CHAPTER 8

Conclusions and suggestions for future work

8.1 Conclusions

Now that the problems of fibre attenuation and chromatic dispersion have been overcome by the use of EDFAs and DSFs, or dispersion compensating techniques, PMD, originally a problem in long haul systems such as (TAT12/13), has become the dominant linear limitation. PMD limits the upgrading of terrestrial systems to bit-rates of 10 Gbit/s and beyond. As a result of this, Telecom operators across Europe have investigated the PMD of their networks (see Appendix B, Table B.1) and its implications in future upgrades.

The investigation of birefringence and the resulting polarisation dispersion which limits the fibre length and bit-rate in single mode fibres was the main aim of the work described in this thesis. The net birefringence in a single mode fibre is normally caused by a combination of linear and circular birefringence due to the two main intrinsic effects in ordinary telecommunication fibres; core ellipticity and twist. Twist is a crucial and important parameter in determining and analysing the birefringence and DGD in optical fibres. The original contribution of this thesis may be summarised by the following four main points:

(a) Theoretical derivation and experimental verification of the DGD and birefringence in the presence of twist [15], [79], [170].
(b) Measuring the intrinsic DGD of different types of telecommunication fibres [117], [118].
(c) Description and analysis, by simulation, of DGD reduction in spun fibre with sinusoidal spin [172].
(d) Measurement and analysis of birefringence in the presence of twist by the use of POTDR, and the estimation of the DGD from the POTDR results [15], [170], [171], [214], [215].

The points (a) to (d) are summarised from (i) to (iv) with reference to the relevant sections:

(i) The heart of the thesis is in Chapter 5 where matrix and vector descriptions for the PSPs as a function of the intrinsic linear birefringence in the presence of elastic twist is derived. The DGD vector description showed that the DGD of twisted fibres increases linearly with length and there exists an ideal twist at which DGD is minimised. It has also been shown that random mode coupling can be easily introduced into the model.

The DGD of different types of fibres such as S-SMF, DSF, spun DSF, DEDF and EDF has been measured as a function of twist. From the measurements performed, the validity of the theoretical model was confirmed by correctly describing the DGD evolution versus twist. The model is also applicable to cabled fibres in general where a small amount of twist is often unavoidable.

(ii) The initial DGD at zero twist of these fibres has been investigated and the results for the fibres are listed in Table 6.1. The lowest DGD value has been measured for spun DSF where the initial DGD is reduced by spinning the fibre during drawing. The DEDFs and EDFs showed the highest DGD values caused by large core ellipticity, whereas for the EDF, the fibre profile is also severely degenerated due to the wet phase doping of the fibre (Appendix C). However, for one of the DEDFs, the core ellipticity seemed to be small and the large DGD could not be explained due to shape birefringence. Further investigation is therefore required. It has been shown in Subsection 6.1.3.4 that the measured DGD (PMD) values for the DEDFs is an order of magnitude higher than the maximum allowed for ultra-high bit-rate long haul soliton transmission, and therefore it is an important issue to significantly reduce the intrinsic origins of DGD, such as core ellipticity for example, in the next generation of DEDFs.

The DGD due to core ellipticity and the resultant thermal stress birefringence, which are the two main effects for internal birefringence in ordinary telecommunication fibres, has been extensively treated in Section 3.3, showing that DSF is more sensitive to core ellipticity than S-SMF due to the higher index difference and smaller core diameter. This agrees with the measured results which show that DSF, in general, has higher initial DGD values than S-SMF (see Table 6.1).

The reduction of the fibre DGD sensitivity to external pressure by twisting the fibre has been investigated (Subsection 6.1.5), as external stress can be induced during cabling and may lead to an increase in PMD in some fibres, as for example, in cabled spun fibres. It has been found theoretically and experimentally that for sensible twist rates (< 8 turns/m), sensitivity to external pressure remains unaffected and, hence, using a modified cable design to reduce stress onto cabled fibre seems to be a more appealing solution for cable manufacturers.

From the measured short length DGD values, the cabled fibre PMD, as under field conditions, has been estimated (for some of the fibres) by using typical polarisation mode coupling lengths (100 m < L_C < 500 m). By knowing the PMD, the bandwidth limitation due to this can be estimated as shown in Section 6.5.

(iii) 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 (Section 6.3). 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 effective sinusoidal spin needed (RMS value) as a function of the initial fibre birefringence to obtain sufficient DGD reduction. It has been shown by measurement and simulation that if the spin is not high enough to reduce sufficiently, the initial DGD peaks of up to half the height of the initial DGD can occur, which could result in a higher PMD in an overall link. For this reason, the empirical equation obtained will be very useful for fibre manufacturers to estimate the necessary spin parameters.

(iv) A conventional OTDR has been modified to a single-channel polarimetric OTDR by using erbium amplifiers to increase the DR, and a $\lambda/4$ plate-polariser combination to analyse the backscattered SOP, and from that to obtain the birefringence characteristics (DGD) along the fibre under test (Chapter 7). The theory for the fibre matrix in the forward direction in the presence of twist, (i), has been extended to include the forward-backward direction with reflection (ideal scattering) in order to analyse the POTDR data in the presence of twist. The theory developed for the backscattered SOP evolution along an optical fibre has been verified by twisting a fibre, and it is shown that if twist is ignored when it is present, it can lead to a large error in the estimated birefringence and DGD of the fibre. It is also shown that the backscattered SOP evolution can be analysed to obtain the linear birefringence and twist along the fibre by two parameters; the periodicity of the SOP evolution and the shape of the SOP evolution as plotted on the Poincaré sphere (Section 7.2).

The simulation results on different fibres using the single-channel POTDR has been confirmed by using a novel four-channel polarimetric OTDR with higher spatial resolution compared to the single-channel POTDR. The simulation model has therefore made a valuable contribution to the parallel PhD project, on the four-channel POTDR, being carried out by the research student, J. G. Ellison.

The offset between the fibre DGD measured using JME and the DPD value calculated from the fibre birefringence measured with the POTDR is given in Table 7.1. The relative difference between these on both the measured S-SMFs and DSFs is around 50%, which is about the value expected from the simulation results in Section 3.3 considering DGD and DPD due to core ellipticity. The result is promising because if the offset is known, the DGD can be calculated from the measured birefringence obtained from POTDR. However, accuracy limits in the measurement results make it difficult to give an exact offset value for future conversion from DPD to DGD. Further work is needed to minimise the error in both the DGD and DPD measurements in order to obtain a more accurate offset value.

An error analysis for polarimetry has been carried out considering noise and errors in the analysing optics (Section 4.4). This error analysis could be adapted to POTDR where the errors in the measured backscattered SOP have been categorised into periodicity error and error in the shape of the SOP evolution on the Poincaré sphere (Subsection 7.5.2). By considering the SNR, the error analysis adequately predicted the expected average error in the measured SOP for both polarimetric OTDRs. Finally, the desired two-point resolution for POTDR as a function of the fibre birefringence is given.

8.2 Suggestions for future work

The only solution for the reduction of PMD is by altering the fibre or cable design, requiring measurement and analysis of the new designs. For proper PMD compensation in deployed systems, the variation of the DGD with wavelength and time has to be understood, requiring again measurements and analysis. The focus of future work should include non-uniform birefringence and random mode coupling in the fibre on the theoretical side, and measurements using POTDR on installed systems on the experimental side. The suggestion for the future in this sense may be summarised as:

(a) Extending the derived fibre models to include non-uniform birefringence and random mode coupling.

(b) The measurement of the polarisation mode coupling length L_C using POTDR in installed fibres.

8.2.1 Random mode coupling in elastically twisted fibres and spun fibres

The models derived for fibres possessing uniform linear birefringence, elastic twist and sinusoidal spin parameters have been verified by experimental work. Random mode coupling and the computation of the resultant DGD has been introduced in Subsection 5.2.3. Future work on the modelling side needs to investigate the following points in the presence of <u>non-uniform birefringence</u> and <u>random mode coupling</u>:

(i) The effect on the DGD when it is minimised through ideal elastic twist.

(ii) The effect of spun fibre with sinusoidal spin on the PMD. Moreover to compare the effectiveness in PMD reduction for spun fibre with either uniform spin or sinusoidal spin.

(iii) More simulation is needed to investigate the unwanted large fluctuation observed in the DGD of spun fibre with sinusoidal spin at small twist rates, as observed in Figure 6.15.

(iv) To investigate second order PMD, the variation of the DGD characteristics with wavelength.

More work needs to be carried out in determining the origin of the intrinsic birefringence in some fibres such as DEDF 1 (see Subsection 6.1.3.4) where the shape birefringence does not seem to be the dominant effect. Another point of interest would be to measure the DGD in EDF and DEDF with pump power. In Reference [184], it was shown that the DGD in EDF increases with pump power and this needs further investigation.

8.2.2 Automation of POTDR data analysis and the measurement of random mode coupling using POTDR

8.2.2.1 Automation of POTDR data analysis

It has been shown that the derived matrix and vector equation (Equation 7.7 and 7.12) can be used to analyse POTDR data in the presence of twist, and to obtain the local linear and circular fibre birefringence by using a best fit. For a customised POTDR, it would be useful to have an algorithm which analyses the POTDR data automatically. The following methods are suggested:

(i) The use of a genetic algorithm where the start parameters (seeds) are the linear birefringence, the fibre twist, the input SOP and the overall rotation of the backscattered SOP. The output SOP for each generation (after mutation and crossover) can then be compared with the measurement results.

(ii) From theory, five backscattered SOPs are adequate to describe the backscattered SOP evolution for uniform twisted fibre. This, in turn, could help to find the unknown parameters for linear and circular birefringence. However, in practice experimental errors in the measured SOP, e.g. due to noise, usually lead to a need to use more than five points. For this reason, there is room for improvement in this direction.

(iii) The most elegant and promising method is based directly on Equation 7.9 and 7.10 which determines the periodicity, L, and shape of the backscattered SOP evolution by an angle α of the resultant rotation vector in the forward or backward direction. The periodicity L may be easily obtained by using an FFT for example, whereas in order to determine the angle α, the shape of the backscattered SOP evolution on the Poincaré sphere has to be analysed. The task is to find the relevant parameters from the three dimensional eight shaped SOP plot on the Poincaré sphere which quantify it uniquely and can be linked directly to the required angle α. Figure B.8 and B.9 in Appendix B show the backscattered SOP on the sphere for increasing twist by simulation and experiment. From these plots, it can be seen that the SOP evolution from zero twist progresses in such a way that the area enclosed in the trace on the sphere at first increases, if the ratio $\gamma/\delta\beta_L$ gets larger and at some point decreases continuously. The circle is opening on the sphere for increasing $\gamma/\delta\beta_L$, and as is indicated in Figure B.9, there seems to be some relation between the size of the SOP trace on the sphere and the angle α.

8.2.2.2 Measurement of the polarisation mode coupling length L_C by using POTDR

The short length DGD may be estimated from the POTDR data as has been shown in Section 7.5.1 for different fibres. It may be possible to measure the polarisation mode coupling length L_C, the missing link needed to estimate PMD from DGD values in cabled fibres (Equation 3.35) from POTDR. The following three methods are proposed to measure L_C:

(i) Modelling of the whole fibre, with linear birefringence and twist distribution along the fibre, from the data obtained with the POTDR. This approach may be time consuming as it requires the total scanning of a fibre with a POTDR and accurate resolution of sections with large PMD values.

(ii) A simpler method is the analysis of the power spectrum of the POTDR data (by using an FFT) which should show a broadening and the appearance of more frequencies in the frequency spectra for increasing fibre perturbations. However, the resolution of the frequency spectra is limited by the sampled fibre length resulting in a broadening and leakage of frequencies (see Figure 7.15).

(iii) A very promising approach, on which some initial work has been carried out, uses the DOP information by integrating the backscattered SOPs along the fibre. The idea arose while analysing the lower DOP values observed in the backscattered SOP using POTDR.

Investigation of the DOP of backscattered light by using a conventional polarimeter

The minimum-maximum DOP has been measured as a function of backscatter length by using a laser (DFB) in cw mode and by adjusting the input SOP. The backscattered light has been measured using a 3 dB coupler and a polarimeter. For short lengths of free-hanging fibres, Figure 8.1, (~100 metre) a maximum-minimum DOP from ~70% to almost 0% has been obtained by adjusting the input SOP, whereas for long lengths (> 9 km) of fibre wound on a bobbin (0.5 m < L_C < 10 m, Section 6.4), the DOP of the backscattered light was seen to be independent of the input SOP showing a value of ~33%.

This first case using a short length of fibre (l ~ 100 m) may be compared to Figure 7.27 where the DOP has been computed by integrating the backscattered SOPs, using the POTDR with short pulsewidths, along the fibre under test, for two different input SOPs. It is interesting to note that the maximum DOP, in Figure 8.1, is about the same as the average DOP observed for the backscattered SOPs measured with the POTDR, which may be another indication that the scattering itself depolarises the light. In the second case, using long lengths of fibre (l > 9 km), this observation is in agreement with the results given in Reference [43] where it is shown theoretically and experimentally that for backscatter lengths >> L_C, the backscattered light is expected to have a DOP of 33%.

Measurements, at different fibre lengths, of the minimum-maximum DOP can be described as a function of backscatter length

Measuring the DOP of the backscattered light as a function of lengths > 100 m and < 9 km as shown in Figure 8.1, showed that there is an underlying function describing the minimum and maximum DOP, and the function is symmetrical around the 33% DOP value. This function is believed to contain information about L_C, and for the DOP versus length. It may have some similarities to the function which describes the PMD as a function of length, Equation 3.35, where the parameters are the DGD and the polarisation mode coupling length L_C.

Implementation for POTDR to measure L_C

If the above is true, the measurement could be performed by using a polarimetric OTDR in two ways; either by integrating the backscattered SOPs along the fibre under test as done in Figure 7.27, or by using different pulsewidths and to let the receiver integrate the backscattered SOPs. For both methods, it will be important to use many input SOPs until the backscattered DOP envelope becomes visible (Figure 8.1). Moreover, the launched pulse has to be fully polarised and depolarisation in the forward direction has to be taken into account if measuring long fibre lengths. For very long fibre lengths (in excess of 20 km), a DFB laser may be preferable to minimise the depolarisation in the forward direction. The depolarisation, as observed with POTDR (DOP ~ 80%), whose exact origin has still to be investigated, would in theory only incur an offset in the above proposed measurement method.

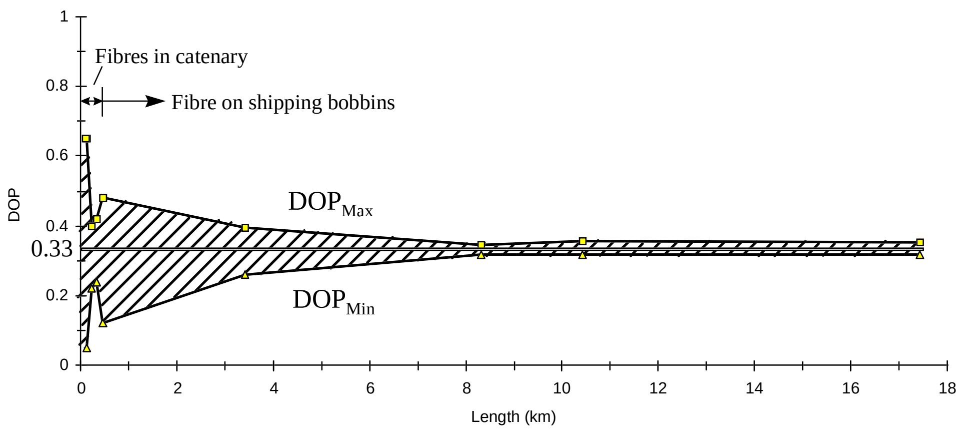

Figure 8.1 DOP from integrated backscattered SOP measurement as a function of backscatter length.

8.2.3 A combined OTDR-POTDR as one instrument

Figure 8.2 shows a possible OTDR-POTDR combination in one instrument, which may minimise the cost and increase the customer demand, compared to just manufacturing an individual POTDR instrument. The POTDR extends the usual OTDR set-up by adding a polarisation controller at the output path, which is computer controlled, and in the return path, an option to switch in a $\lambda/4$ plate-analyser combination for polarimetry. The specification could be as follows: a minimum of 20 dB of dynamic range at 10 ns pulsewidth and a receiver bandwidth of at least 100 MHz. Larger pulsewidths should also be available in order to measure the polarisation mode coupling length as proposed above.

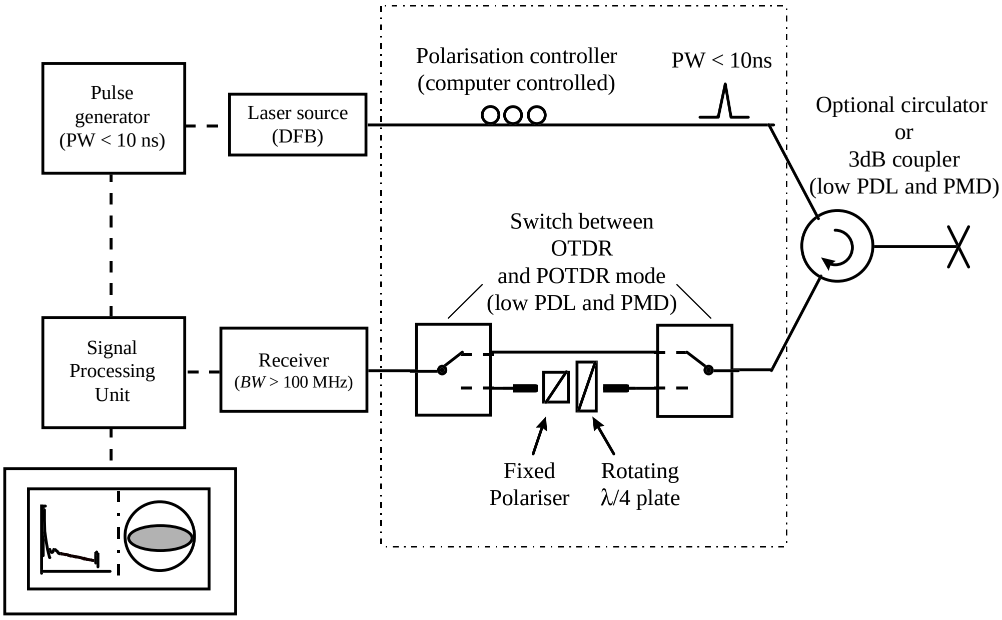

Figure 8.2 Schematic of an OTDR-POTDR combination

For a commercial POTDR, more work needs to be carried out in finding a more accurate conversion factor to calculate the DGD from the measured POTDR data. This could be investigated as shown in Table 7.1 by comparing the POTDR results (giving DPD) with JME results (giving DGD) on different fibres. A tunable OTDR as demonstrated in [218] covering the wavelength range 1.1 - 1.6 μm would be preferable of course but aside from the large pulsewidths used (~500 ns), this is most probably too expensive for practical application.

Recently the use of solitons in OTDR has been proposed [219] in order to improve spatial resolution and dynamic range. One interesting application of a soliton POTDR would be to study soliton propagation and its natural resistance to PMD. At present we can foresee three significant applications for POTDR:

(a) The first is in the area of fibre manufacture where the effect of fine tuning the fiber fabrication process on the DGD of the resulting fibers could be determined by probing sample lengths of fibre using POTDR.

(b) The identification and location of large PMD sections in cabled fibers. If an installed fibre link showed high PMD values from an end to end measurement, POTDR could be used to locate sections with abnormally high PMD values, which could then be replaced by for example cabled spun fibre with low PMD.

(c) The measurement of the polarisation mode coupling length as proposed above. If the polarisation mode coupling length and the short length DGD is known the PMD along the fibre may be calculated using Equation 3.35. This would not only allow PMD to be estimated in cabled fibres but could also be helpful in altering the cable design, in order to achieve ideal polarisation mode coupling lengths so that the cabled fibre exhibits low PMD.