CHAPTER 1 Introduction

1.1 The growing demand for bandwidth in optical fibre systems

The telecommunication industry never seems to tire in its demand for increased bandwidth. At the start of the present era (the 1970s) of optical fibre telecommunication systems, expanding telephone networks were the main impetus for the increasing bandwidth. Nowadays, electronic services like E-mail, World Wide Web (WWW) and Video Conferencing are pushing up the demand for bandwidth even further so that it now doubles roughly every 1½ years [1].

Driven by this ever increasing requirement for bandwidth, optical fibre development has passed through many stages over the last ~25 years. Figure 1.1 shows the progress of the capacity, through different generations of optical lightwave systems, measured in terms of bit-rate times unregenerated transmission distance, the bit-rate distance product. It should be noted that the growth rate of the bit-rate distance product in Figure 1.1 shows the progress of laboratory systems which outpaces that of installed systems.

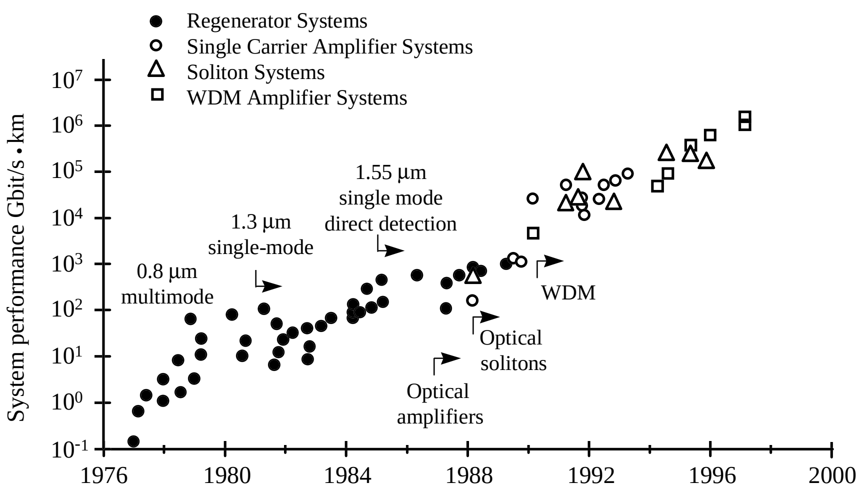

Figure 1.1 Historical evolution of the transmission capacity in lightwave systems [2].

The first generation of lightwave systems in 1978 consisted of multimode graded index fibres operating at 0.85 μm (first transmission window), allowing data rates around 100 Mbit/s with a regenerator spacing in the range of about 10 km determined by the fibre loss of about 3-5 dB/km in this wavelength region. With the availability of semiconductor lasers and detectors in the 1.3 μm wavelength region (second transmission window) where the fibre loss was below 1 dB/km and fibre dispersion is at its minimum, regenerator spacing could be increased considerably. Transmission capacity of up to 5 Gbit/s•km was demonstrated in the early 1980s, which was limited by modal dispersion in multimode fibres. *The second generation* of 1.3 μm optical lightwave systems started with the introduction of single-mode fibres which overcame the problem of modal dispersion and gave transmission capacity of up to 100 Gbit/s•km in the mid 1980s.

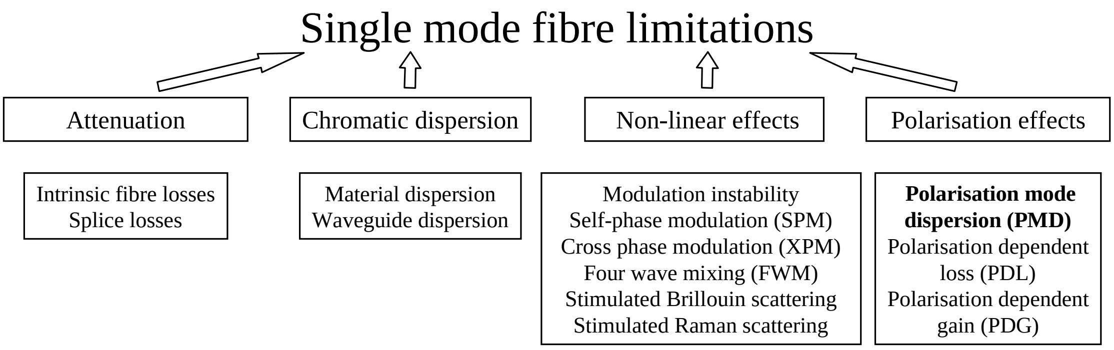

Figure 1.2 Single mode fibre impairments

For single mode fibres, the main limitations on transmission capacity are shown in Figure 1.2, where the attenuation was the prime factor (typically ~0.5 dB/km at 1.3 μm) in limiting the transmission capacity. Improvement in the manufacturing of silica glasses reduced the minimum loss of silica in the 1.55 μm third transmission window to ~0.2 dB/km, but the commercial use of *the third-generation* lightwave systems had to wait until the beginning of the 1990s when single-longitudinal mode lasers which have a narrow linewidth together with dispersion shifted fibres arrived on the market and solved the problem of the large chromatic dispersion at 1.55 μm. These improvements increased the transmission capacity to several hundreds of Gbit/s•km using intensity modulated direct detection (IM-DD) systems. *The fourth generation* of lightwave systems is concerned with the concept of coherent optical communication systems. In the laboratory environment, coherent systems could outperform direct detection systems mainly because of the higher receiver sensitivity and easy compatibility with frequency-division multiplexing. However, although they offered a greater potential they also faced serious obstacles, such as, random polarisation fluctuations leading to signal fading and so far have not been used in a commercial system. In *the fifth generation*

IM-DD using conventional non-return-to-zero (NRZ) pulses combined with wavelength division multiplexing (WDM) increased the bit-rate-time-distance product even further. In parallel with this, non-linear return to zero (RZ) soliton pulse transmission has also been a highly promising development and combined with dispersion management and WDM transmission 10×20 Gbit/s over 1000 km of standard single mode fibre (S-SMF) has been demonstrated [3]. Although the transmission capacity of the later generation systems is quite impressive, the majority of systems employed world wide use the second and third generation NRZ IM-DD over S-SMF, which comprises the vast majority of presently installed fibre (~50×10^6 km).

Perhaps the most significant recent event in optical telecommunications was the introduction of the erbium doped fibre amplifier (EDFA) [4] in 1987. The limitations on the transmission distance due to power loss could then be removed making the optical link virtually transparent. On the other hand, EDFAs force the system to operate in the erbium window ~1.53 to ~1.56 μm and when using S-SMF, transmission at high bit rates will be dispersion limited. However, chromatic dispersion has now essentially been overcome using DSFs together with dispersion management schemes [5], which can also keep the penalties due to non-linear effects within acceptable limits [6]. In transoceanic *optically amplified* systems (TAT12/13, TPC5), the signal is not regenerated as in 3R regenerator (regenerate, reshape and retime) systems, so that the effects shown in Figure 1.2 along repeaters with amplifier noise accumulate over the entire span. Due to the unrepeatered nature of these transoceanic links, the limitations due to polarisation mode dispersion (PMD) now becomes one of the main obstacles in these multi-giga-bit optically amplified transoceanic systems (along with PDG and PDL, Figure 1.2).

PMD limits not just the new generation of links and networks using DS fibre. It also applies as a highly significant limitation in upgrading the transmission bit rate over the vast amount of already installed S-SMFs where the chromatic dispersion at 1.55 μm can now be overcome by one of a range of dispersion compensation schemes demonstrated over the last few years [6]. Using that concept combined with wavelength division multiplexing (WDM), transmission of 8×40 Gbit/s channels over 3×80 km S-SMF has been demonstrated [7] using a pulsed source. However, as indicated in [7], the PMD penalty has been artificially avoided by adjusting the input state of polarisation (SOP). PMD is inherent in the fibre and thus remains one of the principal dispersion mechanisms in optically amplified transmission systems.

1.2 Polarisation effects in optic fibre systems

1.2.1 Differential Group Delay (DGD) and Polarisation Mode Dispersion (PMD)

PMD can limit high bit rate digital systems [8] [9] and leads to non-linear distortions in analogue systems [10]. The origin of PMD lies in the birefringence of optical fibres and components in which signal energy at a given wavelength is resolved into two orthogonal polarisation modes with slightly different propagation velocities, resulting in signal distortion. The resulting difference in group delay between the two polarisation modes is called the differential group delay (DGD), and in short lengths of fibre (e.g. l < 100 m) the DGD is nearly independent of wavelength and increases linearly with fibre length. The DGD in this regime has units of (ps/km). In long lengths of fibre (e.g. l >1 km), the DGD varies randomly with wavelength, and PMD which is commonly expressed as the average value of the DGD over a wide wavelength range must be based on a statistical specification. For fibres that exhibit a large degree of random coupling of energy between the two polarisation modes, PMD scales with the square root of distance and is usually specified in $ps/\sqrt{km}$ [11]. In contrast to chromatic dispersion, PMD cannot be compensated in a passive manner because of its inherently random behaviour with time and temperature.

In Section 6.4, we will relate the measured intrinsic DGDs in different fibres to the expected PMD in cables and highlight the PMD limitations of unspun DSFs. For instance, the TAT12 link specifies a maximum PMD of 0.15 $ps/\sqrt{km}$ [12], which could only be achieved with spun fibre. Spun fibre exhibits low intrinsic PMD due to spinning of the fibre during drawing as will be discussed in Subsection 3.3.5.

1.2.2 Physical origin of PMD

Internal stress combined with elliptic deformation of the core is the dominant source of intrinsic birefringence and PMD in telecommunication fibres. With the recent emergence, on a commercial scale, of the so called *spun* fibre [13], intrinsic PMD could be reduced to very low values. External stresses, however, induced by cabling or residual external twist, can increase the PMD in the fibre. It will be seen throughout this thesis that the role played by fibre twist is a crucial one in determining the PMD behaviour of all the different types of fibre.

1.2.3 Measurement of PMD

There are different PMD measurement instruments on the market which vary in their performance but they all have in common the need to access both ends of the fibre under test [14]. Polarisation optical time domain reflectometry (POTDR), on the other hand, can in principle evaluate the birefringence along the fibre with access to only one end and from that the polarisation dispersion along the fibre may be estimated [15]. The original principle of POTDR was reported in 1980 [16] as an extension of the well known optical time domain reflectometer (OTDR) [17].

1.2.4 Polarisation Mode Dispersion, Polarisation Dependent Loss (PDL) and Polarisation Dependent Gain (PDG) in optical components

The earliest EDFAs and isolators showed very high PMD values [18] (Subsection 6.1.3.4) which were comparable to that of a few hundred kilometre of fibre. However, these values have been reduced by more careful fabrication methods for EDF, and by using a different design of isolator. PDL can occur in directional couplers and isolators and results in power loss [19], whereas PDG occurs in optical amplifiers and causes preferential noise amplification [20]. Both PDL and PDG are mainly problems in long haul systems (> 1000 km) where PDG is the more severe performance penalty [21]. However, polarisation scrambling [22], [23] as employed in TAT12, can almost totally suppress PDG performance limitations.

1.2.5 Polarisation problems in non-telecommunication areas

Although the context of this thesis is mainly confined to fibre transmission systems, we should note that polarisation effects also lie at the heart of a presently steadily growing range of fibre sensor devices. Such as fibre gyroscopes [24] or current sensors [25], where any unwanted disturbance due to polarisation fluctuation in the fibre may disturb the operation of the device.

1.3 Research objectives and structure of the thesis

The aim of this thesis has been to investigate by modelling and measurement the roles that the linear and twist induced circular fibre birefringences play in determining the polarisation dispersion in short lengths of fibre. This complete picture of birefringence could be obtained by measuring and analysing the influence of twist on birefringence and on the polarisation dispersion by the use of a polarimetric OTDR and a PMD measurement equipment. The emphasis of the measurements has been on the intrinsic birefringence and the short length DGD in the fibre itself rather than on the long length PMD, although a relationship between the short length DGD and the long length PMD will be discussed theoretically. The study is half theoretical and half experimental so that we could develop powerful tools for characterising birefringence properties of optical fibres.

In *Chapter 2* the mathematical description of polarisation using the Jones and Mueller calculus is discussed. The Poincaré sphere, the most commonly used tool for visualisation of the SOP, is introduced. The Jones and Mueller vector notation for light travelling in forward-backward direction in a reciprocal media will be defined and Fresnel reflection and Rayleigh scattering in optical fibres is discussed.

In *Chapter 3* the main origins of birefringence effects in standard telecommunication fibres are discussed. The birefringence and DGD due to one of the main internal birefringence effects of core ellipticity will be computed for different fibre parameters of common step index fibres. These results will be important for Chapter 6 when trying to understand the origin of the measured birefringence and DGD, and in Chapter 7 when trying to estimate the DGD from the measured birefringence at a single wavelength. There will also be discussions about the expected birefringence and DGD in fibres with more complicated profiles in the presence of core ellipticity. The maximum allowed PMD in soliton systems using DEDF is considered. PMD in the time domain and in the frequency domain, which is based on the PSP model, is introduced considering polarisation mode coupling length. Commercially available PMD measurement methods are described, where some PMD measurement results on long length of fibres with large difference in their PMD values will be shown. Finally, in this chapter, a short review on first and second order PMD in long lengths of fibre is given with a brief look into PMD compensation techniques.

In *Chapter 4* there is a general discussion about polarimetry and birefringence measurement methods. The optical design and calibration of the real time Stokes polarimeter developed at the University of Essex is treated. Of interest in Chapter 4 is the theoretical error analysis for polarimetry which will be useful in Chapter 7 in trying to determine the expected error in the measured SOP using a polarimetric OTDR. The polarisation matrices of different optical components and two optical fibres, in the forward and forward-backward directions are given, showing that the measured optical elements behave like ideal rotation matrices.

In *Chapter 5*, which is the heart of the thesis, the theoretical model for describing the fibre birefringence and the PSPs (DGD) of the fibre in the presence of twist is derived. This result will be important for the experimental Chapters 6 and 7. It will be shown that the DGD of twisted fibres increases linearly with length, neglecting some small oscillating terms, and that there exists for each fibre an ideal elastic twist which minimises the initial DGD. It is also shown how random mode coupling can be easily introduced in the derived model. A numerical simulation to compute the DGD reduction in recently available commercial spun fibres with sinusoidal spin is introduced, which will be useful in Chapter 6 where such spun fibre is analysed by using twist.

In *Chapter 6*, the detailed experimental results are presented describing the polarisation properties of different types of fibres such as, S-SMF, DSF, spun DSF, DEDF and EDF, with and without twist. The results confirmed the theory developed in Chapter 5 to describe correctly the DGD evolution versus twist. The initial DGD at zero twist of these fibres has been investigated, which allowed the specification of a range of expected DGD values for each type of fibre. The sensitivity of the fibre DGD to external pressure has been investigated for different fibres with and without twist. Spun fibre with sinusoidal spin has been analysed which, in parallel with simulation, helped to develop an empirical equation from which the minimum spin (RMS value) needed can be calculated in order to obtain sufficient DGD reduction. The DGD in forward-backward direction has been investigated.

In *Chapter 7*, the polarimetric OTDR is introduced. This has been used to measure the backscattered SOP evolution along optical fibres. The OTDR and POTDR performance parameters are then defined and given for the used POTDR. The matrix description for the backscattered SOP evolution in twisted fibre is derived by extending the theory developed in Chapter 5. Measurement results on fibres with twist are shown which confirm the developed theory. There is a section about a novel four-channel polarimetric OTDR which enabled the measurement of fibres with larger birefringence due to its higher resolution. At the end of this chapter, the estimated DGD values from the POTDR data are compared with the DGD values measured in Chapter 6 for the corresponding fibres. Moreover, the error in the measured backscattered SOP is analysed and compared with the predicted error from the theoretical analysis of polarimetry in Chapter 4.

Finally in Chapter 8, the work has been summarised and suggestions for future work are made. One of the more interesting points in the future work will be the use of POTDR to measure the polarisation mode coupling length in cabled fibres.

1.4 Main contributions of this thesis

The original contributions of this work are the following:

1) For the first time, a complete analytical solution for the DGD in optical fibres with elastic twist has been obtained. This result is important as small amounts of twist are unavoidable in fibres and cables and it gives a simple equation to calculate the necessary twist rate to obtain a minimum PMD in an optical fibre.

2) The DGD of different types of fibres: S-SMFs, DSFs, spun DSFs, EDFs and DEDFs, have been measured as a function of twist. From the measurements performed, the validity of the theoretical model to correctly describe the DGD evolution versus twist has been confirmed.

3) The initial DGD at zero twist of these fibres has been investigated, which allowed estimation of the expected range of DGD values for each type of fibre. Of particular interest is the initial DGD in the measured DEDFs which has been reported for the first time. It showed DGD values of an order of magnitude higher than for DSFs. This would be a serious problem in ultra-high bit-rate long haul soliton transmission systems if no attempt is made to reduce its value in the next generation of DEDFs.

4) Spun fibre with sinusoidal spin, which has recently become commercially available, has been analysed and modelled by measuring the DGD as a function of externally applied twist. From the measurement results, in parallel with the numerical model to simulate the DGD reduction in such spun fibre with and without external twist, an empirical equation has been obtained. This equation gives the minimum sinusoidal spin (RMS value) needed as a function of the initial fibre birefringence to obtain sufficient DGD reduction.

5) Development of a polarimetric optical time domain reflectometer (POTDR) to measure birefringence characteristics along optical fibres. The POTDR is a modified OTDR with a DFB laser, erbium amplifiers and a $\lambda/4$ plate - polariser combination. The conventional direct detection OTDR was chosen because it is by far the most popular reflectometry instrument used and can be easily adapted for POTDR measurements.

6) Derivation of an analytical solution for analysing the backscattered SOP evolution along an optical fibre in the presence of twist. Experimental POTDR results showing the SOP evolution on the Poincaré sphere as a function of twist have been reported for the first time, verifying the developed theory. From the estimated birefringence using POTDR, the DGD in the fibre has been predicted. The results are essential to the development of a commercial POTDR which would be a useful tool in the quality control of fibre and in the detection of fibre sections having high PMD.