical fiber communications. Solitons shape is determined by applying the inverse scattering method to Nonlinear Schrodinger Equation (NSE) and the resulting pulse envelope is given by eq. (2.16).

$$u(\tau) = \eta \operatorname{sech}(\eta\tau) \tag{2.16}$$

Where η is referred to as the order of the soliton.

The fundamental pulse which maintains its original hyperbolic secant shape over any distance of propagation is great utility in optical fiber communications. In a perfect lossless optical fiber, nonlinearity and dispersion balances in such a way that the pulse maintains its shape as seen in Figure 2.8.

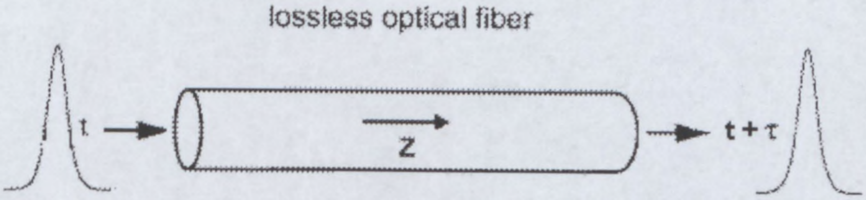


Figure 2.8: Initial and pulse after propagation through lossless optical fiber.

(Adapted from Weinert, & Dehn, 2009)

2.4.8.1 SOLITONS TRANSMISSION

Solitons transmission is governed by interaction between dispersion and nonlinearity. When dispersion is a dominant effect, N << 1 and if SPM dominates N >> 1. In optical fiber communication systems dispersion dominates. The effects of dispersion and nonlinearity in optical fiber cause the shape of the wave to change during propagation. The solution of the two waves acting simultaneously as shown in Figure 2.9 indicates that soliton propagation is stable during data transmission.

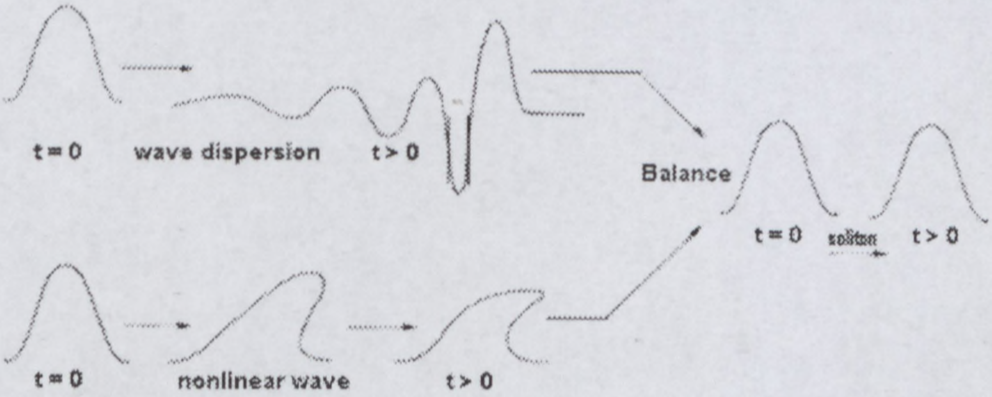


Figure 2.9: Effects of combining dispersion and nonlinearity effects in optical fiber.

(Adapted from Lagarias, et al. 1998)

Increasing the launch power or decreasing the pulse width such that $N \cong 1$ and allowing simultaneous interaction between SPM and dispersion influences the pulse shape as depicted by Figure 2.9.

The relation between propagation distance z the phase of the wave propagating in an infinite uniform medium is given by;

$$\phi(z,\tau)=\frac{2\pi n_0 z}{\lambda}+\frac{2\pi n_2 I(\tau) z_{eff}}{\lambda} \tag{2.17}$$

where z_{eff} is the effective transmission distance.

The value of n_o is approximately 1.5 whereas n_2 is around $3\times10^{-20}m^2/W$ which is very small but in high signal intensity and long transmission distances, the effect of n_2 is significant.

The first term of eq. (2.17) is a linear phase shift that is affected by transmission distance z while the second term depends on both the transmission distance z_{eff} and the intensity variation of the signal $I(\tau)$.

Considering optical fiber attenuation, z_{eff} is effectively less than z implying that optical fiber attenuation reduces the effect of nonlinear phase shift.

$$z_{eff}=\frac{1-e^{-\alpha z}}{\alpha} \tag{2.18}$$

Agrawal, (2001) showed that even though SPM interaction with dispersion results in a parameter N which is a dominating effect, it depends on the pulse peak power.

$$N^2=\frac{L_D}{L_{NL}}=\frac{\gamma P_{in} T_0^2}{|\beta_2|} \tag{2.19}$$

where L_D is the dispersion length,

L_{NL} is the nonlinear length, and

T_0 is the pulse width.

Even though nonlinear effects depend on transmission distance and optical power, it degrades the performance of optical fiber. Both SPM and XPM affects signal phase and causes spectral broadening which leads to increased dispersion.

SPM effect broadens the signal spectrum and does not affect the intensity profile of the signal since the time dependent phase variation causes instantaneous frequency deviation.

Nonlinearity is a factor which cannot entirely be eliminated but, used by virtue of necessity, (Lagarias, et al. 1998).

2.4.8.2 DISTANCE COVERED IN SOLITON TRANSMISSION

Franco, et al. (1998) performed an error-free transmission over a 300km step index fiber link between Roma and Pomezia in France, without inserting in line components. Using a standard 10Gbit/s Synchronous Digital Hierarchy (SDH) line terminal and polarization encoder that alternates orthogonal states of polarization in the data stream, solitons interaction efficiency was reduced by increasing the duty cycle in the data stream.

In order to obtain 10 spans of 50km each they made the link with a 25km cable containing 20 step index (SI) fiber looped back in pairs at a transit station in Pomezia with an optical amplifier introduced at the span end. The chromatic dispersion and polarization mode dispersion of optical fiber link were $D = 16.2 ps / km - nm \; and \; PMD = 0.04 ps / km^{1/2}$. The maximum polarization dependent gain of the amplifiers was $PDG = 0.dB$, whereas the maximum differential group delay was $DGD = 1 ps$.

Grudinin, et al. (1997) demonstrated using a standard fiber with nominal dispersion of 17ps/km-nm a practical solitons transmission system with partial dispersion compensation and obtained an error free transmission for 10Gb/s data over 1000km. The linearly chirped optical fiber gratings were each 75cm long with a 4.5nm bandwidth centred at 1549.5nm on a transmission line comprising 100km spans of standard telecommunications fiber each followed by an erbium doped fiber amplifier.

Knox, et al. (1996) demonstrated that at 1550nm wavelength of standard optical fiber, using dispersion compensation in each amplifier span, solitons data transmission of10Gbit/s over 842.5km is achievable provided the dispersion is kept anomalous.

Andrekson, et al.(1992) demonstrated that when neighbouring solitons are spaced at least 5 pulse widths apart and are stable over a long path length, an error free solitons data transmission at 32Gb/s over 90km with a pulse width of 16ps is possible.

This capacity was among the highest ever reported for a high bit rate system since it gave the advantage of using solitons for transoceanic distances at moderate speeds. Excess gain must be provided in these cases leading to solitons instability and limiting the transmission distance.

2.5 CONCLUSION

The performance of optical communication depends on the combination of optical fiber transmission attributes and the attributes of input power. Data transmission is degraded by data attenuation and signal distortion introduced during transmission in a specific wavelength window. The main factors that affect the performance of optical fiber include its material composition, geometry, light source technology and surrounding environment.

SMF is preferred for long haul systems because of low loss and minimal signal distortion. The services that utilise SMF include data retrieval, banking, video word processing, electronic mail, television, e-commerce and e-learning.

Universities and companies prefer LAN connected multimode fiber system networks because larger optical fiber core and higher fiber NA of multimode fiber reduces loss at these LAN connections. So far optical soliton has posted the best result in terms of data transmission and transmission length covered.

In the next two chapters we look at the effects of the two categories of transmission impairments in relation to data transmission in optical fiber.

CHAPTER THREE

LINEAR OPTICAL EFFFECTS

This chapter provides the background information on optical fibers linear effects and factors that limit transmission distances of a single mode fiber (SMF). Since the introduction of optical fibers in telecommunication industry decades ago, progress has been made in manufacturing optical fibers that exhibit very low signal attenuation and dispersion.

3.1 INTRODUCTION

According to Ip and Kahn, (2008) optical fiber transmission impairments are divided into two categories and compensation techniques of each are quite different. The categories are,

- linear impairments: chromatic dispersion (CD), polarization-mode dispersion (PMD), symbol timing offset, and optical filtering;
- nonlinear impairments: (laser phase noise, self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and nonlinear phase noise (NLPN)

Discussion on the first category follows there after whereas the second category is discussed in chapter 4.

Optical fiber transmission is affected by linear and nonlinear impairments even though it is considered as a perfect transmission media with infinite bandwidth. In practice optical fiber is affected by several limitations as transmission distance increases due to linear and nonlinear effects. But the success of high bit rate long haul optical transmission networks depends upon how the linear and nonlinear effects are managed.

To have optical fiber with the best performance, the following parameters must be controlled due to their effect on transmitted data, laser diode power, adjacent channel x-talk, modulation instability (MI), splicing, N.A. and connectors and bending. They are the major optical fiber impairment and could be categorised as depicted in table 3.1

Table 3.1: Optical fiber impairments

LINEAR	NONLINEAR
fiber loss	Four wave mixing (FWM)
adjacent channel x-talk	cross phase modulation (XPM)
polarization mode dispersion (PMD)	stimulated Brillouin scattering (SBS)
accumulated ASE noise	stimulated Raman scattering (SRS)
group velocity dispersion (GVD)	self phase modulation (SPM)

3.1.1 OPTICAL FIBER ATTENUATION

Attenuation is defined as the power loss that occurs when lightwave propagates over some distance. In optical communications attenuation is referred to as the transmission loss (dB/km),a phenomenon that distorts signal thereby reducing its quality during propagation.

Amplifiers and the transmission distance in any optical fiber network increases noise generated within the network and this in-turn constitutes attenuation. Attenuation depicted in Figure 3.1 is the loss of signal power which is governed by different mechanisms that includes absorption, scattering and radiation. The effect is a function of the distance travelled, the longer the distance the higher the attenuation factor.

Other miscellaneous effect includes micro bending losses, coupling losses between optical fibers and intermediate nodes, and both wave guide and material losses. Waveguide and material losses are caused by propagation of light power into the cladding and coupling losses exist at fiber connectors.

Figure 3.1: Optical fiber pulse loss

In optical fiber, power loss is by governed the optical loss factor and the propagation distance. Attenuation per unit length in dB/km shown below by eq. (3.1) is represented diagrammatically in Figure 3.1 and 3.2 respectively.

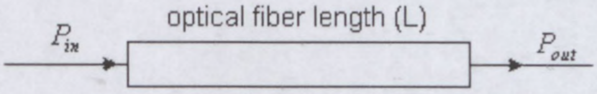


Figure 3.2: Optical fiber power flow

$$P_0 = P_i \exp(-\alpha L)$$

$$= -10\log_{10}\frac{P_0}{P_i} = -10(-\alpha L)\log_{10} e$$

$$= 4.343\alpha L$$

$$Attenuation\,(dB) = 10\log\left(\frac{P_o}{P_i}\right)\alpha = 4.343\alpha \tag{3.1}$$

The spreading of a signal pulse as it travels through the optical fiber is signal dispersion. In optical communication, dispersion is a temporal effect that results in pulse spreading in time and propagates down the optical fiber reaching destination at different times.

Pulse travelling as a bit stream translating into pulse widening at the receiving end of the fiber is shown in Figure 3.2. where they merge together and cause transmission errors. When the pulse is very short, its phase velocity is high and it travels very fast.

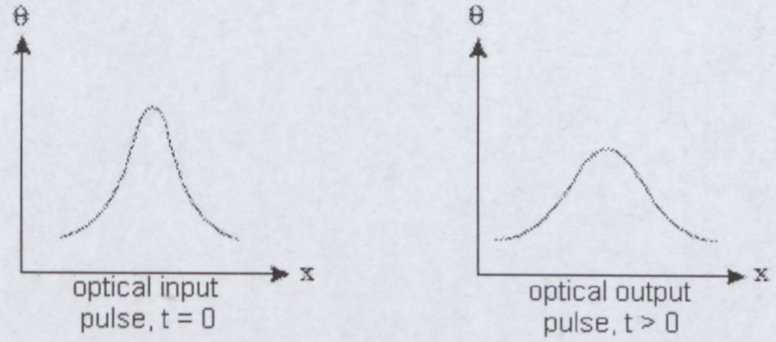


Figure 3.3: Dispersion of a propagating lightwave

(Adapted from Weinert, & Dehn, 2009)

3.1.2 ATTENUATION COEFFICIENT

Optical power travelling through an optical fiber decreases exponentially with distance as a result of absorption and scattering and becoming smaller than the receiver sensitivity. The loss is due to material absorption and Rayleigh scattering as shown in Figure 3.4 and in particular, the wavelength of transmitted light. If P_{in} is the power launched at the input end of a fiber of length *L*, the output power P_{out} is given by eq. (3.2).

$$P_o = P_{in} \exp(-\alpha L) \tag{3.2}$$

where α is called attenuation constant;

P_{in} is the optical signal power at the input of a fiber of length *L*

P_o is the transmitted power

Since fiber loss is expressed using units of dB/km by using this relation, eq. (3.2) is re written as shown in equ.3.3

$$\alpha_{dB} = \frac{10}{L}\log\left[\frac{P_o}{P_{in}}\right] \tag{3.3}$$

Optical fiber loss α_{dB} is dependent on wavelength ad both material absorption and Rayleigh scattering dominantly contribute to the loss, (Agrawal, 2002).

3.1.3 TRANSMISSION WINDOWS

Dispersion, absorption, and scattering are the three properties of optical fiber that cause attenuation in transmitted power thereby limiting high-speed transmission and data efficiency over long distances.

Long haul high speed communication systems rely on SMF which exhibits zero modal dispersion and long amplifier spacing in the second transmission window. Development of Erbium Doped Fiber Amplifier (EDFA) which operates in the third window, 1510-1560nm wavelength band eliminated attenuation through optical amplification and was adopted for long haul high speed communication systems.

The transmission in the third window is seen as a viable method to approaching optical dispersion limits (Agrawal, 1997). The drawback of transmission on wavelength 1550nm systems is the requirement of periodical amplification spaced apart by 60 - 70 Km. Optical amplifiers are valuable for multi channel lightwave systems but they add noise to the optical data.

Because of the absorption peaks, two standard single mode wavelengths which are deployable are $1310\mu m$ and $1550\mu m$ but the deployment of the later has enabled extended transmission distance of the optical fiber.

According to Lee, et al. (2008) and Karalekas, et al. (2008),International Telecommunication Union(ITU),defined the communication bands for SSMF. The bands are named O, E, S, C, L, and U. C-band is the most common transmission band in telecommunication industry because of it's the low optical fiber loss at 1550nm. It makes long transmissions distance over optical fiber possible prior to deployment of regeneration. In this research work, C-band was used for optical fiber simulations.

The O band was the first band to be used for long haul transmissions in SSMF because of zero dispersion and low optical fiber loss characteristics. The need for amplifiers and the nonlinear impairments made the change of long haul transmissions to C and L bands. The combination of optical amplifiers and low optical fiber loss in the C and L bands has established the two bands for long haul systems.

E band is less useful for long distance transmissions because of water peak loss. S band is another popular band for SSMF but the system is limited due to high optical fiber loss in the bands. The U band has high transmission loss which makes it unsuitable for use in long transmission distances, (Karalekas, et al. 2008).

In a 1310nm wavelength window, standard single mode fibers have minimum chromatic dispersion but higher loss. Unfortunately in this wavelength region, standard single mode fibers have a typical chromatic dispersion of 15-20 ps/nm-km, (Rashed, 2011).

Attenuation rate in (dB/km) for the SSMF as a function of wavelength is shown in Figure 3.4 where absorption peak near 1400nm region is caused by water impurities as a result of the manufacturing process of the fiber, (Jansen, et al. 2008).

Most communication systems operate in the C (1530 - 1565nm) band where the gain of EDFA is used for data transmission. Low optical fiber attenuation windows for long haul networks (1550nm), metro area networks (1300nm) and local area networks (0.850nm) are deployed in third, second and first communication windows respectively.

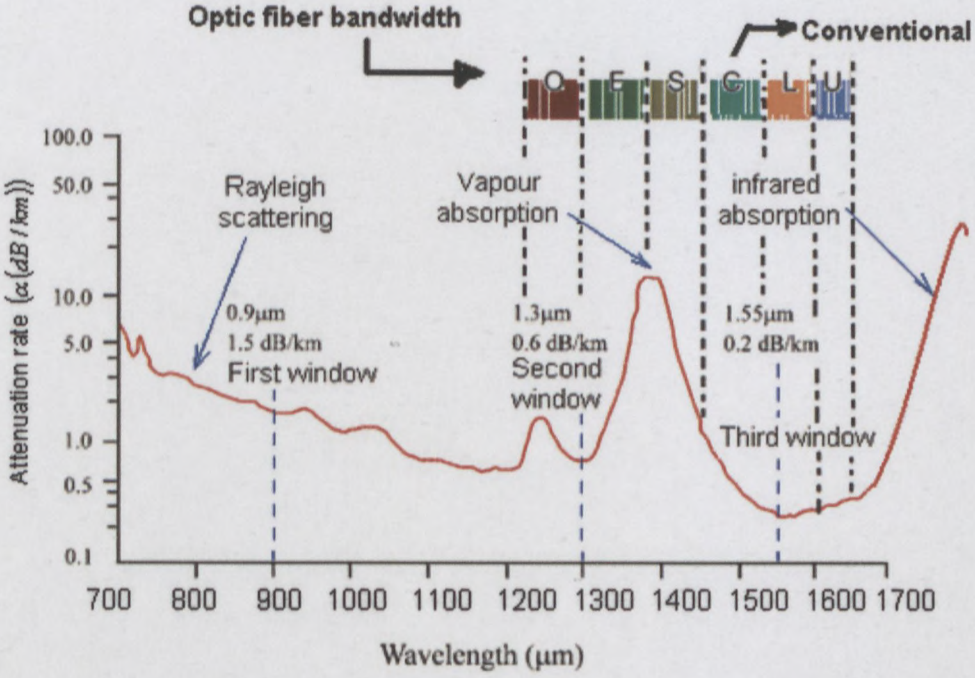


Figure 3.4: Loss characteristics of an optical fiber

(Adapted from Karalekas, et al. (2008)

3.1.4 AMPLIFIED SPONTANEOUS EMISSION (ASE)

Optical amplifiers used in long haul optical fiber communications networks generate optical noise. This noise dominates other noise associated with the network such as shot noise and thermal noise. EDFA used in modern optical systems is a fiber length doped with erbium ions that produce optical gain and lasers are used to pump the gain, creating population inversion that acts as an amplifier through stimulated emission, (Ramaswami, et al., 2010. Agrawal, 2002).

Variation of signal power and ASE with assumed fiber loss and amplifier noise when power launched is 0dBm is illustrated in Figure 3.5 which shows the relationship between the amplifier span length and required power for data transmission to be effected. High power is necessary to overcome spurious noise generated by the optical amplifier as depicted by curve ASE_1 compared to the power requirements for curve ASE_3. The Optical amplifier noise increases the power requirements in ASE_1.

The disadvantage comes into play when the numbers of optical amplifiers are considered for the same optical fiber length in ASE_1 and ASE_3. This increases the design cost requirements and eventually operational cost. The power requirement of cost effective communication network should be above 0dBm but just be about 5dB.

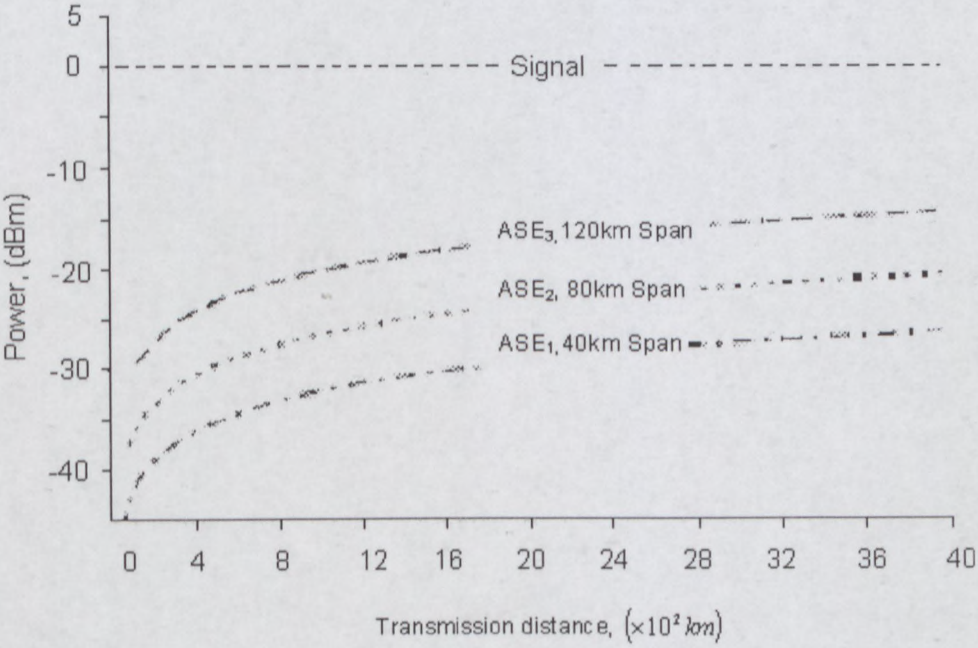


Figure 3.5: Variation of transmission distance with ASE

(Adapted from Agrawal, 2002)

ASE noise in optical fiber network which is the major impairment is due to interaction between generated signals.

Long transmission systems performances are reduced by ASE noise from optical amplifiers in the transmission systems. In transoceanic systems, cascaded amplifiers add noise onto the data stream. ASE-noise changes the pulse energy that affects the pulse position in nonlinear pulse propagation. Safe pulse separation can be maintained by reducing the pulse width and increasing the peak powers, (Kumar, et al. 2008. Talli,& Adams, 2003).

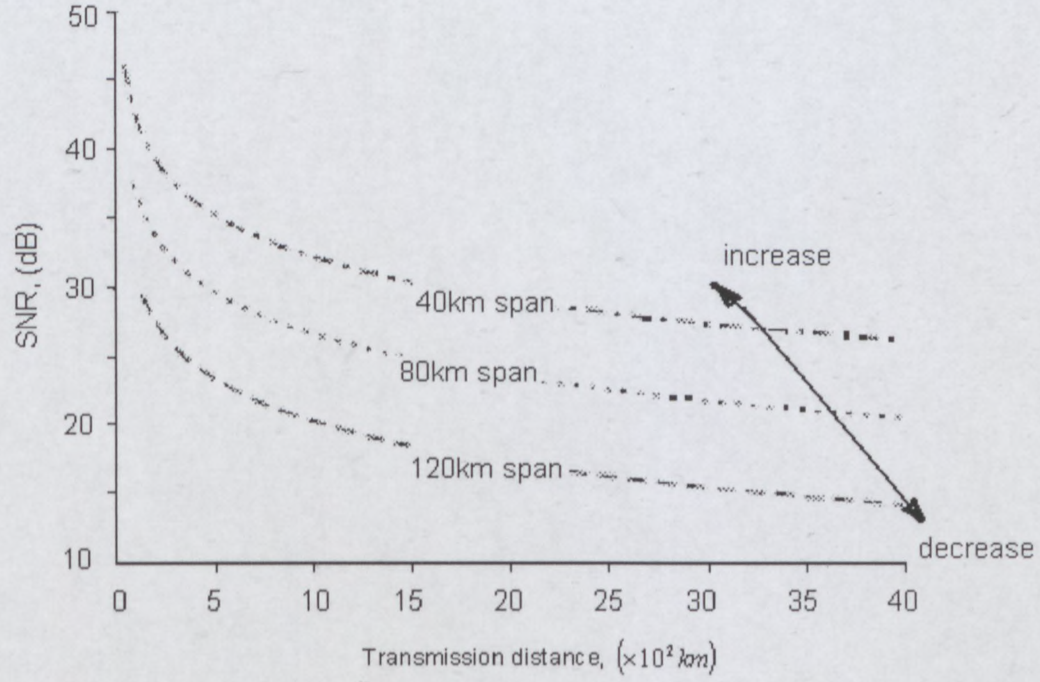


Figure 3.6: Variation of transmission distance with SNR

(Adapted from Agrawal, 2002)

The relation between SNR reductions with increase in transmission distance is shown in Figure 3.6where noise increases with increase in the number of optical amplifiers. The high noise results from a number of line optical amplifiers used to accomplish data transmission. 40km span has several optical amplifiers in the network that contributes to the accumulation of generated noise to the overall SNR.

According to Agrawal, (2002) spontaneous emission that occurs in EDFA generates spectral power density given by;

$$P_{ASE} = F_N (G-1) h\nu \qquad (3.4)$$

where G is the linear gain ratio,

h is Planck's constant,

vis the photon frequency, and FN is linear ratio of noise figure.

3.2 NONLINEAR DISPERSION

The distortion of the optical signal as it travels along the optical fiber is mainly due to consequences of dispersion. The effect causes a different delay to optical signal components arrival time at the receiver.

When electromagnetic pulse propagates along a SMF, pulse broadens leading to increase of the bit error rate which leads to pulse overlapping thereby rendering adjacent pulses meaningless (Agrawal, 1992).

Pulse broadening in optical fiber limits the maximum propagation distance in digital data transmission. Broadened pulses overlap and prevent clear identification of transmitted data, these limits the propagation distance.

In optical fiber transmission the accumulated dispersion ultimately leads to pulse spreading causes inter symbol interference (ISI). As the transmission length increases, the impact of the dispersion becomes more obvious. At high dispersion values the pulses disperse into neighbouring pulse slots causing ISI. Transmitted power is dispersed such that the pulses spread into a wider time interval and exceeds the bit interval. This affects both digital and analogue transmission resulting in inter-symbol interference (ISI) which in itself is an error, (Agrawal, 2002. Olsson, 1989).

Referring to Figure 3.7, it can be seen that dispersion mechanism within the fiber causes broadening of transmitted lightwave as it travels. Pulse broadens and overlaps with its neighbours, becoming indistinguishable at the output.

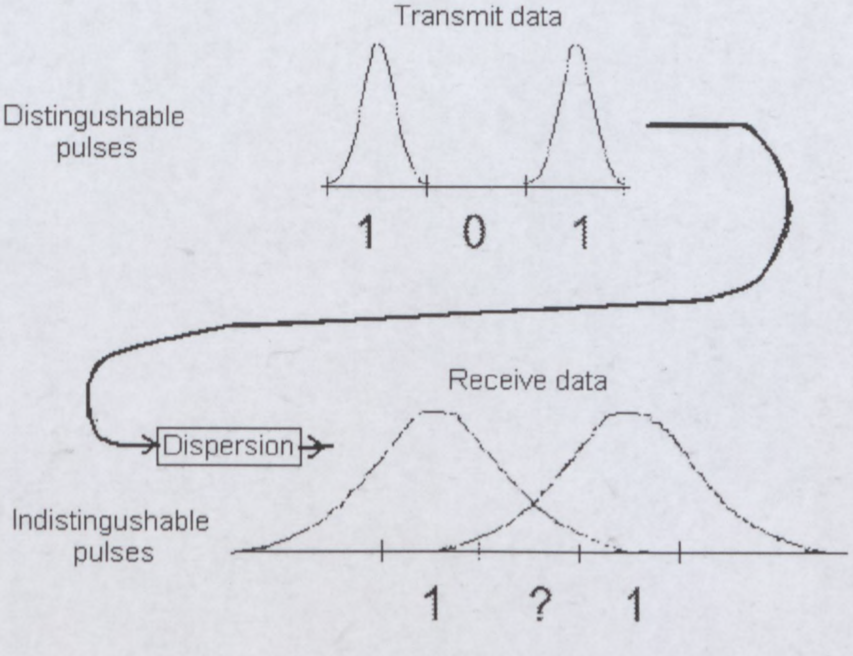


Figure 3.7: Intersymbol interference due to dispersion

(Adapted from Olsson, 1989)

ITU-T G652 SSMF has $\beta_2 = 17 ps/nm-km$ as a nominal value of dispersion parameter at 1550nm. The dispersion for ITU-T may be deployed in SMF, WDM as this is the most commonly deployed transmission media worldwide.

Smaller dispersion (β_2) implies less timing jitter and weaker interaction but lower signal-to-noise ratio (SNR) at the receiver. Dispersion management reduces both timing jitter and improves the SNR and at the same time the increase of pulse interaction limits the system performance, (Pechenkin &Kschischang,2006)

According to Senior et al (1985), ISI effect causes signal attenuation and subsequent signal to noise ratio (SNR). If the pulse spread due to ISI is assumed, then maximum allowable dispersion $\Delta t \max$ is expressed in terms of the transmission rate R by eq. (3.5).

$$\Delta t \max = \frac{1}{4R} \tag{3.5}$$

For standard single mode fiber driven by a directly modulated laser diode transmitter, the pulse spread due to chromatic dispersion is given by eq. (3.6).

$$\Delta t = LD(\lambda)\Delta\lambda \tag{3.6}$$

where Δt = pulse spread (ps),

L = fiber length (km),

$D(\lambda)$ = chromatic dispersion (ps/km-nm),

λ = wavelength (nm), and

$\Delta\lambda$ = spectral width of transmitter output (nm).

The parameter D is typically measured in units of picoseconds per km per nanometer and the km refers to the distance L, and the nm to the wavelength spread.

3.2.1 MATERIAL DISPERSION

Material dispersion is caused by variation of refractive index as a function of the optical wavelength. Materials used for optical fiber fabrication and refractive index of silica changes with optical frequency. This type of dispersion is a very important component of chromatic dispersion in optical fibers because if the medium is dispersive, material dispersion is the dominant dispersion mechanism.

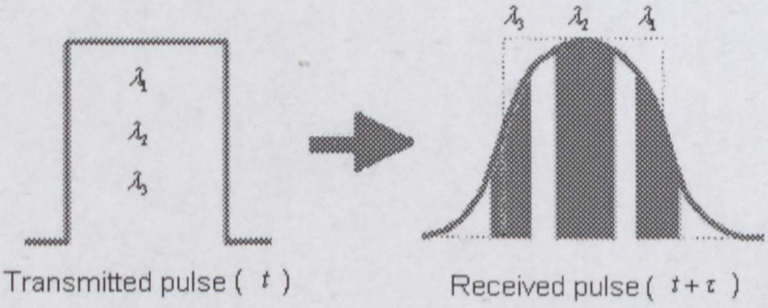


Figure 3.8: Material dispersion

This type of dispersion arises from optical pulses with finite spectral width spreading and progressively broadening in wavelength along the optical fiber as shown in Figure3.8. During this time, energy exchange takes place within the neighbouring pulses resulting into data error recovery at the receiver. The dependent of refractive index on velocity causes pulse spreading as the low frequency component trails.

Material dispersion is negative below zero dispersion wavelength point but changes to positive above that point as shown in Figure3.8.

The time delay taken by a pulse in travelling through a length L of the medium is given by eq. (3.6).

$$\tau(\lambda_0) = \frac{L}{\upsilon_g} = \frac{L}{c}\left[n(\lambda_0) - \lambda_0 \frac{dn}{d\lambda_0}\right] \tag{3.6}$$

If the source has a spectral width of $\Delta\lambda_0$ then the wavelength component within $\Delta\lambda_0$ travels with different group velocity resulting in pulse broadening which can be represented by material dispersion, $\Delta\tau$ shown in eq. (3.7).

$$\Delta\tau = \frac{d\tau}{d\lambda_0}\Delta\lambda_0 = -\frac{L}{c}\lambda_0 \frac{d^2n}{d\lambda_0^2}\Delta\lambda_0 \tag{3.7}$$

Using eq. (3.7), dispersion of the pulse can be quantified through differential eq. (3.8).

$$\frac{d\tau}{d\lambda_0} = -\frac{L}{c}\lambda_0 \frac{d^2n}{d\lambda_0^2} \quad ps/nm \tag{3.8}$$

The dispersion coefficient, *D* of the medium representing the dispersion per unit length of the medium is defined by eq. (3.9).

$$D = \frac{1}{L}\frac{d\tau}{d\lambda_0} = -\frac{\lambda_0}{c}\frac{d^2n}{d\lambda_0^2} \quad ps/(km-nm) \tag{3.9}$$

Spectral variation, $d^2n/d\lambda_0^2$, for pure silica which indicates the wavelength of 1280nm where material dispersion wavelength $d^2n/d\lambda_0^2 = 0$ is shown in Figure 3.9. It shows where the wavelength pulses suffer negligible dispersion as they propagate through pure silica. Below this wavelength point is the normal group velocity dispersion region represented by $d^2n/d\lambda_0^2$ which is positive while above region is known as anomalous group velocity dispersion region which is negative.

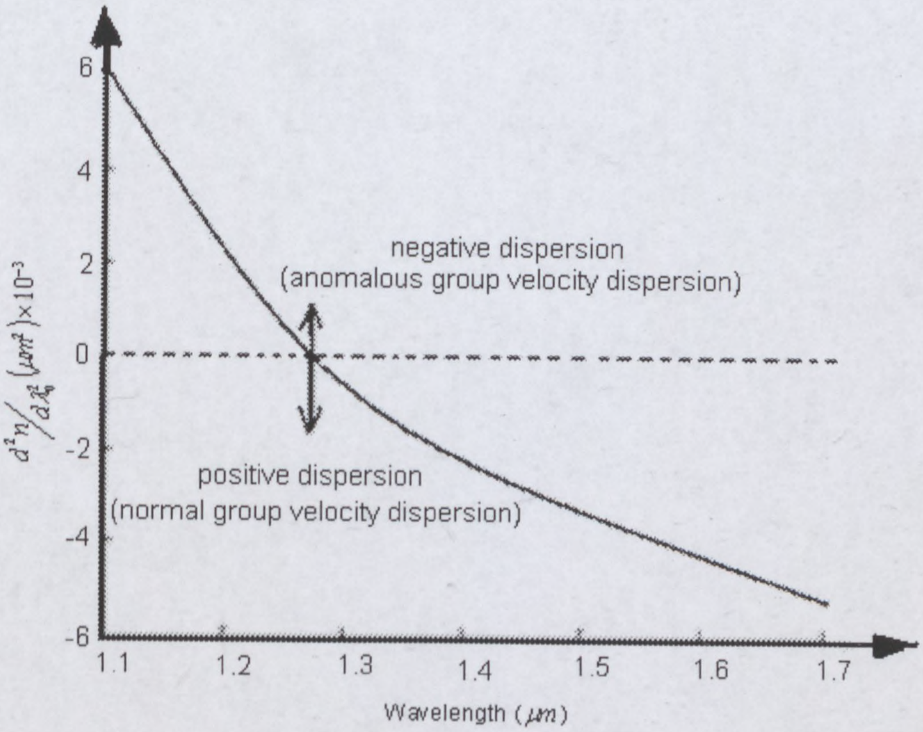


Figure 3.9: Variation of Dispersion with wavelength

(Adapted from Ramachandran, 2007)

Using above analogy, dispersion takes place in both the regions but in the normal dispersion region, longer wavelength components of the pulse travel faster than shorter wavelength components while the reverse works for the anomalous dispersion region, (Ramachandran, 2007)

Material dispersion hence causes pulse broadening because real optical pulses have nonzero spectral width. The spread in wavelength values has a progressive broadening of the optical pulse as it propagates through the optical fiber transferring energy from one pulse to the neighbouring and causing erroneous data at the receiver.

The broadening is caused by the dependence of the wavelength of the refractive index, which in turn depends on the velocity according to the eq. (3.10).

$$V = \frac{c}{n(\lambda)} \tag{3.10}$$

3.2.2 WAVEGUIDE DISPERSION

Waveguide dispersion affects single mode optical fibers when the mode is not completely confined to the core of the fiber. Depending on the size of the core and the index difference between core and cladding, part of the mode will leak into the cladding and experience low index.

As indicated in the above paragraph, about 80% of the optical power travels through the core and 20% of the light which propagates in the clad, travels faster than the light confined to the core and is dependent on wavelength thereby causing dispersion. Waveguide dispersion is present even if the core medium is not dispersive.

Since modal dispersion is not present in single mode fiber, waveguide dispersion is important at wavelengths for which material dispersion is small but it is negative for the entire operating wavelength but small in comparison to material dispersion as seen in Figure 3.10.

Figure 3.10 depicts a zero dispersion coefficients in the second window of communication of the spectral band. In the third window of communication, minimum losses are maintained at the total dispersion coefficient approximated at 17ps/nm-Km.

Waveguide dispersion can be tailored by varying the mentioned parameters and it is possible to shift the zero dispersion wavelength of the optical fiber.

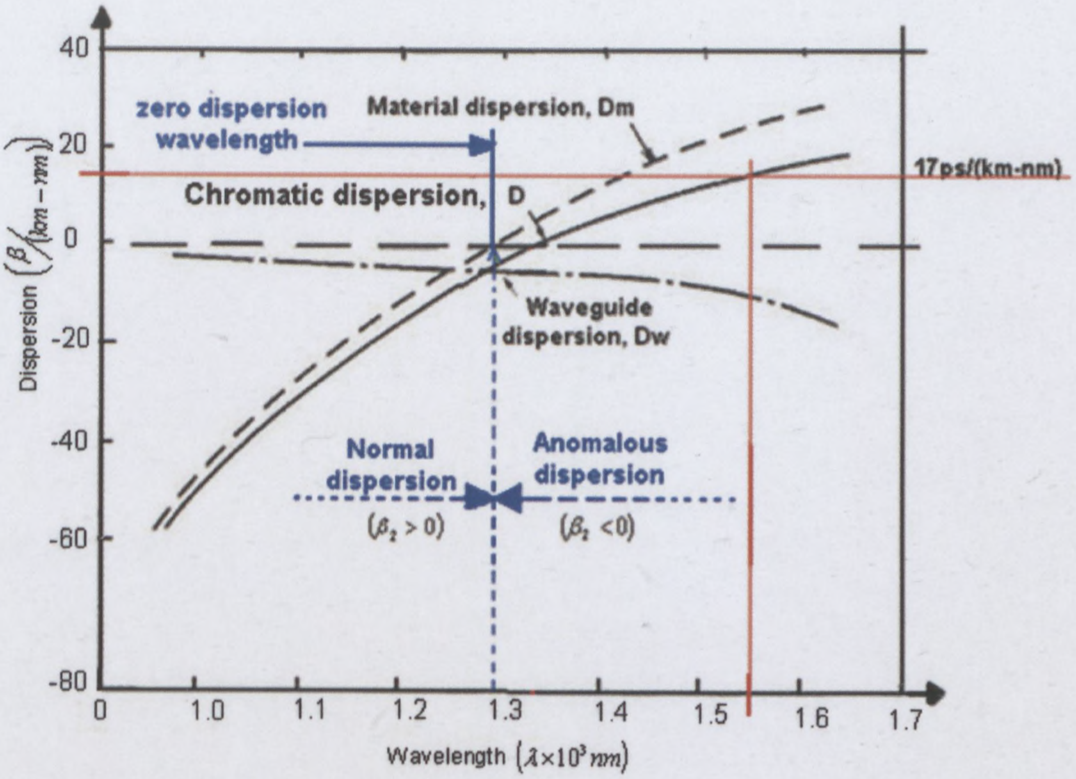


Figure 3.10: Variation of Chromatic dispersion and wavelength

(Adapted from Agrawal, 2008)

Single mode fiber exhibits low attenuation that enables non repeater communication network to cover longer transmission distances. Attenuation is a limiting factor for long transmission distance but its deployment eliminates modal dispersion, the main effect of bandwidth limitation in multi mode fiber.

Waveguide dispersion (D_w) increases Chromatic Dispersion ($D_{chromatic}$), to zero dispersion point before material dispersion (D_m) enhances it further above zero dispersion point as illustrated in Figure 3.10.

Near $1.55\mu m$ wavelength, $15 \le D \le 18\ ps/(km-nm)$is the region where operation of optical fiber is mostly used since fiber loss is low.(C-L band window).

At 1550nm wavelength, attenuation is minimum and new generation of optical communication systems operate at this wavelength even though for SMF, the total chromatic dispersion in the region of 15 - 20ps/nm-km, (Agrawal, 2008).

Standard optical fiber has zero dispersion wavelengths at 1310nm and attenuation of $0.2dB/km$. Negative dispersion value indicates that shorter wavelengths have a higher velocity than longer ones and vice verse for positive dispersion values. Total chromatic dispersion (D) is zero at 1300nm but the optical fiber attenuation is at a minimum in this wavelength.

The total dispersion factor D is the sum of the material dependent term which is due to variation of the refractive index n_1 of silica with the optical carrier frequency and waveguide dependent factor, (Ghatak & Thyagarajan,1997).

$$D_{chromatic} = D_{material} + D_{waveguide} \tag{3.11a}$$

where the material dispersion factor is

$$D_{material} = \frac{\lambda d^2 n_1}{c d\lambda^2} \tag{3.11b}$$

and the waveguide dispersion factor,

$$D_{chromatic} = -\left(\frac{n_1 - n_2}{\lambda c}\right) V \frac{d^2(V_b)}{dV^2} \tag{3.11c}$$

where λ = the operating optical wavelength,

n_1 = the respective refractive index of the core,

n_2 = the respective refractive index of the core cladding,

V = the normalised frequency,

b = the normalised propagation constant, and

$V \frac{d^2(V_b)}{dV^2}$ = a parameter which describes the waveguide dependent dispersion characteristics of an optical fiber.

When the resonance frequencies in the core region are stable at the operating frequency, material dispersion factor does not alter and it can be approximated by the Sellmeier equation.

$$n_j^2 = 1 + \sum_{j=1}^{N} \frac{B_j \lambda^2}{\lambda^2 - \lambda_j^2} \qquad (3.12)$$

where $\lambda_j = 2\pi c/\omega_j$ λ_j = resonance wavelength at which electrons oscillate, and

B_j = the oscillator strength.

Since intermodal dispersion generates both material and waveguide dispersion, pulse broadening is due to chromatic dispersion which energizes different spectral components of the pulse to travel at different group velocities determined by the wavelength.

3.2.3 CHROMATIC DISPERSION (CD)

Chromatic dispersion is a phenomenon used to describe the characteristics of different spectral components of pulses travelling at different velocities. It constitutes a combination of material dispersion and wave guide dispersion that limits performance of single mode fiber and is a critical challenge for telecommunication systems operating at higher data rates.

CD results in pulse spreading due to velocity of light through optical fiber and the total pulse spreading due is given by Sellmeier equation, (Rashed, 2011).

$$\Delta t_{chromatic} = chromatic\,dispersion(ps/km) \times \Delta\lambda(nm) \times fiber\,length(km) \qquad (3.13)$$

Agrawal, (1992) reported that in a single mode optical fiber, dispersion is a parameter of interest and is due to the wavelength dependence of the group velocity v_g. GVD causes different spectral components to propagate along an optical fiber with different group velocities. The group velocity v_g which is related to the propagation constant β as indicated in eq. (3.14b) contributes to the spectral component. The spectral component at a frequency ω would exit an optical fiber of length z at a time delay of t/v_g given that,

$$\frac{1}{v_g} = \frac{d\beta}{d\omega} \qquad (3.14a)$$

Because of the frequency dependence of ω, a pulse having the spectral width of $\Delta\omega$ is broadened by,

$$\Delta T = \beta_2 z \Delta\omega \qquad (3.14b)$$

where $\beta_2 = \frac{d^2\beta}{d\omega^2}$ ps^2/km is called the GVD parameter.

The GVD parameter β_2 is interpreted as the dispersion per unit transmission distance of unit frequency signal spread but in optical communication systems, the wavelength unit is used therefore eq. (3.14b) is rewritten as,

$$\Delta T = Dz\Delta\lambda \tag{3.14c}$$

where $\Delta\lambda$ is the signal spectral width in wavelength units, and

D is the dispersion parameter in the units of ps/(km-nm).

The dispersion parameter D which is used to indicate the amount of dispersion in optical fiber specifications is related GVD by,

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = \frac{-2\pi}{\lambda^2}\beta_2 \tag{3.14d}$$

3.2.4 POLARIZATION MODE DISPERSION

In optical fibers ttemperature variations, bending of the optical fiber, optical fiber geometry non uniformity and optical fiber splice are changes that contribute to the Polarization mode dispersion (PMD) in the system but very difficult to characterize.PMD are a statistical nature and arises from random coupling between the two modes induced by various perturbations from optical fiber.

Birefringence is random change over time due to both imperfections introduced in the manufacturing process or external influences. The possible causes of random birefringence are an oval core shape, outside pressure due to mechanical stress, wind or temperature and both optical fiber bending and twisting.

PMD leads to signal distortions in high speed long haul optical systems because of birefringence. Birefringence has its origin in small departures from the perfect cylindrical symmetry in the core of optical fibers.

Since most communication systems are operated at high bit-rates, the issue of PMD cannot be ignored and higher bit rates increases its value, (Larsen, 2002. Videcrantz, 2002).

Considering a light pulse as consisting of two orthogonal polarizations, fast axis and slow axis, due to optical fiber birefringence, the two modes travel at different group velocities then separates as the pulse propagates along the fiber as illustrated in Figure3.11 below.

Because PMD is random and time varying, this is because environmental causes of birefringence such as temperature or stress variations are random. These effects are small but become important at very high data rates, (Azadeh, 2009).

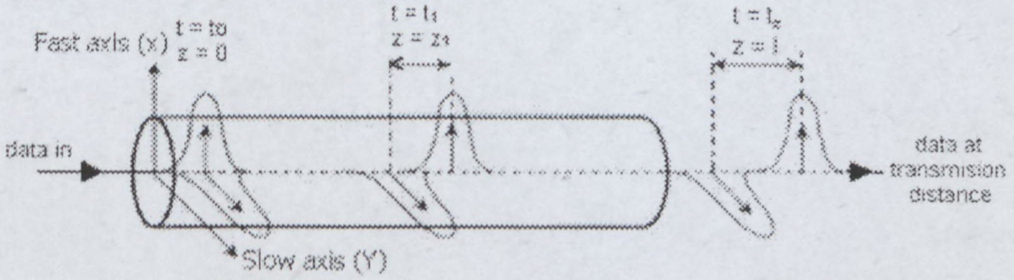


Figure 3.11: Two pulses launched with equal power

(Adapted from Chandrasekhar, 2006)

As shown, after an optical data is propagated over a distance *L*, the effect of differential group delays (DGD) which is equal to $\Delta\tau = \Delta\beta \bullet L$ takes place. The two polarization components x and y experiences different indices of refraction as they propagate with different speeds, causing pulse broadening and dispersion. If the signals are delayed by impairments in the optical fiber, pulse broadens and overlaps the succeeding signal. The delay between the orthogonal polarization states is approximated by,

$$\tau = D_{PMD}\sqrt{L} \tag{3.15}$$

where D_{PDM} is known as the polarization dispersion coefficient, and

L is distance of pulse propagation.

3.2.5 LIMITS OF DISPERSION

Dispersion is a term given to any effect where different components of transmitted signal travel at different velocities in optical fiber and arriving at different times at the receiver. Our goal is to explain the existence of dispersion phenomenon and limitations it sets in transmission systems.

Dispersion limits the distance a signal can travel through an optical fiber, by blurring it. If a pulse is sent every nanosecond and the pulses spread 10ns at the end of the optical fiber, they blur together resulting into total dispersion Δt, given by eq. (3.16).

$$\Delta t = dispersion\,(ns/km) \times dis\tan ce\,(km) \tag{3.16}$$

For the same optical fiber used throughout communication system, the total pulse spreading is the characteristic of the optical fiber dispersion times the optical fiber length. If different types of optical fiber lengths are used the summation of the spreading is used and dispersion measures pulse spreading per unit distance as indicated in eq. (3.16).

Since Chromatic and polarization mode dispersion are independent but contribute to intra modal dispersion in SMF, the total pulse spreading is determined by eq. (3.17).

$$\Delta t = \sqrt{(\Delta t_{chromatic})^2 + (\Delta t_{polarization-\text{mod}\,e})}^2 \tag{3.17}$$

3.3 CONCLUSION

This chapter has discussed the term dispersion in relation to optical fiber, its effects in optical fiber data transmission and limitations. Dispersion is a problem for optical fiber transmission systems because light pulses broaden as a result of chromatic dispersion as they travel. The resulting effect limits both data rate transmission and the optical fiber length through which data is transmitted before successfully decoded at the receiver. These constraints are compounded with the high demand for streaming media over the Internet.

Optical fiber is a good medium for long haul broadband communication but suffers from data loss and dispersion which limits the bandwidth and working distance of the fiber. At the operating windows 1300nm and 1550nm wavelength SMF is an important medium for ultra long high speed and high capacity optical communication systems.

Dispersion is a deterministic factor in deciding the rate of pulse broadening in SMF. Both the bit rate and channel capacity of the optical fiber is limited by dispersive characteristics of the optical fiber material.

Intermodal dispersion does not occur in SMF because injected energy is transported in a single mode. The dispersion factor in a single mode fiber is mainly contributed by material dispersion and waveguide dispersion.

PMD leads to pulse broadening due to random variation in birefringence of the optical fiber length. The impact depends on bit rate and transmission distance hence must be considered during systems' design. Chromatic dispersion within optical fiber enhances signal distortion which can be minimised by the use of high signal power in the optical fiber network. However, the use of high power increases optical fiber nonlinearity that will be discussed in the next chapter.

CHAPTER FOUR

NONLINEAR EFFECTS IN OPTICAL FIBERS

This chapter provides an introduction to various signal degrading effects playing significant role in long haul systems.

Optical fiber nonlinearities are important matters in optical communications and can severely damage data. Accumulation of phase effects along optical fiber is due to nonlinearity which is the result of increased power level.

Nonlinearity is an important aspect in optical communications systems and is due to high light intensity in the optical fiber core. Nonlinearity can couple all other optical fiber effects together when out of control, (noise, dispersion and polarization mode dispersion etc). The problem of nonlinearity increases with the increase in transmission bit-rates.

4.1 INTRODUCTION

At high transmitted powers and high bit rates, the effect of nonlinearity plays a leading role in data transmission. The root cause of nonlinearity is the fact that the index of refraction of many materials, are functions of light intensity and the dependence gives rise to self and cross phase modulation and, four wave mixing.

Optical fiber nonlinearities have useful attributes and characteristics to be avoided in communications and the consequence of the attributes includes,

- increasing signal bandwidth within a given channel,
- modifications of the phase and shape of pulses,
- generation of light in other wavelengths at the expense of power in the original signal, and
- increasing crosstalk between signals at different wavelengths and polarizations.

The speed of lightwave increases with the amplitude but each component of lightwave has different speed because nonlinearity effect on each varies with the amplitude as illustrated in Figure 4.1. The next section will discuss the influence of nonlinearities effects in today's optical communication systems.

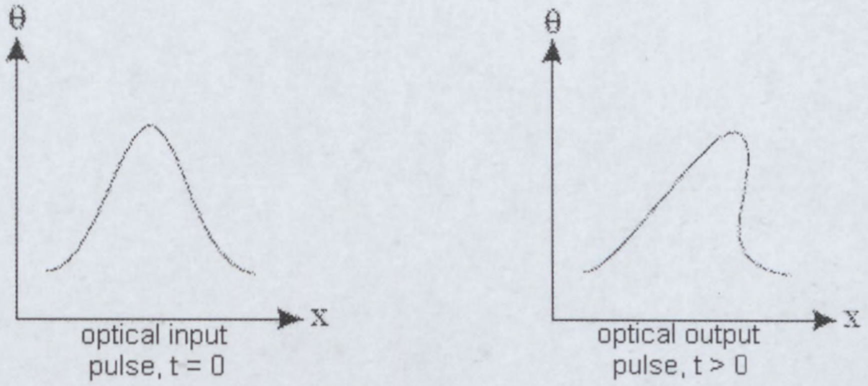


Figure 4.1: Nonlinear effects of lightwave

(Adapted from Weinert, & Dehn, 2009)

4.2 EXISTENCE OF SELF PHASE MODULATION (SPM)

When an input pulse travels through an optical fiber, the high refractive index due to high intensity of light in the core changes both core refractive index and input pulse intensity with time. The variation of lightwave randomly changes different parts of the phase of original pulse and the resulting effect is a pulse broadening which affects high transmission power, hence the name Self Phase Modulation (SPM). (Singh & Singh, 2007.Agrawal, 2002).

Kerr effect which manifests as a new frequency when an optical signal propagates through an optical fiber is a change in the refractive index of a material in response to an applied electric field. In a single mode fiber, Kerr effect induces a spectral broadening and the phase of the signal is modulated according to its power profile the effect is referred to as self phase modulation (SPM).

SPM occurs in single channel systems as a result of optical Kerr effect due to the fact that the refractive index of the fiber has an intensity dependent component. Variation of refractive index with light intensity acts on different parts of the pulse and causes modifications in the phase of the pulse. This modifies different parts of the pulses from different phase shift then creates pulse chirping. Chirping adds spectral content to the lightwave and causes it to be prone to dispersion. This effect is proportional to the transmitted signal power and is significant with intense beams such as those from lasers, (Kohl et al. 2008).

The phase changes caused by SPM cannot be assumed to be linear with respect to frequency as in the case with phase changes due to dispersion. Hence it can not be completely compensated by dispersion in the SMF even thoughit limits the launch power.

SPM does not cause any signal degradation but in the presence of dispersion, phase changes lead to changes in pulse shape, which results in severe signal impairments.

Agrawal, (2001) represented the phase change due to input power in optic fiber by φ_{NL};

$$\varphi_{NL} = \gamma P_{in} L_{eff} \tag{4.1}$$

where φ_{NL} is the phase change caused by input signal, and

γ is the nonlinear coefficient of the optic fiber, and

P_{in} is input power.

The effective length of the fiber of length (L)

$$L_{eff} = \frac{1-\exp(-\alpha L)}{\alpha} \tag{4.2}$$

α represent optical fiber loss and in communication, $L_{eff} \approx \frac{1}{\alpha}$

Eq. (4.1) shows that phase change is directly proportional to the input power which is not the case of intensity modulated systems where power varies with time and effectively frequency chirping the pulses in the data signal. Intensity changes that give rise to the phase change are related to the pulse shape and pattern of the signal making it difficult to predict the resulting phase changes of the signal.

Sabella and Lugli (1999) suggested that refractive index depends on field intensity according to kerr nonlinearity equation,

$$n = n_0 + n_2 \frac{|E|^2}{\sqrt{\mu / \varepsilon}} = n_0 + n_2 I \tag{4.3}$$

where n_0 is linear refractive index,

n_2 is nonlinear refractive index, and I is field intensity.

Nonlinear refractive index alters the phase of signal propagation through the fiber in relation to distance z, by expression;

$$\phi = (n_0 z + \phi_0) + \frac{2\pi}{\lambda} n_2 I_{(t)z} \tag{4.4}$$

and ϕ is initial phase,

$n_0 z + \phi_0$ is linear phase shift, and

$\frac{2\pi}{\lambda} n_2 I_{(t)z}$ is nonlinear phase shift.

If the effects of SPM and chromatic dispersion are nearly equal then chromatic dispersion dominates. SPM can reduce the pulse broadening that is caused by the chromatic dispersion but the broadening is stable if the two effects are equal, (Ramaswami & Sivarajan, 2002).

Intensity modulation of optical signal generates SPM in relation to field intensity due to nonlinear phase shift. The other phenomena, less critical for solitonstransmissions are highlighted in the following sections, (Hamaizi & El-Akrmi, 2009).

4.3 CROSS PHASE MODULATION

Cross phase modulation (XPM) is a process in which intensity of one beam travelling in a nonlinear medium affects the phase of another beam and allows nonlinear pulse compression. Distortion of signal and pulse broadening is asymmetric since the signals propagating depends on intensity two or more optical signals through the optical fiber. XPM effect converts power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels.

Since XPM is inversely proportion to high data rates, lowers influence of data transmission, its advantages in transmission occurs when the entire propagating signals are superimposed to each other. Otherwise, it can lead to severe damage of the systems' performance when compared to SPM, (Singh & Singh, 2007).

4.4 FOUR WAVE MIXING (FWM)

In this section a brief characterization of Four-Wave-Mixing (FWM) method is given. It's the second technique presented based on nonlinearities of the optical fiber. An optical fiber is nonlinear medium, When two different frequency components travel through a wave guide, after interaction a third order optical nonlinearity generates a new optical field which depends on the fields it originated from.

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 \tag{4.5}$$

For intensity conservation, $\frac{h}{2\pi}(\omega_1 + \omega_2 + \omega_3 + \omega_4 = 0)$ (4.6)

and h is the plank's constant.

If the newly generated wave and original waves have the same wavelength, signal interference will decrease signal to noise ratio.

FWM are used in wavelength conversion because when an incoming signal wavelength is utilized by one wave, the other wavelength is converted to allow both signals to travel through optical fiber at the same time, (Singh & Singh, 2007).

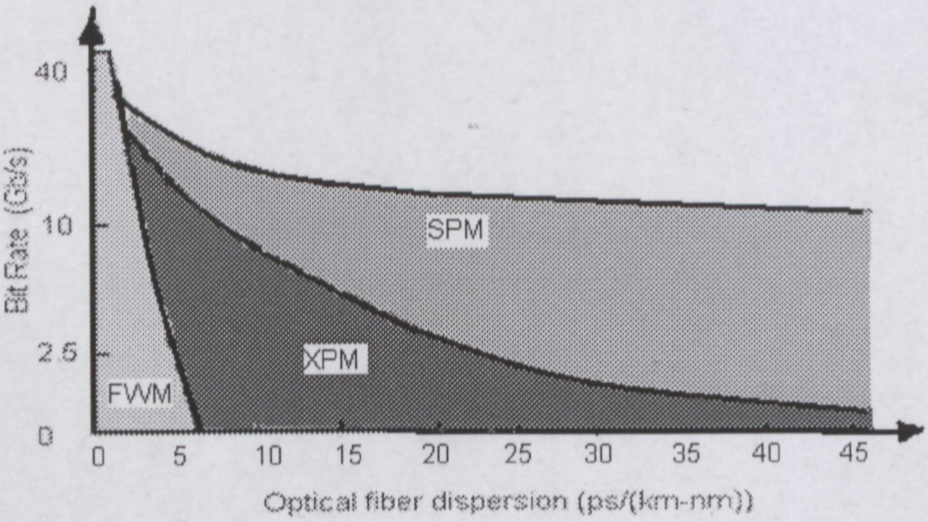


Figure 4.2: Significance of nonlinear impairments in high bit systems

(Adapted from Winzer & Essiambre, 2006)

The dominant nonlinearity for a given spectral efficiency and optical fiber dispersion for important nonlinearity that limits transmission is shown in Figure 4.2.The high bit rates signals are limited mostly by SPM which makes SPM an impairment that should be researched in order to improve data capacity.

4.5 SCATTERING EFFECTS

Non elastic scattering of photons in fibers is another source of nonlinearity which results in stimulated Raman and stimulated Brillouin scattering phenomena. Nonlinear effects limit transmission capacity but can also be used to improve the performance of the system by wavelength conversion. Nonlinearity in the refractive index produces induced modulated phase carrier of the propagating signal, (Kaminow, et al., 2008. Lee, et al. 2002).

4.5.1. STIMULATED BRILLOUIN SCATTERING (SBS)

Interaction between light and sound waves in optic fiber results in SBS which converts light wave frequency and also changes its propagation direction. Since the spectral bandwidth is directly proposal to transmission speed, bit rate induces curve broadening of Brillouin scattering resulting into low pulse peak.

Stimulated Brillouin scattering is a scattering of the pump wave from acoustic wave creating a new wave at the pump frequency. The scattering process must conserve both the energy and the momentum. Pump frequency vanishes in the forward direction (θ = 0) and is maximum in the backward direction (θ = pi). In single mode fibers, light travels in the forward and backward directions as a result, SBS occurs in the backward direction. The backward propagating light scattered from acoustic waves in the optical fiber grows at the expense of forward propagating signal and generates noise at the receiver.

Line width associated with SBS process in optical fiber is narrow at $\lambda = 1550nm$, the effect is independent of a number of channels, (Kohl et al., 2008).

Once power launched into an optical fiber exceeds the threshold level, most of the light is reflected backward through SBS. The reflected light rays limit the launched power to a few milliwatts due to low threshold but in high speed bit stream, pulses propagate at faster rate such that successive pulses build up the acoustic wave, (Agrawal, 2002).

The threshold power level for SBS is estimated by considering noise current I_p, level,

$$P_{th} = I_p A_{eff} \tag{4.7}$$

where A$_{eff}$ is effective core,

and $$\frac{g_B P_{th} L_{eff}}{A_{eff}} \approx 21 \qquad (4.8)$$

where g$_m$ is silica electro-optic coefficient $\sim 5 \times 10^{-11} w/m$, and

L$_{eff}$ is effective interval length defined by eq. (4.2)

4.5.2 STIMULATED RAMAN SCATTERING (SRS)

Stimulated Raman scattering, (SRS) occurs in optical fibers when pump wave photons give up part of energy to generate other photons of reduced energy at a lower frequency. The remaining energy is absorbed and ends up in an excited vibrational state. The process is stimulated if the pump power exceeds a threshold value and occurs in both forward and backward directions in optical fiber.

The pump beating and scattered lightwave in these two directions creates a frequency component at the beat frequency which acts as a source that derives molecular oscillations. Since the amplitude of the scattered wave increases in response to oscillations, a positive feedback loop sets, (Agrawal, 2002).

The threshold power (P$_{th}$) defined as the incident power at which half of the pump power is transferred to the Stokes field at the output end of a optical fiber of length *(L)* is estimated from;

$$\frac{g_R P_{eff} L_{eff}}{A_{eff}} \approx 16 \qquad (4.9)$$

where g_R is the peak value of Raman gain.

For L_{eff}, see equation 4.10 and the threshold power P_{th} for SRS is,

$$P_{th} \approx 16\alpha \frac{\left(\pi\omega^2\right)}{g_R} \qquad (4.10)$$

Raman Effect which turns silica optical fiber into its own distributed amplifier enabled the first experimental studies of such transmission. It affects the performance of WDM systems but is not a limiting factor for single channel lightwave systems due to low optical power. However, it is useful in optical communication systems because of extremely large bandwidth and application in compensating optical fiber losses in modern lightwave systems, (Frazao, et al. 2009).

4.6 CONCLUSION

In this chapter we have discussed mainly nonlinearity in single mode optical fibers such as Self Phase Modulation, (SPM) and stimulated Brillouin scattering, (SBS). While SPM causes spectral broadening which is refractive index related nonlinearity, SBS causes scattering related nonlinearity besides contributing to power gains.

The generation of self phase modulation is to the advantage of solitons pulse formation while either stimulated Raman or Brillouin scattering or four waves mixing are useful when it is desired to generate or amplify additional wavelengths.

In optical fiber transmission non linear effects are nearly undesirable. After attenuation and dispersion, nonlinear effects provide the next major limitation on optical transmission and in some situations they are more significant than either attenuation or dispersion. When nonlinearity is absent, dispersion makes the various frequency components to propagate at different velocities. Non linearity causes the pulse energy to be continually injected, via harmonic generation, into higher frequency modes in the absence of dispersion.

High speed optical fiber systems employ SMF which are prone to Chromatic dispersion (CD) and polarization mode dispersion (PMD). The former arises due to the choice of wavelength whereas the latter, propagation delay when two polarised waves travels in the same plane. Linear and nonlinear are the two approaches already used to compensate fiber dispersion with the former being using chirped fiber gratings and the latter, optical solitons.

High optical power increases nonlinear effects that lead to signal distortion but generation of solitons to transmit low power data in long haul would minimise optical fiber nonlinearity and enhances data stability.

The effect of Raman and Brillouin scattering provides loss of power at the incident frequency but scattering across and the power levels are low. However, they both amplify optical signal by transferring energy from the pump beam whose wavelength is suitably chosen and can be used in designing optical communication systems.

CHAPTER FIVE

PULSE PROPAGATION IN OPTICAL WAVEGUIDES

Optical waveguides has a structure in which higher refractive index region is surrounded by a lower refractive index dielectric material. The arrangement ensures that light propagates in the higher refractive index part of the waveguide by total internal reflection. Both dispersive medium and kerr effects must be considered for propagation of a pulse in an optical waveguide.

5.1 INTRODUCTION

A number of signal degrading effects were identified in the previous chapters and discussion has shown that several of them require increased attention as the optical fiber transmission distance is increased.

Self phase modulation (SPM) and group velocity dispersion can have tremendous influences on the signal quality when acting independently. SPM slows the speed of intense lightwave making the leading edge of the pulse to experience increased index of refraction and the trailing edge, fall off in refractive index. The combination makes the centre frequency of the pulse to increase across the pulse profile. When $\frac{L_D}{L_{NL}} << 1$, the dispersive effects dominate over the nonlinear effects leading to the broadening of the pulse in the time domain.

5.2 WAVE GUIDE FUNDAMENTALS

To understand the lightwave propagation, optical fibers is considered as a cylindrical waveguide then Maxwell's equation is solved in cylindrical coordinates. Nonlinear Schrodinger equation (NSE) is a differential equation used to analyse the non linear characteristics of lightwave propagating in an optical fiber.

A short pulse of light in optical fiber composed of Fourier sum of lightwave with numerous varied frequencies is broadened by dispersion. The effect causes errors in data transmission systems using light pulses to represent digital bits because the pulses will begin to overlap one after some distance.

All electromagnetic waves are described by the electric field vector E, the electrical displacement D, the magnetic field vector H, and the magnetic flux density B. The relationship of the four field vectors was derived by James Clerk Maxwell (1831-1879) and named Maxwell equation (Agrawal, 2001).

5.2.1 WAVE EQUATIONS

Maxwell's equations are used to analyse the propagation of light waves through optical fiber under certain boundary conditions. The equations in a dispersive and nonlinear optical material shown below are both proportional to $e^{j\omega t}$.

$$\nabla \times E = -\frac{\partial B}{\partial t} = \mu \frac{\partial H}{\partial t} = -j\omega\mu H \tag{5.1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t} = (\delta + j\omega\varepsilon)E \tag{5.2}$$

where E is an electric field vector, and

H is magnetic field vector,

Propagation of light in optical fibers can be described by Maxwell's eq. (5.3) and (5.4)

$$\nabla \bullet D = \rho_f \tag{5.3}$$

$$\nabla \bullet B = 0 \tag{5.4}$$

where D a magnetic flux density, and

B is an electric flux density.

The sources of optical electromagnetic field are current density vector J and the charge density ρ_f and in optical fibers, J = 0 and $\rho_f = 0$ since there are no free charges. Given that

$$D = \varepsilon_0 E + P \tag{5.5}$$

$B = \mu_0 H + M = \mu_0 H$, for optical fibers (5.6)

where ε_0 is the vacuum permittivity,

μ_0 is the vacuum permeability,

M is induced electric polarization (M = 0, since glass is not a magnet material), and

P is induced magnetic polarization.

The flux densities D and B are related to the electric and magnetic fields E and H by the following equations;

From eq. (5.3) and (5.4) above:

$$\nabla \bullet \varepsilon E = \nabla \bullet E = 0 \qquad (5.7)$$

$$\nabla \bullet \mu H = \nabla \bullet H = 0 \qquad (5.8)$$

Wave equation is determined by using a vector identity in conjunction with eq. (5.1)

$$\therefore curl \quad (\nabla \times E) = \nabla \times (\nabla \times E)$$

$$= \nabla \times \left(\frac{-\partial B}{\partial t} \right) = \nabla \times \left(\frac{-\mu \partial H}{\partial t} \right)$$

$$= -\mu \frac{\partial (\nabla \times H)}{\partial t} = -\mu \frac{\partial}{\partial t} \left(\frac{\partial D}{\partial t} \right)$$

$$= -\mu \frac{\partial}{\partial t} \left(\varepsilon \frac{\partial E}{\partial t} \right)$$

$$= -\mu\varepsilon \left(\frac{\partial^2 E}{\partial t^2} \right) = -j\omega\mu \nabla \times H_s \qquad (5.9)$$

Using vector identity and eq. (5.7),

$$\nabla \times (\nabla \times E) = \nabla (\nabla \bullet E) - \nabla^2 E$$

$$= \nabla^2 E \qquad (5.10)$$

Equating eq. (5.9) and (5.10) provides equation for E-field.

$$\nabla^2 E - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} = -j\omega\mu(\delta + j\omega t)E_s = 0 \qquad (5.11)$$

and eq. (5.2) is analysed in order to determine wave equation for H-field

$$\therefore\ curl\ (\nabla \times H) = \nabla \times (\nabla \times H) = \nabla \times \frac{\partial P}{\partial t}$$

$$= \nabla \times \left(\varepsilon \frac{\partial E}{\partial t} \right)$$

$$= \varepsilon \frac{\partial}{\partial t} (\nabla \times E) = \varepsilon \frac{\partial}{\partial t} \left(\frac{-\partial B}{\partial t} \right)$$

$$= \varepsilon \frac{\partial}{\partial t} \left(-\mu \frac{\partial H}{\partial t} \right) = \mu\varepsilon \frac{\partial^2 H}{\partial t^2}$$

$$\mu\varepsilon \frac{\partial^2 H}{\partial t^2} = \nabla^2 H \tag{5.12}$$

Eq. (5.10) and (5.11) are wave equations that describes transverse plane waves at the speed of light, since

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \tag{5.13}$$

hence, $\frac{1}{c^2} \frac{\partial^2 H}{\partial t^2} - \nabla^2 H = 0$ (5.14)

$$\frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} - \nabla^2 E = 0 \tag{5.15}$$

The relation between the induced polarisation P and the electric field E is used in describing wave propagation.

Considering that the required optical frequency is far from the resonance frequency of the optical fiber medium and including third order nonlinear effects, the induced polarisation is described by;

$$P(r,t) = P_L(r,t) + P_{NL}(r,t) \tag{5.16}$$

where P_L is the linear part, and

P_{NL} is the nonlinear part.

When eq. (5.14) is simplified, an accurate approximation to the light wave propagation along optical fiber is established. This is achieved by ensuring that nonlinear polarisation (P_{NL})is a small perturbation to the total induced polarization. The nonlinear change in the refractive index of silica fiber is normally $< 10^{-6}$, making $P_{NL} = 0$.

Eliminating magnetic part of eq. (5.16) provides a second order wave equation of the form

$$\nabla^2 \widetilde{E} + n(\omega)\frac{\omega^2 \widetilde{E}}{c^2} = 0 \tag{5.17}$$

5.2.2. NONLINEAR SCHRODINGER EQUATION

NSE incorporates chromatic dispersion, nonlinearity and physical effects of the propagating signal. The basic form of NSE is shown in eq. (5.18).

When equations for magnetic and electric fields are combined together, the electric field envelope E is the amplitude of a Gaussian input pulse which forms a partial differential equation, (Siddamal, et al.. 2011. Kumar& Rao 2009. Agrawal,2008.Agrawal, 1995).

$$i\frac{\partial E}{\partial z} + \frac{i\alpha}{2}E - \frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} + \gamma|E|^2 E = 0 \tag{5.18}$$

When absorption coefficient α = 0, Nonlinear Schrodinger Equation (NSE) for signal propagation in optical fiber in eq. (5.18) is reduced to a single beam soliton equation shown in eq. 5.19) which is can be represented as shown in eq. (5.20).

$$i\frac{\partial E}{\partial z} + \frac{1}{2}\beta_2\frac{\partial^2 E}{\partial t^2} + \gamma|E|^2 E = 0 \tag{5.19}$$

where β_2 is the optical fiber measure of dispersion,

$\gamma = \frac{\omega_0}{c}n_2$ is optical fiber nonlinear parameter,

z is pulse propagation distance along optical fiber,

t is pulse movement measured time, and

$\beta_2\frac{\partial^2 E}{\partial t^2}$ is dispersion effect in optical fiber.

Eq. (5.19) can be normalized in terms of dimensionless quantities form;

$$i\frac{\partial u}{\partial \xi}+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+|u|^2 u=0 \tag{5.20}$$

where $u=\frac{E}{E_0}$ is measure of electric field envelope,

$\xi=\frac{z}{l_d}$ is soliton length, and

$\tau=\frac{t}{t_0}$ is pulse's dimensionless delay time.

If the refraction index is $n=n_0+n_2|E_2|$, the scaling factors for the above parameters are;

t_0 =Solitons width.

$$l_d=\frac{t_0^2}{\beta_2} \tag{5.21}$$

$$E_0=\sqrt{\frac{n_2\omega_0 l_d}{2c}} \tag{5.22}$$

substituting eq. (5.21) to eq. (5.22) yields, E_0.

$$E_0=\sqrt{\frac{n_2\omega_0 t_0^2}{1\beta_2 c}} \tag{5.23}$$

and n_2 is nonlinear kerr coefficient,

ω_0 is pulse carrier frequency, and

c is the speed of light.

Eq. (5.20) describes optical pulse propagation in Single Mode Fiber, (SMF) when PMD and optical fiber losses along the fiber length are assumed.

Parameters β_2 and γ govern the effects of Group Velocity Dispersion,(GVD) that results in pulse temporal broadening and Self Phase Modulation, (SPM) that broadens spectral pulse and simultaneously limits performance of an optical communication system. Eq. (5.21-23) are the components of NSE already discussed.

If hyperbolic secant pulse with a width T_0 and the peak power P_0 is launched into an ideal lossless optical fiber, sech pulse propagates for a long distance without any change of shape. The solution of eq. (5.20) which is a bell shaped waveform called fundamental solitons solution transports optical data, (Kuriakose & Porsezian, 2010).

5.3 LINEAR AND NONLINEAR EFFECTS IN OPTICAL FIBER

Both dispersion and SPM act simultaneously in optical fiber to generate a solitary pulse wave used in lightwave for data transmission in optical fiber. Solitons has experimentally been tested and found to comply with transmission impairments associated with optical fibers. The technique maintained a transmission span of 70km with the simulations reporting higher transmission lengths.

5.3.1 FUNDAMENTAL SOLITONS

Solitons are affected by PMD, amplitude jitter, and pulse interaction but fundamental solitons is stable during propagation and maintain the hyperbolic secant shape during propagation which effectively reduces data transmission errors, (Rashed, 2011. Bohac, 2010).

During negative dispersion, high frequency light travels faster than low frequency light. Intensity induced by SPM opposes the effects of dispersion thereby balancing anomalous dispersion created by negative dispersion and the result of which is solitary wave, soliton. The shorter the solitons pulse duration, the larger its peak is a relation which is not depicted in soliton solution eq. (5.25).

Fig 5.1 shows a fundamental pulse shape generated by laser device used to propagate low power high intensity signals for transmission through optical fiber. The sech shape provides the advantage of infinite bandwidth for the data being transmitted.

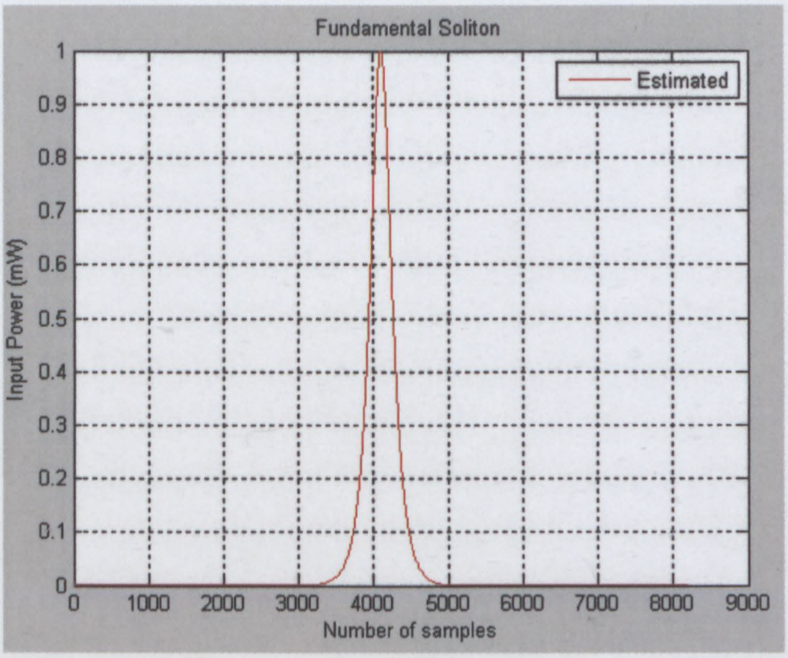


Figure 5.1: Fundamental soliton

The pulse shape of first order solitons shown in Figure 5.1 is generated by applying the inverse scattering method to eq. (5.2) which shows that the solution for the above equation has a form,

$$u(\tau) = \eta \operatorname{sec}h(\eta\tau) \tag{5.24}$$

where η is referred to as the order of the soliton.

In fundamental solitons regime, $\eta = 1$, which is the first order soliton, the pulse does not change its shape at all as it propagates in optical fiber. Fundamental solitons is the most suitable for telecommunication industry because the pulse shape stable.

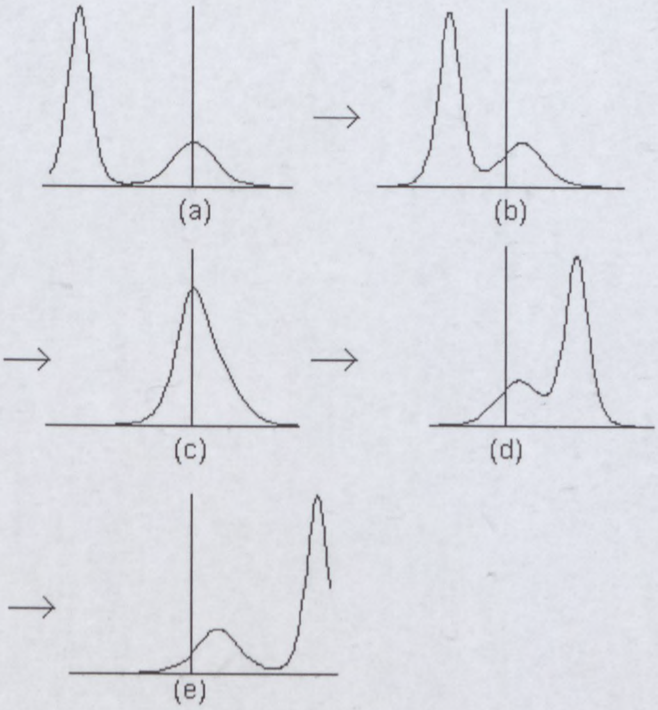


Figure 5.2: Solitary waves travelling with constant shape and velocity

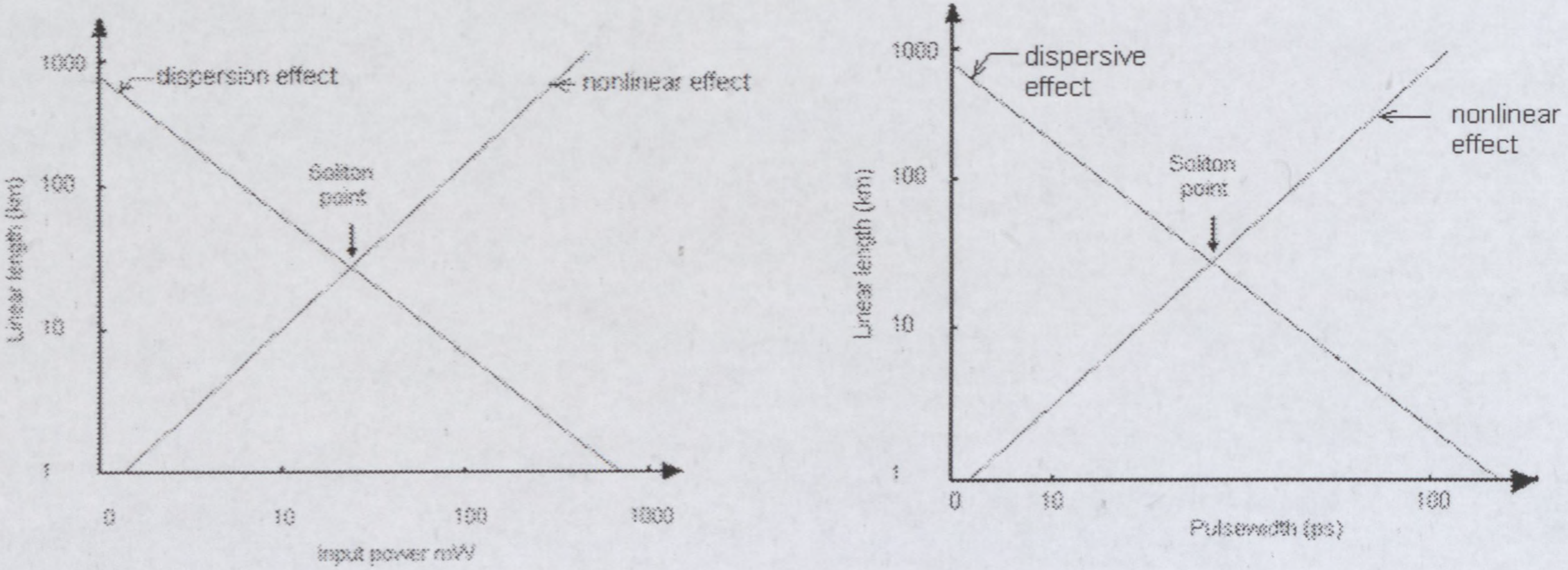
(Adapted from Matusevich & Trofimov, 2009).

Solitary waves behave like particles, each travelling with constant shape and velocity when the waves are located far apart. They then deform when they are close and finally merge into a single wave which again splits into two solitary waves with the same shape and velocity. This is shown in Figure 5.2 where a pulse with high amplitude travels through a pulse with low amplitude and emerging unaffected at the receiving end.

Optical fiber loss broadens the pulse width of solitons and increases the soliton period but this broadening in the pulse width is related to the optical fiber loss unlike the broadening effect of dispersion.

The stability of solitons stems from the balance of nonlinearity and dispersion which emanates from the balance between dispersion and nonlinearity. Nonlinearity drives the solitary wave to concentrate further and the wave ceases to exists when imbalance occur between the two competing effect.

5.4 EFFECTS OF INPUT POWER AND PULSE WIDTH ON SOLITONS



(a) (b)

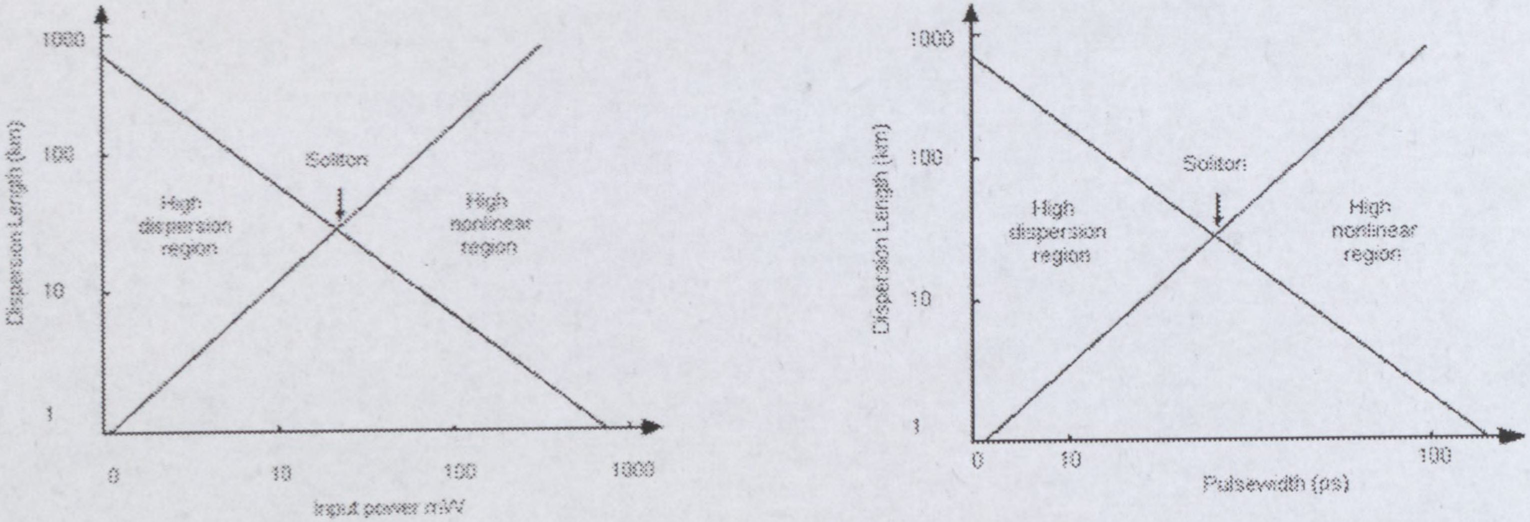
Figure 5.3: Variation of Linear length and (a) Input power, (b) Pulse width

When optical fiber effective lengths L_e are comparable to both dispersion and nonlinear lengths, $(L = L_D, L = L_{NL})$, both dispersion and nonlinearity do not effect pulse propagation. This is shown in Figures5.3 and 5.4 where the effective length which is related to optical fiber loss, is the length that the solitons travel before the transmitted power is reduced below detectable level.

$$Le \approx \frac{1}{\alpha}. \text{ (from equ. 4.2)} \qquad (5.25)$$

A condition where optical fiber's effective length ($L_{e,}$) is longer than the nonlinear length, ($L = L_{D,}\ L \geq L_{NL}$), dispersive length is also larger than nonlinear length is shown in Figure 5.3a. Since nonlinearity length is inversely proportional to optical power, self phase modulation effect takes place resulting in pulse spectrum expanding.

$$\text{Nonlinear length} = L_{NL} = \frac{1}{\gamma P} \qquad (5.26)$$



(a)

(b)

Figure 5.4: Variation of dispersion Length and (a) Input power, (b) Pulse width

When effective length optical fiber (L_e) is longer than the dispersive length, $(L \geq L_{D,}\ L = L_{NL})$, nonlinear length is larger than dispersive length. Pulse broadens as it propagates on the optical fiber since dispersion length is proportional to the square of the pulse width as illustrated in Figure 5.4b. Narrower pulses have significant dispersive effects because of small dispersion length are smaller. Broadening does not affect pulse spectrum but only separates the frequency components within the signal being propagated.

$$\text{Dispersion length} = L_D = \frac{\tau^2}{|\beta_2|} = \frac{\tau_0^2 2\pi c}{|D|\lambda^2} \qquad (5.27)$$

Both Figures5.3 and 5.4 shows two conditions in which to input power and pulsewidth varies with the change in the former. The point at which the two effects cancel out is assumed and eq. (5.27) depicts the distance the solitary wave travels in the optical fiber. If optical fibers effective length $L_{e,}$ is longer than both dispersion and nonlinear lengths, $(L \geq L_{D,}\ L \geq L_{NL})$, the effects of dispersion and nonlinearity cancels out.

The simultaneous effect of anomalous dispersion $(-\beta_2)$ and nonlinearity creates an opposite frequency chirp which has no effect on either the pulse or its spectrum broadening resulting into soliton. SPM generates red shifted frequencies at the leading edge and blue-shifted frequency at the trailing edge as seen in Figure 5.5. With the correct compensation of SPM for the effect of dispersion, the optical pulse propagates without changing its envelope thus generating solitons, a solution of NSE equation shown in eq. (5.19).

In the normal dispersion regime, red shifted frequencies travel faster than blue shifted frequencies. When the pulse broadens, SPM leads to an enhanced rate of pulse broadening compared to linear broadening.

The blue part of the lightwave shifts the pulse leading edge whereas the red part of the lightwave shifts the trailing edge of light pulse resulting into anomalous dispersion. SMF operating at a wavelength of 1550nm is the anomalous dispersion region as shown in Figure 5.5.

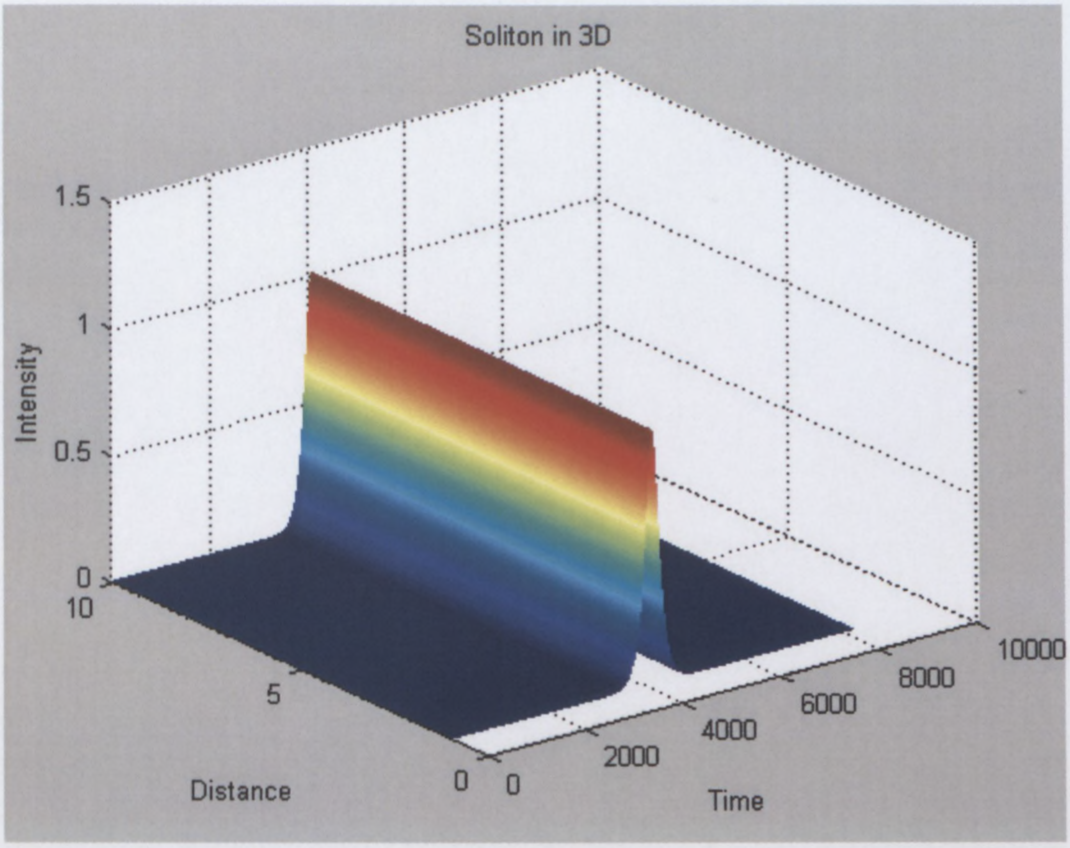


Figure 5.5: 3D Fundamental soliton propagating without loss

From eq. (5.28), when N = 1, the dispersion length $L_D$equals the nonlinear length L_{NL}, an indication that the solution exists when optical fibernonlinearity exactly balances the optical fiber dispersion. Unchirped solitons pulse which is a linear function of distance (Z) propagates through the optical waveguide.

The choice of appropriate launch power for a given optical fiber dispersion and the pulsewidth all contributes to the same. This is because pulse broadens due to GVD and compresses due to SPM.Figure5.5 shows the stable propagation of a solitons pulse over a dispersion length without any change in its shape and amplitude.

As shown in the Figure 5.2 the pulse remains undistorted as it propagates due to the delicate balance between the dispersion and the power of the pulse. Influence of optical fiber loss determines the choice of P_0 to ensure that soliton order N = 1.

$$N = \sqrt{\frac{\gamma P_0 T_0^2}{|\beta_2|} = 1} \qquad (5.28)$$

N governs the effects of SPM and GVD on pulse evolution but normal dispersion occurs when $\beta_2 > 0$ such that N < 1 and when N > 1, pulse narrows. When data propagates through the optical fiber, solitons amplitude changes in relation to loss. The effect reduces the first order solitons amplitude to zero after two soliton period, (Wang, 2006. Zhang, et al. 2001).

Solitons simulation diagram of a loss-less optical fiber transmission for 10km is shown in Figure 5.5 with the intensity set at 1mW and dispersion -17dB/km. It illustrates the resiliency of fundamental solitons when power is kept at low level in optical fiber systems as depicted in Figures 5.1 and 5.2.

The concern of the optical fiber designers are to eliminate the impairments which in effect is not practical then transmit data without the use of EDFA.

5.5 CAPACITY AND DISTANCE IN OPTICAL FIBER NETWORK

The wide band is considered when implementation of the optical fiber replaces other data transmission media to meet capacity demand and the fundamental limitations. Optical fiber transmission performance measures both capacity and distance. This is because higher capacities are always achieved over short distances.

According to Desurvire, (2004), both linear and nonlinear parameters in optical fiber make it impossible to compare the different system approaches as to their capacity cum distance performance potentials. Dispersion and other nonlinearities limit optical fiber capacity, the higher the ISI the more difficult it is to achieve the same capacity of distance as with lower ISI.

5.5.1. LIMITS ON SOLITONS TRANSMISSION

Gordon and Haus (1986) predicted that amplifier noise would induce frequency modulation because amplification is accompanied by generation of spontaneous emission noise. Haus effects result from velocity modulation induced by the frequency modulation which generates jitter in arrival times of the soliton pulses. The jitter contributes to the bit error rate which limits high data stream transmission to less than 40km.

5.6 CONCLUSION

In chapter 3 and 4 it was discussed that dispersion broadens pulses and nonlinear effect narrows the pulse but the balances between the two effects lead to the stabilization of the pulse on propagation. If optical fiber losses and nonlinearity are eliminated, dispersion compensation can fully counter pulse broadening.

Maximum transmission distance is determined by numerous factors including the signal dispersion, optical fiber nonlinearity and PMD. The pulse broadening imposes inherent limitations on the data transmission. A long transmission distance in telecommunication industry is the goal of solitons technology.

The need for high data capacity to be transmitted over long distances provides the following to consider, the distance to be covered in a single span, the backscatter and attenuation of the span leads to Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD).

Dispersion has an exponential decreasing profile similar to the fiber loss profile. If the solitons peak power P_0 decreases exponentially with L, the requirement of $N = 1$ is fulfilled at every point along the fiber if β_2 decreases in the same ratio.

Iqbal, (2007) developed a matlab code for Split Step Fourier Method, (SSFM) a method used to solve coupled mode theory equations. The simulation results based on Iqbal are shown in the next chapter.

CHAPTER SIX

6. ANALYSIS OF SOLITONS TRANSMISSION

Simulations are useful tools for understanding the main requirements and performance of a system. They don't provide the actual results and limitations for systems as in the case of real devices but the approach simplifycomplex design, (Mollenauer & Gordon, 2006).

6.1. INTRODUCTION

Most communication systems operate in hostile environments and operation at high data rates is constrained with power and bandwidth. The combination of a complex system and environment leads to design and analysis of problems that is to be simulated. The characteristics of a system under study can be established at various points or changed and the effects of the changes on the performance observed.

The main performance characteristics in solitons transmission systems are the pulse duration, pulse width, pulse power and pulse repetition rate. A short pulse of a given peak power requires low dispersion but the pulse duration determines the maximum repetition rate achievable in solitons propagation.

6.2. FUNDAMENTAL SOLITONS

The GVD and SPM effects compensate each other leading to soliton pulse evolution. Since solitons keeps initial shape during propagation through the optical fiber, it represents a balance between narrowing effect of SPM and broadening effect of dispersion. Lasers are used to generate soliton pulse since solitons requires low power.

Optical fiber loss has evolved from 1000dB/km to the present day 0.15dB/km and the latter was used in simulation. Different optical fiber lengths for both solitons and non solitons were simulated as shown in the next sections (as see also appendix D).

6.2.1. OPTICAL FIBER POWER

When power within an optical fiber is small, optical loss and index of refraction are independent of signal power. High optical power changes the characteristics of the optical fiber to nonlinearity thereby enhancing the loss and index of refraction. It also aids the generation of nonlinear effects that reduces the transmission distance.

As explained in Chapter 5, minimum power realized the conditions of linear and nonlinear parameters for the formation of solitons. Furthermore, increasing the input power does not provide significant improvement. From eq. 3.1 the effective transmission length is derived from,

$$P_z = Pe^{-\alpha Z} \tag{6.1}$$

The integral solution of eq. 6.1 provides an estimate of the effective length of the transmission distance in relation to the optical fiber loss which is an approximation of effective optical fiber length. (See eq. 6.2)

$$P_{Le} = \int_{z=0}^{L} P_z dz$$

$$L_e = \frac{1-e^{-\alpha L}}{\alpha} \tag{6.2}$$

With the transmission length taken as infinite, the loss factor sets the effective propagation length to approximately 20km.

$$L >> \frac{1}{\alpha},$$

$$L_e \approx 20km \tag{6.3}$$

6.3. SPLIT STEP FOURIER METHOD

NSE is the model equation used for numerical analysis of sech pulse propagation in optical fiber. The equation is solved using Split Step Fourier Method (SSFM) since the method separates linear and nonlinear components of eq. (6.4) before separately solving as previously stated in chapter 5.

$$\frac{\partial E}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} - \frac{\alpha}{2}E + i\gamma\left|E^2\right|E \tag{6.4}$$

The representation of eq. (6.4) in linear and nonlinear components was shown by Agrawal, (2008)

$$\frac{\partial E}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} - \frac{\alpha}{2}E + i\gamma\left|E^2\right|E = (D+N)E \tag{6.5}$$

when $\gamma = 0$, eq. (6.5) reduces to linear components of NSE

$$\frac{\partial E_N}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} - \frac{\alpha}{2}E = DE_{NSE} \tag{6.6}$$

when $\alpha = \beta = 0$, eq. (6.5) reduces to nonlinear components of NSE

Solving eq. (6.6) in time domain results in

$$E_N(t, z+h) = \exp\left(i\gamma\left|E^2\right|h\right)E(t,z) \tag{6.7a}$$

$$E(w, z+h) = \exp\left(i\frac{\beta_2}{2}(\omega)^2 h + \frac{\alpha}{2}h\right)E_D(\omega, z) \tag{6.7b}$$

After obtaining the propagation equations, several simulations were performed to show how solitons propagation is influenced by several impairments.

6.4. SIMULATION RESULTS

In this section propagation of solitons is simulated under different transmission length. Gaussian pulses are used and numerical simulations are performed using SSFM with the assumption that dispersion is anomalous at minimal losses.

The lengths that were simulated are, 200, 350, 450, 500, 600, 650, 700, 800 km with the input power maintained at 1mW for all simulation lengths.

Matlab simulation results were slow due the speed of the processor and limited simulation length to700km. The maximum length was initially set then varied until deployable span length of 100km was experimentally used as the reference length. The assumption was that power at 100km distance would be converted to useful data.

6.4.1. EFFECT OF OPTICAL FIBER LOSS

Table 6.1: Optical fiber loss parameters

PARAMETERS	**VALUE**
Optical fiber loss(α)	0.15dB/km
Splice loss (P_c)	0.1dB
Connector loss (P_s)	0.75dB
Safety margin (P_m)	3dB
Optical fiber length (L)	100km

Table 6.1 shows the parameters used in simulation of optical fiber when matching and other impairments are considered. Power loss due parameters (table 6.1) are lumped together in order to reduce complexity.

The peak power of fundamental solitons decreases exponentially with propagation according to eq. (2.11). In Chapter 2 it was stated that the loss due to optical length overrides those due to splicing and connectors. Assuming that the above statement is true then eq. (2.11) is then written as shown below.

$$P_o = P_i \exp(-\alpha L) \tag{6.8a}$$

and power in the optical fiber is governed by eq. (6.8b)

$$P_0 = \frac{1}{\gamma L_{NL}} \tag{6.8b}$$

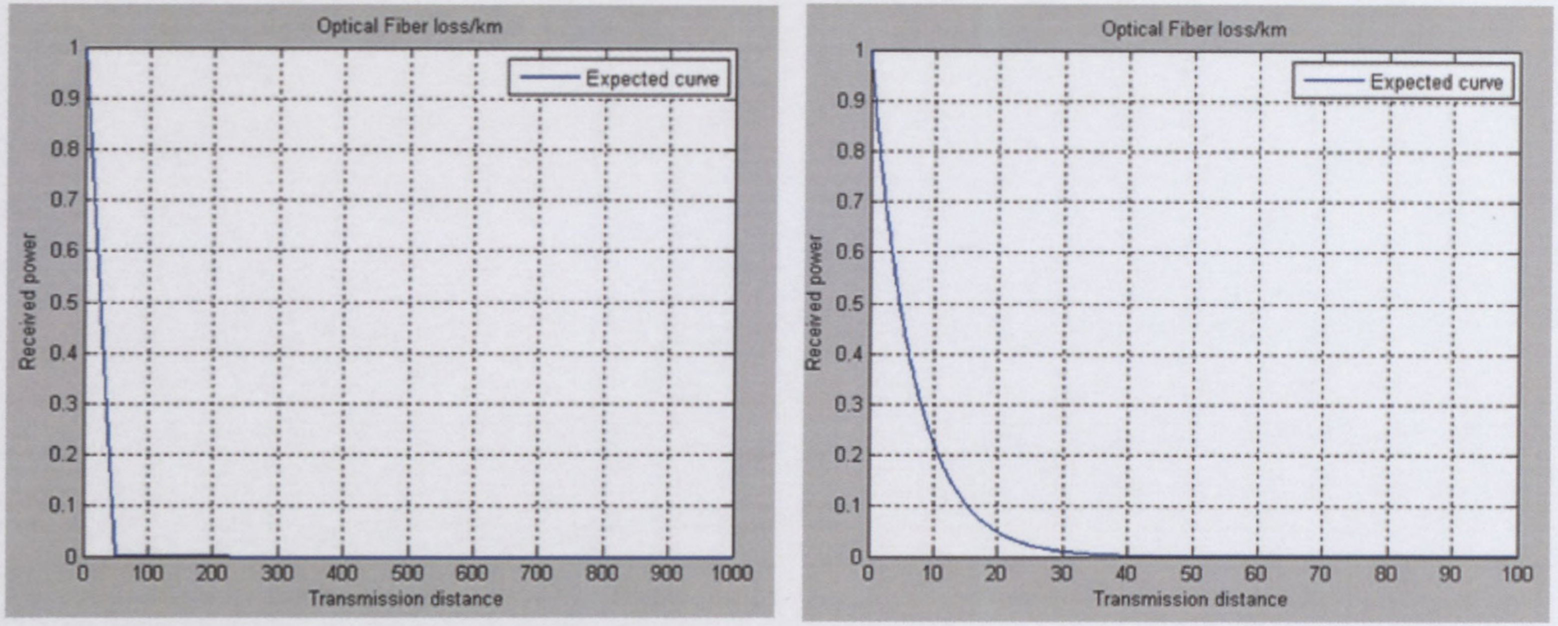
Fundamental pulse was simulated for a distance of 100km with a loss of 0.15dB/km to determine the effect of loss on solitons with the varying length.

As discussed above, simulation theoretically shows the behaviour of how input pulse is transmitted through optical fiber. The parameters are shown in table 6.2 below.

Table 6.2: Optical fiber simulation parameters

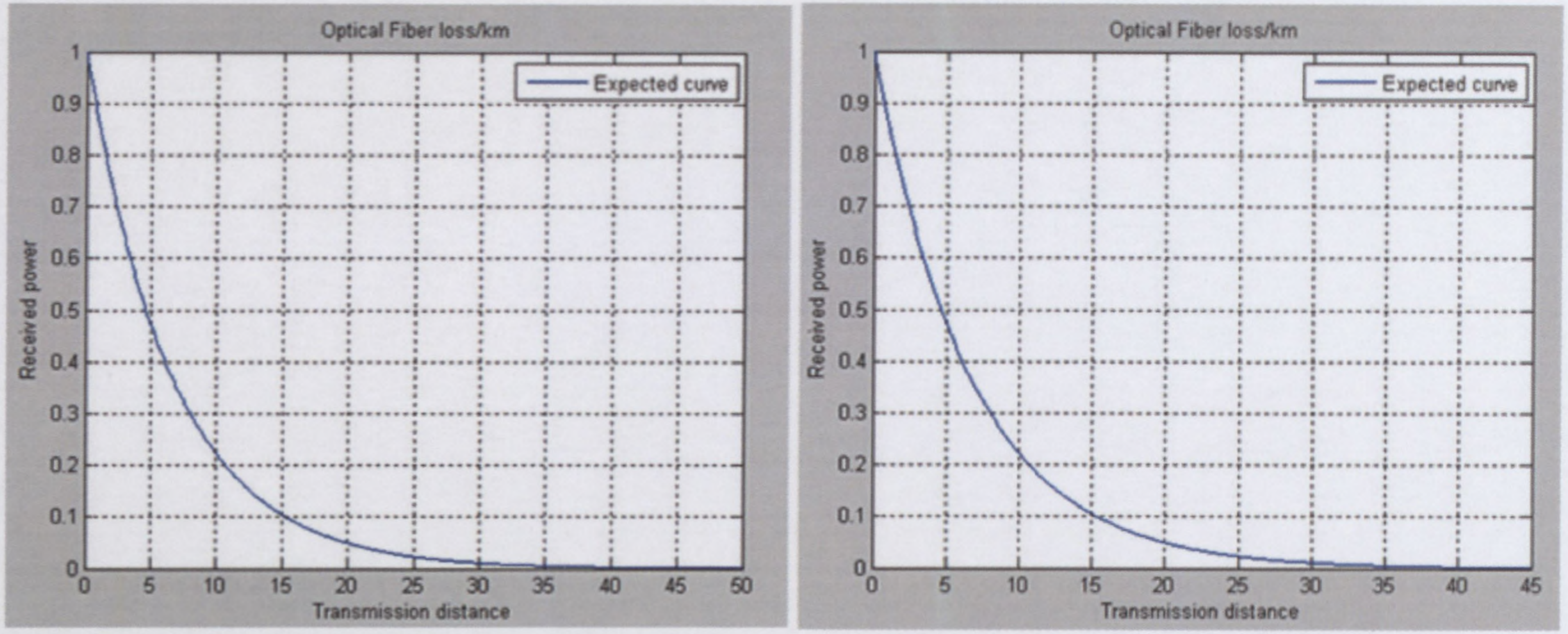
Parameters	**Magnitude**
Input power	1mW
Fiber loss	0.15dB/km
Pulse Period	125ps
wavelength	1550nm
Dispersion coefficient	-17ps'nm-km
Optical fiber length	700km

Simulations in nonlinear media for different transmission lengths are shown in Figures 6.1, 6.2 and 6.3. When operating wavelength is chosen, the dispersion does not change and pulse duration can only be changed by changing by changing solitons period. From eq. (6.6) pulse nonlinearity and the dispersion are the only variable parameters of the optical fiber.



(a) Optical length of 1000km (b) Optical length of 100km

Figure 6.1: Characteristics of optical power as a function of Optical fiber length



(a) Optical length of 50km

(b) Optical length of 45km

Figure 6.2: Characteristic of optical power as a function of Optical fiber length

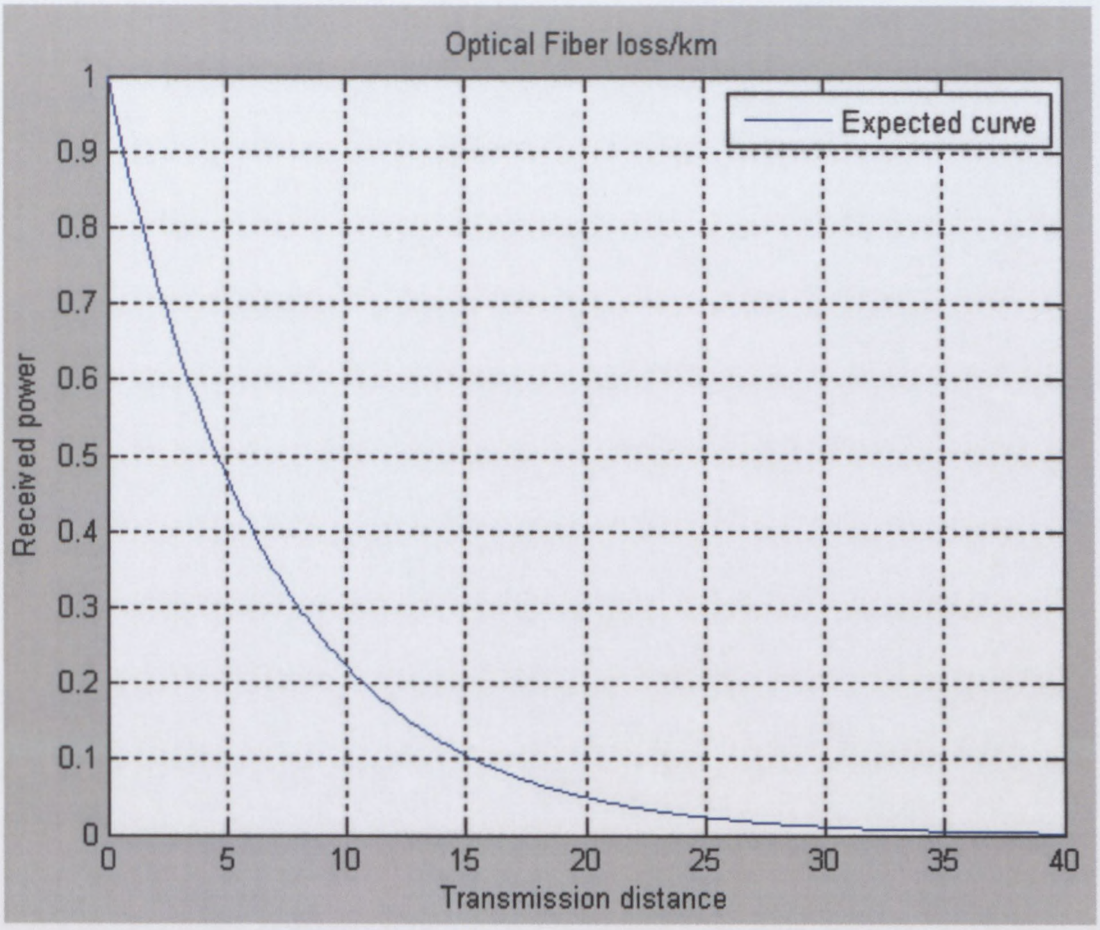


Figure 6.3: Optical power characteristic for a length of 40km

Besides the parameters mentioned in chapter 2, many optical parameters were assumed but the critical analysis of the curve shows that once the intensity reaches 0.48mW which relates to the optical length of 5km,optical fiber requires a regenerator for non solitons system as shown in Figure 6.3.

OPTICAL FIBER LOSS ON SOLITONS PROPAGATION

In the earlier chapter, it was stated that fundamental solitons is capable of transmitting data over a long distance without being affected by optical fiber parameters. Relationship between the linear and nonlinear lengths is shown in eq. (6.9) and (6.10) and N represents the order of soliton. Both dispersive and nonlinear lengths of the optical soliton are defined by,

$$L_D = \frac{T_0^2}{|\beta_2|} \tag{6.9a}$$

$$z_0 = \frac{\pi}{2} L_D \tag{6.9b}$$

$$L_{NL} = \frac{1}{\gamma P_0} \tag{6.10}$$

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} \tag{6.11}$$

where P_0 is the power of electromagnetic waves

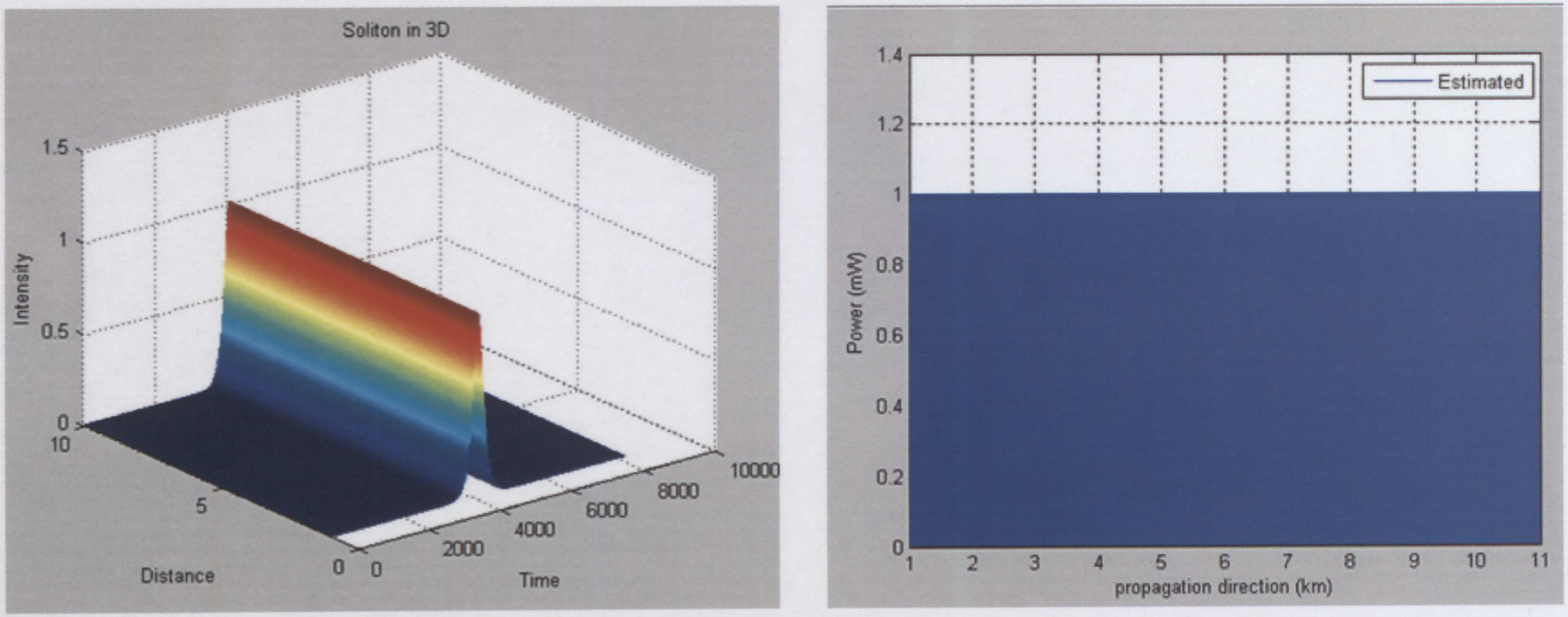
T_0 is the width of incident pulse.

Table 6.3: Solitons simulation parameters

PARAMETER	**VALUE**
Optical fiber loss (α)	0.15dB/km
Optical fiber nonlinearity (g)	0.003W/m
Soliton order (N)	1
Initial pulse width (t_0)	125e-12s
Input power (P_0)	0.001W
Dispersion length for soliton (L_d)	-
Constant (π)	3.1415926535
Step size (h_1)	1000
Pulse shape	Gaussian
Transmission fiber dispersion (β_2)	-17ps/nm-km
Max. span length used	700km

Table 6.3 presents the optical fiber parameters that were used in the simulation to arrive at the figures shown in the next sections. Varying optical fiber loss and nonlinearity introduced distortion that limited transmission distance. The effect of varying the step size enabled simulation code to set maximum transmission length for the various lengths.

TRANSMISSION SIMULATION DIAGRAMS



(a) 3D

(b) Transmission distance

Figure 6.4: : Intensity profile of single order solitons without loss for a span of 10km

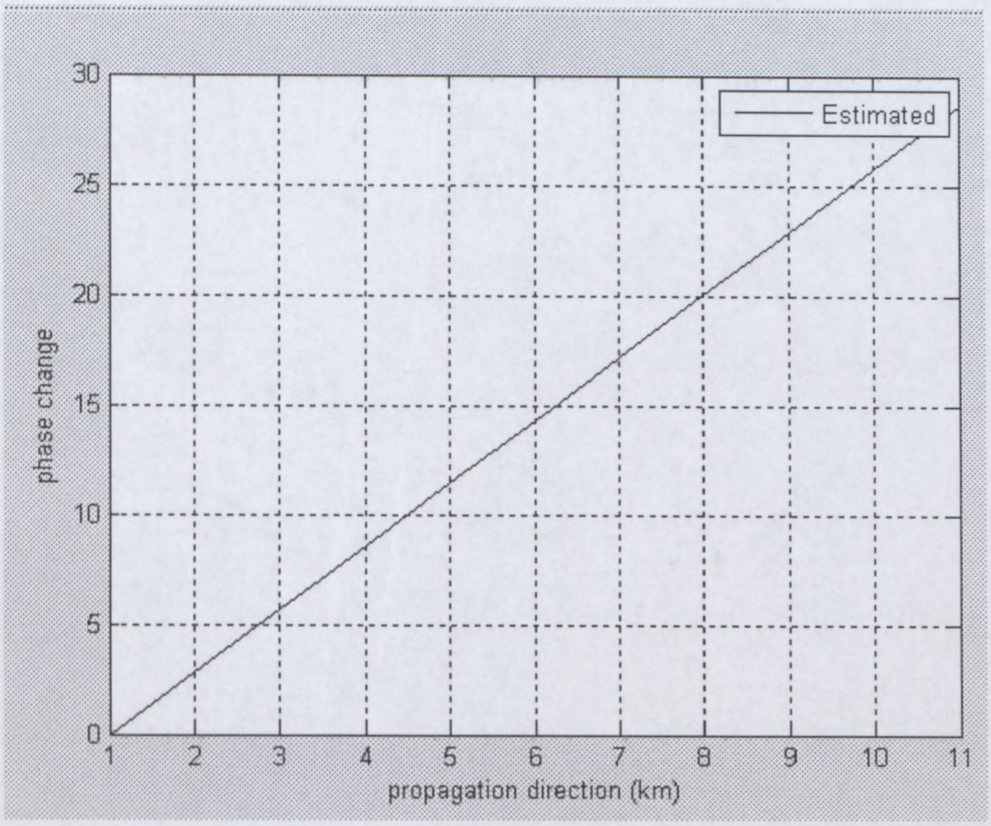
When N=1 (fundamental solitons) pulse propagates along the optical fiber does not suffer from dispersion, its amplitude remains same throughout transmission distance and it maintains its original shape, this is fundamental solitons as illustrated by Figure 6.4b. The effect is due to optical fiber non linearity exactly matching the GVD effect. This shows that solitons are very stable against perturbations and even if $0.5 \leq N \leq 1.5$, pulse tends to fundamental solitons for solitons length, $(\xi = 1)$, (Agrawal, 2005).

Larger pulse width generated higher dispersion which limited the transmission length. The pulse adjusts itself during propagation to form hyperbolic secant pulse, solitons. This occurs when GVD is negative ($\beta_2 < 0$), SPM induced chirp is positive and the two chirp contributions cancel each other as seen in Figure 6.4.

A lossless medium in which distortion of solitons amplitude is not affected by either time or frequency domains, irrespective of the distance over which transmission is metered is shown in Figure 6.4.In the absence of impairments, intensity remains constant even when the optical length is increased. The soliton period of the power is a function of transmission length for the optical fiber dispersion with initial value of loss factor being zero and the pulse power is maintained at 1mW when L_D balances L_{NL}. In all the above cases optical fiber is assumed to be lossless.

Experimentally, input pulse duration of 125ps and the fundamental power of 1mW for soliton did not generate the power length curve at 1000kmdue processor speed. The simulations shown in Figure 6.4 compares propagation of a laser beam with a practical solitons where the initial beam profile is hyperbolic secant and remains the same as initial profile when propagation length is changed.

The 3D image shows that spreading out of energy as solitons propagates does not begin until after a long distance is covered. The propagation is done in the Fourier domain and the amplitude of the initial pulse remains the same as the solitons propagates and the phase changes with the propagation distance. This is contributed to the fact that beam intensity is given as the square of absolute value of amplitude.



6.5: Phase variation with transmission distance

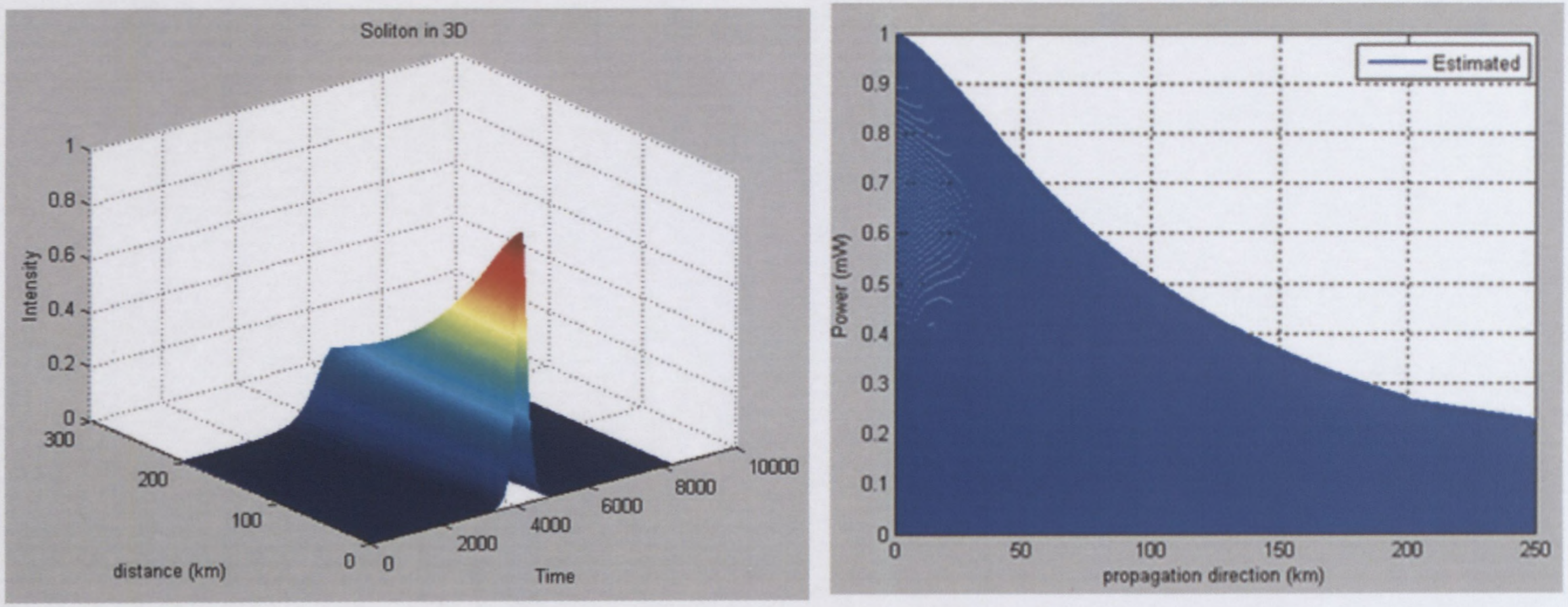
If a Gaussian pulse propagation in Figure 6.5 is considered in the normal dispersion regime (β_2> 0) and for fundamental pulse, dispersion increases to counter pulse broadening caused by SPM and this leads to an enhanced rate of broadening. The phenomenon is further shown in Figures 6.6 to 6.10. They depict simulation based on a practical application of optical fiber in real situation.

Primarily, research was to determine the minimum optical fiber length within which intensity is maintained at detectable level, unique observation of the simulated curves show that power remained above 0.52mWas the length is varied up until 100km then reduces as the accumulation of the optical fiber loss increases with the transmission length.

In a lossless optical fiber, the balance between the optical fiber nonlinearity and dispersion effects creates the solitary wave. Solitons then maintains its amplitude during propagation for long transmission distance.

Between transmission lengths 50-250km, the changes in input power is observed to be between 0.75 and 0.25mW, (0.5mW). The practicality of which is the choice of receiver sensitivity which converts the received power to the required data.

Effectively, this provides an indication of the number of regenerators that might be necessary in an optical fiber to establish communication network.



(a) Optical fiber length, 250km

(b) Optical fiber length, 250km

Figure 6.6: Evolution of (a) peak intensity with distance, (b) pulse broadening

Immediate observations that can be made from Figure 6.6 are that pulses spread as the distance is increased and is contributed to chromatic dispersion. Simulationshowsthat energy spreads out as solitons amplitude decreases. A pulse width of 125ps with a peak power of 1mW is propagated through a lossy passive single mode optical fiber of dispersion parameter $-17\, ps / nm - km$.

In the above simulation, amplitude is constant while the phase changes as the length is increased. The propagation length was maintained until 250km and the 3D plot shows intensity draining out at a slow rate as the length increases.

When the loss is set to zero soliton propagation is not affected even after a long transmission distance, a condition depicted in Figure 6.4. After transmission length of 100km, the initial pulse broadens due CD its magnitude shifts as a result of accumulated loss. Effectively, the effect of CD is double fold, the initial power magnitude is reduced and the pulsewidth increases with increase in transmission length.

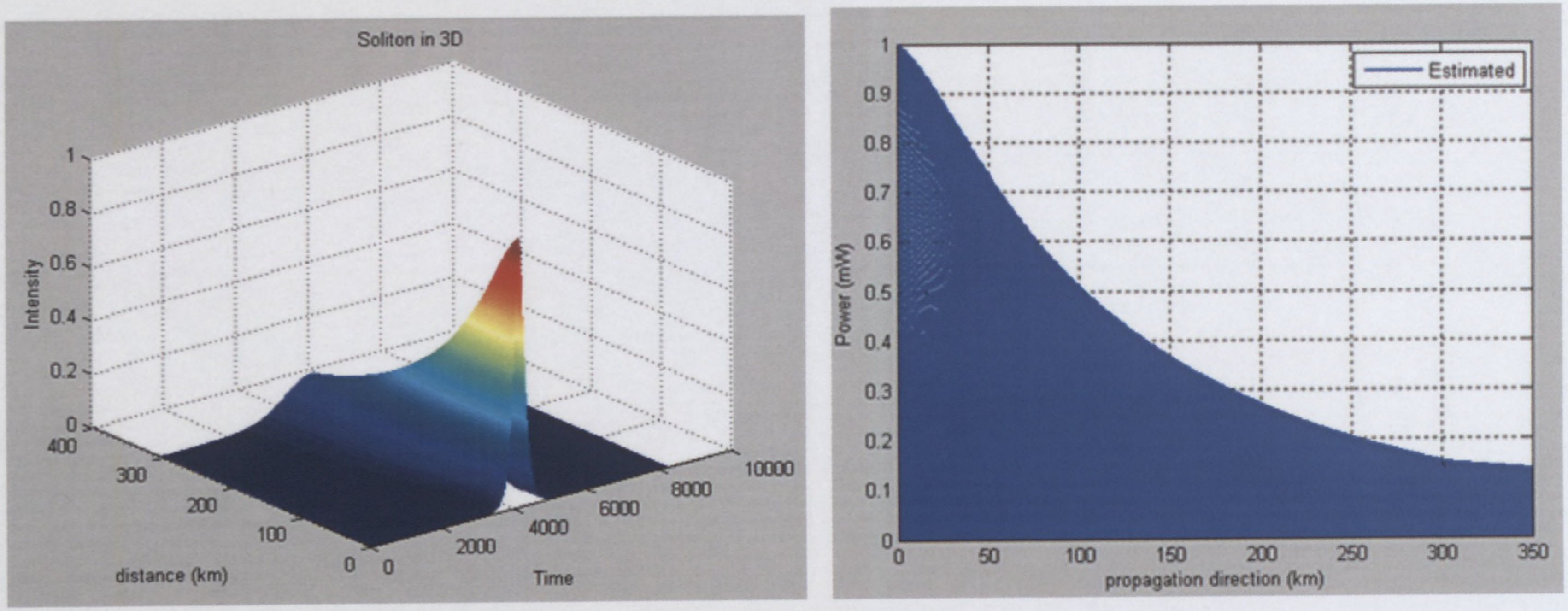
Comparison of Figures 6.6 and 6.7 shows the impact of loss as double fold since initial intensity is reduced and the pulse width increased and remains stable as the intensity approaches 0.01mW when the length approaches 700km.

The profile of the transmitted data with a loss factor $\alpha = 0.15 dB/ km$ and the optical fiber nonlinearity set at 0.003 is shown in the simulation Figures. The parameters used were meant for single mode fiber (SSMF) and have been in place since 2009. The figure shows that upon reaching 100km of transmission length, intensity falls below 0.5mW

To see how optical power varies as the propagation distance of the optical fiber increases, dispersion parameter used in simulation was set at -17ps/nm-km. The waveform generated after 100km is significantly different from those of higher propagation distances. The latter experiences accumulation of attenuation due to dispersed pulse envelope.

The power of the fundamental pulse reduces when it travels a few solitons periods due to optical fiber loss as can be seen in Figure 6.7 where the propagation of solitons pulse transmission is 350km.

Unlike the lossless case, the dispersion effect is dominant and Solitons peak power decreases due to the optical loss since nonlinear effect is not strong enough to cancel the group velocity dispersion effects. The graph shows that pulse peak decreases exponentially with distance as was predicted by the perturbation analysis. This is because perturbation analysis is not valid for long distances since long distances are propositional to the pulse width, (Blow et al. 1987).

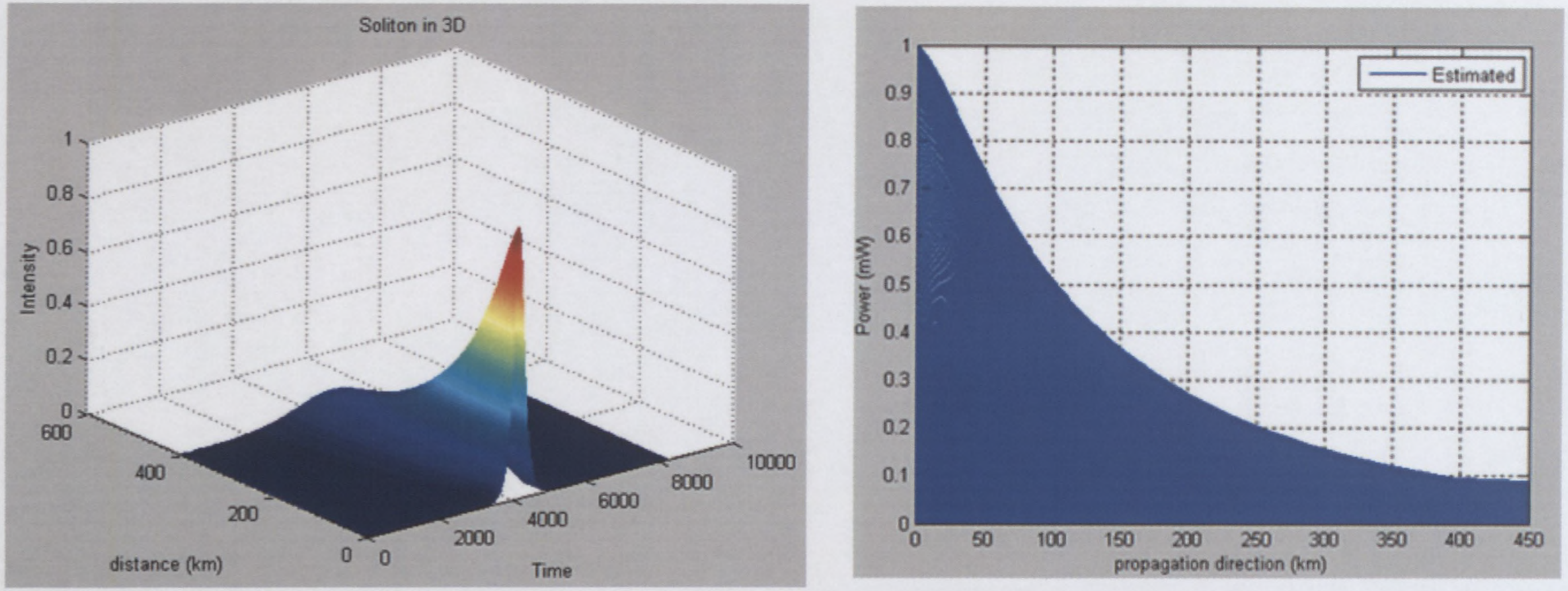


6.7: Nonlinear pulse propagation with optical fiber length of 350km with optical fiber loss

When propagation with the ratio $\frac{L_D}{L_{NL}} >> 1$,the nonlinear effects dominate over the dispersive effects leading to the compression of the pulse as depicted by Figure 6.8, (Vijayakumar & Nair, 2007).

A comparison between simulation in Figures 6.6 and 6.7 indicates that with an increase in transmission length, the beam distracts at a faster rate. This is due to different step size and the actual transmission span for the optical fiber is determined by the optical fiber parameters and associated impairment.

The laser pulse shape maintained its shape along the transmission path as the intensity reduces with the increase in transmission length.



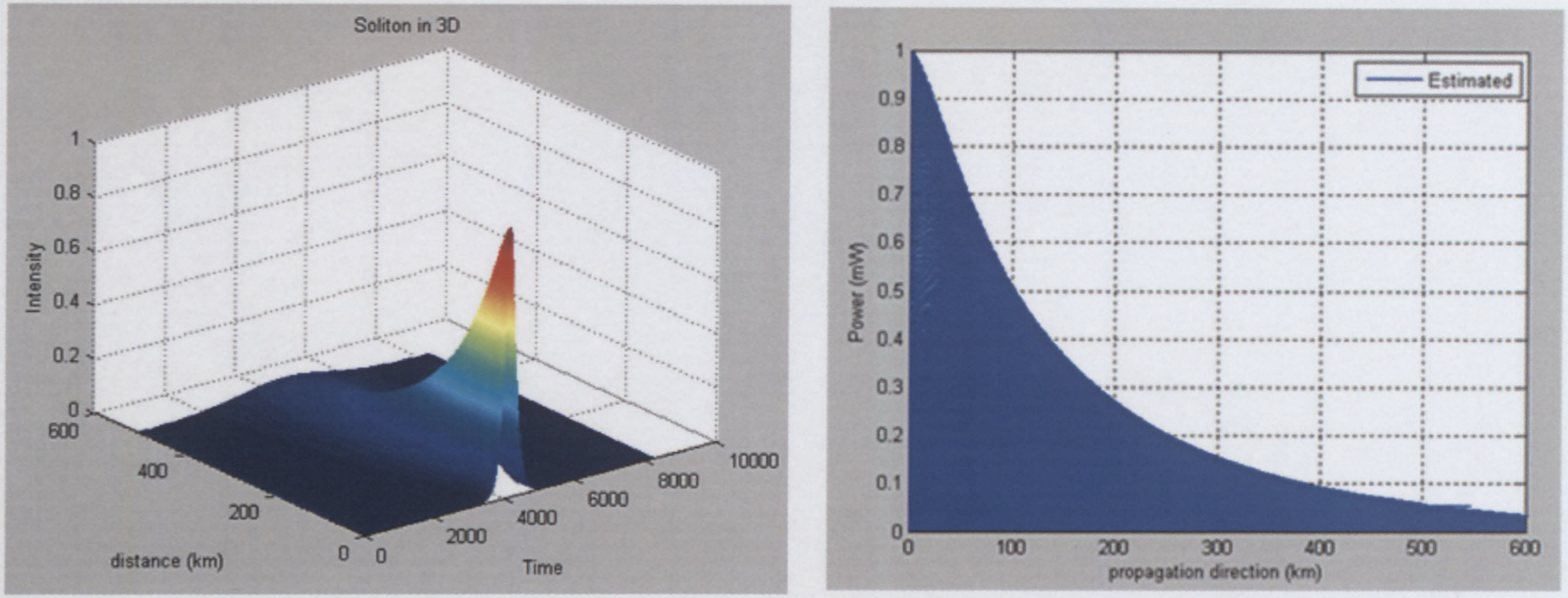
(a) Optical fiber length, 450km (b) Optical fiber length, 450km

Figure 6.8: Nonlinear pulse propagation with optical fiber length of 450km with loss

Since data transmission is affected by long distance propagation due to optical fiber loss, laser intensity reduces almost to zero as the distance is increased as illustrated by Figure 6.9,(Wang et al. 2006).

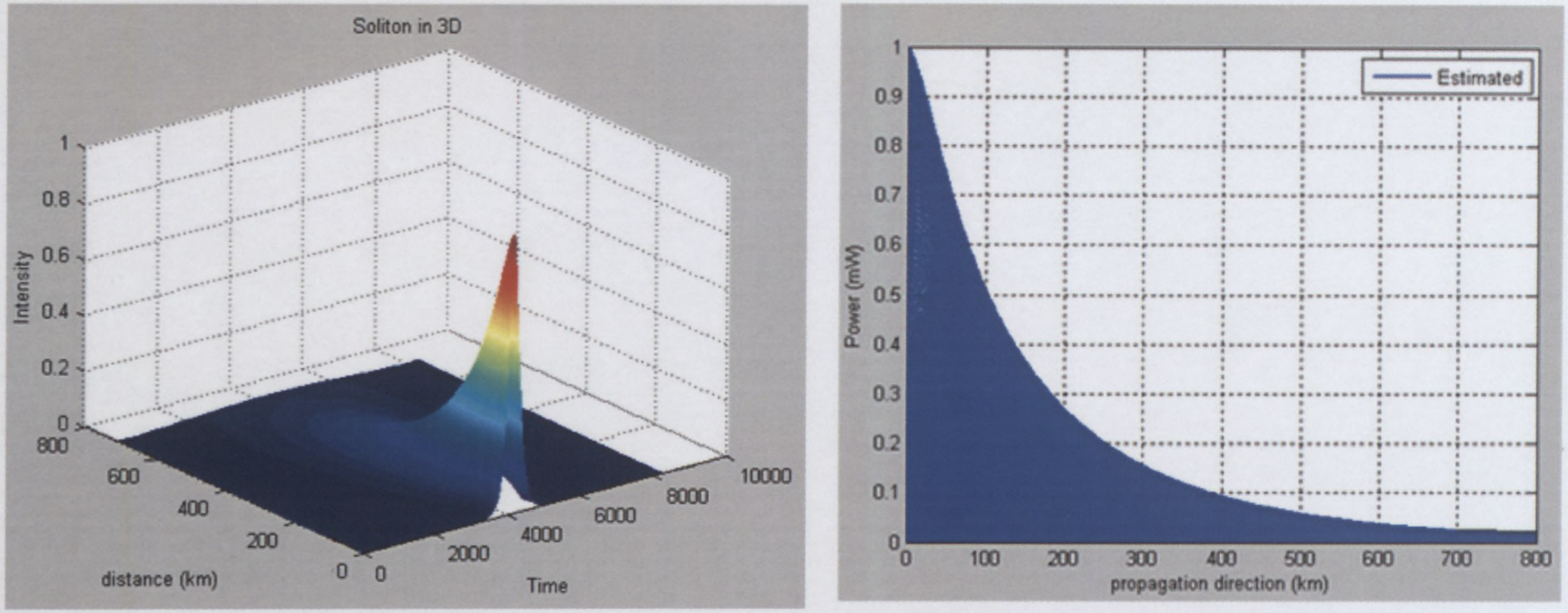
As transmission intensity decreases is slow for solitons, for non solitons the decrease is considerably which implies that solitons technique is a better technique and covers the longer transmission length.

In reference to simulation diagrams (i.e Figures 6.9 and 6.10), pulse decreases along the optical fiber due to dispersion. Although attenuation is minimal, pulse energy at the input is the same as that at the output. Pulse at the output is broader than pulse at the input of the optical fiber due to time dispersion.



(a) Optical fiber length, 600km (b) Optical fiber length, 600km

Figure 6.9: Nonlinear pulse propagation with optical fiber length of 600km with loss



(a) Optical fiber length, 800km (b) Optical fiber length, 800km

Figure 6.10: Nonlinear pulse propagation with optical fiber length of 800km with loss

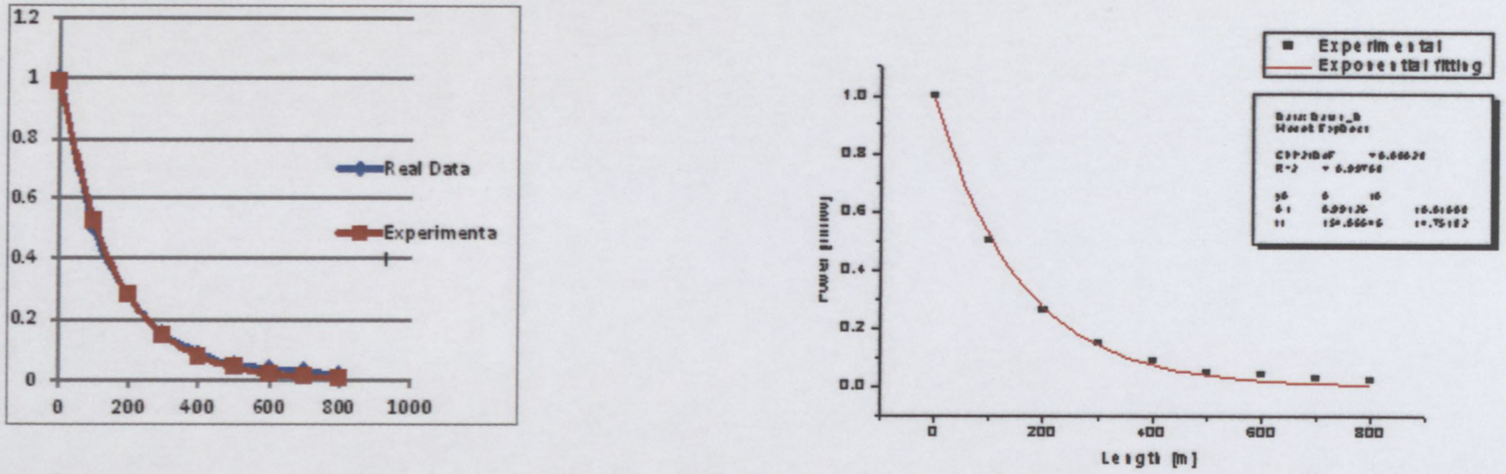
To show that intensity varies as the distance is increaased, several lengths were set and the summary of the transmission length verse intensity is shown in table 6.3.

Table 6.4: Transmission distance verse minimum intensity

FIGURE	TRANSMISSION LENGTH (KM)	MINIMUM INTENSITY
Fig 6.6	250	0.24
Fig 6.7	350	0.14
Fig 6.8	450	0.08
Fig 6.9	600	0.04
Fig 6.10	800	0.02

Using eq. (6.8) to establish the actual point at which intensity reduces to zero in case of soliton propagation, Figure 6.11 shows that with increased transmission distance, and other parameters assumed as previously done with soliton transmission, the curve approaches zero power beyond 800km.

The curve provides a true comparison of the maximum length to which intensity fades in the two scenarios thereby depicting soliton system as being the best technique in long haul optical data transmission. The two curves were plotted using mechanical design software used to establish various complex simulation equations.



(a) (b)

Figure 6.11: Graphical representation of soliton simulation in an optical fiber with loss

COMPARATIVE ANALYSIS AND RECOMMENDATIONS

Table 6.4 shows comparison of two transmissions simulated and the distance covered by each technique. At a transmission length of 5km, non soliton power (intensity) was 0.48mW where as in the case of solitons techniques intensity is approximately 0.99mW, (see Fig 6.6).

Table 6.5: Optical transmission verse Solitons

Length(km)	**OPTICAL TRANSMISSION** Power (mW)	**SOLITONS TRANSMISSON** Power (mW)
5	0.48	-
10	0.20	-
15	0.10	-
20	0.05	0.9
25	0.03	0.85
30	0.02	-
35	0.01	-
40	0.00	-
50	-	0.75
100	-	0.52

In the discussion, cut-off power point occurred at a transmission length of 40 km (Figure 6.3) for non solitons where as in the case of solitons intensity continued beyond 800km, which was the longest length the processor generated simulation curve as shown in Figure 6.10.

Considering a transmission length of 25km, the ratio of the maximum transmission distance of solitons to non solitons is approximately 28:1 (0.85/0.03) which effectively rate solitons technique as the best. Simulation graphs of solitons show that the wave is stable with the transmission span if other impairments are assumed.

For short distances the pulse peak reduction is slow but at large distances, reduction does not follow the exponential decrease due accumulation of loss along optical fiber length.The assumption made on the estimation should provide the impression of the required artefact in terms of optical fiber requirements.

Broader pulses have larger loss coefficients so they enter the linear regime earlier than narrow pulses. Hence, the first order soliton with a shorter pulse width is advantageous in optical fiber communication system. This does not imply that the first order solitons with a shorter pulse duration and smaller loss coefficient broadens less compared to the first order soliton with longer pulse duration.

It should be noted that these results conforms to the pulse width of 125ps in which the loss coefficient was 0.15dB/km. Since the loss coefficient is a function of pulse duration, different pulse duration simulated generated different span lengths as indicated in the results.

6.6. CONCLUSION

Simulation diagrams in the previous sections show that pulse width increases and the amplitude of solitons decreases along the optical fiber due to dispersion. Although the loss is minimal, pulse energy is maintained but the amplitude decreases.

Optimisation is achieved on the basis of the choice for the technique that covers a long distance under the same conditions. From the simulation results, soliton maintained its shape for a longer transmission length compared to non soliton.

As the transmission length increases, the peak optical power decreases due loss factor. Soliton does not maintain its shape during transmission because dispersion and non linearity does not evenly compensate each other at every point along transmission path. This occurs when input power to a lossy optical fiber is low and it strengths dispersion to make solitons loose its shape.

We reported that the performance of optical fiber is affected by either CD or SPM. We varied the number of parameters for simulation purpose and concluded this does not improve data transmission. Simulation provided optimum performance allowing intensity of 0.52mw transmission to reach 100km of uncompensated standard single mode optical fiber.

For the case of a nonlinearity of SSMF we performed an experiment where the optical power has been varied from linear to nonlinear regime. The last simulation demonstrated that in optical fiber solitons pulse performs better than non solitons in terms transmission length covered.

Simulation of fundamental soliton with a pulse width 125psshow that the use of the first order solitons in optical communication systems increases transmission distance compared to the non solitons. The changes in solitons amplitude are due to loss as depicted by the two dimension diagram Figure 6.10.

Since optical fiber loss has effects on solitons shape, at 100km transmission length, intensity is reduces to near zero for non solitons and 800km length for solitons. However, the magnitude of intensity at this level requires very sensitive optical receiver.

CHAPTER SEVEN

7 CONCLUSION AND RECOMMENDATION

This chapter presents the summary and conclusions made in the research work together with the recommendations for future work. The aim of the research was to identify a technique to optimise data transmission in optical fiber.

The project started with research on a number of optical fiber data transmission techniques currently in use (Chapter 2), so as to provide a better understanding of how data is affected in optical fiber network. Important aspect in fulfilling the aim of the research was identified in chapter 3 and 4 where dispersion and optical fiber nonlinearity effects were discussed.

The experiment involved varying the optical fiber loss(α), nonlinearity parameter(γ), and input power relative to optical fiber length. A series of simulation of soliton in optical fiber cable were performed and the results of the simulation are discussed in Chapter 6. (see appendix D).

7.1 CONCLUSIONS

The use of solitons technique to optimise data transmission is not affected by speed of electronic devices. Standard optical fiber is mostly affected by fiber nonlinearity, PMD and CD that limits data transmission length. Solitons pulses arise due to high nonlinear power threshold and SPM. Increased dispersion tolerance improves SNR and the overall result is increased span length.

Long transmission distance was achieved by maintaining an optical fiber loss and dispersion constant with a low input power. The consistency of the method was demonstrated through several simulations by varying optical fiber transmission length. This has shown the the practicability of optical fiber in real world.

Characteristics of solitons are described in relation to their shape, formation within a particular region and interaction while maintaining their shape except during phase shift. Their immense potential is an important innovation in optical telecommunications and natural digital solution which holds a key to the next innovation in practical optical fiber speed over long distances like transcontinental networks communications systems.

The Matlab simulation code has offered a useful opportunity to theoretically demonstrate the analysis of nonlinear effects of optical fiber. It should be noted that the technology of solitons is developing at fast rate both in engineering and science with a tendency to create changes in capacity of optical data transmission.

A comprehensive simulation of transmission distance for both soliton and non soliton proved a rather simple and in-expensive experiment. For now, Solitons could be considered as a better technique for long transmission.

7.2 RECOMMENDATION FOR FUTURE WORK

As explained in Chapter 3, the existence of both fast axis and a slow axis in single mode optical fiber results to difference in arrival times of the data. Two perpendicular polarizations of transmitted data propagate at the same speed if optical fibers were perfectly round resulting in zero PMD.

Since PMD is affected by environmental changes – such as temperature and vibration – and optical fiber movements, which are not easy to compensate but limits transmission distance, dispersion and nonlinearity are not evenly distributed along the optical length. The rapid changes perturb propagation and causes low intensity waves along transmission path. In view of the above, I recommend that a further research be done on the parameters that affect PMD.

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10. LIST OF FIGURES

11. LIST OF TABLES

12. APPENDICES

A

The fiber bandwidth is divided into number of different bands that various technologies use for transmission. Bands symbols, names and ranges can be viewed in Table A1

Table A1: Spectral band designations for optical communication

Band	Description	WavelengthRange [nm]	
		Lower limit	Higher limit
O	Original	1260	1360
E	Extended	1360	1460
S	Short Wavelengths	1460	1530
C	Conventional (Erbium window)	1530	1565
L	Long Wavelengths	1565	1625
UL	Ultra long Wavelengths	1625	1675

B EXECUTION TIME

The following error information appeared after every execution of the Matlab code for soliton propagation (see Ch 6).

```
Elapsed time is 39700.617906 seconds.
??? Error using ==> figure
Error using ==> figure
Out of memory.Type HELP MEMORY for your options.
```

```
CPU time:      3.9701e+004
```

The processor ran out of memory 11hrs after execution,

$$i.e \quad \frac{3.9701e004}{60 \times 60} \approx 11.0277777778 \text{ hrs}$$

C MATLAB CODE FOR OPTICAL FIBER LOSS

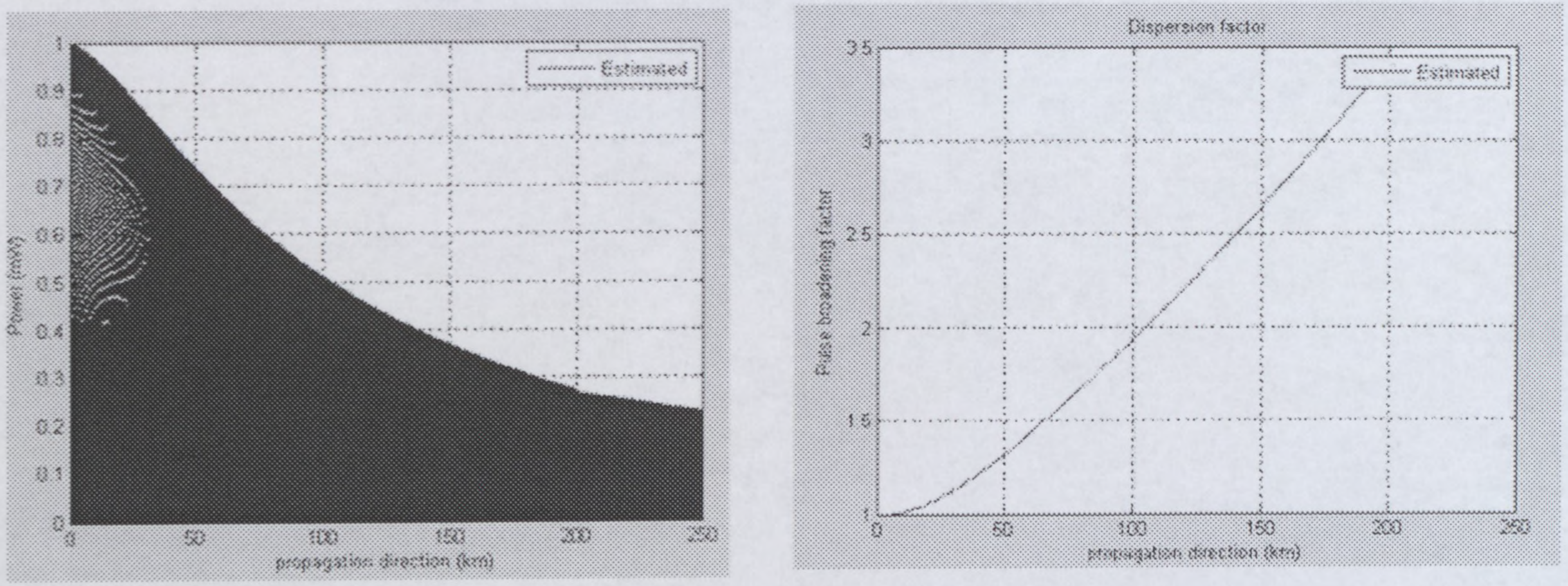
```
alpha=0.15;             %fiber loss parameter in db/km

Pi=1;                   %input power in mW

L=0:50:1000             %length of fiber in Km

Po=Pi*exp(-alpha.*L)  %calculation of received power;

plot(L,Po, '-')         % graph of input pulse

title('Optical Fiber loss/km')

gridon

xlabel('Transmission distance')

ylabel('Received power')

legend('Expected curve')

holdoff
```

APPENDIX D

The diagrams that follows in appendix D depicts the effects of pulse broadening in the absence ofregenerators (amplifiers) as the transmission distance increases in relation to the originally transmitted power.The transmission distance isa comparison criterion for different transmission techniques.

Based on equations, analysis and the assumed impairments associated with optical fiber, Figs.12.1 – 12.11 are used to depict variation of transmission distance verse intensity. Figures further demonstrate that the dispersion is affected by transmission distance. With nonlinearity, intensity amplitude is constant when impairments are controlled and the two parameters, dispersion and nonlinearity compensate each other.

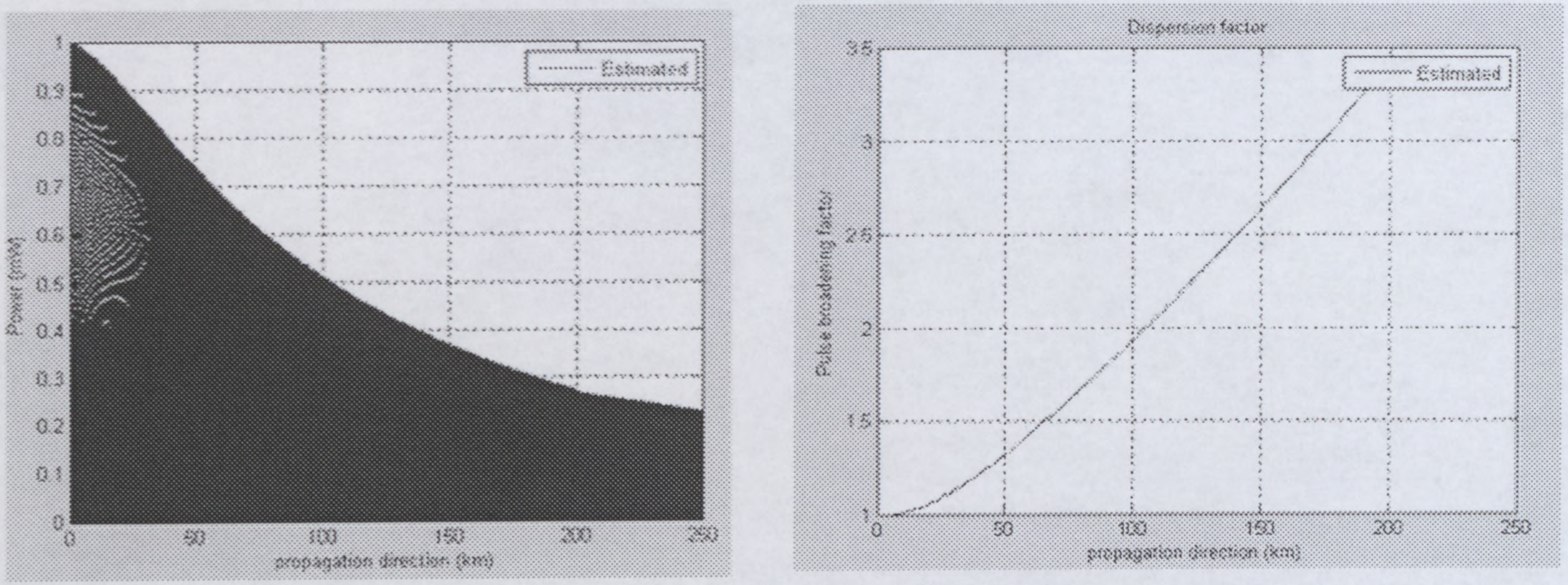
D SIMULATION DIAGRAMS SHOWING PULSE BROADENING VARIATION



(a) Optical fiber length, 250km

(b) Optical fiber length, 250km

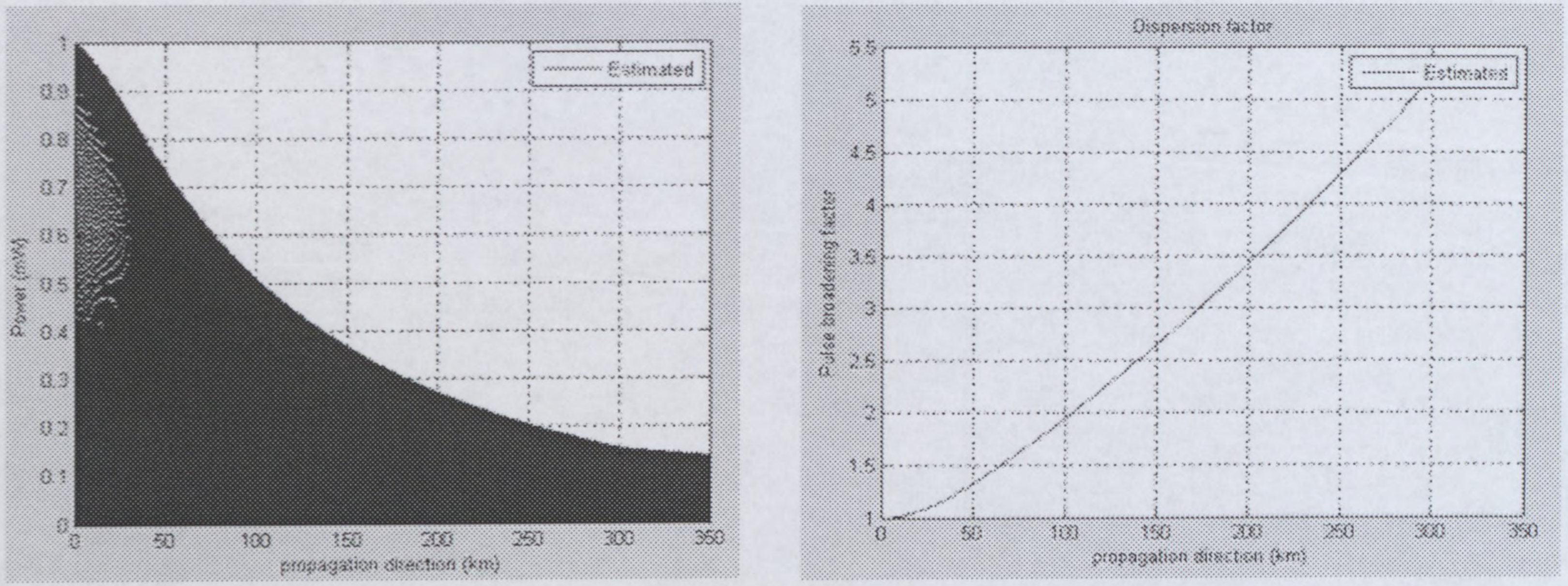
Figure 12.1: Evolution of (a) peak intensity with distance, (b) pulse broadening



(a) Optical fiber length, 250km

(b) Optical fiber length, 250km

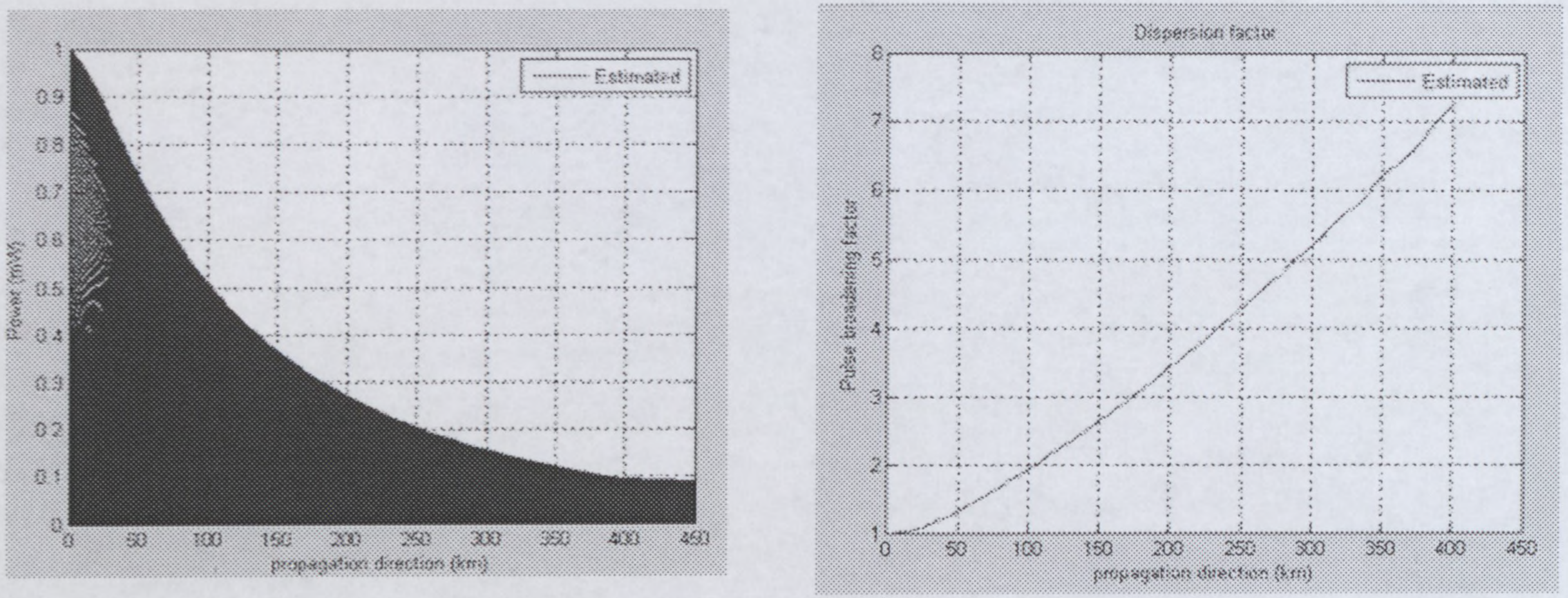
Figure 12.2: Evolution of (a) peak intensity with distance, (b) pulse broadening



(a) Optical fiber length, 350km

(b) Optical fiber length, 350km

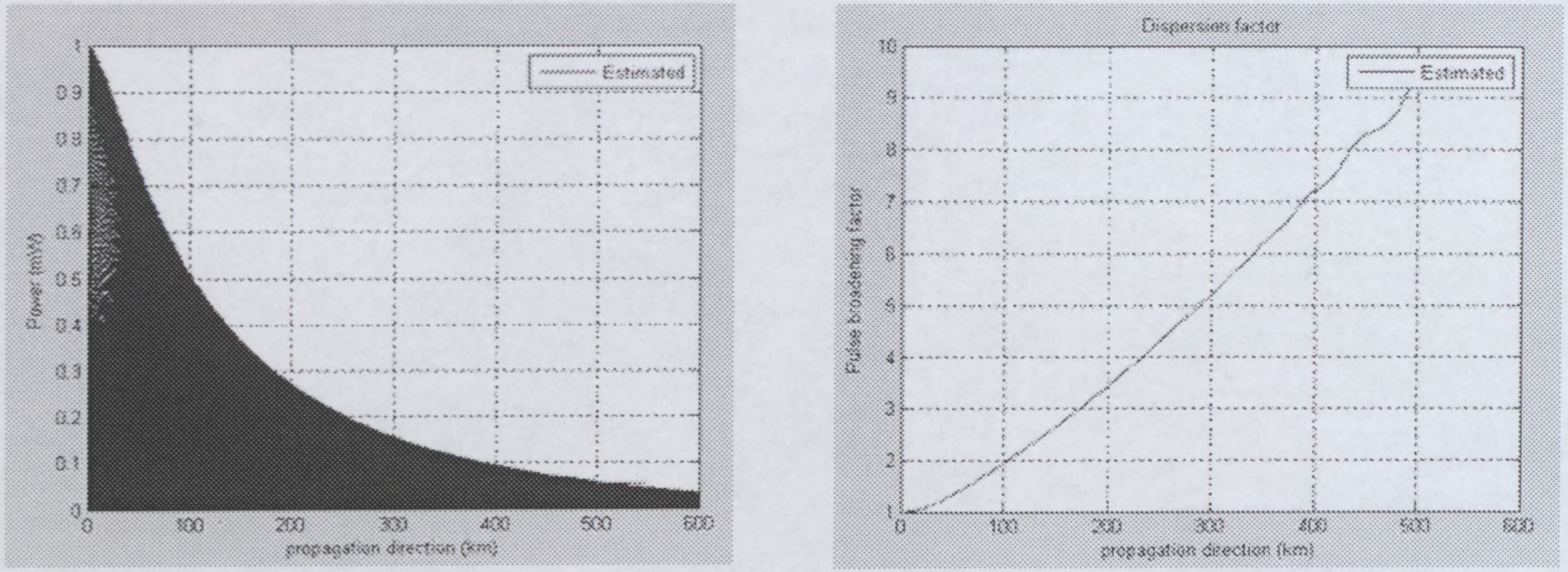
Figure 12.3: Evolution of (a) peak intensity with distance, (b) pulse broadening



(a) Optical fiber length, 450km

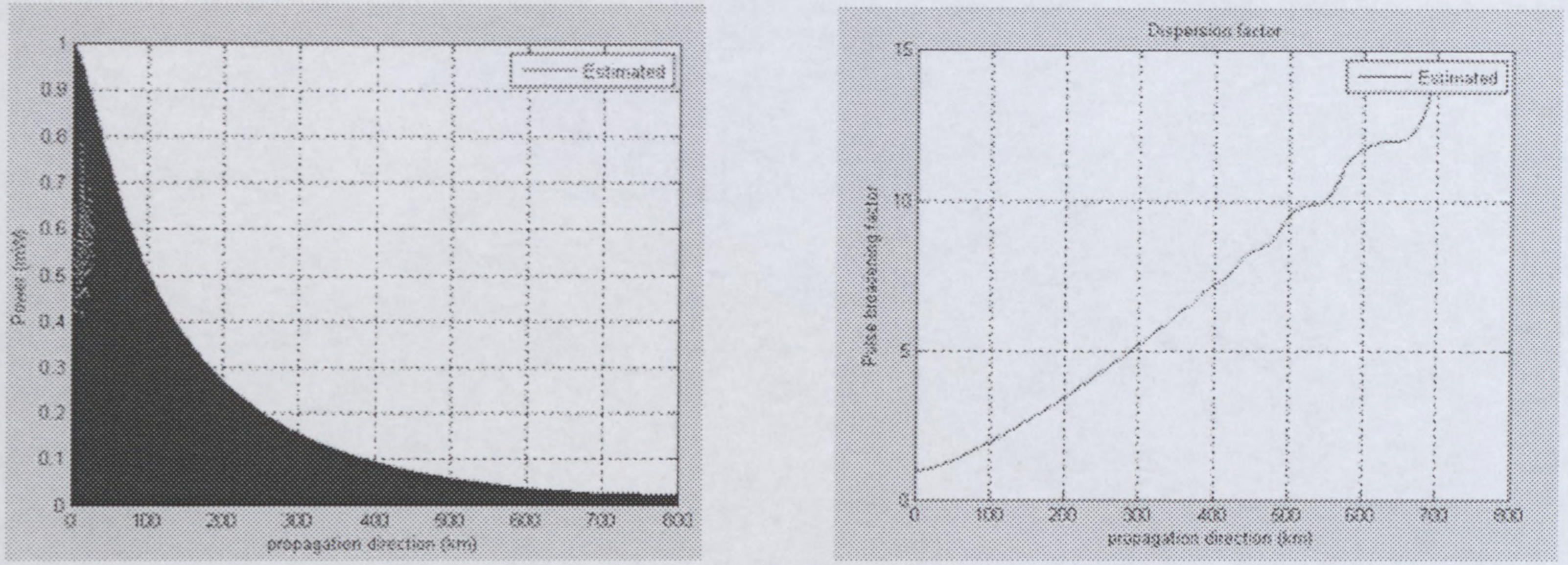
(b) Optical fiber length, 450km

Figure 12.4: Evolution of optical power as a function of (a) optical fiber length, (b) pulse broadening



(aOptical fiber length, 600km (b) Optical fiber length, 600km

Figure 12.5: Characteristics of optical power as a function of (a) optical fiber length, (b) pulse broadening



(a) Optical fiber length, 800km

(b) Optical fiber length, 800km

Figure 12.6: Characteristics of optical power as a function of (a) optical fiber length, (b) pulse broadening