DISPERSION COMPENSATION IN WAVELENGTH-DIVISION MULTIPLEXED OPTICAL FIBRE LINKS

By

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ABSTRACT

Lightwave systems used in the core transport network of telecommunication systems operate in the second transmission window. The 1550 nm wavelength region exhibits the lowest attenuation coefficient, thus expanding the repeater distance in the network. However, the influence of the large dispersion coefficient associated with the second transmission window limits the operating speed of the network to 2.5 Gbit/s or less. In order for the network to operate at higher bit-rate, a dispersion management scheme is needed. In this research, the performance of negative dispersion fibre used as a dispersion compensating module is investigated.

The negative dispersion fibre used in this study was the AVANEX PureForm DCM. The dispersion coefficient of the DCM measured at 1525 nm, 1545 nm and 1565 nm were given as \(-918 \text{ ps/nm}\cdot\text{km}\), \(-987 \text{ ps/nm}\cdot\text{km}\) and \(-1047 \text{ ps/nm}\cdot\text{km}\) respectively. The optimal operating condition of the DCM was obtained by considering various dispersion management configurations i.e. post-compensation, pre-compensation and symmetric compensation. The DCM was tested on a single span, single channel system operating at a speed of 10 Gbit/s with the transmitting wavelength of 1551.2 nm, over 60 km of convention single mode fibre. Furthermore, the performance of the system at 55 km and 65 km were also used to examine the results for the over- and under compensation links respectively.

The results obtained for 100% dispersion cancellation for the pre-, post- and symmetric configuration showed an increase in the extinction ratio of 2.09 dB, 2.72 dB and 2.37 dB respectively. Similarly, the Q-factor was estimated to equal 13.67, 11.296 and 13.167 respectively. The results indicate similar performance for all the configurations considered, analysis of the eye-diagrams reveals that the post-compensation configuration would ultimately yield the best results. This is due to the fact that eye diagram recovered from this setup has minimal deformation.
The experiments for an extremely over-compensated link, i.e. 40 km, showed an increase from 9.49, obtained with no compensation, to 10.63. However, for the extremely under-compensated link i.e. 80 km, the extinction ratio only manages to improve from 4.88 dB to 8.63 dB.
ACKNOWLEDGEMENT

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# TABLE OF CONTENT

## CHAPTER 1 : INTRODUCTION

1.1 Historical development of communication systems ............................ 2

1.2 The aim of the project ........................................................................ 8

1.3 Outline of the study ........................................................................... 9

1.4 Reference .......................................................................................... 11

## CHAPTER 2 : FUNDAMENTALS OF OPTICAL FIBRE

2.1 Introduction ...................................................................................... 13

2.2 Cylindrical optical waveguide ............................................................. 16
   2.2.1 Step index fibre ........................................................................... 16
   2.2.2 Graded index fibre ..................................................................... 17

2.3 Characteristics of optical fibre ............................................................. 18
   2.3.1 Optical losses ............................................................................ 18
   2.3.2 Fibre dispersion ......................................................................... 20
   2.3.3 Fibre non-linearties ................................................................. 27

2.4 Geometric description of beam propagation in optical fibre ................ 29
   2.4.1 Fibre numeric aperture ............................................................. 30

2.5 Electromagnetic analysis of wave propagation ...................................... 32

2.6 Solving the wave equation .................................................................. 34
   2.6.1 Split-step Fourier method ......................................................... 35
   2.6.2 Symmetric split step Fourier method ....................................... 36

2.7 Reference .......................................................................................... 37

## CHAPTER 3 : FUNDAMENTALS OF WDM SYSTEMS

3.1 Introduction ...................................................................................... 39

3.2 Selection of system components .......................................................... 42
   3.2.1 Carrier wavelength ................................................................. 42
   3.2.2 The LED or Laser choice ......................................................... 42
A.2. Eye diagram

A.3. Reference

APPENDIX B: Q-FACTOR ANALYSIS

B.1. The Q-factor in more detail
Definition of the Q-factor

B.2. Method of determining Q-factor

B.3. Analysis of results by the synchronous sampling method
B.3.1 No compensation
B.3.2 Pre-compensation
B.3.3 Post-compensation
B.3.4 Symmetric compensation

B.4. System Performance based on SNR

B.5. Reference

APPENDIX C: AVANEX 2 DCF

APPENDIX D: MATLAB CODE & EXPERIMENTAL RESULTS

D.1. Matlab code for Eye-diagram an PDF plot

D.2. Measurement results
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Core radius of fibre [nm]</td>
</tr>
<tr>
<td>$A$</td>
<td>Pulse amplitude</td>
</tr>
<tr>
<td>$A_{\text{eff}}$</td>
<td>Effective area of fibre [nm$^2$]</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplifier Spontaneous Emission Noise</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
</tr>
<tr>
<td>APD</td>
<td>Avalanche photodiode</td>
</tr>
<tr>
<td>$B$</td>
<td>Bit-rate [GB/s]</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>$C$</td>
<td>Chirp parameter</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacitance [F]</td>
</tr>
<tr>
<td>CFBG</td>
<td>Chirped Fibre Bragg Grating</td>
</tr>
<tr>
<td>CSMF</td>
<td>Conventional single mode fibre</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>$D$</td>
<td>Dispersion [ps/nm km]</td>
</tr>
<tr>
<td>$\hat{D}$</td>
<td>Differential operator</td>
</tr>
<tr>
<td>$D_{\text{mat}}$</td>
<td>Material dispersion [ps/nm km]</td>
</tr>
<tr>
<td>$D_{\text{PMD}}$</td>
<td>Polarization mode dispersion [ps/$\sqrt{\text{km}}$]</td>
</tr>
<tr>
<td>$D_w$</td>
<td>Waveguide dispersion [ps/nm km]</td>
</tr>
<tr>
<td>DC</td>
<td>Dispersion Compensator</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion Compensating Fibre</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>$E_j(r,t)$</td>
<td>Electric field</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-Doped Fibre Amplifier</td>
</tr>
<tr>
<td>$F$</td>
<td>Frequency [GHz]</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg Grating</td>
</tr>
</tbody>
</table>
\( FWM \) = Four-Wave Mixing
\( GVD \) = Group Velocity Dispersion
\( I \) = Intensity \([W/m^2]\)
\( k_0 \) = Free space wave number \([1/m]\)
\( L \) = Fibre length \([km]\)
\( L_D \) = Dispersion length \([km]\)
\( L_{\text{eff}} \) = Effective fibre length \([km]\)
\( L_{NL} \) = Non-linear length \([km]\)
\( m \) = Order of Super-Gaussian pulse
\( m_x \) = Cross-phase modulation index
\( M_{\text{sys}} \) = System margin
\( n \) = Refractive index
\( n1 \) = Refractive index of the core
\( n2 \) = Refractive index of the cladding
\( \bar{n} \) = Mode index
\( \bar{n}_g \) = Group index
\( \hat{N} \) = Non-linear operator
\( NRZ \) = Non-Return-to-Zero bit format
\( OA \) = Optical Amplifier
\( P \) = Power average in single channel \([\text{dBm}]\) or \([mW]\)
\( P_0 \) = Peak power \([mW]\)
\( \bar{P}_{\text{rec}} \) = Receiver sensitivity \([\text{dBm}]\)
\( \bar{P}_{tr} \) = Average launched power by transmitter \([\text{dBm}]\)
\( PMD \) = Polarization Mode Dispersion
\( Q \) = Q-factor
\( R \) = Resistance \([\Omega]\)
\( RZ \) = Return-to-Zero bit format
\( S(\omega) \) = Shape of pulse spectrum

\( SBS \) = Stimulated Brillouin Scattering

\( SNR \) = Signal-to-Noise Ratio

\( SMF \) = Single-Mode Fibre

\( SMSR \) = Side Mode Suppression Ratio

\( SPM \) = Self-Phase Modulation

\( SRS \) = Stimulated Raman Scattering

\( t \) = Time [s]

\( T \) = Pulse width at time at the point T [ps]

\( T_0 \) = Pulse width at the 1/e intensity point [ps]

\( T_B \) = Allocated bit slot period [ps]

\( T_{fibre} \) = Rise-time of the fibre [ps]

\( T_{GVD} \) = Rise-time of the fibre group velocity dispersion [ps]

\( T_{mod} \) = Rise-time of the fibre modal dispersion [ps]

\( T_r \) = Rise-time [ps]

\( T_{rec} \) = Rise-time of the receiver [ps]

\( T_{sys} \) = Rise-time of linear systems [ps]

\( U(0, T) \) = Normalized incident field amplitude

\( U(z, T) \) = Normalized field amplitude at some point ‘z’ along the fibre

\( V \) = Normalized frequency

\( V_{out} \) = Output voltage [V]

\( V_s \) = Velocity of sound in material [m/s]

\( WDM \) = Wavelength Division Multiplexing

\( XPM \) = Cross-Phase Modulation

\( z \) = Distance travelled by a pulse along a fibre [km]

\( Z_{eff} \) = Effective distance of fibre [km]
LIST OF SYMBOLS

\( \alpha \) = Fibre loss [dB/km]
\( \beta \) = Propagation constant
\( \beta_2 \) = Group velocity dispersion parameter [ps\(^2/\text{km}\)]
\( \beta_3 \) = Third order dispersion [ps\(^3/\text{km}\)]
\( \delta \omega \) = Frequency chirp
\( \gamma \) = Fibre non-linearity coefficient [W\(^{-1}\text{km}^{-1}\)]
\( \Delta \lambda \) = Wavelength (channel) spacing [nm]
\( \Delta \tau \) = Differential group delay [s]
\( \Delta \nu_B \) = Brillion linewidth [MHz]
\( \Delta \nu_L \) = Laser linewidth [GHz]
\( \Delta \nu_s \) = Channel separation [GHz]
\( \Delta T \) = Degree of broadening [s]
\( \lambda \) = Wavelength [nm]
\( \nu_B \) = Brillion frequency shift [GHz]
\( \nu_g \) = Group velocity [km/s]
\( \sigma \) = Root-mean-square value of pulse width [ps]
\( \sigma_\lambda \) = Root-mean-square of spectral width of the pulse [nm]
\( \phi(L) \) = Phase of light signal
\( \phi_{\text{max}} \) = Maximum phase shift
\( \phi^{NL} \) = Non-linear phase shift
\( \omega \) = Angular frequency [rad/s]
LIST OF FIGURES

Figure 1-1: The early switchboard ----------------------------------------------- 3
Figure 1-2: The evolution of fibre optics in terms of the attenuation. --------------- 5
Figure 1-3: BL product and the operating wavelength of each of the lightwave systems. - 8
Figure 2-1: Tyndall experiment----------------------------------------------------- 13
Figure 2-2: Light confinement in a cladded waveguide ----------------------------- 14
Figure 2-3: Illustration of transmission in step index fibre ------------------------ 17
Figure 2-4: Light propagation in graded index fibre ------------------------------- 18
Figure 2-5: The attenuation in fused silica fibre. ------------------------------- 19
Figure 2-6: The wavelength dependence of the refractive index n and the group index 

\[ n_g \] of pure silica.--------------------------------------------------------------- 21
Figure 2-7: The variation of \( \beta_2 \) with respect to the wavelength for pure silica ---- 23
Figure 2-8: Theoretical chromatic dispersion for fused silica fibre --------------- 23
Figure 2-9: The total dispersion in fused silica fibre. -------------------------- 25
Figure 2-10: Illustration of the variation of the s.o.p in the direction of propagation ---- 27
Figure 2-11: Total internal reflection ----------------------------------------------- 29
Figure 2-12: Condition for TIR ----------------------------------------------------- 31
Figure 3-1: A basic WDM link ------------------------------------------------------- 40
Figure 4-1: Block diagram of conventional telecommunication system with an electronic 
regenerator (a), telecommunication link with optical amplifier (b). --------------- 53
Figure 4-2: Basic EDFA architecture in the forward pumping mode------------------- 56
Figure 4-3: Energy-level diagram of Erbium ions in silica-based fiber and fluoride-based 
fiber. The wavelength in nm corresponds to the difference of photon energy between  
two levels, ----------------------------------------------- 56
Figure 4-4: Gain profile of Erbium-doped fibre amplifiers -------------------------- 58
Figure 4-5: Four-wave mixing with three injected waves at frequencies \( f_1, f_2 \) and \( f_3 \). The 
generated frequencies \( f_{ijk} \) ----------------------------------------------- 60
Figure 8-1: The experimental set-up of the laser characterization. The first configuration is represented by solid line used to observe the integrity of the optical signal. The second configuration (dotted line) is used to analysis the data being transmitted. -- 95

Figure 8-2: The optical spectrum of the emitted signal of the Agilent j7230 Omniber OTN. -- 96

Figure 8-3: The corresponding eye-diagram obtained from data generated by the source (Omniber OTN). -- 97

Figure 8-4: The experimental set-up for measuring the effects of chromatic dispersion in a WDM system. LA represents line attenuator and ISD are insertion devices, which the Dispersion Compensator (DC) unit. -- 101

Figure 8-5: Network configuration for (a) Post, (b) pre and (c) symmetric compensation. -- 102

Figure 8-6: The Q-factor for various lengths of fibre spans in the Siemens WDM system. -- 103

Figure 8-7: The eye diagram observed at different lengths in the network at (a) 40 km, (b) 55 km, (c) 70 km and (d) 80 km. The power scale 256 µW/div, the timescale was set to 20 ps/div. -- 104

Figure 8-8: The eye diagram of an under-compensated link for (a) post-compensation, (b) pre-compensation and (c) symmetric-compensation. Power scale set to 200 µW/div and timescale was set to 20 ps/div. -- 106

Figure 8-9: The eye diagram of a fully compensated link for (a) post-compensation, (b) pre-compensation and (c) symmetric-compensation. Power scale set to 200 µW/div and timescale was set to 20 ps/div. -- 108

Figure 8-10: illustrates the eye diagram of an over compensated link for (a) post-compensation, (b) pre-compensation and (c) symmetric-compensation. Power scale set to 200 µW/div and timescale was set to 20 ps/div. -- 109
CHAPTER 1: INTRODUCTION

1.1 Historical development of communication systems ------------------------------------- 2
1.2 The aim of the project ------------------------------------------------------------------------ 8
1.3 Outline of the study --------------------------------------------------------------------------- 9
1.4 Reference -------------------------------------------------------------------------------------- 11
Chapter 1: Introduction

1.1 Historical development of communication systems

People have been communicating since the early humans grunted and scratched pictures on cave walls. Simple systems such as signal fires, reflection mirrors and more recently signalling lamps have provided successful information transfer systems [1]. Due to the nature of these early systems, the communication system was limited to transmitting over a maximum distance of 10 km at a rate approximately 1bps. Transmission distance increased to approximately 100 km when the French engineer, Claude Chappe proposed that relay or regeneration systems be placed in between the transmission system and its receiving end. The regeneration system was a series of semaphores mounted on towers. A human operator relayed the message from one tower to the next [2].

By 1830, Samuel Morse invented the telegraph. This invention enabled the transmission of coded messages using electrical impulses transported over copper wire. The message was first converted into a sequence of long or short electrical impulses and then transmitted in this form. This technique of associating characters with electrical impulses was called the Morse Code Keying Technique [4]. This system achieved a bit rate of ~10b/s and with the use of intermediate relays a transmission distance of ~1000 km could be achieved.

In 1876 Alexander Graham Bell took the telegraph one step further by showing that voice could be converted directly into electrical energy and transmitted over copper wire, the signal is then converted back into sound at the receiving end. The only prerequisite of his system, he named the telephone, was that a copper connection should exist between the two parties. The earliest telephone required a different pair of wires for each possible connection to another phone. This technology proved inaccessible to the general public seeing that a large amount of wire would be required for a fraction of the population. In light of this constraint, a switch board was invented. The switch board is a remote switching device that connected the lines of two telephones [5]. The human operator on
the switch board manually connected the terminals of the calling party to that of the receiving party as is depicted in figure 1 below.

![Connection established by a human operator](image)

**Figure 1-1: The early switchboard**

In 1940 the coaxial cable replaced the wire pairs. This system operated at 3 MHz and was capable of carrying 300 voice channels or 1 television channel. This type of transmission medium proved limiting due to the frequency dependent cable losses that increased rapidly as the frequency exceeds 10 MHz [4]. The system was considered to be bandwidth limited. The introduction of microwave systems in the late 1940s alleviated the bandwidth limitation of the coaxial system. This system extended the carrier frequency to ~4 GHz. The system was capable of achieving a bit rate of 100 Mbit/s. However, as the demand to transmit at a faster rate increased, the coaxial system proved inadequate because of its typically small repeater spacing (~ 1 km), which consequently rendered the system costly. Telecommunication system was now faced with the constraint of overcoming frequency limitations and the attenuation losses of the medium.
An unlikely successor of the microwave and coaxial system came in the form of fibre optics in the late 1960s. Though research in the field of optical fibre was ever present during the time of coaxial and microwave systems, renewed interest in optical communication was stimulated in the early 1960s with the invention of the laser. This device provided a powerful coherent light source together with the possibility of modulating at high frequency. Thus laser as a means of carrying information could not go unnoticed, seeing that light has an information carrying capacity of 10000 times that of the highest radio frequency being used at the time [2].

However, a laser beam could not be transmitted in open air, seeing that its operation is adversely affected by the environmental conditions. It is in light of these attributes of the laser that Charles Kao and Charles Hockman proposed that optical fibre be used as the transmission medium for this technology. Kao and Hockman further proposed that the attenuation of the medium should be less than 20 dB/km to ensure effective transmission. At the time optical fibre exhibited losses of ~10.000 dB/km.

Owing to these requirements researchers postulated that the high optical losses of the fibre were the result of the impurities in the glass and not the glass itself. Glass researchers began to work on the problem of purifying glass. In 1970 Drs Robert Maurer, Donald Keck and Peter Schultz of Corning succeeded in developing a glass fibre that exhibited attenuation of less than 20 dB/km. Over the years the fibre properties progressively improved and by the 1980s, an attenuation of 0.2 dB/km was possible. Figure 2 shows three curves, the top dashed curve corresponds to the 1980s fibre, the middle dotted curve corresponds to the late 1980s fibre while the bottom solid curve corresponds to the modern fibre.
Optical fibre systems were developed over the years in a series of generations that can be closely tied to the operating wavelength.

The earliest fibre optic systems were developed at an operating wavelength of about 850 nm. This wavelength corresponds to the so-called “first window” in a silica based optical fibre. The 850 nm region was initially attractive because the technology for light emitter at this wavelength had already been perfected in visible indicator LEDs. The low cost silicon detector could also be used at the 850 nm wavelength at the receiving end. This optical system was referred to as the first generation lightwave system. A bit rate of 45 Mbit/s could be achieved with repeater spacing of 10 km [6]. The system performed relatively well in comparison to the coaxial counterpart.

As the technology progressed, the first window became less attractive owing to its relatively high, 3 dB/km loss limit. The second generation which was deployed in the early 1980s focused on using a transmission wavelength near 1.3 µm so as to take advantage of the low attenuation (<1dB/km) and low dispersion.
This system used sources and detectors that were based on InGaAsP semiconductors. The bit rate of this system was limited to about 100 Mbit/s due to the modal dispersion of the multimode fibre [7]. Single mode fibre was incorporated and by 1981 a 2 Gbps signal was transmitted over 44 km of single mode fibre without repeaters [8]. By 1987 the second-generation systems were operating at 1.7 Gbps with repeater spacing of 50 km.

The third generation was based on operating at 1.55 µm referred to as the “third window” It offered the theoretical minimum optical loss for silica based fibre, which is about 0.2 dB/km. However, the deployment of this system was delayed due to the relatively large dispersion associated at this wavelength. To solve these problems, two approaches were considered. The first approach was to develop single frequency lasers and the second was to develop dispersion shifted fibre at 1.55 µm [9]. In 1990 the 1.55 µm systems operating at 2.5 Gbps were commercially available and were capable of operating at 10 Gbps over a distance of 100 km. Best results were obtained by using Dispersion Shifted Fibre (DSF) in conjunction with single mode lasers. The typical repeater spacing was ~70 km.

The inception of Erbium doped fibre amplifiers (EDFA) used to amplify signals gave birth to the fourth generation lightwave system. These systems are based on the use of optical amplifiers to increase the repeater spacing. In 1991 signals could be transmitted over 14.300 km at 5 Gbps without electronic regeneration [10].

The system capacity was systematically increased through the use of wavelength division multiplexing (WDM). In 1996 twenty 5 Gbps signals were transmitted over 9100 km, providing a total bit rate of 100 Gbps. However, dispersion presented itself as a significant limiting factor in this system.

In order to overcome the dispersion problem inherent in the fourth generation network, the fifth generation system employed the use of optical solitons in transmission. Optical solitons are pulses that preserve their shape during propagation in a lossless fibre by counteracting the effect of dispersion through the fibre non-linearties [10].
Experiments using stimulated Raman scattering (SRS) as a non-linearity were performed successfully to compensate for both the dispersion and losses in transmitting signals over 4000 km. The year 1989 saw the first use of EDFAs as agents of amplifying solitons. However, by 1994, a demonstration of soliton transmission over 9400 km was performed at a bit rate of 70 Gbps by multiplexing seven 10 Gbps channels [10].

Recent efforts have been directed towards realizing greater capacity utilization of fibre systems by multiplexing a large number of wavelengths. These systems are referred to as dense wavelength-division multiplexing (DWDM) systems. This is the basis of the operation of the sixth generation system. This system aimed at reducing the wavelength separation of 0.8 nm which is currently in operation to less than 0.5 nm. Controlling the wavelength stability and the development of wavelength de-multiplexing devices are critical to these efforts.

Seemingly advances are already being made for systems that could combine DWDM, optical time-division multiplexing (OTDM) and optical code-division multiple access (OCDMA) systems. These systems would be capable of operating at 40 Gbps and higher bit rates. The operation of the five light systems is well summarized in the figure below, which illustrates the bit rate product of each system against a timeline.
Figure 1-3: BL product and the operating wavelength of each of the lightwave systems [4].

### 1.2 The aim of the project

This research project mainly focuses on lightwave systems operating at 1.55 µm, in which the aim is to investigate the performance of negative dispersion fibre in the application of dispersion compensation of system operating at STM-64 bit rate. Firstly, an optical communication system, that employs DCF as dispersion compensators, was simulated using the OptSim simulation package. The results obtained were compared to already documented literature of DCF and dispersion compensation. Secondly, a test network was implemented for actual experiment results. The performance of the DCF for various dispersion mapping configurations was recorded.
1.3 Outline of the study

The primary intention of this research is that its core thesis be comprehensible to any reader who has a general background in physics and mathematics. Therefore, a relatively thorough introduction to the field of fibre optics is given in Chapter 2. First, a brief discussion of the history of fibre optics is presented. In section 2.2 the various type of fibres are considered and a comparative study is drawn. Section 2.3 follows with the theory of ray optics to illustrate basic light propagation through fibre optics. In section 2.4 a more intricate analysis of wave propagation in the dielectric is presented by means of Maxwell’s equations analysis. Finally, in section 2.5 the most convenient numerical method of solving the wave equation is proposed.

In Chapter 3 the architecture and system topology of WDM systems is presented. The major components of a WDM link are presented, and a thorough analysis of performance measurement (such as power budget, rise time budget, Q-factor and BER) used in these systems is suggested to give a good understanding of the operation of WDM systems. A brief discussion of the standards set by the international telecommunication union for operation of WDM system is also considered.

Chapter 4 focuses on the factors that limit the performance of WDM systems. The dispersion and the non-linearities of the fibre are discussed in more detail seen as they contribute significantly to the factors limiting WDM. Though aspects of the telecommunication link such as stimulated Brillion scattering (SBS) stimulated Raman scattering (SRS) and four wave mixing are considered negligible at this point, a brief discussion of the nature of these phenomena is presented. This chapter is concluded by presenting the need for dispersion compensation as a means of improving the utilization of the bandwidth in WDM systems.

In Chapter 5 dispersion compensating fibre is discussed. In section 5.2 a brief discussion on the design of DCF is presented. In section 5.3, the property of DCF is discussed and finally, section 5.4, presents a review of some techniques of dispersion management with
DCF. Chapter 6 presents a review of the results obtained from the simulation package OptSim, while Chapter 7 gives the review of results obtained from the characterization of the standard single mode fibre and the negative dispersion fibre. In Chapter 8, the results obtained in laboratory experiments are presented. In section 8.2 the characteristics of the test network are reported. Furthermore the required system optimization procedures are discussed. In section 8.3, various experimental set-ups are discussed and the relevant results recorded, and in section 8.4 relevant conclusions are drawn. Finally, Chapter 9 outlines the summary of the entire conclusion drawn from the preceding chapters are reviewed. Further, conclusion is reached by way of projecting possible future work regarding the field of optical communication systems.
## 1.4 Reference


CHAPTER 2 : FUNDAMENTALS OF OPTICAL FIBRE

2.1 Introduction

2.2 Cylindrical optical waveguide
   2.2.1 Step index fibre
   2.2.2 Graded index fibre

2.3 Characteristics of optical fibre
   2.3.1 Optical losses
   2.3.2 Fibre dispersion
   2.3.3 Fibre non-linearties

2.4 Geometric description of beam propagation in optical fibre
   2.4.1 Fibre numeric aperture

2.5 Electromagnetic analysis of wave propagation

2.6 Solving the wave equation
   2.6.1 Split-step Fourier method
   2.6.2 Symmetric split step Fourier method

2.7 Reference
2.1. Introduction

The first experiment illustrating the viability of fibre optics dates back to the 1870s when John Tyndall demonstrated that light used internal reflection to follow a specific path [1]. By using a jet of water that flowed from one container to another through a curved pipe. Tyndall illustrated that a beam of light directed at the entrance of the pipe would follow a zigzag path through the pipe when water was made to flow in the pipe.

![Figure 2-1: Tyndall experiment](image)

This simple experiment marked the first research into the guided transmission of light. Shortly after Tyndall experiment, William Wheeling suggested that light could be transferred from one room to another by using mirrored pipes. As a result, rooms in a building could be illuminated by a single central light source. This concept was referred to as “piping light”.

At the time the concept proved ineffective due to poor light source and consequently the project had a premature ending.
Only in the 1950s did the Wheeling concept of “piping light” see the light of day when Brian O’Brien of the American optical company and Narinder Kapany, the man who first coined the term “fibre optics” in 1956, developed the first fibroscope. This image-transmitting device used the first all-glass fibre. The early all-glass fibres experienced large amount of optical losses thus limiting the transmission distance. This was because the transparent transmitting rod (typically composed of silica glass with a refractive index of 1.5) was surrounded by air and as a consequence, excessive losses occurred at any discontinuities of the glass-air interface.

This realization motivated scientists to develop glass fibres that included a separate glass coating. The fibre was made of two layers. The innermost region of the fibre referred to as the core, was used to transmit the light while the glass coating or the cladding prevented the light from leaking out of the core by reflecting it within its boundaries. Figure 2-2 illustrates basic propagation of guided light.

![Light confinement in a cladded waveguide](image)

**Figure 2-2: Light confinement in a cladded waveguide**
The invention of the cladded Waveguide structure is what led to the suggestion that optical fibre be used in telecommunication. In order to understand the transmission mechanisms of optical fibres, it is necessary to consider the optical wave guiding of cylindrical wave guides. Such a fibre can be viewed as an open optical waveguide, which may be analysed using ray theory. However, the concept of geometric optics is only accurate when the core of the fibre is relatively large \((a \sim 10 \times \lambda)\). In a case where the core is very small, such as in single mode fibres, the ray optic theory is no longer efficient and electromagnetic mode theory must be used to give a complete solution.

This chapter will be divided into the following sections. In section 2.2, a brief discussion on various fibre types will be presented. In section 2.3 the characteristics of optical fibre are reviewed. Section 2.4 will continue with an analysis of wave propagation through fibre optics in terms of the ray theory. This is aimed to develop some of the fundamental parameters associated with optical fibre transmission. In section 2.5, wave propagation is considered in terms of the electromagnetic mode theory, which makes use of Maxwell’s equation. Finally, in section 2.6 methods of solving the wave equation numerically will be considered.
### 2.2. Cylindrical optical waveguide

#### 2.2.1 Step index fibre

Thus far the optical fibre has been treated as a clad waveguide structure, where the refractive index is constant across the radius of the core and then exhibits an instantaneous (step) change to a slightly lower refractive index which represents the cladding envelope of the fibre. Fibre with this type of index profile is termed step index fibre and its refractive index profile may be defined as follows:

\[
  n(r) = \begin{cases} 
  n_1 & r < a \\ 
  n_2 & r \geq a 
  \end{cases} 
\]  \hspace{1cm} (2-1)

Fibre with relatively large core diameter (50 µm or greater) is said to be multimode. This is because the large core diameter allows many modes to propagate within the core of the fibre. Conversely, thin optical fibre with a core diameter of the order of 2-10 µm, is said to be monomode fibres because only one transverse electromagnetic mode is allowed to propagate through the core. Figure 2-3 (a) shows modes travelling in a multimode fibre and figure 2-3 (b) shows transmission through a single mode step index fibre.

![Index profile](image1)

![Transmitted pulse](image2)

(a)
2.2.2 Graded index fibre

In graded index fibre, the refractive index of the core does not remain constant throughout the entire core. Instead, it decreases with radial distance from a maximum value of $n_1$, at the axis, to a constant value $n_2$ beyond the core radius in the cladding. The index variation may be represented as follows:

$$n(r) = \begin{cases} n_1 \left(1-2\Delta \left(\frac{r}{a}\right)^\alpha \right)^2 & r < a \quad \text{(core)} \\ n_1 \left(1-2\Delta \right)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases} \quad (2-2)$$

Where $\Delta$ is the relative refractive index difference and $\alpha$ is the profile parameter, which gives the characteristics refractive index profile of the fibre core.

Graded index fibre is favoured to step index fibre in multimode applications of fibre optics communication. This is due to the fact that the intermodal dispersion in graded index fibre is considerably lower than that of step index fibre. The graded index with a near parabolic profile ($\alpha = 0.5$) produced the best results in multimode optical fibre applications. Figure 2-4 illustrates light propagation through a graded index fibre.
2.3. Characteristics of optical fibre

2.3.1 Optical losses

Once power is coupled into the fibre, the optical signal will interact with the fibre. One of these interactions is the attenuation of the light signal as it moves through the medium.

Attenuation is caused by two physical effects, which are absorption and scattering. Absorption has an effect of removing photons, when they interact with atoms and molecules of the medium while scattering redirects the light out of the core of the fibre.

Absorption occurs when the energy of the photon is equal to a difference between two electronic energies. A major cause of absorption is the presence of $OH^-$ radicals, which results from the presence of water ($H_2O$). The $OH^-$ enters the fibre through either a chemical reaction (during fibre manufacturing) by-product, or as humidity in the operating environment. The main $OH^-$ absorption peak occurs at 1400 nm and the second peak at 950 nm, while the lowest absorption occurs in the wavelength window around 1300 nm and 1550 nm.
Scattering losses occur when the photons see a variation in the core’s refractive index. This phenomenon is termed Raleigh scattering and is considered as an intrinsic loss in optical fibre and therefore sets the lower limit on fibre losses.

Thus the attenuation in optical fibre is obtained by considering effects of absorption and scattering simultaneously. The lowest attenuation occurs at wavelengths 1300 nm and 1550 nm with the corresponding values of 0.5 dB/km and 0.2 dB/km, respectively. The 1550 nm window is favoured in telecommunication applications seeing that it is the theoretical minimum for fused silica fibre. Figure 2-5 illustrates the attenuation in silica optical fibre.

![Figure 2-5: The attenuation in fused silica fibre [2].](image-url)
2.3.2 Fibre dispersion

2.3.2.1 Chromatic dispersion

The interaction between an electromagnetic wave and bound electrons of a dielectric medium is in general dependent on the optical frequency, $\omega$, of the signal. This property of optical transmission through a dielectric medium manifests itself in optical fibre primarily due to the frequency dependence of the refractive index of the core. It is referred to as chromatic dispersion.

The refractive index of optical fibre is well approximated by the Sellmeier equation [3].

$$n^2(\omega) = 1 + \sum_{j=1}^{m} \frac{\beta_j \omega_j^2}{\omega_j^2 - \omega^2}$$  \hspace{1cm} (2-3)

where $\omega_j$ is the resonance frequency and $\beta_j$ is the Sellmeier parameter, synonymous to the strength of the Jth resonance.

Chromatic dispersion plays a significant role in pulse propagation in fibre optics because it governs the group velocity of the pulse travelling in the fibre. Figure 2-6 displays the frequency dependence of the refractive index of silica fibre.
Figure 2-6: The wavelength dependence of the refractive index $n$ and the group index $n_g$ of pure silica [3].

Mathematically, the effects of dispersion can be accounted for by considering the Taylor expansion series of the mode-propagation constant, $\beta$ given below [3]:

$$\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1 (\omega - \omega_0) + \frac{1}{2} \beta_2 (\omega - \omega_0)^2 + \frac{1}{6} \beta_3 (\omega - \omega_0)^3 + \cdots \quad (2-4)$$

Where
The parameter $\beta_1$ is inversely proportional to the group velocity of the pulse envelope. The group velocity dispersion (GVD) parameter $\beta_2$ is used to determine the degree of broadening of a pulse during propagation. $\beta_1$ and $\beta_2$ are expressed as follows in terms of the refractive index $n(\omega)$.

$$\beta_1 = \frac{1}{c} \left[ n + \omega \frac{dn}{d\omega} \right] = \frac{1}{v_g}$$

$$\beta_2 = \frac{1}{c} \left[ 2 \frac{dn}{d\omega} + \omega \frac{d^2n}{d\omega^2} \right] = \frac{\omega}{c} \frac{d^2n}{d\omega^2}$$

And the dispersion coefficient is:

$$D_{mat} = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2$$

The wavelength at which $\beta_2 = 0$ is referred to as the zero-dispersion wavelength $\lambda_0$.

Figure 2.7 shows the variation of $\beta_2$ with wavelength for silica fibre.
Figure 2-7: The variation of $\beta_2$ with respect to the wavelength for pure silica

Figure 2-8: Theoretical chromatic dispersion for fused silica fibre
Chapter 2: Fundamentals of fibre optics

The figure above depicts the theoretical dispersion curve. In actual glass fibre, the dispersion exhibits a slightly different behaviour. This variation can be accounted for by noting that the fibre core may have a small amount of dopant such as $\text{GeO}_2$ and $\text{P}_2\text{O}_5$, thus the effective refractive index is slightly lower than the material index $n(\omega)$. In addition to the chromatic dispersion, the wavelength dependence of the mode size leads to a second component of chromatic dispersion. The fraction of the mode that propagates in the cladding of the fibre increases with increasing wavelength. As the refractive index of the cladding is lower than the refractive index of the core, the group velocity of a pulse increases as the wavelength increases. This gives rise to a negative component of the chromatic dispersion, called waveguide dispersion.

Waveguide dispersion ($D_w$) depends on the fibre design parameters such as the core radius and the core-cladding index difference $\Delta$. The contribution of $D_w$ to $\beta_2$ is considered negligible except near the zero dispersion wavelength, where the two are comparable. The total dispersion is the mathematical addition of $D_w$ and $D_{\text{mat}}$.

$$D_{\text{chrom}} = D_w + D_{\text{mat}}$$  \hspace{1cm} (2-7)

Consequently it always results in shift of $\lambda_0$ to longer wavelengths because $D_w$ and $dD_w$ is negative through out the range of wavelength of interest. The ability to alter the $\lambda_0$ by varying the fibre parameter is of great interest in telecommunication seeing that dispersion shifted fibre has application in this field. Figure 2-9 illustrates the total dispersion in fused silica fibre as a function of wavelength.
Figure 2-9: The total dispersion in fused silica fibre

The zero dispersion wavelength is a critical point when propagation is considered as it differentiates between the normal dispersion regime ($\beta_2 > 0$) and the anomalous regime ($\beta_2 < 0$). The classification of dispersion regime is significant in view of the fact that soliton propagation can be supported provided one operates in the anomalous regime [3].

### 2.3.2.2 Polarization-mode dispersion

In a fibre that is perfectly cylindrical, there exist two orthogonally polarized degenerate modes. This fibre is considered to be ideal. However, in real fibres that have shape and stress variations, the symmetry between these orthogonal axes can be broken. At such points, the optical fibre typically exhibits a small difference in the refractive index for a particular pair of orthogonal polarization state. These factors remove the degeneracy of the fibre and result in one of the properties of optical fibres known as birefringence. The following relation is often used to measure the degree of birefringence [2]:

\[
\text{Birefringence} = \Delta n = n_{x} - n_{y}
\]
Chapter 2: Fundamentals of fibre optics

\[ B = \left| \bar{n}_x - \bar{n}_y \right| \]  \hspace{1cm} (2-8)

Where \( \bar{n}_x, \bar{n}_y \) is the average refractive index of the x and y direction respectively.

This aspect makes the fibre appear as a retardation plate with an inherent phase difference between the two polarization states.

A linearly polarized light will remain linear only when the polarization of the light coincides with one of the orthogonal axes. Otherwise, a phase difference will be induced between the components if the light’s orientation was to vary. The state of polarization would therefore also change.

The state of polarization (s.o.p) will vary with the propagation length. The beat-length is used to associate the birefringence to the fibre length. The beat length \( (L_B) \) is defined as the smallest distance that a light pulse must propagate through the fibre in order to return to its original polarization state.

\( L_B \) is related to \( B \) in the following manner:

\[ L_B = \frac{\lambda}{B} \]  \hspace{1cm} (2-9)

Figure 2-10, illustrates the variation of the s.o.p with respect to the beat length. Birefringence results in different propagation time of waves travelling in these polarization modes. The slight time difference between the polarization states is called the differential group delay, \( \Delta \tau \). This property of fibres causes a fundamental limitation in telecommunication systems and is referred to as polarization mode dispersion (PMD). PMD causes pulse broadening which is in a sense similar to the effects of GVD. In contrast to GVD, the PMD in optical fibre is not easily determined because the birefringence is not constant and varies randomly due to variations during the fibre
Figure 2-10: Illustration of the variation of the s.o.p in the direction of propagation

drawing and processing. Random temperature fluctuation and random stresses add to the statistical nature of the PMD. Consequently, PMD is estimated by means of statistical approximations, and as a result compensation cannot be achieved with passive components.

2.3.3 Fibre non-linearities

As the intensity of the electromagnetic wave increases, the response of the dielectric medium starts to exhibit non-linear behaviours. The origin of this non-linearity is related to the enharmonic motion of the bound electrons, when a high intensity filed is applied. Consequently the relation between the induced polarization $\mathbf{P}$ and the electric field $\mathbf{E}$ is non-linear. A general relation between $\mathbf{E}$ and $\mathbf{P}$ is often satisfied by the following expression [3]:

$$P_0 = \varepsilon_0 \left( \chi^{(1)} \cdot E + \chi^{(2)} : EE + \chi^{(3)} : EEE + \cdots \right)$$  \hspace{1cm} (2-10)
Chapter 2: Fundamentals of fibre optics

Where \( \varepsilon_0 \) is the vacuum permittivity and \( \chi^{(i)} \) is the Jth order susceptibility.

Most of the non-linear effects in optical fibres originate from the non-linear refractive index \( n_2 \), which renders the total index of refraction intensity dependent and is expressed in (2-9) below [3].

\[
\tilde{n}(\omega,|E|^2) = n(\omega) + n_2 |E|^2
\]  

(2-11)

Where \( n(\omega) \) is the linear part given by (2-3), \(|E|^2\) is the optical intensity and \( n_2 \) is the non-linear index coefficient, which is related to \( \chi^{(3)} \) by [3]:

\[
n_2 = \frac{3}{8n} \text{Re}(\chi^{(3)}_{xxx})
\]  

(2-12)

The intensity dependence of the refractive index leads to a number of non-linear effects that inhibits the performance of communication systems such as WDM. Some of the non-linear effects that are of great concern include self-phase modulation (SPM) and cross-phase modulation (XPM). These effects will be discussed in greater details later.

The other phenomenon that contributes to the non-linear effect is caused by stimulated inelastic scattering in which energy is transferred from the optical signal to the non-linear medium. This transfer of energy causes vibrations in the silica molecules and manifests itself in one of two ways.

The first is known as stimulated Raman scattering (SRS). This results when the energy transferred causes molecular vibration, which in turn modulates the incident light and generates new optical frequencies. Furthermore, the molecular vibration also provides optical amplification to newly generated frequencies. This is known as Raman gain.
The second effect is termed stimulated Brillouin scattering (SBS). SBS results when the vibrations generate an acoustic wave that travels in the same direction as the incident optical signal. The acoustic wave acts as a Bragg grating that reflects the light in the opposite direction. Because it is moving, the Doppler shift gives rise to a frequency shift in the scattered light.

2.4. Geometric description of beam propagation in optical fibre

The ray description of light propagation in fibre is based on the phenomenon of total internal reflection (TIR). The theory of TIR states that when a beam is incident at the boundary between two media where the incident medium is of a higher refractive index than the second medium and the angle of incidence exceeds a critical value $\theta_c$, the light will be totally reflected. Beyond this angle light is no longer transmitted into the second medium, instead it is reflected into the original medium. Figure 2.11 illustrates the phenomenon of TIR.

![Optical Waveguide](image)

Figure 2-11: Total internal reflection
The critical angle is easily evaluated by considering Snell’s law [2]:

\[
\frac{n_1}{n_2} \sin \theta_1 = \frac{n_2}{n_1} \sin \theta_2
\]

\[
\theta_1 = \sin^{-1}\left(\frac{n_2}{n_1} \sin \theta_2\right)
\]  \hspace{1cm} (2-13)

For critical angle condition, \(\theta_2 = 90^\circ\) hence the critical angle is obtained as:

\[
\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)
\]  \hspace{1cm} (2-14)

Owing to the index step between the core and the cladding, it follows that the theory of TIR is applicable in optical fibre if the angle of incidence to the core-cladding interface is greater than the critical angle.

### 2.4.1 Fibre numeric aperture

Having shown that light propagation through fibre optic can be explained by the theory of geometric optics it is also important to consider the mechanism of launching light into the fibre. In order to ensure that TIR condition occurs, the numerical aperture and the acceptance angle of the fibre must be known. The numerical aperture (NA) of the fibre is parameter that is solely defined by the refractive indices of the core and the cladding of the fibre. The acceptance angle is defined as the largest possible angle that could ensure light coupling into the waveguide. The relation between the NA and the launch angle can be developed by considering the pictorial illustration of figure 2-12.
Figure 2-12: Condition for TIR

The NA is defined as:

\[ NA = n_i \sin \alpha_i \]  \hspace{1cm} (2-15)

Where \( \alpha_i \) is the largest acceptance angle.

\( \alpha_i \) is determined from TIR conditions at the interface between \( n_1 \) and \( n_2 \) as follows:

\[ \min (\theta_1) = \sin^{-1}\left(\frac{n_2}{n_1}\right) \]

\[ \max (\alpha_i) = 90^\circ - \theta_1 \]

\[ n_i \sin (\alpha_i) = n_1 \sin (90^\circ - \theta_1) \]

\[ = n_1 \cos (\theta_1) \]

\[ = n_1 \sqrt{1 - \sin^2 \theta_1} \]

\[ = n_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} \]

\[ NA = \sqrt{n_1^2 - n_2^2} \]  \hspace{1cm} (2-16)
\[ \alpha_i = \sin^{-1} \left[ \frac{NA}{n_i} \right] \] (2-17)

The numerical aperture is also used to determine another parameter (in wave propagation) that is of fundamental importance, the mode characteristic fibre. The mode characteristic of the fibre is related to the NA by the normalized frequency, \(V\), of the waveguide structure, which is given as [2]:

\[ V = \frac{2\pi a}{\lambda} \times NA \] (2-18)

For single mode fibre, \(V \leq 2.405\).
Thus the mode characteristics of the optical fibre can be varied by adjusting the radius, \(a\), of the core or by varying the NA of the fibre.

### 2.5. Electromagnetic analysis of wave propagation

The basis for electromagnetic wave propagation is generally based on Maxwell’s equations. For a medium that is non-magnetic with a zero conductivity, the vector relation maybe written in terms of the electric (\(\mathbf{E}\)) and the magnetic (\(\mathbf{H}\)) field, the electric flux density (\(\mathbf{D}\)) and magnetic flux density (\(\mathbf{B}\)) as the curl equations [3]:

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

\[
\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}
\] (2-19)
And the diversions conditions:

\[ \nabla \cdot D = \rho_f \]  
\[ \nabla \cdot B = 0 \]  

Where \( \nabla \) is the vector operator. The four field vectors are related in the following manner:

\[ D = \varepsilon E + P \]  
\[ B = \mu H \]  

where \( \varepsilon \) is the dielectric permittivity and \( \mu \) is the magnetic permeability of the medium, \( P \) is the induced electric polarization.

In the absence of free charges in the medium, \( \rho_f = 0 \). By using Maxwell’s equations and some mathematical manipulations, the wave equation is obtained as [3]:

\[ \nabla \times \nabla \times E = -\mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 P}{\partial t^2} \]  

The induced electric field polarization, \( P \), is given as:

\[ P(r, t) = P_L(r, t) + P_{NL}(r, t) \]  

where \( P_L \) represents the linear and \( P_{NL} \) the non-linear part of \( P \).

It is important to include the non-linear part, seeing as the shape of the spectrum of the propagating pulse is affected by both the fibre dispersion and the fibre non-linearities. Thus a basic propagation equation can be represented as follows [3]:
\[ \nabla^2 E - \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P_L}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2} \] (2-24)

Where \( \nabla^2 \) is the Laplacian operator.

To obtain the wave equation for the slowly varying amplitude, Fourier analysis is considered. The equivalent wave equation is [3]

\[ \frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i \gamma |A|^2 A \] (2-23)

Where \( A \) is a slowly varying function of the distance \( z \), \( \beta_n \) is the \( n^{th} \) derivative of the linear propagation parameter and \( \gamma \) represents the non-linear coefficient. A more intricate analysis of the electromagnetic wave propagation is beyond the scope of this dissertation, therefore the reader is advised to turn to [14] for a detailed analysis.

### 2.6. Solving the wave equation

Numerical methods are often necessary to solve non-linear partial differential equation. Numerical methods that can be used to solve such equations can be classified into two categories namely the finite–difference methods and the pseudospectral methods. Pseudospectral methods are generally faster but suffer from inaccurate results.

The split-step Fourier method is often used to solve pulse propagation problems in non-linear dispersive medias. This finite-difference technique is considerably faster than most because it incorporates the use of the fast Fourier transform algorithm.
2.6.1 Split-step Fourier method [3]

The philosophy behind the split-step Fourier method can be well understood by considering the following equation:

\[
\frac{\partial A}{\partial t} = \left( \hat{D} + \hat{N} \right) \cdot A
\]  \hspace{1cm} (2-26)

where \( \hat{D} \) is the differential operator that accounts for the dispersion and absorption in a linear medium.

\( \hat{N} \) is the non-linear operator that governs the effect of the fibre non-linearities. \( \hat{D} \) and \( \hat{N} \) are given as follows:

\[
\hat{D} = -\frac{1}{2} \beta \frac{\partial^2}{\partial T^2} + \frac{1}{6} \beta_t \frac{\partial^3}{\partial T^3} - \frac{\alpha}{2}
\]  \hspace{1cm} (2-25)

\[
\hat{N} = i \gamma \left[ |A|^2 + \frac{2i}{\omega_0} A \frac{2}{T} \left( |A|^2 A \right) - T_r \frac{2|A|^2}{2T} \right]
\]  \hspace{1cm} (2-26)

An approximate solution to (2-26) is obtained by making the following assumptions.

I. The dispersive and non-linear behaviour acts independently of each other

II. A small distance \( h \), accurately describes the optical field during propagation

The propagation from \( z \) to \( z + h \) is carried out in two stages. In the first step, the non-linear operator acts alone \( (\hat{D} = 0) \). In the second step, the dispersive element acts alone \( (\hat{N} = 0) \).

Mathematically, this operation is represented by the equation bellow.
The execution of the exponential operator is performed in the Fourier domain. The Fourier transform of the differential operator \( \hat{D} \) is obtained by replacing \( \frac{d}{dt} \) by \( i\omega \), and \( \omega \) is the frequency in the Fourier domain.

In the Fourier domain, the differential operator \( \hat{D} \)'s equivalent \( \hat{D}(i\omega) \) is just a number, thus the evaluation of equation (2-29) is straightforward. When the FFT algorithm is used the process is relatively fast. The split step Fourier method is, however, inaccurate. The SSF method is accurate only to the second order in a step size \( h \) [3].

2.6.2 Symmetric split step Fourier method

The accuracy of the SSF method can be improved by adopting a different procedure to propagation over distance \( h \) (\( z \rightarrow z + h \)).

In the new procedure, the effect of the non-linearities is included in the middle of the segment rather than at the segment boundary. Mathematically this can be represented as follows:

\[
A(z + h, T) = \exp \left( \frac{h}{2} \hat{D} \right) \exp \left( h \hat{N} \right) A(z, T) \tag{2-29}
\]

This method is referred to as the symmetric split step Fourier method (SSSF). The SSSF poses a single advantage over the SSF: the accuracy of the result is of the 3\textsuperscript{rd} instead of the 2\textsuperscript{nd} order in the incremental step \( h \).
2.7. Reference


CHAPTER 3 : FUNDAMENTALS OF WDM SYSTEMS

3.1 Introduction

3.2 Selection of system components
   3.2.1 Carrier wavelength
   3.2.2 The LED or Laser choice
   3.2.3 The detector choice
   3.2.4 Optical fibre

3.3 System design analysis
   3.3.1 Link power budget
   3.3.2 Rise-time budget

3.4 Reference
3.1. Introduction

Due to the vast information carrying capacity of light, the deployment of optical fibre as a transport system was initiated in the 1980s. This system proved very efficient for a market that was mainly carrying voice traffic.

The inception of the World Wide Web (internet) transformed the market trend from a predominantly voice traffic to carrying data as well as video traffic. The growth in internet traffic caused the capacity of the fibre network to rapidly saturate and it implies that the network would experience fibre exhaustion. Attempts to alleviate the vast traffic on the network included using time-division multiplexing (TDM) techniques and increasing the operating speed of the system. However, due to the chromatic dispersion of the fibre, the baud rate for a single optical channel eventually reached its limit [1]. Furthermore, the transformation from the existing network, the 2.5 Gbps (OC-48 or STM16) transmission system, to the 10 Gbps (OC-194 or STM64) would prove costly seeing that the transmitting and receiving terminal of the network would have to be replaced.

An important technique of super-imposing numerous wavelengths on a single fibre was thus suggested. This multiple wavelength system is referred to as wavelength-division multiplexed (WDM) systems.

The WDM systems proved to be economically viable because it is less expensive to update the terminal equipment of WDM than it is to install new fibre cables with the aim to increase system capacity. However, transmission on long-haul fibre was inefficient because regeneration of WDM signals implied that an optical-to-electrical conversion of the signal must be performed. This is followed by the electrical amplification of each wavelength separately and finally an electrical-to-optical conversion is performed prior to the multiplexing of the signal that is required for re-transmission of the signal.
This limitation was alleviated with the inception of the erbium-doped fibre amplifier (EDFA). The EDFA with gain spectrum ranging from 1525-1560 nm and typical gain range of 25 -50 dB [2] Figure 3-1 shows the diagram of a WDM fibre optic link.

Figure 3-1: A basic WDM link
The essential components of a WDM system include a tuneable laser used at the transmitting side of the system to generate the different wavelengths. Wavelength multiplexer and de-multiplexers are used to combine and separate channels in and out of the fibre respectively.

A post-amplifier is used to counteract the insertion loss of the multiplexer at the transmitter. Similarly, a pre-amplifier is used to increase the sensitivity of the receiver. It is also customary to include an in-line amplifier to cater for the attenuation of the fibre. As for any other system, it is important that the system is transparent. In order to do so, international standard organizations such as (ITU-T) define standard wavelength channels for optical systems [3]. A common standard is the laser wavelength spacing of 100 GHz between channels, shown in table 1. This standard applies to systems that use 4, 8, 16 or 32 channels.

In order to gain a better understanding of WDM systems, one needs to consider the functionality of each component in the system. Therefore section 3-2 will give an overview of the components of a typical WDM system. In section 3-3, a brief discussion on system parameter is presented. Finally, in section 3-4 an analysis of performance measurement of the system will be discussed.
3.2. Selection of system components

3.2.1 Carrier wavelength

It is essential that the carrier wavelength be one at which a satisfactory detector is available and one where the fibre cable has acceptable loss and dispersion. In short wavelength systems applications, like data bus on premises, the fibre loss and dispersion are not very critical. Hence, sources emitting in the 0.82-0.9 µm region are used [4], to limit the overall cost of the system. In long-haul systems, where the transmitting distance exceeds 30 km, a source that operates at long wavelengths is required. Typically wavelengths in region of 1.300-to-1.600 µm are used. More recently the 1.550 µm wavelength has been often used in long-high-bit-rate system because of the small attenuation at this particular wavelength [5].

3.2.2 The LED or Laser choice

In addition to the wavelength related factor discussed above, the choice of carrier generator is influenced by the modulation method, modulation bandwidth and cost. The cost factors don’t only include the cost of the LEDs or laser itself but they also include the cost of the associated driving circuit [6]. Because the laser is a threshold device, which is significantly influenced by ambient temperature, it is necessary to operate at driving currents only 10-30% above the threshold. Consequently, the laser driving circuits are intrinsically more expensive than those of an LED [7].

In systems operating in the 0.82-0.9 µm region, the LED spectral width in combination with the wavelength dispersion of silica fibre yields a bit rate distance product of about 140 Mbits/km. This is adequate for on-premises applications.
In long-haul systems, the use of a laser source takes precedence over LEDs because the power coupled into the fibre by a laser exceeds that of an LED by a significant margin. Furthermore, for high bit rate systems, the narrower spectral width of the laser is needed to reduce the effect of the large dispersion associated with longer wavelengths.

In WDM systems, distributed feedback (DFB) lasers and distributed Bragg reflector (DBR) lasers are commonly used because of their capability to emit light of a narrow linewidth (in order of $10^{-4}$ nm).

Prior to transmission, a stream of data is imposed onto the light signal. This is known as modulation of light. A light source can be modulated one of two ways, either by a direct or external modulation scheme. In the direct modulation scheme, the laser is turned on and off to generate logic states 1 or 0 respectively. In practice, the effects of switching the laser on and off, introduces turn-on transients, which may lead to changes in the carrier density resulting in a shift of the carrier frequency. The phenomenon whereby the frequency is altered is known as chirping [8]. Chirping leads to spectral broadening of the pulse and will increase the effects of dispersion significantly should one wish to operate in the 1550 nm region.

In order to avoid the extra chirp in the input signal, the laser is continually switched on. This type of operation is called continuous wave (CW), and an external modulator is used to inscribe the data onto the light by using the selected coding format [9].

### 3.2.3 The detector choice

Silicon type detectors, operating between 0.8-0.9 µm, provide useful quantum efficiency and are available in both the PIN and APD (avalanche photodiode) type. The germanium detectors are also available for long wavelength systems. The choice between a PIN and
APD type detector is essentially one of cost. The PIN-APD cost situation is analogous to that of the laser-LED.

The avalanching process in the APD has a sharp threshold that is sensitive to ambient temperature. Such sensitivity may lead to the requirement of dynamic control of a relatively high bias voltage. It follows that the APD control and driver circuits are more expensive than the PIN devices. Therefore, a low cost system will be more readily achievable with a PIN detector. However, the penalty in receiver sensitivity is significantly higher in APD than it is in PIN detector. Hence system design must take into consideration trade-off inherent with different components.

### 3.2.4 Optical fibre

Optical fibres are classified into these three major groups: step-index single mode fibre, step-index multimode fibre or graded index multimode fibre as discussed in the previous chapter. In WDM systems, step index SMF is used as a transmission medium, essentially because the power loss is a minimum [10]. Though multimode fibre can have application in telecommunication, the intermodal dispersion inherent in this fibre increases to intolerable levels when the transmission is over long fibres [11].

There are other types of fibre that are useful for application in WDM system. Dispersion shifted fibres (DSF) are manufactured such that the zero-dispersion wavelength is moved to a desired wavelength. Generally, the wavelength is shifted to 1550 nm so as to obtain an operating wavelength at a minimum loss and dispersion. However, DSF do not perform satisfactorily in WDM systems because some dispersion is required in order to minimize the effects of the fibre non-linearities. Dispersion flattened fibre is said to have the best performance in WDM systems because of the non-zero group velocity dispersion at 1550 nm [12].
It follows that dispersion-flattened fibre is inherently more expensive than standard SMF, consequently SMF is used in lightwave systems in order to minimise the cost.

### 3.3. System design analysis

System analysis is necessary to any designer because it predicts the performance of a set of components used in the link. This preliminary stage in system design is useful in isolating problem areas prior to the installation of the physical system.

Two analyses are usually carried out to ensure that the system performs satisfactorily: the link power budget and the system rise-time budget analyses. The power budget analysis is used to determine the power margin between the output power of the transmitter and the minimum receiver sensitivity needed to ensure a specified bit error rate (BER) [8]. The power loss between transmitter and receiver can be allocated to the connector, splices and fibre losses. Should the system not meet the desired performance, components used in the link must be varied. This process is iterated until the desired performance is met. Once the power budget has been established, a system rise-time analysis is performed to ensure that the desired overall performance is achieved.

#### 3.3.1 Link power budget

The link power budget is determined by establishing the minimum power required to fall on the photodiode in order to ensure a certain BER. In lightwave system a BER = $10^{-9}$ is considered acceptable [8]. The light coupling efficiency of the transmitter, the loss of the fibre and the sequential loss contributions of each element in the link determine the power received at the detector. The power budget can be simply expressed as follows:

$$\bar{P}_{tr} = \bar{P}_{rec} + \bar{P}_{loss} + M_{sys} \quad (3-1)$$
Where $\bar{P}_{tr}$ is the average transmitted power, $\bar{P}_{rec}$ is the average received power, $\bar{P}_{loss}$ is the lost power and $M_{sys}$ is the system margin.

The system margin is normally provided in the analysis to incorporate components ageing, temperature fluctuations and possible future addition of components in the system. A link margin of 6-8 dB is generally used for systems that might not require future additional components. The power loss is given as follows:

$$\bar{P}_{loss} = \alpha_f L + \alpha_{con} + \alpha_{splice}$$  \hspace{1cm} (3-2)

Where $\alpha_f$ is the attenuation of the fibre is dB/km, $L$ is the fibre length in km, $\alpha_{con}$ is the connector losses and $\alpha_{splice}$ is the splice losses.

### 3.3.2 Rise-time budget

The dispersion limitation of an optical fibre link must be determined because it sets the upper limit for the transmission bit-rate. The rise-time budget analysis is a convenient method for establishing the allowable bit rate in the optical system. The rise time budget analysis is essentially a measure of how fast the system responds to a step stimulus. There are four basic elements that limit the speed of response of an optical system: these are the transmitter rise-time $t_{tx}$, the fibre rise time that comprises of the GVD rise-time $t_{GVD}$ and the intermodal dispersion rise-time $t_{mod}$, and finally the receiver rise-time. Hence the system rise-time is the sum of the above-mentioned factors. The system rise time is written as follows:

$$t_{sys} = \left( \sum_{i=1}^{N} t_i^2 \right)^{\frac{1}{2}}$$  \hspace{1cm} (3-3)
In order to adhere to international standards, the total system rise time of a digital link should not exceed 70% of the bit period for the non-return-to-zero (NRZ) data format.

Similarly the rise time should be less than 30% of the bit period for a return-to-zero (RZ) data format. The bit period is defined as the reciprocal of the bit rate.

The fibre rise time is generally determined by the $t_{GVD}$ in WDM systems because multimode fibres are seldom used; hence the intermodal dispersion rise time is never considered in the analysis. The group velocity rise time can be approximated by:

$$t_{GVD} \approx |D|L \sigma_\lambda$$

(3-4)

Where $\sigma_\lambda$ is the half-power spectral width of the source and D is the dispersion of the fibre. Note that equation (3-4) is only accurate when one considers a continuous, jointless fibre.

In practice, an optical link might consist of a series of concatenated fibres that may have different dispersion characteristics. It is therefore difficult to predict the bandwidth (and hence the rise time). More complex methods of evaluating the rise time can be considered but are beyond the scope of this discussion.

The designer generally knows the rise time of the transmitter and receiver. The transmitter rise time can be primarily attributed to the light source and its drive circuitry [10].

The receiver rise time results from the time response of the photodetector and the 3 dB electrical bandwidth of the receiver front end. The rise time of the receiver front end can be explained by modelling as the step response of a low pass filter [12].

$$g(t) = \left[1 - \exp\left(-2\pi B_{rx} t\right)\right] \times u(t)$$

(3-5)
where $B_{rx}$ is the 3 dB electrical bandwidth of the receiver and $u(t)$ is a unit step function.

The rise time, $t_{rx}$, is defined as the time it takes for the signal to rise from 10%-90% of its final value. If $B_{rx}$ is expressed in MHz then the receiver front-end rise time in nanoseconds is given by:

$$ t_{rx} = \frac{350}{B_{rx}} $$

(3-6)

Thus the system rise time can be rewritten as:

$$ t_{sys} = t_{tx}^2 + D^2 \sigma^2 L^2 + \left( \frac{350}{B_{rx}} \right)^2 $$

(3-7)

where all the times are given in nanoseconds.
Chapter 3: Fundamentals of WDM systems

3.4. Reference


CHAPTER 4 : LIMITATIONS AND OPTIMIZATION TECHNIQUE OF A WDM SYSTEM

4.1 Introduction ........................................................................................................................................... 51
4.2 Fibre losses ............................................................................................................................................... 52
4.3 Fibre non-linearities .......................................................................................................................... 54
4.4 Amplification mechanism in Erbium doped fibre .............................................................................. 54
4.5 Self–phase and cross-phase modulation (SPM & XPM) .................................................................... 58
4.6 Other non-linear effects .................................................................................................................. 59
  4.6.1 Four Wave Mixing (FWM) ........................................................................................................... 59
  4.6.2 Stimulated Brillion Scattering (SBS) ......................................................................................... 60
  4.6.3 Stimulated Raman Scattering (SRS) ......................................................................................... 60
  4.6.4 Technique for eliminating FWM, SBS & SRS ........................................................................ 61
4.7 Chromatic dispersion ......................................................................................................................... 61
4.8 Dispersion management schemes .................................................................................................... 63
  4.8.1 Dispersion mapping with NDFs ............................................................................................... 63
4.9 Reference .............................................................................................................................................. 64
4.1. Introduction

In the preceding chapters, pulse evolution along the fibre link was discussed. The fundamental properties of optical fibre were presented and finally, the operation of basic lightwave systems such as WDM was also discussed. The integration of the abovementioned topics is used to form the basis of the discussion undertaken in this chapter.

Owing to the architecture of WDM systems, the various properties of optical fibre impose a number of limitations in the operation of such lightwave structures. The primary factors limiting WDM systems are: the fibre chromatic dispersion and the fibre non-linearities. However with clever optimisation techniques it is possible to reduce the effects of a number of limitations mentioned above.

This chapter is divided into the following categories: In section 4.2 the constraints imposed on the system due to fibre attenuation are presented. Section 4.3 discusses fibre non-linear effects. Section 4.4 follows with a brief introduction to the operation mechanism of EDFAs so as to give better understanding how optical amplification enhances non-linear effects in lightwave systems. In section 4.5, the major non-linear effects, such as SPM and XPM that limit WDM systems are analysed. Section 4.6 explores other non-linear effects and the optimisation technique is used to eliminate these effects. Finally in section 4.7 and 4.8, the limitations due to chromatic dispersion are studied and techniques for dispersion compensation suitable for WDM system are presented.
4.2. Fibre losses

Most optical communication systems operate in the 1.55 $\mu$m window which provides the lowest attenuation. However, in long distance transmission the fibre attenuation can degrade the signal considerably and thus sets a limit as to how far one can transmit without errors. In order to overcome limitations imposed by fibre losses, regenerator stations are placed periodically along the fibre link. The regenerator station’s main purpose is to recondition the signal before any further transmission.

In the past electronic regenerators were used. The basic function of an electronic regenerator is to perform an optical to electrical conversion, where in the electrical domain the signal is re-amplified and re-shaped (2R), and then converted back to the optical domain for retransmission. This system performed adequately well for low bit-rate. However as the operating bit-rate increases, electronic regeneration are no longer feasible because of the speed limitation of electronic equipment, hence equipment modification is required. Furthermore for multiple channel systems, such as WDM, each individual channel requires its own regenerator. The cost for adopting the system to higher operating bit-rates proves to be too costly given the vast magnitude of the already deployed equipment.

This constraint can be easily overcome by employing the use of an all optical (AO) repeater station. In an AO station, an optical amplifier is used to boost the signal power. The most useful optical amplifier for telecommunication applications is the Erbium Doped Fibre Amplifier (EDFA). This is primarily because it operates optimally in the 1.55 $\mu$m window and it is independent of the signal format, thus simultaneous amplification of all channels can be performed. Figure 4.1 illustrates optical systems with an electronic regeneration station in comparison to that employs optical amplifier for signal conditioning.
It is however imperative that this device presents some disadvantages. This is because, the amplification mechanism of EDFAs is known to enhance other limiting factors in WDM systems, this topic are addressed in subsequent section in this chapter.

Figure 4-1: Block diagram of conventional telecommunication system with an electronic regenerator (a), telecommunication link with optical amplifier (b).
4.3. Fibre non-linearities

The manifestation of fibre non-linearities is governed by the expression [1]:

\[ n = n_1 + n_2 P \]  

(4-1)

Hence, the index of refraction is related to the optical intensity by the non-linear coefficient \( n_2 \), thus the refractive index may exhibit non-linear behaviour if the contribution of the \( n_2 \) term is large. In WDM system, the total optical power of carrier in the fibre is the sum of the optical intensity of each and every sub-carrier channels that have been multiplexed. Furthermore, in long haul transmission, EDFAs are used amplify the signal to counteract the attenuation of the fibre, thus the contribution of the non-linear coefficient \( n_2 \) becomes significant. Therefore the non-linearity effects are enhanced in the system.

There are four non-linearity effects that are important in lightwave systems: Self-Phase Modulation, Cross-Phase Modulation, Four Wave Mixing and Stimulated Scattering. However, before considering the abovementioned limiting factors, it is worth discussing the mechanism of amplification of EDFAs in order to understand the source of the non-linear effects.

4.4. Amplification mechanism in Erbium doped fibre

The principal of optical amplification of EDFAs is governed by two phenomenon that occurs at the molecular level in silica-based optical fibre that has been doped with erbium ions \( \text{Er}^{3+} \) [2]. When an electromagnetic wave is incident to an atom, the electrons in the ground states may be excited to higher states which are usually unstable and as a result, electrons fall back down to the ground level. This in turn may cause the emission of electromagnetic radiation.
Two forms of emission usually occur namely, stimulated and spontaneous emission. Stimulated emission is said to occur when the transition of the excited electron from a high energy level down to the ground level is stimulated by a photon. The energy is released in the form of light and the photon is emitted in the stimulating beam thus amplifying the beam.

Spontaneous emission, on the other hand occurs when the excited electrons fall to the ground level without any stimulation by other photons. The electromagnetic field radiated from this emission has a random phase, random polarization and random direction and is called spontaneous emission noise. Spontaneous emission noise can cause stimulated emissions of other excited electrons resulting in its own amplification and it is then referred to as amplified spontaneous emission (ASE) noise. ASE is undesirable in optical systems because it enhances non-linear effects that degrade the signal.

It is important to note that any form of optical amplification occurs only when the amount of stimulated emission exceeds that of absorption. This implies that the number of excited electrons is larger than those in the ground state. This condition is termed population inversion [3]. Population inversion can be achieved by injecting sufficient energy into the medium (EDF) [3].

As mentioned before, population inversion can be achieved by exciting electrons of the ground state by means of injecting photons. A high power laser is used to perform this task, the process is commonly known as ‘pumping’. Fig. 4.2 shows a basic setup for EDFAs. The operating wavelength of the pump laser must correspond to the wavelength at which an energy difference exists between the distinctive energy bands of the medium i.e. doped fibre. Fig. 4.3 shows the energy level diagram of erbium ions in silica-based fibre. The wavelength indicates the location of the energy difference occurring between 2 levels.
Figure 4-2: Basic EDFA architecture in the forward pumping mode. Where the symbols, S: fiber splice, WSC: wavelength selective coupler, EDF: Erbium-doped fiber [2].

Figure 4-3: Energy-level diagram of Erbium ions in silica-based fiber and fluoride-based fiber. The wavelength in nm corresponds to the difference of photon energy between two levels [4].
When erbium-doped fibre is pumped with a laser 980 nm, the electrons in the ground state \((E_1)\) are excited to the \(E_3\) band and then fall down to the \(E_2\) band due to the emission of photons. Subsequently the excited electrons will return to the ground level \(E_1\). A large amount of population inversion occurs in this mode of operation because the lifetime of electrons in level \(E_3\) is only 1 \(\mu\)s which is considerably smaller than the spontaneous emission lifetime between \(E_2\) and \(E_1\) band of \(\sim 10\) ms. Hence, electrons falling from \(E_3\) accumulate at the \(E_2\) band before falling back to the ground level, thus creating a high population inversion.

Pumping at 980 nm creates a high population inversion, thus a good signal-to-noise ratio is attainable. However this configuration suffers from poor amplifying efficiency due to the large energy difference between \(E_3\) and \(E_1\). Pumping at 980 nm serves well in applications that require a high SNR such as pre-amplification of received signals.

An amplifier operating with a 1480 nm pump laser creates a relatively lower population inversion, but the pump efficiency is considerably high. This mode of operation is well suited for the amplification of signals transmitted over long span of fibre.

The three important wavelengths at which energy bands exists in erbium doped fibre are 980 nm, 1530 nm and 1480 nm as previously depicted in fig. 4.3. A combination of the sublevels of the entire energy band yields a continuous energy wave across the usable bandwidth. However, the population of the sublevels is not uniform over the entire energy band, consequently the gain profile is not uniform but rather peaks at around 1532 nm and the gain profile of EDFAs is wavelength-dependent as shown in fig. 4.4.
Chapter 4: Limitation and optimization technique of WDM system

Figure 4-4: Gain profile of Erbium-doped fibre amplifiers

The non-uniform gain profile of EDFAs poses a serious problem in WDM systems seeing that individual channels experience a varying gain, resulting in different SNR. Therefore gain equalization is needed to normalize the SNR in all channels across the system. Some techniques of gain equalization with passive filters have been proposed [5]-[10].

4.5. Self–phase and cross-phase modulation (SPM & XPM)

The intensity dependence of the refractive index of a non-linear medium is often manifested through phase modulation of the signal propagating through the media [3]. The phase modulation occurs when the power across the pulse is non-uniform, as a result the various spectral components of the pulse experience different intensity. This in turn causes the refractive index, as seen by each component, to vary and consequently the components of the signal travel with different velocities. This mechanism of light
propagation induces a non-linear phase shift across the pulse. The varying phase implies that the instantaneous optical frequency across the pulse differs from the central frequency. This frequency difference can be viewed as a frequency chirp. This implies that new frequency components are generated and as a result the optical spectrum of the pulse is broadened. The degree of broadening dependents on a number of factors such as the length of the fibre, the fibre dispersion and the pulse shape just but to name a few. Thus phase modulation induces spectral broadening of a pulse.

The two forms of phase modulation are self-phase (SPM) and cross-phase modulation (XPM). SPM refers to the phenomenon that occurs when a phase modulation across a pulse is as a result of it own intensity variations thus broadening the optical spectrum of the pulse. On the other hand, XPM is similar to SPM in the sense that the optical spectrum is broadened. However, the induced non-linear phase shift on a certain channel is caused by the power variations of the neighbouring channels since the index of refraction of the fibre depends on the total optical power of all channels.

This manifestation of fibre non-linearities leads to interchannel interference (ICI), also called crosstalk.

### 4.6. Other non-linear effects

#### 4.6.1 Four Wave Mixing (FWM)

Power dependence of refractive index also causes intermodulation products among optical signals traveling along the fiber. If there are three optical waves propagating along the fiber with frequencies denoted by \( f_1, f_2, \) and \( f_3 \), the FWM process will generate an additional nine optical signals at frequencies \( f_{ijk} = f_i + f_j - f_k \) where \( i, j, \) and \( k \) can be 1, 2, or 3 as seen in Fig. 4.5 These new generated signals can interfere with the desired signals [11].
Figure 4-5: Four-wave mixing with three injected waves at frequencies $f_1$, $f_2$ and $f_3$. The generated frequencies $f_{ijk}$.

4.6.2 Stimulated Brillouin Scattering (SBS)

This non-linear effect is due to the interaction between the optical signal and acoustic vibrations in the fiber. Its resultant effect will exhaust the energy of the incident optical signal and generate another counter-propagating signal scattered back to the transmitter [2].

4.6.3 Stimulated Raman Scattering (SRS)

Stimulated Raman Scattering is the result of interaction between the incident light and molecular vibrations. When two optical waves having different wavelengths travel along the fibre, the longer-wavelength will be amplified via the energy transfer from the shorter-wavelength wave. This nonlinear effect will cause excess signal loss in the shorter wavelength channel [3].
4.6.4 Technique for eliminating FWM, SBS & SRS

Among all of these nonlinearities, the FWM is the most deleterious effect [11] in WDM systems because all channels are equally spaced, and the new generated signals will coincide with the intended signals. This results in crosstalk and depletion of intended signals. The efficiency of FWM requires phase matching for all channels [12]. This condition can be met if the system operates in the zero dispersion wavelength regions and if the channel spacing are uniform and relatively small. Thus the efficiency of the FWM can be reduced if the system operates in the non-zero dispersion region and if the channel spacing is large, thereby ensuring a large dispersion discrepancy amongst channels. However, these two conditions cannot be met simultaneously because the large channel spacing reduces the bandwidth utilization of system. Thus in common WDM practice, the system is set to operate in the non-zero dispersion region. Nevertheless, the FWM efficiency is reduced considerably due to the dispersion discrepancy amongst the channels caused by the dispersion slope of the fibre.

4.7. Chromatic dispersion

As a series of pulses travel along a fibre, the pulses broaden or disperse. The dispersion experienced by a pulse arises from the material and waveguide properties of the fibre. The most dominant effect caused by the above mentioned properties of fibre is known as chromatic dispersion.

Chromatic dispersion is significant in optical light propagation owing to the fact that a light pulse is not monochromatic, thus is comprises several spectral components i.e. wavelengths. The spectral dependence of the refractive index results in different wavelengths propagating at different velocities through the fibre, a phenomenon referred to as group velocity dispersion (GVD) [2].
Chapter 4: Limitation and optimization technique of WDM system

The GVD has the effect of retarding the slower spectral components of the light signal whilst accelerating the faster frequency components. This in turn results in a broadened signal arriving at the output of the fibre. Consequently, the energy of adjacent signals overlaps each other thereby resulting in intersymbol interference (ISI) at the output end of the line.

The degree of broadening is thus proportional to the linewidth of the optical pulse. A narrow linewidth can be obtained by using a laser source, however the amount of tolerable broadening is limited by the timeslot allocated to a single pulse i.e. the system bit-rate. In fact the dispersion limit is inversely proportional to the bit-rate squared \([2]\). As the optical network tends to higher bit rates, the tolerance of dispersion in the system drastically decreases and ISI must be kept at a minimum seeing that it increases the probability of erroneously allocating a logic ‘1’ to ‘0’ in the decision making circuit of the receiver, or the converse. Fig. 4.6 illustrates the effects of dispersion on adjacent pulses.

![Figure 4-6: The effect of GVD in WDM system](image)

*Return to zero (RZ) format pulses*

*Insufficient Zero Level*

*Indistinguishable Pulses*

*Distinguishable Pulses*
Chapter 4: Limitation and optimization technique of WDM system

It is therefore clear that dispersion not only limits the transmission distance of optical communication links, it also limits the operating bit-rate of the system. Dispersion management schemes need to be considered to realise faster and less costly optical communication systems [14]. The most attractive dispersion management schemes include the use of Chirped Fibre Bragg Gratings (CFBGs) and Negative Dispersion Fibre (NDF), also known as Dispersion Compensating Fibre (DCF). These two devices are offered over other dispersion compensators because they are cost effective and can be easily adapted in most optical networks.

4.8. Dispersion management schemes

4.8.1 Dispersion mapping with NDFs

Dispersion compensation in WDM systems operating at 1550 nm can be achieved by employing dispersion mapping techniques. In this technique, fibres of opposing dispersion coefficient are made to alternate along the length of the optical link. In general NDFs have a large dispersion in comparison to standard SMFs, thus a relatively short NDF can compensate for dispersion accumulated over long links of SMFs [14].

NDFs are easy to install and require little modification to an already existing system. The major disadvantage of NDF is that it exhibits a large attenuation in signal power, as a result more optical amplifiers are generally deployed in the system. This in turn enhances the other limitations in the system because the non-linear attributes of this fibre is considerably higher.
4.9. Reference


CHAPTER 5 : DISPERSION CANCELLING FIBRE

5.1 Introduction ................................................................. 67
5.2 Fibre Design ............................................................... 68
5.3 Properties of dispersion compensating fibre ................. 70
5.4 Dispersion Management of WDM systems .................. 73
5.5 Reference: ................................................................. 76
5.1. Introduction

In order to meet the growing demand of bandwidth for internet and other related communication applications, future long-haul systems are required to operate at bit-rate of 10 Gbit/s, 40 Gbit/s or even higher. In high capacity systems, dispersion compensation is critical.

The transmission fibres in the existing network are the standard non-zero dispersion fibres (NZDF) with nominal value for dispersion equal to $+17 \text{ ps/nm·km}$. Although these fibres were deployed several decades ago, they are still preferred by system designers today because the high dispersion of the fiber is used efficiently to impair the non-linear manifestation of fibre in WDM systems. However, the accumulation of dispersion in these fibres limits the transmission distance to approximately 60 to 300 km for 10 Gbit/s systems and 4 to 18 km for 40 Gbit/s systems if dispersion compensation is not employed [1]. Hence dispersion compensation is required to increase the transmission distance in systems operating at high bit-rates. Furthermore, the DC device is required to have a sufficiently large bandwidth in order to achieve simultaneous compensation across all the channels. This implies that the DC device must be capable of dispersion slope compensation.

Several dispersion and dispersion slope compensating devices have been demonstrated, including single-mode and higher-order-mode dispersion compensating fibres, fibre Bragg grating devices, virtual image phased array devices and planar waveguide devices. Although many of these devices have great potential, including tuneable dispersion, single mode dispersion compensating fibres (DCF) are still the only one that is widely deployed [2].

Section 5.2 briefly describes the design of DCF. In sections 5.3, some of the properties of DCF are discussed and finally in section 5.4 application of DCF in optical communication is presented.
5.2. Fibre Design

Standard non-zero dispersion fibers (NZDF) used in optical networks are silica-based optical fibres and the system driving this network is usually made to operate near 1550 nm in order to capitalize on low attenuation in this region. In silica based fibres, the material dispersion component is positive and dominates the overall dispersion properties of the NZDF.

The waveguide component, on the other hand, is negative in this wavelength region, and typically exhibits a minimum at longer wavelengths. Because waveguide dispersion is derived by the refractive index and the core-cladding geometric properties of the fibre [2], the contribution of the waveguide dispersion can be varied by proper adjustment of the refractive index differences and widths of the layers making up the fiber refractive index profile. Consequently, the position and depth of the waveguide component minima can be controlled and thereby control of the overall fiber dispersion and dispersion slope can be achieved.

Generally a narrow and high index core region is required to obtain a large negative total dispersion. A refractive index difference of approximately 2% can be achieved by doping the fibre with high $GeO_2$ content. The combination of a relatively small core effective area, $A_{eff}$, and a high $GeO_2$ doping increase the non-linear effect of the fibre. Thus clever refractive index profile design is required to minimize the fibre non-linearities associated with DCF.

Several refractive index profiles for a DCF have been proposed, which includes a matched-cladding type, a W-shaped type and a segmented core type designed essentially to reduce the fibre non-linear coefficient by increasing the core effective area. However, the W-shaped type is a widely used design for DCF because negative dispersion slope can be achieved. The performance of this fibre depends more on the depth of the depressed cladding [3]. These index profiles are shown in Fig. 5.1.
Figure 5-1: Various refractive index profiles used for dispersion compensating fibres (DCF)

Most dispersion slope compensating fibres reported today use one of these designs. The triple-cladded design has the advantage that it offers the fibre designer more degrees of freedom to simultaneously optimize important fibre parameters like dispersion, dispersion slope, loss, effective area, cutoff wavelength, and bend loss performance. Even more complex designs are under consideration for future fibres where parameters such as fourth-order dispersion also require control [4].
5.3. Properties of dispersion compensating fibre

As discussed in previous chapters, CSMFs are characterized by the large core radii ($\sim 5 - 6 \, \mu m$). This core-cladding geometry reduces the contribution of the negative waveguide dispersion component thus causing the zero-dispersion wavelength to occur at 1300 $nm$ and a positive dispersion coefficient of $\sim 17 \, ps/\, nm\cdot km$ at 1550 $nm$. In order to achieve a negative dispersion coefficient, DCFs have a relatively small core radius ($\sim 1.5 \, \mu m$) and are doped with relatively high $GeO_2$ compared with the CSMFs. The core-cladding geometry of DCF ensures that the negative waveguide dispersion is large, see fig. 5.2. On the other hand, the high $GeO_2$ doping alters the profile of the material dispersion of the fibre. See fig. 5.2 for a comparison of material dispersion for pure and doped silica fibres.

![Figure 5-2: Illustrates the material dispersion component of pure silica fibre in comparison to $GeO_2 (16.3\%)$ doped fibre](image-url)
Hence proper geometric design of the fibre and sufficient doping, a total dispersion of a fibre can be made negative. Fibres with these properties are referred to as negative dispersion fibres (NDF) and are well known as DCF. Fig. 5.3 shows the waveguide dispersion of CSMF in comparison to DCF.

Unfortunately, the total loss of DCF is increased because of this doping, partially because the Rayleigh scattering loss increases with increasing concentration of GeO₂ doping, and the non-linear coefficient of the fibre is also relatively large in comparison to that of CSMF. The values of fibre loss ($\alpha$) and non-linear coefficient ($n_2$) for DCF are typically $6.1 \text{ dB/km}$ and $6.1 \times 10^{-20} \text{ m}^2/\text{W}$ respectively.

Figure 5-3: Illustrates the waveguide dispersion component for pure silica fibre and that for fibre doped with GeO₂ at 16.3% with core radius = 1.5 microns
The application of DC requires that DCF be cascaded to the CSMF that forms the backbone of the existing optical fibre network. However, the addition of DCF will impair the performance of the system by virtue of the inherently high loss of this fibre. Furthermore, the non-linear limitation of the system will be increased due to the large $n_2$. Thus, a measure of the dispersion compensation efficiency for DCFs is given by the figure of merit (FOM), which is defined as the ratio of the dispersion coefficient and the total loss and has a unit of $\text{ps/(dB} - \text{nm)}$. For this reason, DCF are designed such that the FOM is relatively large. This implies that the DCF must have a large dispersion coefficient so that a small span of DCF can compensate dispersion of a significantly larger span of CSMF. A ratio of 1:5 is common amongst fibre manufactures. However, in a recent paper, a novel DCF design capable of providing very high dispersion values has been proposed [5].

![Figure 5-4: Illustrates the total dispersion of CSMF and the dispersion curve of a DC fibre designed with $a = 1.5$ microns, $\Delta = 0.2\%$ and $n_1 = 1.470521$](image)
5.4. Dispersion Management of WDM systems

The transition from using wavelengths in C-band to those in the L-band for long-haul high-speed transmission systems is primarily fuelled by the relatively low loss of the L-band window. Although operation in the C-band, around the zero-dispersion wavelength, would ensure that the system doesn’t incur dispersion limitations, it would certainly impose a distance limitation due to the large attenuation coefficient. Furthermore, the effects of the fibre non-linearities would be prevalent because the phase matching condition required for SBS, SRS and FWM to be manifested will be met in the absence of dispersion. Four Wave Mixing causes cross-talk amongst neighbouring channels thus degrading the system performance. In an attempt to minimize non-linear effect, the transmission distance must be reduced. However, this limitation can be alleviated by operating away from the zero-dispersion window. The inherent differential group delay caused by chromatic dispersion inhibits phase matching between the spectral components, and in so doing, minimizes fibre non-linear effects, thereby increasing the transmission distance. However, the transmission performance of long-haul systems that relies on wavelength multiplexing to optimize the usable bandwidth would then be limited by the fibre dispersion.

The concept of dispersion management in long-haul arises from the need to control the effects of fibre non-linearities by tailoring the accumulated dispersion to keep the interaction length small, but at the same time maintaining the end-to-end dispersion at a minimum.

Dispersion management is often achieved by introducing sufficient negative dispersion to the fibre link, thereby reducing the total accumulated dispersion at the receiver. Total dispersion management requires that equation (5-1) is satisfied [9].

\[
D_{\text{CSMF}}L_{\text{CSMF}} + D_{\text{DCF}}L_{\text{DCF}} = 0 \tag{5-1}
\]
The length of a DCF required to cancel dispersion in CSMF is in a ratio of 1:5 [2]. This ensures that the system is not subjected to further limitations due to the properties of the DCF. Fig. 5.5a illustrates dispersion management in the WDM system. Equivalently, fig. 5.5b depicts the accumulated dispersion profile in the system.

Figure 5-5: (a) Dispersion management in a WDM system, (b) depicts the dispersion profile of the link [2].
Dispersion management can be achieved with various combinations of fibre layout. The widely implemented configurations are post-compensation depicted as type 1 in the schematic below, and pre-compensation depicted as type 2. The accumulated dispersion and relative power for both pre- and post-configuration are depicted in figure 5.6 (b).

Figure 5-6: (a) Two configurations of dispersion management schemes, type1 represents the post-compensation (SMF + DCF) and type 2 is pre-compensation (DCF + SMF); (b) The accumulated dispersion of link with type 1 (dashed lines) and type 2 (solid line) [8]. Fibre parameters are as follows; SMF: 0.21 dB/km, $+17 \text{ps/nm.km}$, DCF: $-100 \text{ps/nm.km}$, 0.6 dB/km.
Chapter 5: Dispersion cancelling fibre

5.5. Reference


CHAPTER 6: OPTSIM SIMULATION RESULTS

6.1 Introduction ................................................................................................................. 79
6.2 Simulation results ........................................................................................................... 82
6.3 Conclusion ..................................................................................................................... 84
6.4 Reference ...................................................................................................................... 85
6.1. Introduction

In order to improve the bandwidth utilization efficiency of embedded SMF when operating at high bit rates, dispersion management is required. Thus far, extensive simulation work has been conducted some of which includes simulation of dispersion compensation for dispersion shifted fibre [1, 2], simulation of dispersion compensation of SMF assuming linear propagation [3], post compensation using DCF [4, 5] and the performance of WDM systems with DCF in the pre-compensation configuration [6].

In this chapter, we discuss some of the results obtained from various dispersion management schemes. The optical simulation package, OptSim, was used for simulating WDM systems. The dispersion compensation configuration used in these simulations included the post compensation and pre-compensation methods. See figure 5.4 for a pictorial representation.

At the transmitter, four wavelengths spaced by a 200 GHz grid are each intensity modulated with a Mach-Zehnder modulator. The Mach-Zehnder modulator is fed by a 10Gbit/s $2^{23} - 1$ PRBS signal modelled as a super-Gaussian pulse. The four 10 Gbit/s channels are multiplexed and launched into the fibre. Figure 6.1 shows the frequency range of the four channels used in the simulation.

The fibre link was modelled as a cascade of 9 spans of 80 km sub-links with EDFAs at the beginning of each span [7]. Each amplifier applied a gain $G$ equal to the fibre loss of the preceding section.
Figure 6-1: (a) shows the optical spectrum of the transmitted signal, (b) shows a magnification of channel 2
At the receiver, the wavelengths are extracted by an optical 3rd order Butterworth filter, with a 3dB bandwidth of 40 GHz. The signal is then passed through a square-law detector and an electrical second order Butterworth filter with a 3 dB bandwidth of 6.5 GHz. Finally, the performance of the system is evaluated by calculating the Q-factor using equation (6.1).

$$Q = \frac{|\mu_i - \mu_0|}{\sigma_i + \sigma_0}$$  \hspace{1cm} (6.1)

Where \((\mu_i, \mu_0)\) are the means and \((\sigma_i, \sigma_0)\) the standard deviation of the zero and one pulse respectively.
6.2. Simulation results

The 720 km fibre link was subdivided into 9 spans SMF of 80 km length. Each span in
the link was cascaded to 8.3 km of DCF in various positions. The Q-factor was recorded
for each dispersion management configuration. Figure 6.2 bellow shows Q-factor versus
the average channel input power.

![Figure 6-2: The Q-factor versus the average channel input power for post-
compensation, pre-compensation and symmetric compensation. The post-
compensation is indicated by diamonds, the pre-compensation by circles and
symmetric compensation by squares.](image)
The eye diagram is also used to demonstrate the effect of the various dispersion compensation configurations on the eye opening vis-à-vis to the uncompensated signal. Fig. 6.3 shows the eye diagrams obtained at the optimal Q-factor at 720 km.

Figure 6-3: The eye diagram for a) at the transmitting end b) post-compensation c) pre-compensation and d) sym-compensation for a signal after propagating through 720 km of SMF as obtained from the OptSim simulations
Chapter 6: OptSim simulation results

6.3. Conclusion

For dispersion compensation based on dispersion mapping of positive and negative dispersion fibre, the input power into both the fibres are critical elements that govern the performance of the system. This is due to the influence of fibre non-linearities which dominate the propagation regime when the input power levels are high.

The results depicted in figure 6.2 are the testimony to the above statement. The Q-factor is seen to decrease rapidly as the intensity of the input signal is increased. However, the post compensation scheme is significantly more tolerable to high input level than the pre- and symmetric-compensation schemes.

The pre-compensation configuration appeared to be particularly more sensitive to high input power because of the high power being launched directly into the DCF enhances the non-linear effect, such as SPM and XPM. This effect is observed by analysing the eye diagram. Although the eye-opening is relatively large for all the configurations considered, the overshoot of the one level is extremely high for the pre-compensation scheme fig. 6.3 (c), thus indicative of the enhanced non-linear effects.

Similarly, the performance of the symmetrically compensated link shows a dependence on the input power level. However, it performs relatively better than the pre-compensation.

It is thus concluded that the post-compensation technique yields the best results because of the ability to minimize the influence of the fibre non-linearities on the propagation regime of light pulses travelling through optical fibre.
6.4. Reference


7.1. Standard single mode fibre (SMF)

The single mode fibre used in these experiments is similar to the G652 fibre used in standard telecommunication applications. Hence, the behaviour of an optical communication system could be obtained by simply determining the fundamental characteristics of the fibre, such as the fibre attenuation and the chromatic dispersion. The theoretical approximation of the fibre loss and dispersion are specified in the ITU-T recommendation G.709 as 0.2 dB/km and 17 ps/nm.km respectively.

7.1.1 Measurement of chromatic dispersion

The conventional phase-shift technique [1, 2] was used in the experiment. The technique employs methods based on the transverse time of a modulated signal. The basic measurement set-up is outlined in Fig. 7.1. Light from a tuneable laser is intensity modulated and applied to the fibre under test. The transmitted signal is detected and the phase of its modulation is measured relative to the electrical modulation source. This measurement is repeated at interval across the wavelength of interest. The phase shift of the detected signal allows the group delay of the fibre to be determined using the equation bellow.

\[
\Delta \tau_\lambda = -\frac{\phi_{\lambda + \Delta \lambda} - \phi_{\lambda - \Delta \lambda}}{360^0 f_m} \frac{\Delta \lambda}{2}
\]

(7.1)

Where \(\phi_{\lambda 1} - \phi_{\lambda 2}\) is the relative phase of the modulated light signal, evaluated for wavelength \(\lambda\).
Chapter 7: Dispersion measurement results

Figure 7-1: Experimental set-up for chromatic dispersion measurement implemented for the differential phase shift method

The chromatic dispersion is thus attained by differentiating the group delay w.r.t. the wavelength. The dispersion per unit length of fibre is obtained by scaling this value by the inverse of the fibre length.

\[
D_\lambda = \frac{1}{L} \frac{d \Delta \tau}{d \lambda}
\]  
\[ (7.2) \]

The tuneable laser used in this set-up was the Photonetic laser. The wavelength observed ranged from 1480 nm – 1580 nm. The wavelength sweep was set with a resolution of 0.1 nm and the laser output power was 1 \( mW \). The polarization controller used in this set-up was the FPC 560. This device is used to change the polarization of the light to vertically polarized light for the Mach-Zehnder modulator.
The alternating electric field that feeds the Mach-Zehnder modulator was generated by the Hewlett Packard 8712B RF network analyser. The modulating frequency $f_m$ was set to 500 MHz.

Two fibres of different length were tested. The output signal from the fibre is detected using a photo-detector and then amplified to facilitate signal comparison between the transmitted and received signal. This operation was performed by the HP network analyser. The network analyser displays a phase reading bounded between 180 and -180 degrees, thus the true phase measured is obtained by ‘unwrapping’ the recorded phase. This experiment was repeated for fibre lengths of 3.98 km and 9.998 km. Fig. 7.2 shows the dispersion curves for the respective fibres. The result obtained for the dispersion curve is expectedly very noisy due to the derivative operation, hence in both cases a low pass. Hence, Butterworth filter is used to smooth the curve. The parameters of the Butterworth filter were as follows: $N = 3$ and $w_c = 0.0140$. 
Figure 7-2: The dispersion coefficient measured for fibre lengths (a) 3.98 km and (b) 9.998 km
7.2. Negative dispersion fibre (NDF)

The fibre used for dispersion compensation is the AVANEX PureForm DCM. The dispersion and attenuation specification of this fibre is as follows: insertion loss of 0.4 dB, fibre loss of 4.3 dB and the dispersion coefficient of -918, -987 and -1047 ps/nm at wavelengths of 1525, 1545 and 1565 nm respectively.

The length of this fibre was measured, using the Hewlett Packard OTDR E6000B, as 7.883 km and the attenuation was recorded as 0.4 dB/km. Fig. 7.3 illustrates the dispersion characteristics of the NDF used in the dispersion compensation system.

![Figure 7-3: illustrates the dispersion characteristics of the AVANEX PureForm DCM NDF with total length of 7.883 km](image)
7.3. Conclusion

From the measurement results of the above section, one concludes that the dispersion coefficient of the G652 is approximately 17 ps/nm.km as specified by the ITU-T document G709. The above measurement also shows that the dispersion coefficient of the AVANEX PureForm DCM at wavelengths in the region of 1530 nm is approximately –930 ps/nm. Thus, this particular negative dispersion fibre would compensate 60 km of G652.

7.4. References


# CHAPTER 8: EXPERIMENTAL RESULTS

8.1 Introduction  .......................................................... 94

8.2 Characteristics of system equipment and system optimisation  ............................... 95
   8.2.1 Transmitter characteristics ........................................... 95
   8.2.2 Characteristics of the receiver ........................................ 98
   8.2.3 System optimisation procedure and requirements .................... 99

8.3 Experimental set-up and measurements .............................................. 100
   8.3.1 Zero dispersion compensation ....................................... 103
   8.3.2 Under compensation (90% dispersion cancellation) ................. 105
   8.3.3 Full compensation (100% dispersion cancellation)............... 107
   8.3.4 Over compensation (110% dispersion cancellation) ................ 108

8.4 Conclusion ................................................................. 111
Chapter 8: Experimental results

8.1. Introduction

The effects of chromatic dispersion in WDM structures were tested on the Siemens MTS 1c WDM system. The Siemens WDM system is designed to launch 16 channels of STM16 (2.488 Gbps) signals with 200 GHz channel spacing or a single STM64 (10.71 Gbps) channel. The performance of the entire system was measured by examining the eye diagram of the signal at the receiving end. The parameters obtained from the eye diagram used for performance analysis were: the extinction ratio (EX), the signal-to-noise ratio (SNR) and the Q-factor. The abovementioned parameters are defined in APPENDIX A.

Three experiments were performed to analyse the effects of dispersion and dispersion compensation in lightwave systems.

In the first experimental set-up, the network was tested with no dispersion compensation. In the second set-up, dispersion compensation was introduced in the network in various configurations. The configurations considered included pre-, post- and symmetric-compensation. The first experiment aimed to establish:

i. the dispersion limit of an STM64 system

ii. the optimal operating length for the dispersion compensator used in this particular experiment

The second experiment aimed to evaluate the performance of the Negative Dispersion Fibre (NDF), AVANEX PureForm DCM, which was used as dispersion compensator.

This chapter is divided in the following manner. In section 7.2, a description of the network used in the experiment is presented. In particular, the characteristics of the transmitter and the receiver will be discussed. Furthermore, the optimisation procedures and requirements for the Siemens WDM system are reviewed. Section 7.3 follows with a description of the various experimental set-ups and the results obtained thereof. Finally, in section 7.4 the results are summarized and relevant conclusions drawn.
8.2. Characteristics of system equipment and system optimisation

8.2.1 Transmitter characteristics

The transmitter used in all the experiment was the Agilent j7230 Omniber OTN communication analyser. The 10G module, just to put simply, it is a narrow band laser emitting at 1532.68 nm that is directly modulated to generate a 10 Gbit/s signal. The laser characterization was performed by connecting the OTN to the Anritsu B7260 optical spectrum analyser (OSA) as depicted in figure 8.1 below.

![Diagram of experimental set-up]

Figure 8-1: The experimental set-up of the laser characterization. The first configuration is represented by solid line used to observe the integrity of the optical signal. The second configuration (dotted line) is used to analysis the data being transmitted.
In a similar set-up, an optical power and wavelength meter was connected to the OTN to obtain the mean launch power and the operating wavelength. Furthermore, the quality of the data generated from the Omniber is interrogated by connecting a to the Agilent Infiniium digital communication analyser (DCA). The eye diagram and subsequent parameters are examined. In order to maintain a certain level of consistency in the reading, the power level of signals going into the DCA must be set to -6 dBm and was assumed as the reference level ($P_{\text{ref}}$).

A variable optical attenuator (VOA) is used to adjust the power level to $P_{\text{ref}}$ for signal analysis. Figure 8.2 shows the optical spectrum of the emitted signal and figure 8.3 shows the eye-diagram.

![Figure 8-2: The optical spectrum of the emitted signal of the Agilent j7230 Omniber OTN](image)

**Figure 8-2**: The optical spectrum of the emitted signal of the Agilent j7230 Omniber OTN
Figure 8-3: The corresponding eye-diagram obtained from data generated by the source (Omniber OTN)

Table 8.1 below shows the parameters of the optical signal in comparison to the recommended values specified by the ITU-T G691 documentation.

<table>
<thead>
<tr>
<th></th>
<th>ITU-T G691</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMSR</td>
<td>30</td>
<td>47.29 dB</td>
</tr>
<tr>
<td>3 dB bandwidth</td>
<td>N/A</td>
<td>0.02 nm</td>
</tr>
<tr>
<td>Mean launch power</td>
<td>+2 to -2</td>
<td>-0.38 dBm</td>
</tr>
</tbody>
</table>
The transmission module of the OTN is set to generate a $10^{23} - 1$ pseudo random bit sequence (PRBS) which is mapped into a virtual container (VC) to form a concatenated payload. In this structure, the data being carried has no structured mapping or channelization, thus the entire payload is used to carry the service. A payload of this format is referred to as a contiguous concatenated payload and it’s often used to carry broadband services. Contiguous concatenation yields a more accurate bit error rate (BER) result by virtue of the fact that the bulk of the data is tested as opposed to a single channel which consequently is 1/63 of the entire SDH frame. APPENDIX D gives a more detailed explanation of contiguous concatenation used in BER tests.

### 8.2.2 Characteristics of the receiver

The receiver used in this experiment included the Agilent 86100B Infinium DCA wideband oscilloscope and the Agilent j7230 Omniber OTN. The receiver module of the OTN is used for BER testing; however the sensitivity of this receiver is fixed to a value of -26 dBm [1], thus yielding a $BER = 10^{-15}$ in every experiment. The sensitivity of this module is appropriately obtained by measuring the BER, for every interface, for the duration of the test. See APPENDIX D.
Table 8.2: shows the EX, SNR and the Q-factor obtain at the transmitter end

<table>
<thead>
<tr>
<th></th>
<th>ITU-T G691</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX</td>
<td>10</td>
<td>13.72</td>
</tr>
<tr>
<td>BER (bits/s)</td>
<td>$1 \times 10^{-12}$</td>
<td>$1 \times 10^{-12}$</td>
</tr>
<tr>
<td>SNR</td>
<td>13</td>
<td>13.68</td>
</tr>
</tbody>
</table>

The second receiver was the Agilent Infiniium wideband oscilloscope DCA. The oscilloscope is primarily used to plot the eye diagram of the received data. The integrity of the data is analysed by extracting parameters, such as EX and SNR from the eye-plot. Furthermore, the Q-factor is also evaluated for performance analysis. The method used to estimate the Q-factor from the eye plot is called asynchronous technique. APPENDIX B gives a description of this technique. In Table 8.2, the EX, SNR and the BER measured at the transmitter are displayed.

### 8.2.3 System optimisation procedure and requirements

In order for the Siemens WDM systems to operate optimally the following requirements have to be met:

i. The total dispersion in the link is limited to 1600 ps/nm [1].

ii. The link power budget is limited to 25 dB [2].

iii. The optical level into the optical amplifier module (Booster and Pre-amp) must range between -13 dBm and -16 dBm. Failure to maintain these input levels results in damage of the module or simply the failure to initiate the laser operation.
In order to adhere to the above optimisation requirements:

i. An insertion device (ISD) such as a line attenuator is placed before each amplification stage to regulate the input level into the OA.

ii. The link span was limited to 100 km with the aim of not exceeding the 1600 ps/nm dispersion.

iii. In line attenuators were incorporated into the fibre span with the aim to maintain the link budget at the specified value of 25 dB.

Finally, the power level into the DCA was always set to the reference level, $P_{\text{ref}}$.

### 8.3. Experimental set-up and measurements

In this section, the performance of the negative dispersion fibre (NDF) as a dispersion compensator for the Siemens WDM system is evaluated. Figure 8.5 illustrates the experimental set-up used in the laboratory.
Figure 8-4: The experimental set-up for measuring the effects of chromatic dispersion in a WDM system. LA represents line attenuator, ISD is the insertion devices, which the Dispersion Compensator (DC) unit, VOA is a variable optical attenuator and B & P represents the Booster and Pre-amplifier respectively.

In the first experiment various lengths of fibre span were tested and no dispersion compensation was present in the network. This is aimed to establish the dispersion limit of the system. For the second set of tests, dispersion compensation of various degrees was introduced in the fibre network. 90% dispersion cancellation is referred to as under compensation where 100% and 110% dispersion cancellation are referred to as full- and over-compensation respectively. Furthermore, the pre-, post- and symmetric-
configurations of the dispersion compensator were considered. Figure 8.6 below shows the set-up used for the pre-, post- and symmetric-compensation.

(a)

(b)

(c)

Figure 8-5: Network configuration for (a) Post-, (b) pre- and (c) symmetric-compensation. LA represents line attenuator, ISD is the insertion devices, which the Dispersion Compensator (DC) unit, VOA is a variable optical attenuator and B & P represents the Booster and Pre-amplifier respectively.
8.3.1 Zero dispersion compensation

The main objective of this experiment was to establish the amount of dispersion that the WDM system could tolerate without any dispersion compensation. The theoretical limit for a 10 Gbps system is approximately 40 km for standard single mode fibre [3]. A set of measurements for fibre lengths ranging from 40 km to 120 km was conducted. In each experiment, the eye-pattern was analysed and the BER was estimated based on the SNR reading from the DCA, the method used to estimate the BER and the Q-factor is described in APPENDIX B. For high-speed SDH/SONET links, say the STM-64 rate which operate at 10 Gbps, a BER reading below $1 \times 10^{-12}$ is required.

Figure 8.7 shows the BER obtained for various lengths of fibre spans and figure 8.8 shows the corresponding eye-pattern obtained for each span of fibre.

![Figure 8-6: The Q-factor for various lengths of fibre spans in the Siemens WDM system](image)
Figure 8-7: The eye diagram observed at different lengths in the network at (a) 40 km, (b) 55 km, (c) 70 km and (d) 80 km. The power scale 256 µW/div, the timescale was set to 20 ps/div.
Table 8.3 shows the extinction ratio and signal-to-noise ratio evaluated at the corresponding fibre lengths.

<table>
<thead>
<tr>
<th>Fibre length (km)</th>
<th>EX</th>
<th>SNR</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>9.27</td>
<td>5.31</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>50</td>
<td>9.49</td>
<td>4.99</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>55</td>
<td>9.19</td>
<td>4.55</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>60</td>
<td>9.89</td>
<td>4.53</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>65</td>
<td>9.8</td>
<td>4.72</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>70</td>
<td>8.8</td>
<td>3.81</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>80</td>
<td>4.88</td>
<td>2.69</td>
<td>$10^{-1}$</td>
</tr>
</tbody>
</table>

**8.3.2 Under compensation (90% dispersion cancellation)**

Under-compensation was achieved by setting the fibre length to 65 km. Table 8.4 shows the results obtained for the pre-, post- and symmetric-compensation of an under-compensated link. Correspondingly, figure 8.9 depicts the eye diagram for each configuration.
Figure 8-8: The eye diagram of an under-compensated link for (a) post-compensation, (b) pre-compensation and (c) symmetric-compensation. Power scale set to 200 $\mu$W/div and timescale was set to 20 ps/div.
Table 8.4: shows the EX, the SNR and the BER obtain for pre-, post- and symmetric-compensation for an under-compensated link

<table>
<thead>
<tr>
<th>DC Config.</th>
<th>EX</th>
<th>SNR</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>11.55</td>
<td>9.36</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Post</td>
<td>11.22</td>
<td>11.95</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Symmetric</td>
<td>11.62</td>
<td>12.92</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

**8.3.3 Full compensation (100% dispersion cancellation)**

A fibre length of 60 km was used for the full compensation set-up. Table 7.4 shows a comparison between the different configurations used in dispersion compensation. The corresponding eye diagrams are depicted in figure 8.10.

(a) ![Eye diagram](image_a)

(b) ![Eye diagram](image_b)
Figure 8-9: The eye diagram of a fully compensated link for (a) post-compensation, (b) pre-compensation and (c) symmetric-compensation. Power scale set to 200 µW/div and timescale was set to 20 ps/div.

Table 8.5: shows the EX, the SNR and the BER obtain for pre, post- and symmetric-compensation for an fully compensated link

<table>
<thead>
<tr>
<th>DC Config.</th>
<th>EX</th>
<th>SNR</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>11.73</td>
<td>10.17</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Post</td>
<td>11.1</td>
<td>13.12</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Symmetric</td>
<td>11.38</td>
<td>14.25</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>

8.3.4 Over compensation (110% dispersion cancellation)

The fibre span was set to 55 km in order to achieve over compensation of 110%. Table 8.6 shows the results obtained for this particular set-up. The corresponding eye diagrams for the pre-, post- and symmetric-compensation are displayed in figure 8.11.
Figure 8-10: illustrates the eye diagram of an over compensated link for (a) post-compensation, (b) pre-compensation and (c) symmetric-compensation. Power scale set to 200 µW/div and timescale was set to 20 ps/div.
Table 8.6: shows the EX, the SNR and the BER obtain for pre-, post- and symmetric-compensation for an over compensated link

<table>
<thead>
<tr>
<th>DC Config.</th>
<th>EX</th>
<th>SNR</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>10.68</td>
<td>11.96</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Post</td>
<td>11.06</td>
<td>12.75</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Symmetric</td>
<td>11.787</td>
<td>13.49</td>
<td>$10^{-11}$</td>
</tr>
</tbody>
</table>
8.4. Conclusion

From the experiments performed in the preceding chapter, one can assess the performance of the WDM system. The performance assessment is achieved with conformance to the ITU-T recommendation specification namely the G709, G642 and G691.

The transmitter parameter of the Agilent J7230 omniber OTN laser source is well within the recommended values specified by the G691 ITU-T document. The mean launch power was recorded as -0.38 dBm, the EX ratio was measured to be 13.92 dB, the 3 dB bandwidth was measured to equal 0.12 nm and finally, the SMSR was 47.29 dB. The recommended values of the abovementioned parameter are -2-2 dBm, 10 dB and 30 dB for the mean launch power, the extinction ratio and the SMSR respectively. The 3 dB bandwidth is yet to be specified.

The second experiment, the dispersion limit of the Siemens MTS-1c is determined. The result obtained indicates that transmission length in access of 35 km will result in dispersion limitations. This result is consistent with the ITU-T specification and the theoretical dispersion limit [14].

Dispersion cancelling fibre used as the dispersion compensating module is characterized by its maximum dispersion, and thus dictates the average fibre span for the link to be compensated.

The Avanex is capable of full dispersion cancellation of G652 fibre of length 60 km for an operating wavelength of 1532 nm. Various configurations such as pre-, post- and symmetric-compensation were considered. Furthermore, the performance of the under and over compensated link was also considered.
Chapter 8: Experimental results

The extinction ratios recorded for a fully compensated link (i.e. 60 km G.652 fibre) were 11.73, 11.1, and 11.38 for pre-, post- and symmetric-compensation respectively. These figures are well above the minimum specified value of 10. Similarly, the under compensated link performed adequately well, yielding extinction ratios of 11.55, 11.22 and 11.62 for the pre-, post- and symmetric-compensation respectively.

The over compensated set-up yields similar results with EX ratio above 10 dB. From the above results, one can conclude that the influence of the DCM impacts significantly on the overall performance of the link.

However, it is worth noting that, the eye opening increases considerably when dispersion compensation is employed. It thus yields a good extinction ratio and relatively high Q factor for all the configurations considered. The performance of the system under different configuration is well differentiated by analysis of the rise time (eye width) and the signal-to-noise ratio.

It is shown that the pre-compensated link yields the shortest rise-time period, this indicates that the pulse is probably restored to a rectangular shape. It is also worth noting that the curve decays up to the 60 km length and systematically increases as one exceeds the 60 km mark. This indicates that full-compensation would yield better results.

The analysis of the SNR shows that the symmetric compensation yields the highest SNR thus indicating that the noise level (overshoots) are kept at a minimum. Similarly, the curve also shows that this maximum occurs at 60 km, thus reinforcing that full compensation would yield the best results.

Finally, the above analysis confirms the results obtained with OptSim, that chromatic dispersion in high speed optical communication system can be considerably reduced with the aid of negative dispersion fibre.
CHAPTER 9 : CONCLUSION

9.1 Conclusion

9.2 Future work
9.1. Conclusion

A long haul optical communication system that uses the existing network of standard single mode fibre as the core transport medium usually operates in the 1550 nm region. In order to increase the capacity of this network wavelength-division multiplexing is normally employed. However, the properties of fibre such as chromatic dispersion and fibre non-linearities cause manifestations such as pulse broadening, SPM, XPM, SBS, SRS and FWM. These phenomena in turn inhibit the overall performance of lightwave systems.

Fibre non-linearities is a result of the non-linear dependence of the fibre refractive index on the average intensity of the signals propagating within the fibre. Thus it is standard practice that the mean launch power for WDM systems does not exceed 10 mW. Under these conditions SPM, XPM, SRS, and SBS become negligible. Furthermore, the relatively high dispersion coefficient associated with the 1550 nm region inhibits FWM by preventing the phase matching condition required for the FWM phenomenon to be manifested. Chromatic dispersion (CD) thus remains the singular most important limitation in lightwave systems.

Using the experimental set-up shown in fig. 8.5, the impact of dispersion compensation using DCF was investigated. Furthermore, the influence of dispersion mapping was also investigated by considering various methods of combining the transmission fibre and the DCF. The experiment demonstrates that the position of the DCF with respect to the transmission fibre is of uttermost importance seeing that different performance levels was obtained with different dispersion compensation configurations.

The experiment also showed that the amount of negative dispersion introduced, with respect to the total accumulated dispersion of the transmission fibre, also impacted on the performance of the system.
In the single channel optical system experiment, it was found that the system performance gradually improved as the total dispersion of the transmission fibre tended toward that of the DCF and in a similar fashion, the system performance decreased as the total dispersion of the G652 fibre exceeded that of the DCF. At 40% over-compensation, the EX ratio was seen to increase from 9.49 dB, obtained with no compensation, to 10.63, 11.28 and 10.59 for the post-, pre- and symmetric-compensation respectively. At 36% under compensation, the EX ratio was seen to increase from 4.88 to 8.64 dB, 9.19 dB and 7.22 dB for the post-, pre- and symmetric-compensation respectively.

An average improvement of 1.44 dB and 3.47 dB was obtained for the under-compensation and over-compensation respectively. Although the margin of improvement for the under- exceeds the over-compensation case by a factor of 2, the EX ratio for the under-compensated case is still below the recommended value of 10 dB. Thus, one would favour over-compensation over the under-compensated configuration. Full compensation was considered for dispersion values of 90%, 100%, and 110% of the total dispersion of the DCF.

The EX ratios obtained for 55 km of transmission fibre (equivalent to 90% of the total dispersion of the DCF) was 9.19 dB. This result seen to improve by 2.41 dB, 1.49 dB and 2.597 dB for the post-, pre- and symmetric-compensation respectively.

At a 100% compensation, the EX ratio was seen to increase by 2.09 dB, 2.72 dB and 2.37 dB for the post-, pre- and symmetric-compensation respectively. The EX ratio with no compensation was 9.01 dB.

Similar results were obtained for the 110% compensation. An improvement to the EX ratio was recorded as 2.21 dB, 2.54 dB and 2.6 dB for the post-, pre- and symmetric-compensation respectively. The EX ratio with no compensation was 8.9 dB.
Chapter 9: Conclusion

For all the cases and dispersion configurations considered in the above summary, the extinction ratio was recovered and exceeded the required value of 10 dB specified by the ITU-T recommendation G703. Furthermore, analysis of the Q-factor also revealed that system performance had exceeded the minimum requirement of 6 by a large margin.

From the above summary, one may conclude that for a single channel, single span optical communication system operating at OC-192 or STM-64 rate, the dispersion distance limit increased from 35 km to 80 km by introducing dispersion management into the network. The post- and symmetric-compensation configuration yielded the highest Q-factor. This is because the OSNR was kept at a minimum by ensuring that the Kerr effect of the DCF was kept at minimum.

The symmetric compensation configuration should always be employed in lightwave systems to ensure that the performance of the network is independent of the direction of travel of the signal.

9.2. Future work

This document reports mainly on the performance of DCF in the application of dispersion compensation for a single channel, single span optical system operating a 10 Gbps. It is imperative that the performance of the DCF in multi-span system be studied. This is important because in conventional optical communication systems, regeneration stations are situated 600-800 km apart with boosting stations spaced by 60-80 km. This implies that numerous DCFs are required in order to compensate the accumulated dispersion in each span. Literature suggests that in a multi-span system, the pre-compensation configuration yields better result than the post-compensation case. This allegation should be verified.
The ability of chirped fibre Bragg grating as dispersion compensator has been extensively researched and documented. It would however be interesting to have experimental results to support this theory. Furthermore, ultra-long CFBG can also be tested for simultaneous compensation of a multi-channel system.
REFERENCES


APPENDIX A: DEFINITION OF CERTAIN FIGURES OF MERIT

A.1. Extinction ratio (EX) ................................................................. 125
A.2. Eye diagram ......................................................................... 125
A.3. Reference ........................................................................... 126
A.1. Extinction ratio (EX)

The extinction ratio is the measure of the amplitude of the digital modulation on the optical carrier. The EX ratio can be used to specify the distance over which a fibre optic system can reliably transmit and receive a signal [1]. EX is defined as the ratio of the average optical energy in a logic one bit to the average energy in the corresponding bit zero, as in (B.1).

\[
EX = 10 \log_{10} \left( \frac{P_1}{P_0} \right)
\]  

(B.1)

Where \(EX\) = extinction ratio

- \(P_1\) = average optical power in logic one pulse
- \(P_0\) = average optical power in logic zero pulse

The EX ratio is a technique of interrogating the receiver on its ability to properly detect the transmitted data so as to accurately determine whether each transmitted bit is a logic one or a logic zero. This figure of merit is used to establish the quality of the physical transmission.

A.2. Eye diagram

The eye diagram is used to indicate whether or not the receiver can identify the start of a frame, de-multiplex the tributary signals, and extract the payload. The ability of the receiver to perform the above function is often compromised due to the chromatic dispersion along the fibre that can cause the optical pulse to spread into adjacent bit period, thereby causing what is known as inter-symbol interference.

The eye pattern is obtained by sweeping an oscilloscope at a sweep rate that is lower than the bit rate of the system under test [2] and then superimposing all possible pulse
sequence. This is performed of two bit period. The pattern generated from this technique resembles the human eye, hence it’s called the eye diagram. Inter-symbol interference, which is a result of chromatic dispersion, can cause the eye to close thereby introducing errors in the detection process of the receiver.

A.3. Reference


## APPENDIX B: Q-FACTOR ANALYSIS

### B.1. The Q-factor in more detail

- Definition of the Q-factor ................................................................. 128

### B.2. Method of determining Q-factor ........................................... 134

### B.3. Analysis of results by the synchronous sampling method

- B.3.1 No compensation ........................................................................ 140
- B.3.2 Pre-compensation ..................................................................... 142
- B.3.3 Post-compensation ................................................................... 144
- B.3.4 Symmetric compensation .......................................................... 146

### B.4. System Performance based on SNR ......................................... 148

### B.5. Reference .................................................................................. 150
B.1. The Q-factor in more detail

Definition of the Q-factor

The Q-factor is a measure for the quality of the analog signal, which is usually defined by its signal-to-noise ratio (this is also the mathematical definition of the Q-factor). The Q-factor is defined by the difference of the mean values of the two signal levels divided by the sum of the noise rms values (standard deviations) at the two signal levels. This can be expressed by the following equation.

\[ Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \]  

(B.1)

The analog representation of a digital signal on the time scale toggles between the states “0” and “1” depending on the data pattern to be sent. To make the data stream visible however the time scale can only show a “snapshot” with a restricted number of bits as theoretically it would go to infinity. If the data signal is triggered to the bit rate and superimposed into the same picture, the so-called “eye diagram” or “eye pattern” is generated (figure B.1).

![Figure B.1: Illustration of eye-diagram generation](image-url)
Figure B.2: Illustration of signal sampling into bins

As the illustrations show the signal is more likely to be at the “0” or “1” level rather than in a transient state. The likelihood of certain signal level occurring can be described in a diagram, derived from sampling the data stream and collecting the sampling points for certain amplitude levels in bins (figure B.2). Real signals are also influenced by noise which causes the most likely amplitude levels to spread out.

The higher the sampling rate (samples per second) and smaller the bins, the more accurate the diagram generated by this method. Assuming an infinitely high sampling rate and small bin size, the filling level of the bins can be normalized and represented by a single curve (figure B.3). The normalized curve is known as the Probability Density Function (PDF).

Figure B.3: Deriving the PDF from the bins
Only the sample values at the detection time are of importance when detecting a binary signal. A PDF can be derived from the “bin” method but only for detection samples (figure B.4).

**Figure B.4: Deriving the PDF from detection point samples**

It can be assumed that the PDF deriving from the “bin” method is the sum of two separate PDFs representing the two binary states “0” and “1”. Each binary state has a Gaussian distribution known as a “bell curve”.

The signal distributions show the two most likely or mean values which are related to the binary “0” and binary “1” levels (figure B.5). As the real signal is affected by noise it shows slight deviations from the most likely amplitude values. The spreading through noise power is called standard deviation. The more noise a signal level contains, the broader the standard deviation. The mean value is often denoted as $\mu$ and the standard deviation as $\sigma$ in mathematical equations.
Figure B.5: PDF with Gaussian distributions

To determine whether a binary “0” or “1” has been sent, one must first ascertain whether the signal is on the “0” level or “1” level. The threshold level for decision lies between the two mean values of the PDF shapes. There is a small probability however of a binary level becoming distorted by noise for example and jumping over the threshold level. In this case, the detection point will be misinterpreted. There are two possibilities whereby a misinterpretation can be made:

- “0” is detected as “1” or
- “1” is detected as “0”

The probability of this particular type of misinterpretation is reflected in figure A6. An optimum threshold can be found when looking for the smallest area covered, thus providing lowest probability of misinterpretation. One could assume that the optimum threshold lies at the intersection of the two PDF shapes. This is only true when both bell curves are identical. Real systems however always have slightly different shapes for the two signal levels. In this case the optimum threshold level does not necessarily cross the intersection point.
The probability of misinterpretation or error probability can also be expressed as bit errors per total transmitted number of bits – the so-called Bit Error Ratio or BER.

\[
\text{BER} = \frac{\text{bit errors}}{\text{total number of bits}}
\]

Figure B.6: BER in the PDF diagram

The detection of the binary level during the pulse width is not only dependent on the detection threshold but also on the detection time. The detection time is often expressed as sampling phase. This comes from the definition of the pulse width in radians. The pulse width itself may be defined to cover the range from 0 to \(2\pi\) (see in figure B.7).

The center of the eye opening provides optimal conditions for the detection of the binary signal and is defined as the sampling phase with the highest vertical eye opening (figure B.7).
Figure B.7: Optical eye with optimum detection point

Assuming that the signal distributions are Gaussian, the Q-factor can also be expressed as BER and vice versa.

Let’s go back to the initial definition of the Q-factor to understand how it relates to the BER. The difference in the mean values produces the vertical eye opening. The higher the difference, the better the BER will be as the two bell curves drift away from each other and have less overlap. This difference is divided by the sum of the noise distributions which are represented by the width of the bell curves. Increases in noise result in more overlap in the two bell curves resulting in a higher BER.

There are two fundamental methods for determining the Q-factor: the histogram method and the Pseudo-BER method. Though the processes behind each method differ, the intention of them is to estimate the BER for the optimum threshold which is directly related to the Q-factor. The histogram method samples the signal and collects the sampling points into bins as shown in the previous chapter. The Pseudo-BER method, however, determines the BER for different threshold levels representing different areas under the PDF curve. With the BERs at different threshold levels, an extrapolation can be made for the estimated BER at the optimum threshold.
**Table 1: Methods to determine Q**

<table>
<thead>
<tr>
<th>Fundamental method</th>
<th>Sampling</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histogram method</td>
<td>Asynchronous</td>
<td>Voltage histogram</td>
</tr>
<tr>
<td></td>
<td>Synchronous</td>
<td>Digital sampling scope</td>
</tr>
</tbody>
</table>

**B.2. Method of determining Q-factor**

*Asynchronous sampling (voltage histogram)* – All the amplitude values of the eye diagram (including the amplitude values of the transient regions) are sampled asynchronously resulting in a histogram representing the PDF of the complete signal including the transient regions (figure A8).

Figure B.8: Asynchronous sampling

The main objective in acquiring an evaluation of the performance is to determine the PDF of the optimum sampling phase which would be $\pi$ (in this particular case). The
contribution of the transient regions to the overall PDF is to “hide” the PDF of the sampling phase. The transient region samples fill up the center between the two means. Two possible solutions for correction are the “cut and flip” or the “cut and delete” methods (figure B.9). The idea behind this is that the histogram’s edges are influenced only by the noise distributions but not by the transient. In the first case, the edges representing noise distributions are flipped inside to get a more appropriate model of the PDF. In the second case, the center (which is affected by the transient samples) is omitted leaving the edges for evaluation.

The characteristics of the asynchronous sampling method make it very difficult to fit the Gaussian functions to the measurement results which are necessary for the BER calculation. The BER calculation for the signal will not give a high accuracy for the optimum sampling phase as the PDF needs to be prepared to provide a better estimation. Until now, the exact estimation of the Q-factor from the asynchronous sampling histogram could not be accurately proved. Although this technique has restrictions for performance monitoring, it remains a very powerful tool for detecting small signal degradations.

Figure B.9: “cut and flip” and “cut and delete” method
**Synchronous sampling (digital sampling scope)** – The main restriction of asynchronous sampling is that the transient regions affect the result. To overcome this restriction and gain higher accuracy, synchronous sampling must be performed. Synchronous sampling needs a clock recovery and is therefore more complex. The sampling phase is locked to the optimum phase and can therefore give a more accurate result of the BER estimation. Synchronous sampling concentrates more on the detection phase rather than the whole signal (figure B.10).

![Synchronous sampling histogram method](image)

**Figure B.10: synchronous sampling histogram method**

One disadvantage of this method is that the digital sampling scopes used often do not have the sampling rate needed for Q-factor measurements. A typical sampling rate would be 100,000 samples per second. Assuming a 10 Gbps signal (10,000,000,000 bits per second) is received, only one bit out of 100,000 would be sampled. An additional disadvantage is that due to the low statistical probability of a sample being affected during measurement occurring at the tail of the Gaussian function, the samples tend to be concentrated at the “0” and “1” levels.
This gives a good estimation around the mean values of the two Gaussian distribution functions although the estimation of the correct standard deviations and hence the bell curve is difficult to determine. The shape of the bell curve however contributes greatly to the BER estimation as the evaluation takes place mostly at the tail of the bell curve. Although this method gives a higher degree of accuracy than the asynchronous histogram method, it is still not very accurate and mostly shows lower Q-factor values (higher BER) than the more accurate synchronous Pseudo-BER methods which are described next.
B.3. Analysis of results by the synchronous sampling method

The asynchronous sampling method described in the preceding section was used to estimate the Q-factor of the system under test. The eye-diagram was regenerated by super-imposing 20 waveforms, retrieved from the Agilent DCA, using the Matlab software. The histogram and pdf plot for the “1” and “0” level are determined by asynchronously sampling at the point on the eye where the EX ratio is largest. Matlab can then estimate the mean and the standard deviation of both logic states and the Q-factor is calculated using equation A.1.

Figure B11 below shows the eye diagram generated from the power reading obtained from the Agilent Omniber OTN receiver at the transmitting on of the WDM link.

Figure B11: Eye diagram measured at the transmitting end. Eye diagram regenerated with the Matlab package. The shaded region represents the sampling point used for the histogram generation.
The histogram and the corresponding probability distribution function for this eye-diagram are shown in figure A12 bellow.

![Histogram and PDF](image)

Figure B12: shows the histogram plot and the pdf for the ‘ones’ and ‘zeros’ levels of the eye diagram. The mean and rms noise for the ‘1’ and zero level equal

\[ \mu_1 = 7.956 \times 10^{-4}, \quad \sigma_1 = 3.34 \times 10^{-5}, \quad \mu_0 = 4.1495 \times 10^{-10}, \quad \sigma_0 = 2.509 \times 10^{-5}, \] respectively.

Using equation A.1, the Q-factor can be obtained. The bit error ratio is then calculated with the equation bellow [3].

\[
BER = \left( \frac{1}{\sqrt{2\pi}} \right) e^{\left( \frac{Q^2}{2} \right)} \right) / Q
\]  

(B 2)

In this particular experiment the Q-factor was estimated to equal 13.4871 and the BER calculated to be \(10^{-43}\).
The Q-factor and BER was computed for all the experimental set-up considered, however for demonstration purposes, only the results obtained for the 100 % compensation (60 km) configuration will be presented.

B.3.1 No compensation

The figure bellow depicts the eye diagram (a) and the PDF (b) obtained for a 60 km link with no dispersion compensation in place. The shaded area represents sampling point for the generation of the histogram plot.
Figure B.13: shows the histogram plot and the PDF for the ‘ones’ and ‘zeros’ levels of the eye diagram for a 60 km link without DC.

The mean and rms noise (standard deviation) for the logic state “1” and “0” were equal to $\mu_1 = 8.785 \times 10^{-4}$, $\sigma_1 = 1.3718 \times 10^{-5}$ and $\mu_0 = 9.175 \times 10^{-7}$, $\sigma_0 = 6 \times 10^{-5}$ respectively.

The Q-factor was equal to 4.6636 and the BER = $1.6 \times 10^{-6}$
B.3.2 Pre-compensation
Figure B.13: Depicts the eye diagram (a) and PDF (b) plot for a 60 km link with pre-compensation set-up

The mean and rms noise (standard deviation) for the logic state “1” and “0” were equal to $\mu_1 = 7.687 \times 10^{-4}$, $\sigma_1 = 7.2 \times 10^{-5}$ and $\mu_0 = -4.766 \times 10^{-7}$, $\sigma_0 = 2.15 \times 10^{-5}$ respectively. The Q-factor was equal to 8.2178 and the BER = $10^{-16}$. 

![PDF plot for a 60 km link with pre-compensation set-up](image)
B.3.3 Post-compensation

(a)
Figure B.14: Depicts the eye diagram (a) and PDF (b) plot for a 60 km link with post-compensation set-up

The mean and rms noise (standard deviation) for the logic state “1” and “0” were equal to $\mu_1 = 7.896 \times 10^{-4}$, $\sigma_1 = 4.3 \times 10^{-5}$ and $\mu_0 = 9.175 \times 10^{-6}$, $\sigma_0 = 2.39 \times 10^{-5}$ respectively.

The Q-factor was equal to 11.8132 and the BER $= 10^{-32}$
B.3.4 Symmetric compensation

(a)
Figure B.15: Depicts the eye diagram (a) and PDF (b) plot for a 60 km link with symmetric-compensation set-up

The mean and rms noise (standard deviation) for the logic state “1” and “0” were equal to 
\[ \mu_1 = 8.42 \times 10^{-4}, \quad \sigma_1 = 3.459 \times 10^{-5} \] and 
\[ \mu_0 = 1.108 \times 10^{-5}, \quad \sigma_0 = 2.357 \times 10^{-5} \] respectively.

The Q-factor was equal to 14.1875 and the BER = 10^{-43}
From inspection of the eye diagram it is clear that the system’s performance is considerably improved by employing dispersion management with DCF. However, the results obtained in the above analysis are somewhat unrealistic. This primary due to the limited number of samples used to estimate the parameters (mean and standard deviation) of the eye diagram. Hence, an alternate parameter needs to be used in order to accurately predict the performance of the system under test.

**B.4. System Performance based on SNR**

The parameter used to evaluate the performance of the system is the electrical signal to noise ratio (SNR) measured at the receiving end. See APPENDIX D for the measured results. The equation B.3 was used to obtain the BER from the SNR.

\[
BER = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{1}{2\sqrt{2}} \frac{V}{\sigma} \right) \right] \tag{B.3}
\]

Where \( V \) is the on or “1” level and \( \sigma \) is the rms noise. Thus \( V/\sigma \) is referred to as the signal-to-rms noise.

When using equation B.3 the following conditions have to be met [4].

I. \( \sigma_1 = \sigma_0 = \sigma \); the noise level for the “1” and “0” level must be equal

II. For the “0” state the laser is completely switched off.

III. The decision point (threshold level) is equal to \( V/2 \).
In order to adhere to the above requirement, the following assumptions were considered.

I. $\sigma_1 = \sigma_0 = \sigma$; This would represent the worst case scenario of SNR of a signal

II. Although the laser is never completely switched off for the “0” state, for the purpose of increasing the reaction time of the laser, the logic state “0” can be assumed to equal zero because of the miniscule magnitude of the bias voltage of the zero state (in the order of $10^{-6}$ V).

III. Hence, the threshold level can be assumed to equal half the value of the on level.

Figure B.15 shows the BER as a function of the signal to noise ration when $\sigma_1 = \sigma_0$.

Figure B.15: Illustrates the BER as a function of the signal to noise ration when $\sigma_1 = \sigma_0$ and $\mu_0 = 0$. 
The bit error ratio obtained for the Pre-, Post- and Sym-compensation of a 60 km link, using the SNR method, are $10^{-7}$, $10^{-9}$ and $10^{-12}$ respectively. These results are more accurate because they correlate well with the EX ratio measurement on the eye diagram.

**B.5. Reference**


APPENDIX C: AVANEX 2 DCF
APPENDIX D: MATLAB SIMULATION CODE & EXPERIMENTAL RESULTS

D.1. Matlab code for Eye-diagram an PDF plot ---------------------------------------156

D.2. Measurement results ------------------------------------------------------------------ 159
Appendix D

D.1. Matlab code for Eye-diagram an PDF plot

```matlab
clear all
close all
clc

eye = [];
load waveform1.txt

% PLOT THE EYE-DIAGRAM

for n = 1:1:10
    wave = ['waveform',num2str(n),'.txt'];
data = load(wave);
data = data';
eye  = [eye;data];
end

t   = [1:1:length(data)];
time = ((8/6)*10e-10)/length(data);

figure(1)
for r=1:1:n
    plot(t,eye(r,:),'.','MarkerSize',.5)
    hold on
    grid on
end
xlabel('sample'),ylabel('Power (W)');
axis([min(t) max(t) -6e-5 16e-4 ])
```
% DETERMINING THE SAMPLING POINT ON THE EYE-DIAGRAM
% HISTOGRAM PLOT FOR THE "1" AND "0" LOGIC STATE

datahist = [];
wave = ['waveform1.txt'];
waveref = load(wave);
SamplePoint = 1750:1:2250;
DecPoint1 = 7e-4;
DecPoint0 = 2.2e-4;
DecPoint01 = 4e-4;

high = [];
low = [];
g = 1;
v = 1;
for n = 1:1:n
    wave = ['waveform',num2str(n),'.txt'];
data = load(wave);
dataS = data(SamplePoint);
dataS = dataS';
datahist = [datahist dataS];
end

for r=1:1:length(datahist)
    if (datahist(r)>DecPoint1)
        high(g) = datahist(r);
g = g + 1;
    else
        if(datahist(r)<DecPoint0)
            low(v) = datahist(r);
            v = v + 1;
        end
    end
end
% GENERATE PDF FOR THE 'ONES' AND 'ZEROS' FROM THE HISTOGRAM

[Onehist,bins1]  = hist(high,100);
[Zerohist,bins0] = hist(low,100);

figure(2)
histfit(high,bins1), grid on
hold on
histfit(low,bins0), grid on

title('Histogram pdf fit for "1" && "0"')
ylabel('Count/pdf')
xlabel('Power level (W)')

mu1 = mean(high);
mu0 = mean(low);
sig1 = std(high);
sig0 = std(low);

Q    = abs((mu1-mu0)/(sig1+sig0))
BER2 = (1/(Q*sqrt(2*pi)))*exp(-(Q^2)/2))
## D.2. Measurement results

### Zero compensation results

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<th>EyeD65</th>
<th>EyeD70</th>
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<td>49.9</td>
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<td>SNR [s]</td>
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<td>4.55</td>
<td>4.53</td>
<td>4.72</td>
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<tr>
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### Pre-compensation results

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<th>EyeD65dc</th>
<th>EyeD70dc</th>
<th>EyeD80dc</th>
<th>EyeD120</th>
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<td>118</td>
<td>118</td>
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<td>458.63</td>
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<td>406.15</td>
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## Post-compensation results

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<th>EyeD70dc</th>
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## Symmetric compensation results

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<td>Jitter p-p [ps]</td>
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