

**Polarisation Mode
Dispersion Compensation

Techniques and
Measurement Requirements**

David J Ives

May 2003

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1. EXECUTIVE SUMMARY

1.1 Introduction

The installation of vast amounts of fibre capacity, during the 90s boom years, without proper control of the polarisation mode dispersion has left a legacy of dark fibre some of which has large PMD. In order to use this fibre for new high speed digital links the PMD must be assessed and may require compensation to remove its signal degrading effects.

1.2 PMD Compensation

PMD compensation systems have been in the design stage for many years with the major optical fibre system suppliers all able to demonstrate working prototypes however a commercially available product is not available. These compensation systems have a PMD compensation element that is controlled by a complex algorithm from an error signal. Thus there are three elements; the derivation of the error signal from the optical data stream, the control algorithm and the PMD compensation element.

In order to give any significant system improvement the compensation will need sufficient complexity to compensate 1st, 2nd and higher order PMD. However the compensated bandwidth seems to be linked to the uncompensated PMD that will limit the ultimate capacity of even compensated links.

1.3 Measurement Requirements

System designers would like PMD compensation penalties or gains but these depend on the system design, modulation format, etc... In terms of specific optical parameters the PMD compensation ability (ie the compensated PMD), the optical compensated bandwidth and the tracking speed are most significant.

1.4 Measurement Methods

Of the currently available PMD measurement techniques none are ideal due to the narrow band nature of the compensated system and the dynamic aspect of the compensation. It is likely that the PMD compensation will need to be frozen for the duration of any measurements. This leads to the polarimeter based measurement techniques as the most favoured due to their ability to measure higher order PMD. The assessment of PMD compensation ability and optical compensated bandwidth rely heavily on accurate PMD emulation in the absence of high PMD real fibre. Tracking speed might be assessed using the wavelength dependence of a PMD emulator and tracking the operating wavelength to vary the PMD.

1.5 Acknowledgements

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2. POLARISATION MODE DISPERSION

2.1 Overview

The solution of the electromagnetic wave equation for single-spatial-mode optical fibre produces two orthogonal polarised modes. In ideal circularly symmetric optical fibre these modes are degenerate with identical propagation constants. In real fibres asymmetries in the core geometry and internal stress removes the degeneracy leading to different propagation constants for the two modes. The fibre layout and external stresses also destroy the degeneracy in ideal circularly symmetric optical fibres. In general the fibre becomes birefringent with different refractive indices for the two polarisation modes.

The asymmetries of the core and any internal and external stress are not generally constant along the length of the fibre. They vary in strength and direction such that the birefringence varies randomly along the length of the fibre. This leads to the splitting of the two polarisation modes into a multiple of modes and is considered a high polarisation mode coupled regime. In such a regime a short depolarised optical input pulse, in the absence of chromatic dispersion, will lead to an optical output that is a Gaussian pulse with an RMS width equal to the polarisation mode dispersion (PMD).

The transmission of a polychromatic source through a high polarisation mode coupled fibre leads to a range of output states and in general a depolarising of the light. Over a limited source bandwidth there exist two orthogonal input polarisation states which lead to two orthogonal output states which are independent of the source frequency (to first order). These are known as the principle states of polarisation (PSP)^[1]. To first order there is a phase difference between the states that is proportional to the source frequency (i.e. a time delay between the states independent of frequency) and this leads to a differential group delay (DGD).

2.2 Mathematical Basis (Stokes Vector)

The Stokes vector description of polarised light is an intensity-based description. The polarisation state of fully polarised light can be described by the three element Stokes vector:

$$\mathbf{s} = \begin{pmatrix} s_1 \\ s_2 \\ s_3 \end{pmatrix} \quad (1)$$

where the vector is normalised such that $|\mathbf{s}|^2 = s_1^2 + s_2^2 + s_3^2 = 1$. The polarised Stokes vector, $\mathbf{s}$, lies on the surface of the Poincaré sphere.

$$s_1 = \frac{I_V - I_H}{I_V + I_H}, \quad s_2 = \frac{I_{+45} - I_{-45}}{I_{+45} + I_{-45}} \quad \& \quad s_3 = \frac{I_R - I_L}{I_R + I_L}. \quad (2)$$

Where I_V is the intensity measured through a vertical linear polariser, I_H through a horizontal linear polariser, I_{+45} through a polariser at 45° , I_{-45} through a linear polariser at -45° , I_R through a right hand circular polariser and I_L through a left handed circular polariser.

The transmission of a fibre system that does not include polarisation dependent losses is described by:

$$s_O = R(\omega) s_I \quad (3)$$

where s_I is the Stokes vector describing the input polarisation state, s_O describes the output polarisation state and $R(\omega)$ is a three by three rotation matrix that describes the transfer function of the system as a function of the optical frequency, ω .

The evolution of the output state of polarisation as a function of optical frequency is described by:

$$\frac{\partial s_O}{\partial \omega} = \frac{\partial R(\omega)}{\partial \omega} s_I = \frac{\partial R(\omega)}{\partial \omega} R(\omega)^{-1} s_O = \Omega \times s_O. \quad (4)$$

where the input state s_I is fixed. The vector Ω is a function of length and optical frequency and has a magnitude equal to the differential group delay (DGD= $\delta\tau$) and a direction along the principle state of polarisation (PSP).

The polarisation mode dispersion (PMD= $\Delta\tau$) is the root mean square DGD with the average taken over either wavelength or an ensemble of similar fibres.

$$\Delta\tau = \sqrt{\frac{\sum_{i=1}^N \delta\tau_i^2}{N}} \quad (5)$$

It is possible to expand $\Omega(\omega)$ around ω_0 to get the polarisation effects over larger frequency bandwidths^[2].

$$\Omega(\omega) = \Omega(\omega_0) + (\omega - \omega_0) \cdot \left. \frac{\partial \Omega(\omega)}{\partial \omega} \right|_{\omega_0} + \dots = \Omega(\omega_0) + (\omega - \omega_0) \Omega_{\omega}(\omega_0) + \dots \quad (6)$$

where Ω_{ω} is referred to as the second order PMD vector. For highly mode coupled fibres the RMS first and second order PMD magnitudes are related through:

$$|\Omega_{\omega}^2| = \frac{|\Omega^4|}{3}. \quad (7)$$

2.3 Mathematical Basis (Jones Calculus)

The Jones vector^[3] description of polarised light is an electric field based description. The electric field of the light is described by a two element vector which describes the magnitude and phase of the electric field in the two orthogonal polarisation states.

$$E = \begin{bmatrix} a \\ b \end{bmatrix}_{XY} = a|X\rangle + b|Y\rangle \quad (8)$$

where $|X\rangle$ and $|Y\rangle$ are unit vectors along the X and Y axis. The vector is normalised such that $|a|^2 + |b|^2 = 1$.

A two by two transfer matrix M can describe the propagation of polarised light through a system. The output state E_O is related to the input state E_I through

$$E_O = M E_I \quad (9)$$

For a loss less medium $M=U$ and

$$U(\omega) = \begin{bmatrix} u_1(\omega) & u_2(\omega) \\ -u_2^*(\omega) & u_1^*(\omega) \end{bmatrix} \quad (10)$$

where $|u_1(\omega)|^2 + |u_2(\omega)|^2 = 1$.

The differential group delay between the two principle states of polarisation is given by $\delta\tau$,

$$\delta\tau = 2\sqrt{|u_1'|^2 + |u_2'|^2} \quad (11)$$

where ' represents the differential with respect to optical frequency, ω .

2.4 Impact of PMD on Transmission Systems

The effect of polarisation mode dispersion on a transmission system is to cause eye closure which reduces the signal to noise ratio and increases the likelihood of transmission errors. The effect of first order DGD alone is to split the signal into two, delaying one part with respect to the other. The effect is minimised when the input polarisation state is aligned with a principle state of polarisation and maximised when the two principle states of polarisation are equally excited.

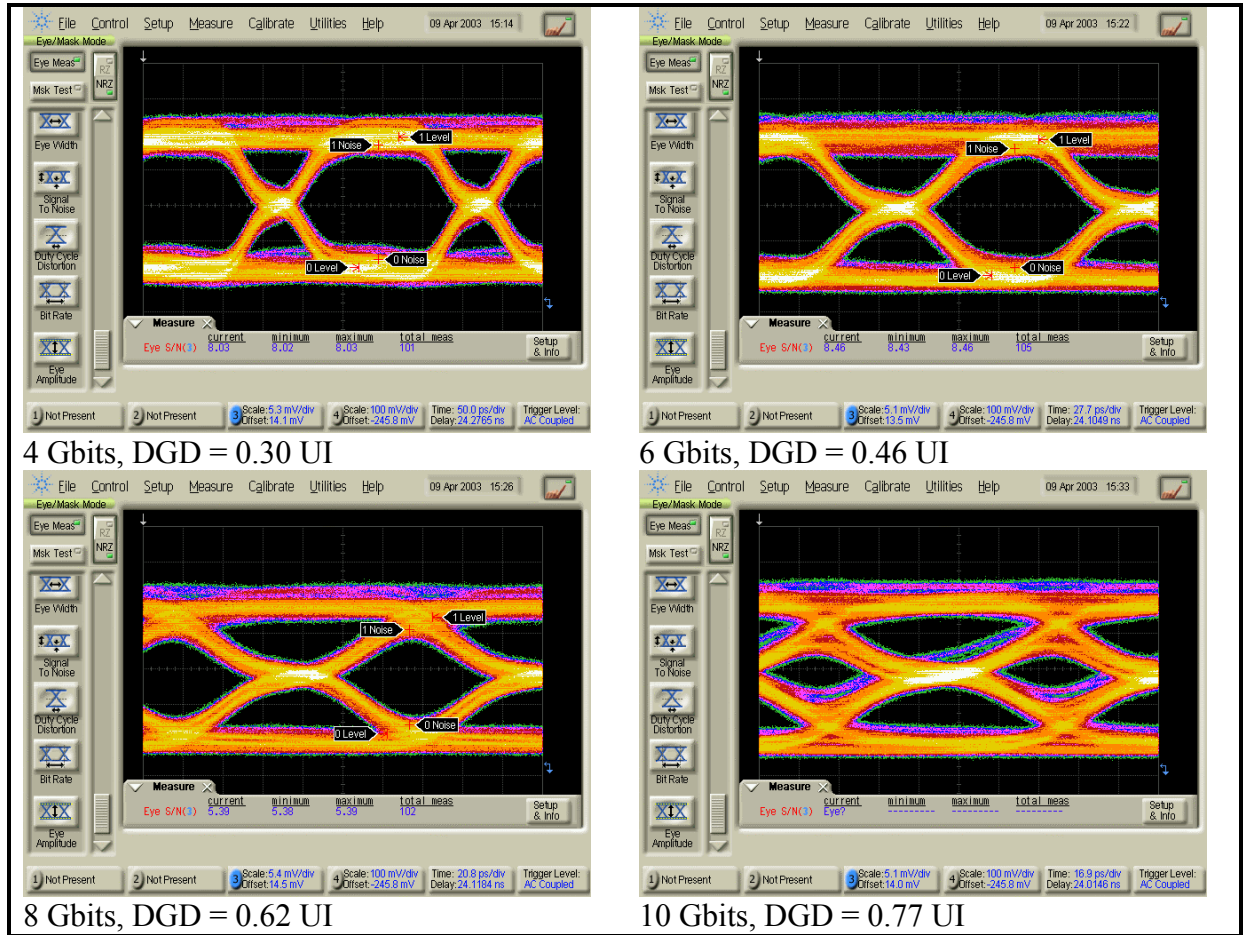


Figure 1 Measured effect of 77ps of DGD on various data rates.

The effect of first order DGD on a simple NRZ transmission system was measured. A pseudo random pattern generator was used to amplitude modulate, using a LiNbO₃ modulator, a CW laser. The polarisation state was aligned so as to equally excite the two PSP of a length of HiBi fibre with a DGD of 77 ps. The resulting eye diagrams are shown in Figure 1. A simulation was calculated based on; a pseudo random bit pattern, a first order DGD transfer function, and ideal intensity detection followed by a low pass 5th order Bessel filter with a 3 dB frequency set at 0.75 of the bit rate. The eye patterns are shown in Figure 2.

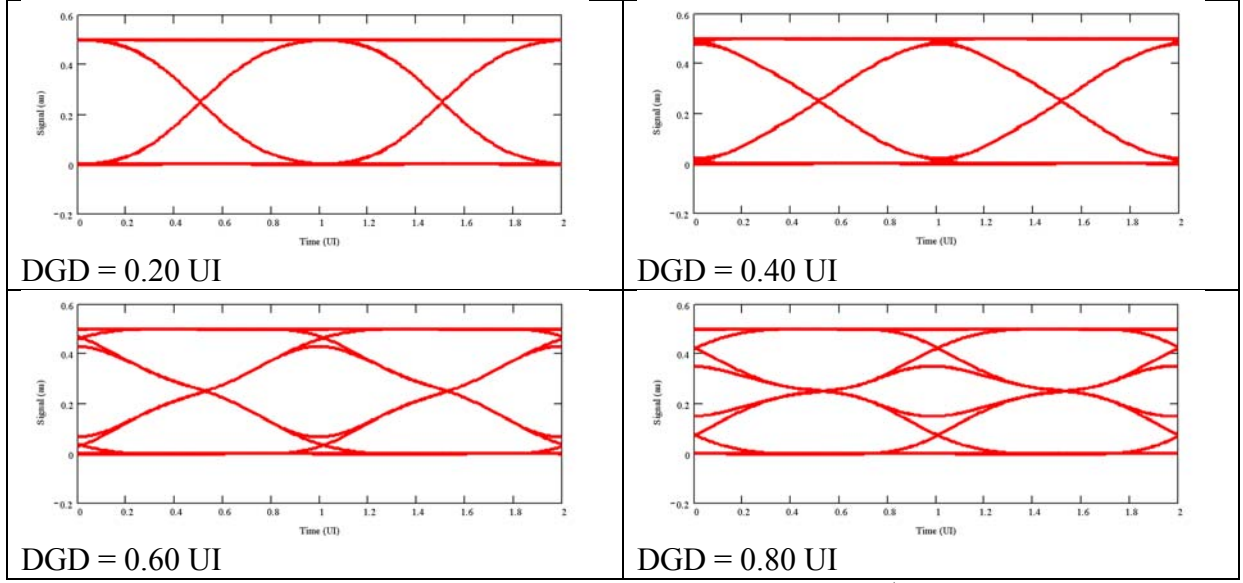


Figure 2 Eye diagrams for simulated bit pattern and various 1st order DGD.

The parameter of interest to system designers is the power penalty of any signal degrading effect. This turns any signal degradation into an effective requirement to increase the signal to noise. From the eye diagrams the signal quality, Q , can be calculated as

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad (12)$$

where μ_1 is the mean one level, μ_0 the mean zero level, σ_1 is the standard deviation of the one level and σ_0 the standard deviation of the zero level all taken at the decision point. The Q can be related to the expected bit error rate based on an assumed Gaussian statistical probability of the noise such that the BER is approximated by

$$\text{BER} \approx \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right). \quad (13)$$

For a BER of 10^{-9} a Q of 6 is required. The question is what is the power penalty due to the first order DGD degradation. Considering the noise free simulations we calculate the basic s/n that is required to maintain the Q at 6. Assuming the noise add in quadrature this gives

$$Q_{\text{Resulting}} = \frac{1}{\sqrt{\frac{1}{Q^2} + \frac{1}{\left(\frac{s}{n}\right)^2}}} \quad (14)$$

Thus the signal to noise that can be accepted for a BER of 10^{-9} is given by

$$\left(\frac{s}{n}\right)^2 = \frac{36Q^2}{Q^2 - 36} \quad (15)$$

and the power penalty is

$$20 \log\left(\frac{s}{n}_{b-b}\right) - 20 \log\left(\frac{s}{n}\right) = 10 \log\left(\frac{Q_{b-b}^2}{Q_{b-b}^2 - 36}\right) - 10 \log\left(\frac{Q^2}{Q^2 - 36}\right) \quad (16)$$

where Q_{b-b} is the back to back Q without the degrading effect under consideration.

Using this method to analyse the measured data of Figure 1 and the simulated data of Figure 2 the power penalties shown in Figure 3 were obtained. These are worst case penalties since the PSP were equally excited.

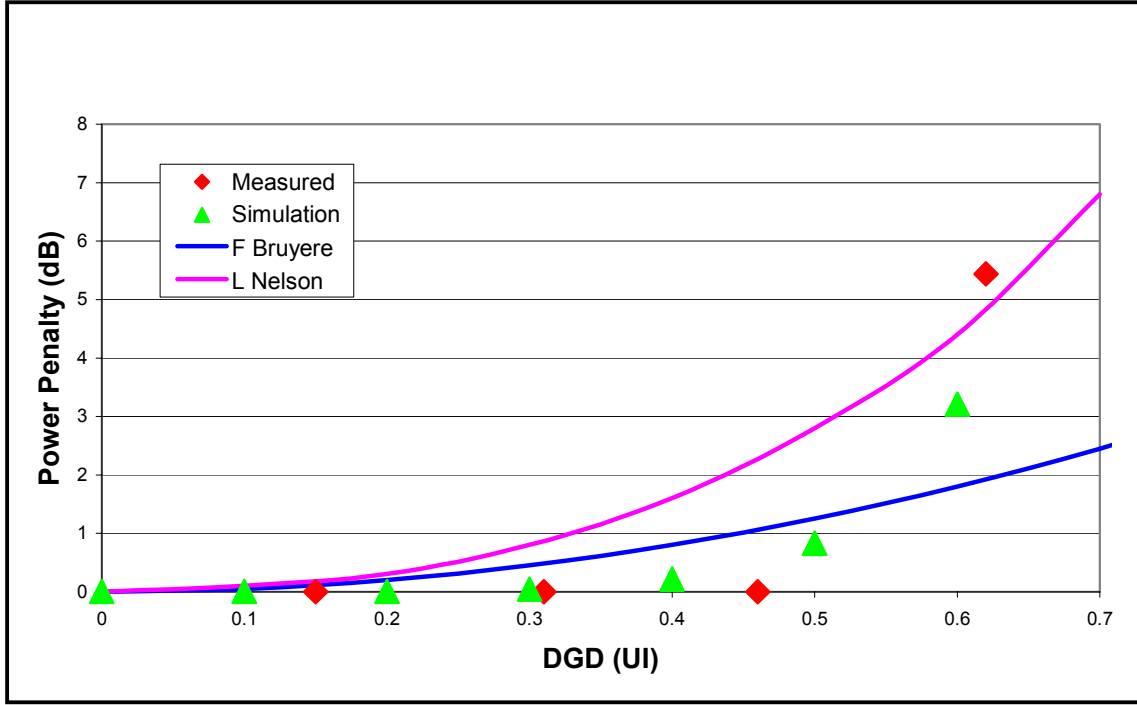


Figure 3 Power penalties for first order DGD, measured, simulated and published F Bruyère^[4], L Nelson^[5].

While the power penalties depend on the exact system arrangement; modulation format, bandwidth, filtering there appears to be a significant degradation for first order DGD greater than 0.5 UI.

The effect of chromatic dispersion is to reshape and broaden the optical pulses. The normalised chromatic dispersion is given by

$$C_0 = \frac{1}{2} \left(\frac{\beta_2 z}{T_{\text{bit}}^2} \right) \quad (17)$$

Figure 4 shows the measured and simulated effect of chromatic dispersion where $C_0 = 0.06$.

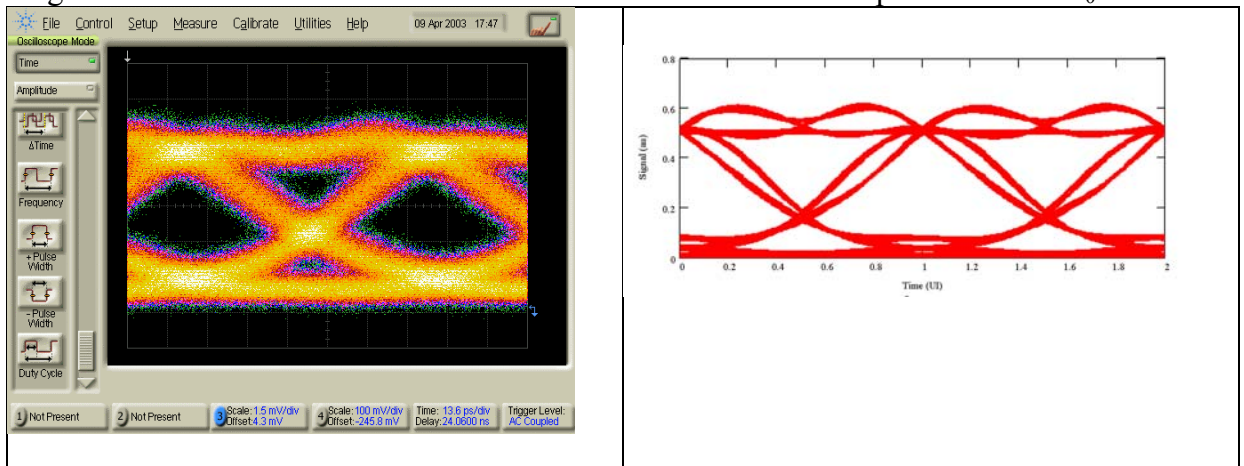


Figure 4 Measured and simulated eye diagrams for chromatic dispersion $C_0 = 0.06$.

The simulation was used to calculate the power penalty due to chromatic dispersion and is shown in Figure 5 along with the published results of F Bruyère^[1].

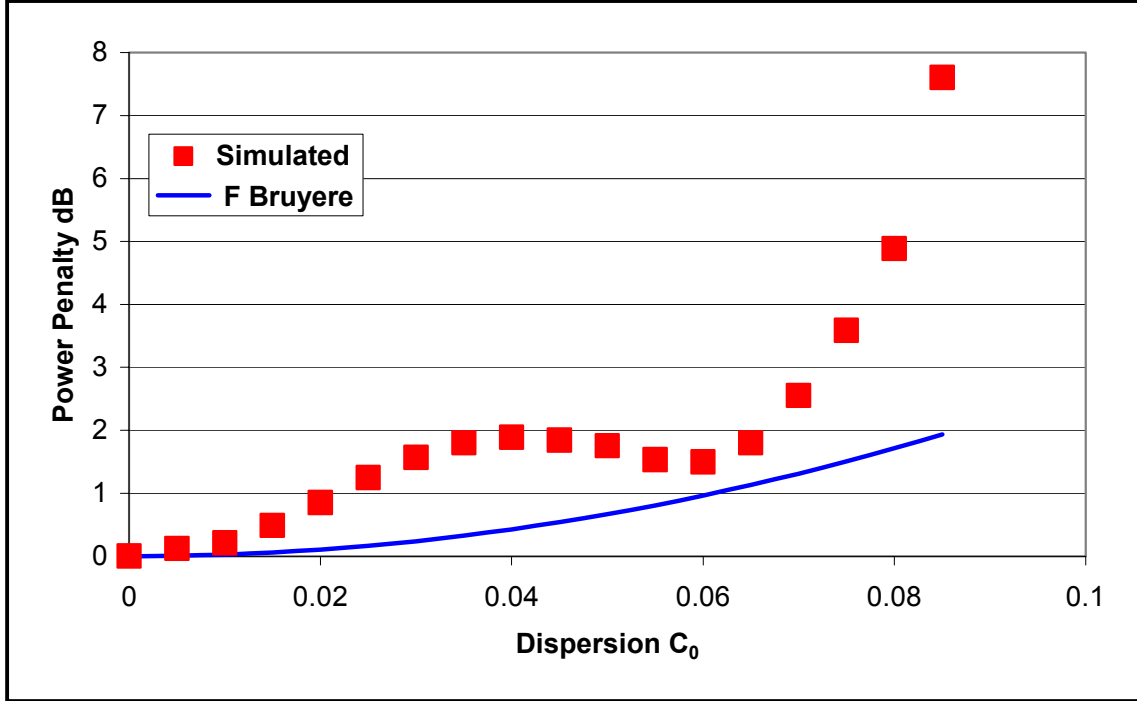


Figure 5 Power penalty due to chromatic dispersion.

Again there is a discrepancy between the exact power penalties however a normalised chromatic dispersion of around 0.05 appears to be significant.

For any optical system containing real fibre there will be significant polarisation mode coupling that will lead to second-order PMD. The second-order PMD consists of two parts, the change of DGD with optical frequency and the change in direction of the PSP with optical frequency. The second-order PMD, Ω_ω is given by

$$\Omega_\omega = \frac{\partial \Omega}{\partial \omega} = \frac{\partial \delta \tau}{\partial \omega} PSP + \delta \tau \frac{\partial PSP}{\partial \omega} \quad (18)$$

where the magnitude of the second term is on average approximately three times that of the first.

Figure 6 shows the measured and simulated eye for an 8 Gbit signal passed through a Lyot depolariser with birefringent lengths ~ 58 ps and 116 ps joined at 45° . The input polarisation state was aligned with a principle axis giving a maximum DOP. A Lyot depolariser exhibits a constant DGD but a varying PSP leading to second-order PMD.

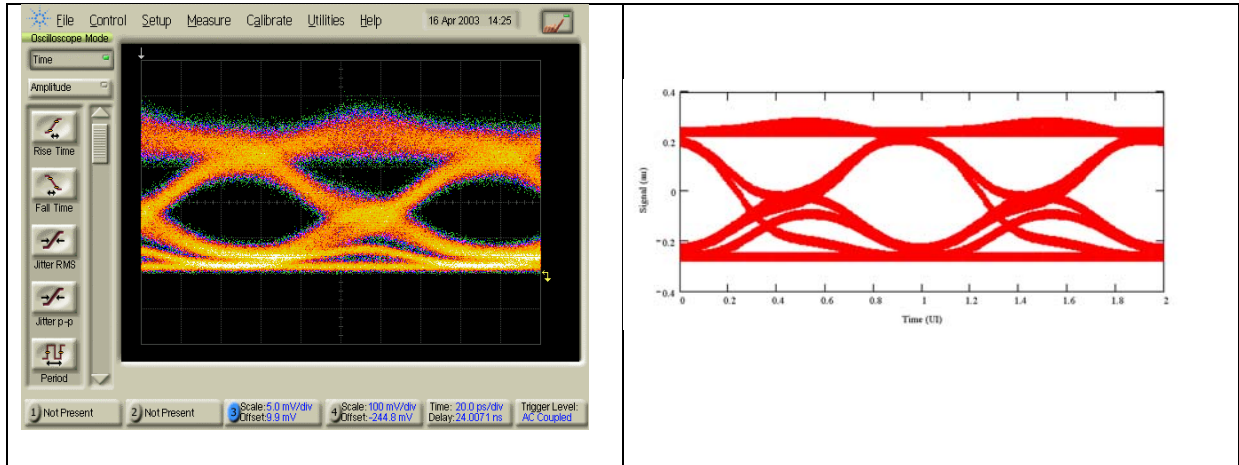


Figure 6 Measured and simulated eye diagrams for Lyot depolariser.

Similar to chromatic dispersion a normalised second-order PMD of 0.05 is likely to be significant.

2.5 PMD of Installed Links

The PMD of installed systems can vary considerably depending on the quality of the fibre, cable design etc... Reported values vary from $0.1 \text{ ps.km}^{-1/2}$ to $10 \text{ ps.km}^{-1/2}$. There is also the question of how fast the PMD vector evolves, as this will determine the speed of any tracking that may be required. A number of studies show differing results depending on the cable route. For buried cables the evolution is slow with periodic variations over timescale of 24 hours, while suspended cables show fast variations due to wind.

3. PMD COMPENSATION TECHNIQUES

3.1 Overview

PMD compensation falls into two basic types: electrical PMD compensation and Optical PMD compensation.

The electrical PMD compensation relies on fast signal processing to remove the effect of PMD. Since the detected electrical signal is the square of the optical field this can only be partially successful.

In this report optical PMD compensation is considered. Here an adaptive optical system is used to compensate the PMD in the optical path. Such a compensation system is independent of the optical data format.

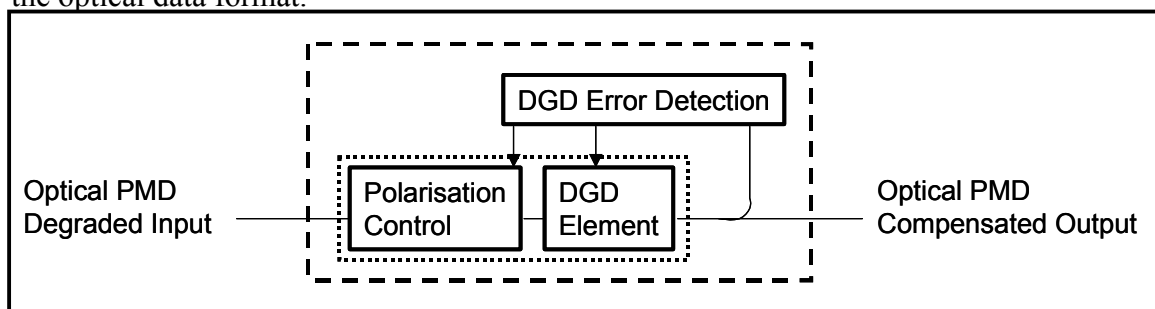


Figure 7 Block diagram of an Optical PMD compensation system

There are three basic parts to an optical adaptive PMD compensator, see Figure 7;

- 1) A PMD detector giving a PMD error signal,
- 2) A DGD or PMD compensation element,
- 3) An adaptive polarisation controller to align the compensation element with the system.

3.2 PMD Compensation Schemes

There are a number of optical PMD compensation schemes employing increasing complexity^[6]. These range from a simple launch end polarisation controller to align the optical signal with the PSP to receiver end schemes based on a large sequence of DGD elements with polarisation rotators between each element. Some of the simpler schemes are shown in Figure 8.

Associated with each scheme is the number of degrees of freedom (DOF) which the scheme can compensate. The PMD of a fibre link will vary with a limited number of degrees of freedom over a specified wavelength range. The higher the PMD the more DOFs. In order for a fibre system to be fully compensated the DOF in the compensator will need to equal or exceed the DOF of the PMD.

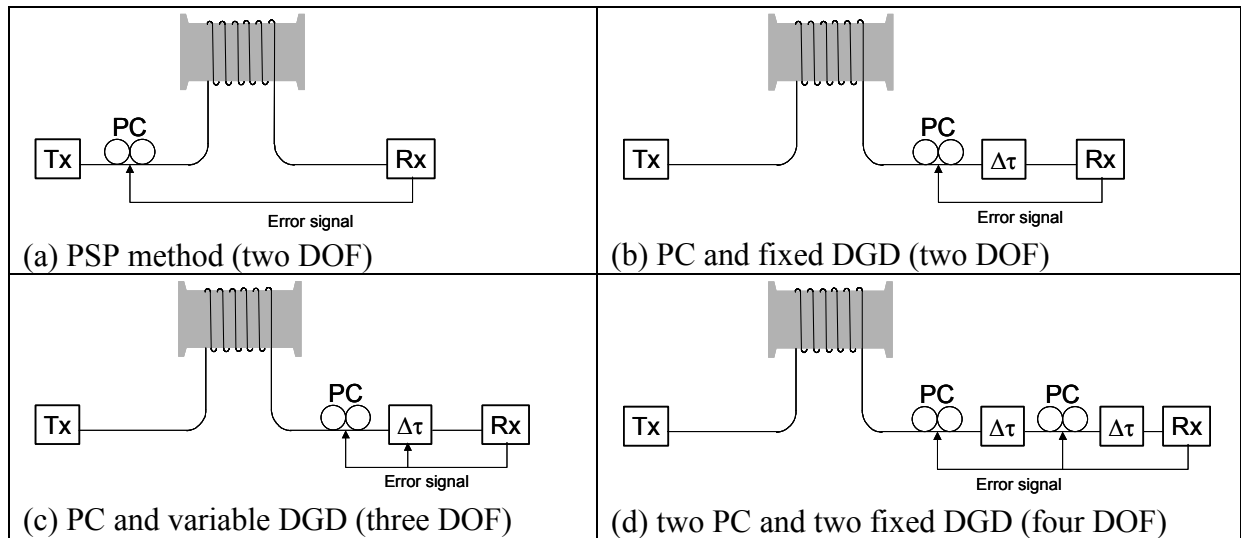


Figure 8 Optical PMD compensation schemes

3.3 PMD error signal

PMD compensation involves minimising the PMD of the optical transmission system and PMD compensator combined by cancelling the PMD of the optical transmission system with the DGD elements within the PMD compensator. Since the PMD of the optical transmission system will evolve with time the PMD compensator is an active adaptive system. This active system requires an error signal that is used to control the adjustment of the PMD compensation elements. The PMD error signal is minimised for optimum optical transmission performance. The PMD error signal is a measure of the DGD in the transmission path for the optical channel and must be calculated from some aspect of the transmitted data signal. A number of methods are being used to determine the first-order PMD error signal based on:

- 1) Spectral Analysis,
- 2) Autocorrelation,
- 3) Degree of polarisation,
- 4) Arrival Time Variation.

3.3.1 Spectral Analysis

A PMD error signal is derived by looking at the power within a spectral component of the transmitted data signal. In the presence of first-order DGD the transmitted data signal will be divided into two with each part having a differing time delay before being recombined at the detector. This looks like a Mach Zender interferometer and will give a sine modulation in the frequency spectra. The depth of the modulation depends on the alignment of the PSP with the input signal and the period depends on the DGD.

Measurements of the electrical power spectrum of the received data were made using the same optical system as used for paragraph 2.4. The electrical spectrum was measured with an electrical spectrum analyser. The spectra for the signal aligned with a PSP and aligned to equally excite the two PSP are shown in Figure 9. The ratio of the two spectra is independent of the bit rate and shows a frequency notch at ~6.5 GHz.

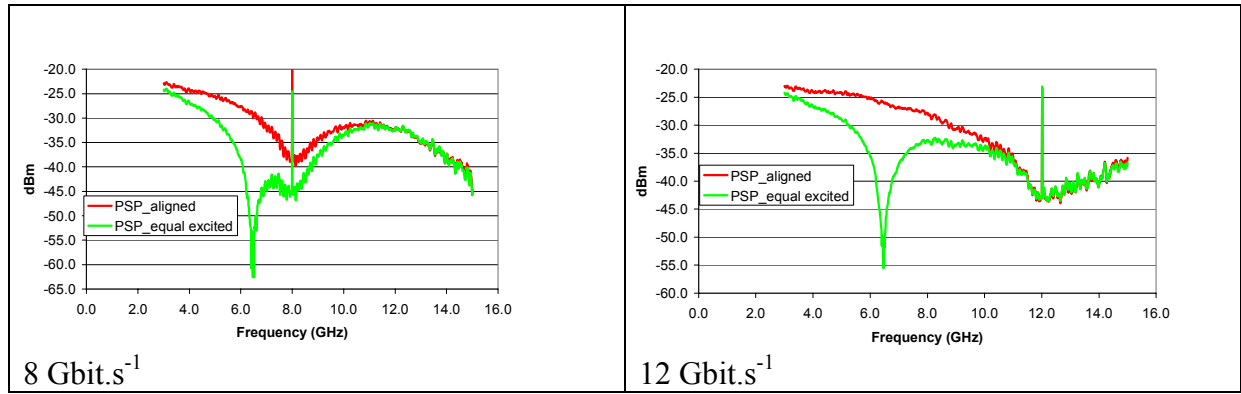


Figure 9 Electrical power spectra of a received signal transmitted through 77 ps of HiBi fibre.

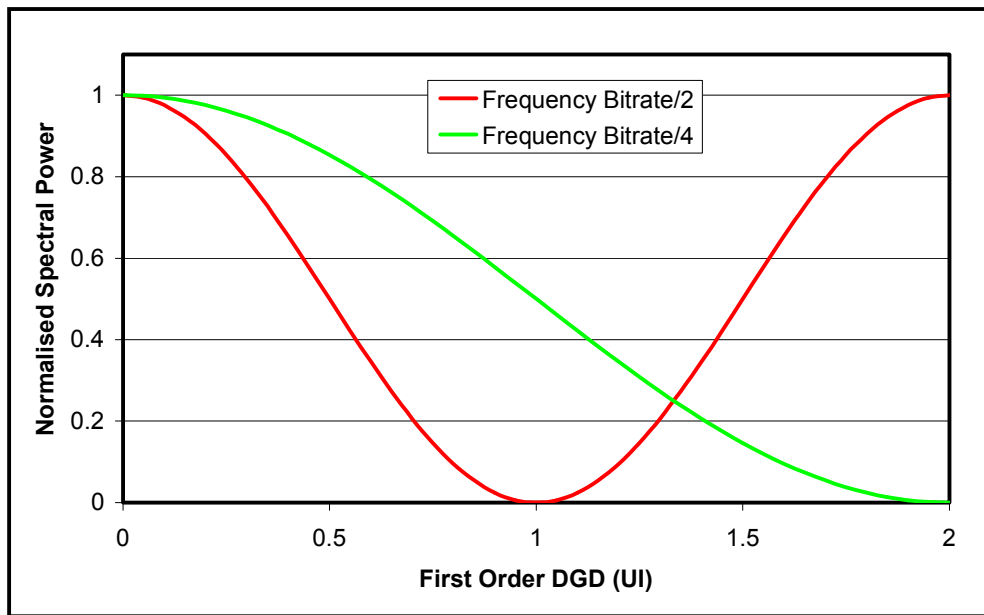


Figure 10 Calculated normalised spectral power as a function of first-order DGD.

Figure 10 shows the calculated normalised spectral power through a bandpass filter at half and quarter of the bitrate as a function of the first-order DGD. The sinusoidal variation of spectral power with first-order DGD can be seen. In order to keep the DGD at 0.5 UI or lower the filter with half the bitrate is most sensitive however there is the ambiguity for large DGD. Lower frequency spectral components will also need to be monitored to remove this ambiguity.

The use of the spectral power at half the bitrate is most sensitive when the PSPs are equally excited.

3.3.2 Autocorrelation

This is a more complex form of spectral analysis where the difference between the expected spectrum and the measured spectrum are used to calculate the error signal. For a return to zero modulation scheme it is possible to look at the autocorrelation of the optical signal to maximise the peak power. This can be done both in the electrical domain or the optical domain.

3.3.3 Degree of Polarisation

The degree of polarisation of the optical signal is reduced after transmission through an optical system with PMD. This is because the output polarisation state will be a function of the optical frequency. Thus the various components modulated signal will arrive with differing polarisation states leading to a depolarisation of the optical signal.

The degree of polarisation (DOP) of the optical signal from the test system of paragraph 2.4 was measured using a polarimeter. The effect of 77 ps of first-order DGD are shown in Figure 11 where the optical signal was aligned to equally excite the two PSPs.

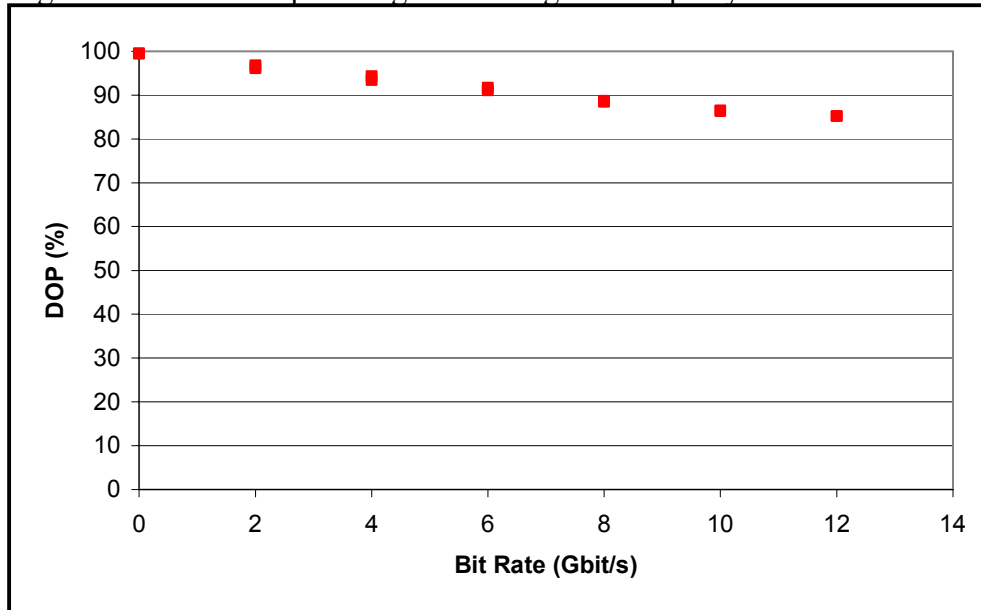


Figure 11 Measured DOP for signal passed through 77ps of DGD.

The measurements of Figure 11 show the same trend as reported by N Kikuchi^[7] but the DOP tends to be larger. This may be due to the limited bandwidth of the modulator giving a slightly smaller than expected spectral width and the limited modulation depth leading to slightly more carrier power. The expected trend is for the DOP to decrease towards 50% for large DGD. The sensitivity of this technique to first-order DGD depends on the alignment of the PSP and also the modulation format. N Kikuchi^[7] show much better sensitivity for optical duo-binary modulation. The technique is independent of the optical data rate and thus can be made optically transparent.

3.3.4 Arrival Time Variation

The DGD is measured using the timing within the optical data signal^[8]. An additional polarisation scrambler is inserted at the transmit end of the optical system. This scrambler varies the polarisation state of the input signal over the whole of the Poincaré sphere. The received optical signal is detected in the normal way and the clock recovered. The variation of the clock phase from the local oscillator is due to the variation in the transit time of the optical system as the input polarisation state evolves. For an ideal compensated system this variation is zero.

3.3.5 Second-Order PMD Detection

The detection of higher order PMD is less well established. It is proposed that the difference

in the slope of the eye for positive and negative slope transition can give information about higher order PMD^[9].

3.4 DGD compensation

Lengths of HiBi fibre can provide simple fixed DGD elements. The length of such fibres will be optimised for the uncompensated system PMD. Variable DGD elements can be realised using bulk optics as, for example, in Figure 12.

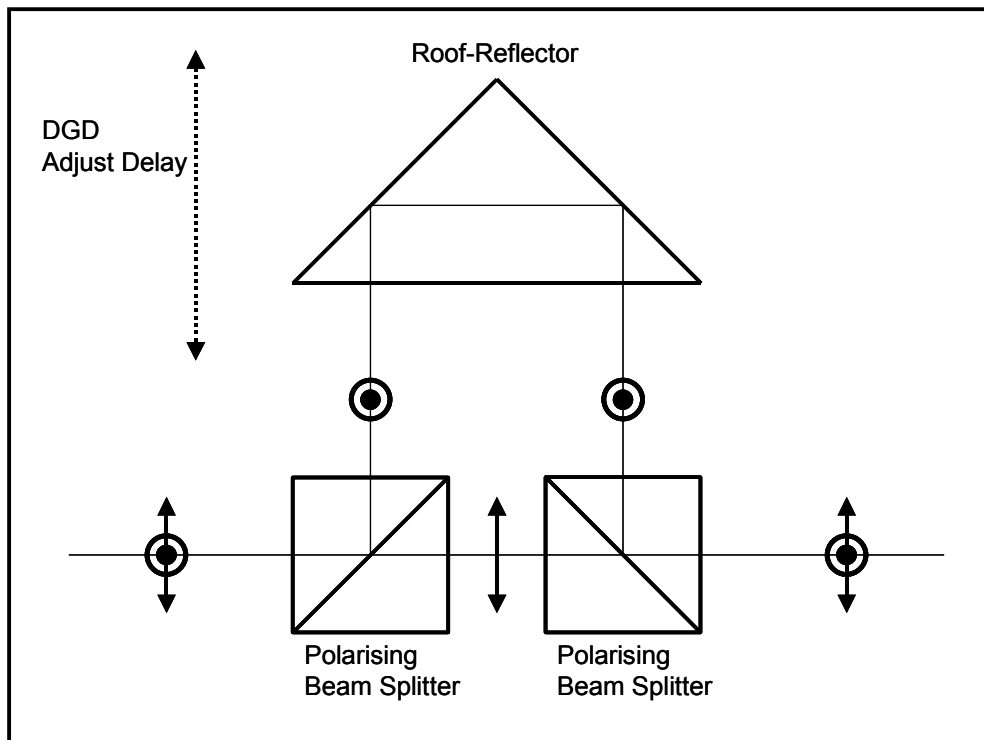


Figure 12 Possible arrangement of a bulk optic variable DGD element

3.5 Adaptive polarisation control

Polarisation controllers are used to align, for compensation, the PSP of the DGD compensation element with the PSP of the fibre system. Such polarisation controllers need to be electronically controllable, fast enough to respond to changes in the system PSP direction and endless so that PSP can be continuously tracked without the need to reset the polarisation controller with the risk of temporarily losing the track. There are two technologies that fulfil these criteria, those based on liquid crystal and those on the electro-optic effect.

The liquid crystal based polarisation controllers consist of a number (four) of liquid crystal elements aligned with their birefringent axes at 45° to the previous element. The electrical control adjusts the birefringence of each element but does not affect the alignment.

The electro-optic based polarisation controllers are based on Lithium Niobate LiNbO_3 technology^{[10][11]}. The set of three electrodes allows the control of both the horizontal and vertical electric fields across the waveguide, see Figure 13. This allows the birefringence and the birefringence axis to be set across the waveguide giving an electro-optic Soleil-Babinet compensator.

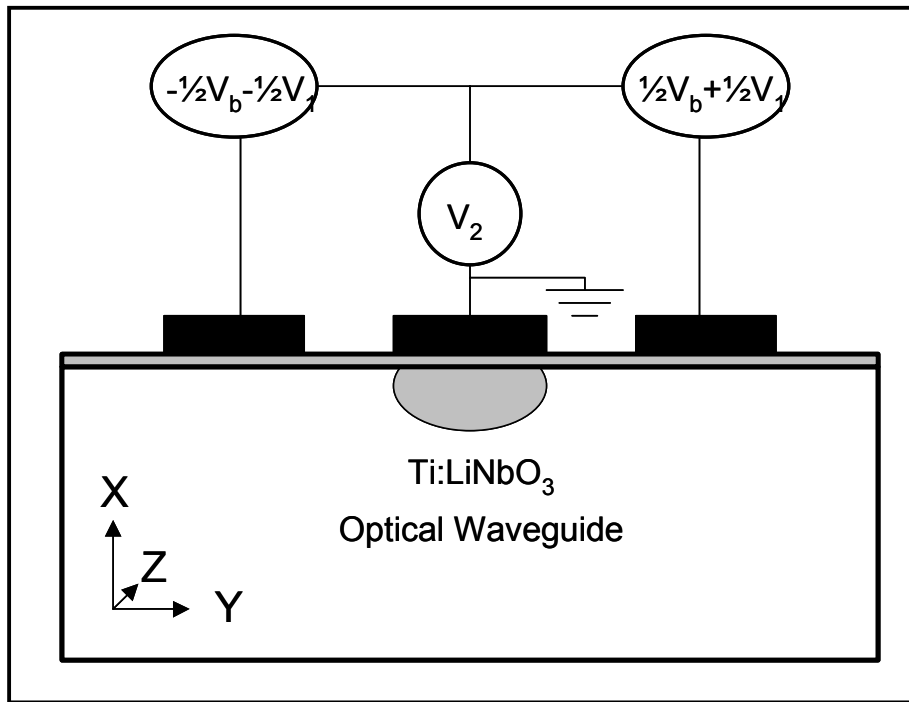


Figure 13 Cross section of LiNbO₃ polarisation control element.

3.6 Combined DGD Compensation and Polarisation Control

Using Lithium Niobate technology where the waveguide propagates in the Y direction this leaves the natural birefringence of the LiNbO₃ across the waveguide that provides the DGD elements. A complex electrode structure provides a periodic control field in the Y direction that causes mode coupling between the X and Z modes. The waveguide is broken into elements each containing in phase and quadrature mode couplers. This allows the electrical control of the alignment of each DGD element building up a PMD with first and second-order components that cancels the PMD of the optical fibre system being compensated. R Noé et al^[12] have demonstrated such a device with 73 mode converters controlling a total DGD of 43 ps, that can accurately compensate DGD of up to 30 ps for 20 Gbit.s⁻¹ systems.

4. PMD COMPENSATED SIMULATIONS

4.1 Fixed DGD Compensation (2 DOF)

Consider a compensation scheme similar to that shown in Figure 8b where a fixed DGD is used in conjunction with a polarisation controller to reduce the average PMD of the optical system. The DGD of the optical system with high polarisation mode coupling will be a sample from a Maxwellian distribution. The fixed DGD will be aligned to reduce this DGD leading to a modified distribution. This modified distribution is given by

$$P(\delta\tau) = \sqrt{\frac{2}{\pi}} \left[\frac{(T + \delta\tau)^2}{\alpha^3} e^{-\frac{(T + \delta\tau)^2}{2\alpha^2}} + \frac{(T - \delta\tau)^2}{\alpha^3} e^{-\frac{(T - \delta\tau)^2}{2\alpha^2}} \right] \quad \text{for } \delta\tau < T \quad (19)$$

$$\sqrt{\frac{2}{\pi}} \frac{(T + \delta\tau)^2}{\alpha^3} e^{-\frac{(T + \delta\tau)^2}{2\alpha^2}} \quad \text{for } \delta\tau > T$$

where $\delta\tau$ is the compensated DGD, T is the fixed compensating DGD and α describes the uncompensated system PMD ($=\sqrt{3} \alpha$). This simplifies to the Maxwellian equation for $T = 0$.

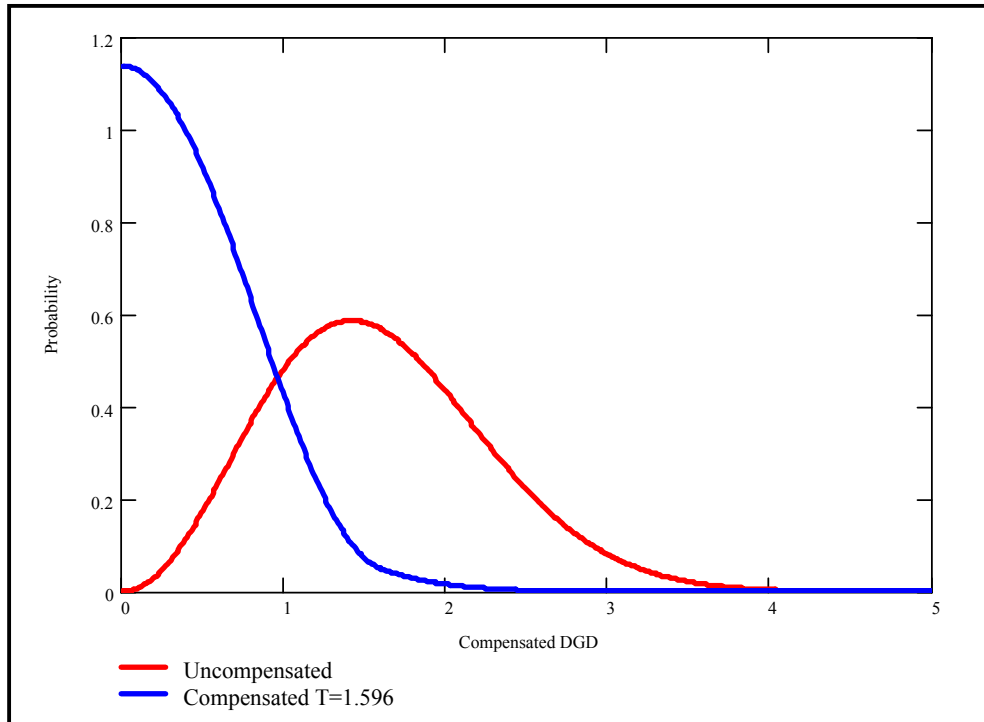


Figure 14 Compensated DGD probability for fixed DGD compensation.

Figure 14 shows the probability distributions for an uncompensated system and that compensated with the optimum fixed DGD where $\alpha = 1$. Figure 15 shows the RMS PMD of the compensated system for different fixed DGD. The RMS PMD of the uncompensated system is $\sqrt{3}$ and with the optimum fixed DGD of $\sqrt{(8/\pi)}$ the RMS compensated PMD is 0.673. This is an improvement of a factor of 2.5 in the RMS PMD however the tails of the distribution are different such that the maximum DGD only improved by approximately 1.5 for a probability of 10^{-5} .

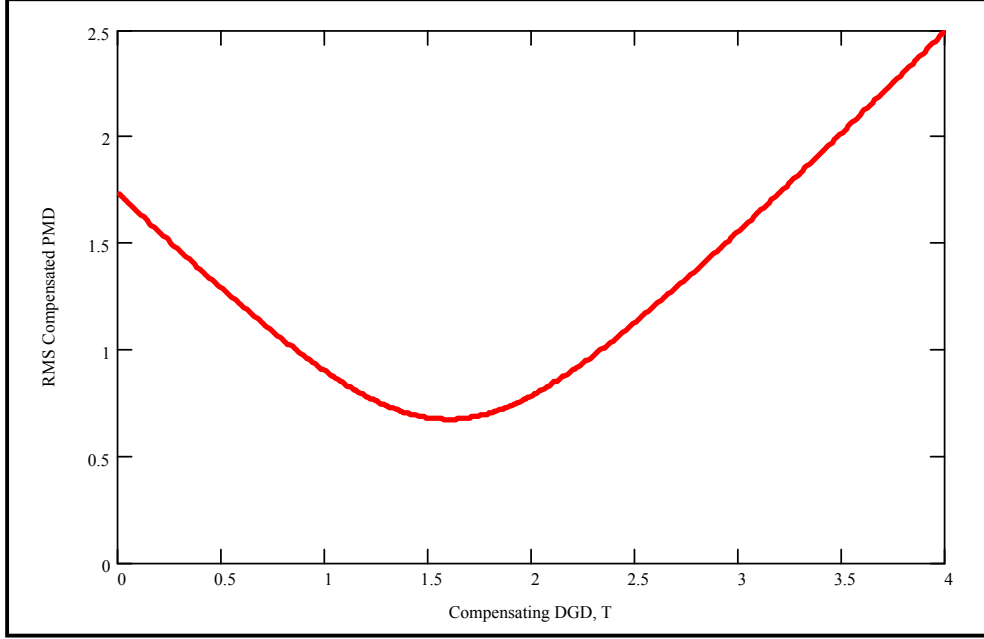


Figure 15 RMS compensated PMD versus fixed compensating DGD.

Since the compensation is a fixed DGD the higher-order PMD will have the same distribution as the uncompensated system. Thus the higher-order PMD will appear larger than expected for the compensated PMD and the compensated bandwidth will depend on the uncompensated PMD.

Simulations of fibre were performed using the random rotation of the birefringence model^[13]. Each element of the fibre is assumed to be a linear birefringent element where the angle, θ , of the birefringence axis follows a random process

$$\frac{\partial \theta}{\partial z} = \sqrt{\partial z} \sigma_{\theta} v \quad (20)$$

where v is an independent random variable taken from a Gaussian distribution with zero mean and unit standard deviation. σ_{θ} determines the coupling length $L_c \sim 4/\sigma_{\theta}^2$. The simulation took 200 elements each 50 m long with modal birefringence of 1 fs.m^{-1} , $\sigma_{\theta} = 0.2$ giving a coupling length of 100 m. This gave an uncompensated PMD of 1043 fs with a second order PMD magnitude of $6.301 \times 10^5 \text{ fs}^2$. The ratio of the RMS PSP rotation to the RMS DGD change was $\sqrt{8.5}$ compared with the statistical accepted value of $\sqrt{8}$.

Providing compensation based on a fixed DGD element aligned using a polarisation controller with two degrees of freedom to cancel as far as possible the DGD of the simulated fibre gave a compensated PMD of 403 fs with a second order PMD magnitude of $6.301 \times 10^5 \text{ fs}^2$. The fixed DGD element was optimised at 961 fs as per figure 15. Figure 16 shows the uncompensated and compensated histograms of DGD and 2nd order PMD magnitude. It can be seen there was no effect on the 2nd order PMD. Comparing the 2nd order PMD to the residual first order DGD the ratio of the RMS PSP rotation to the RMS DGD change was $\sqrt{8.5}$ as before.

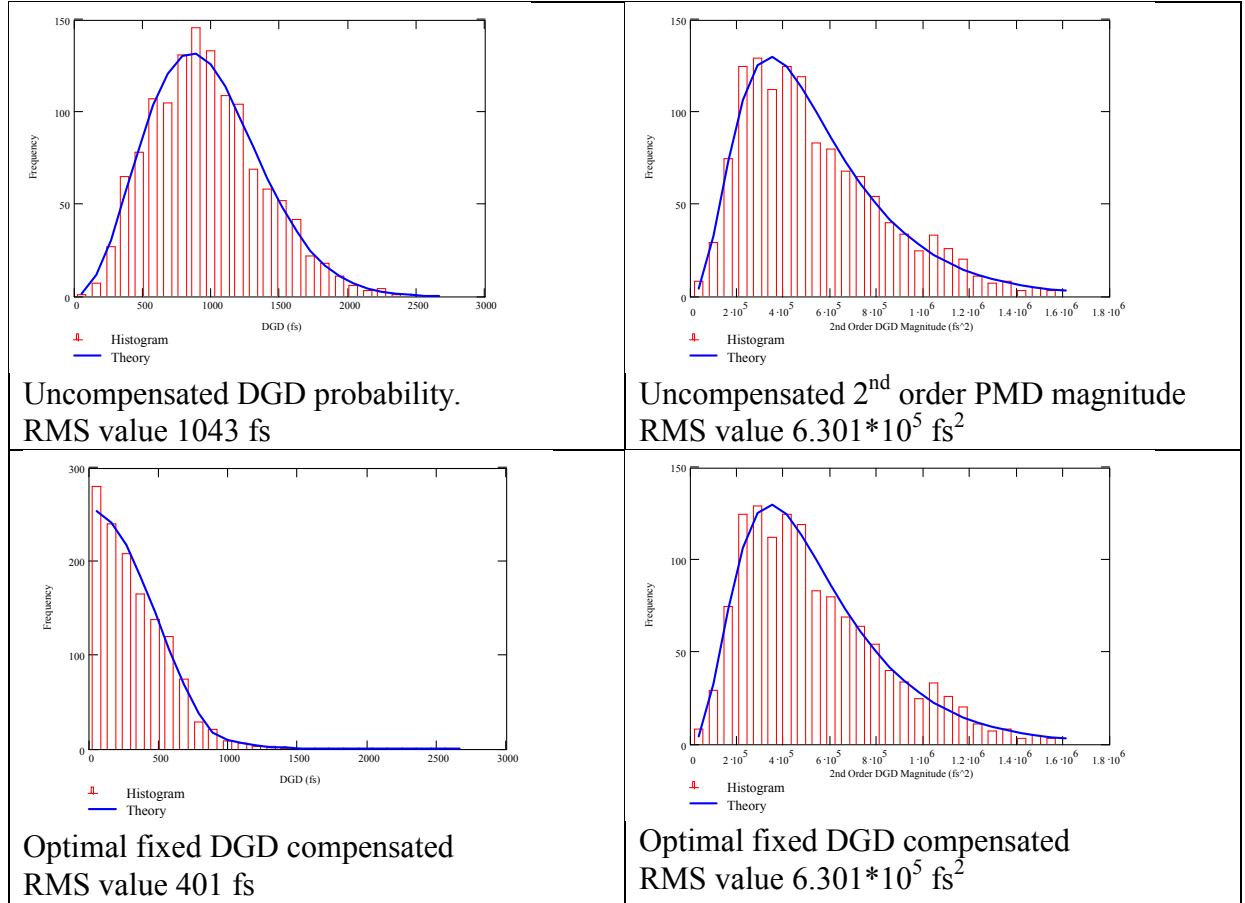


Figure 16 Uncompensated and compensated PMD distributions.

4.2 Variable DGD Compensation (3 DOF)

Taking the same simulated fibre from section 4.1 and compensating the first order DGD exactly. The compensated DGD is zero while the 2nd order PMD magnitude showed the same distribution as in figure 16. The RMS 2nd order PMD magnitude was $6.301 \cdot 10^5 \text{ fs}^2$. The only difference is that there is no 1st order PSP to compare the 2nd order vector with such that all the 2nd order PMD must be considered as DGD dispersion.

4.3 Two Compensating Fixed DGD Elements (4 DOF)

Taking the same simulated fibre from section 4.1 and compensating based on two fixed DGD elements, each with DGD of $\delta\tau$, with two polarisation controllers as shown in figure 8d. The two DGD elements give a variable DGD from 0 to $2\delta\tau$ and also supply some compensating 2nd order PMD in terms of a PSP rotation. The RMS compensated 1st and 2nd order PMD is shown in figure 17. It can be seen that in order to fully compensate the first order PMD each DGD element must be greater than 1.5 times the RMS PMD however the optimum 2nd order PMD compensation occurs when each DGD element is approximately 0.85 times the RMS PMD.

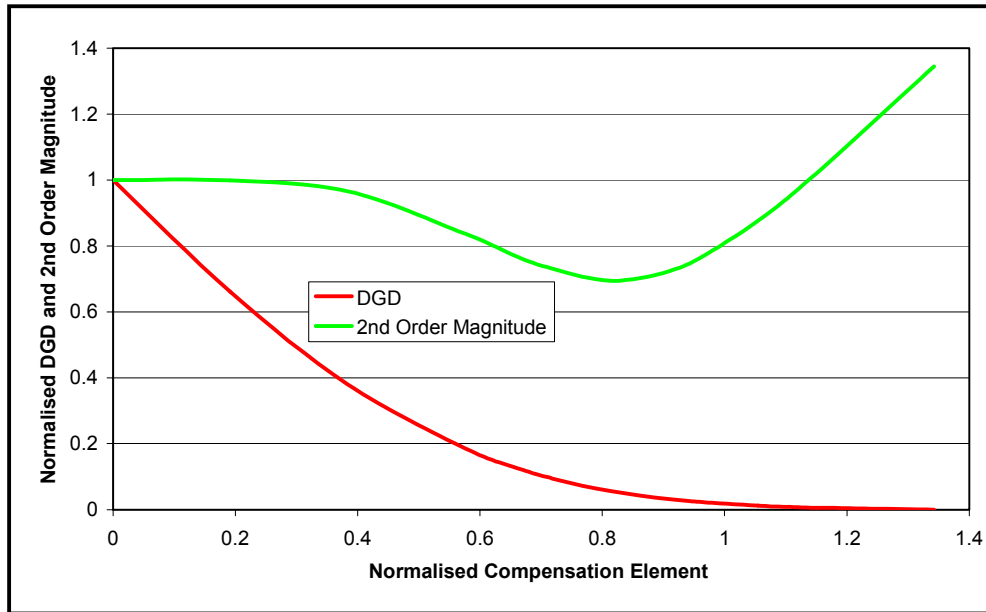


Figure 17 Effective of 4DOF compensation on RMS DGD and RMS 2nd order PMD magnitude.

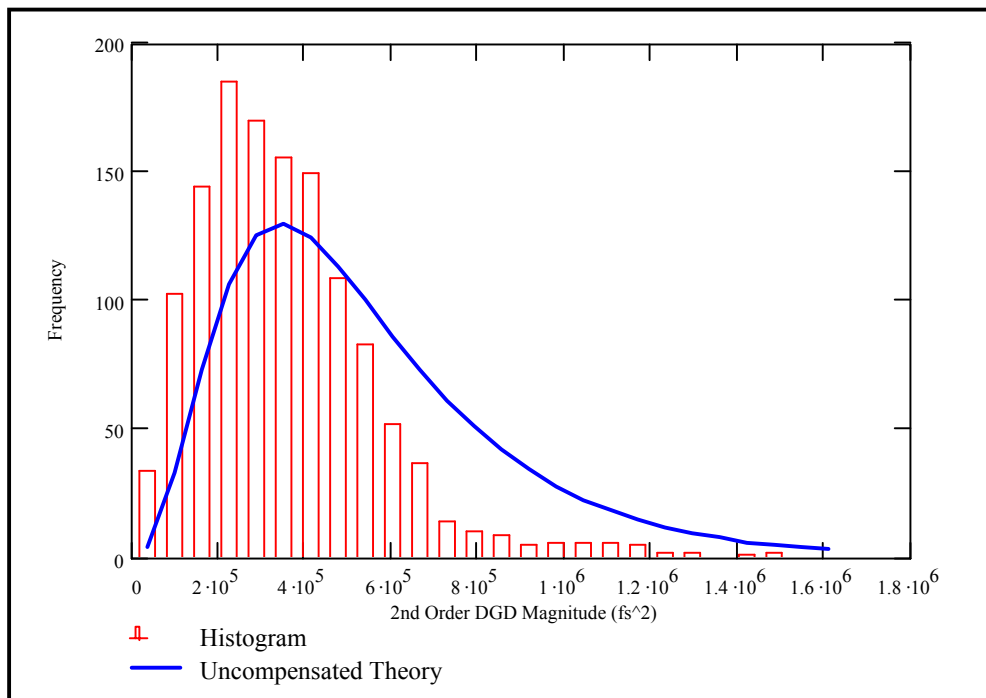


Figure 18 Histogram of compensated 2nd order PMD magnitude.

4.4 Compensated Optical Bandwidth

Taking the same simulated fibre from section 4.1 and compensating at the centre optical frequency, the PMD either side of the compensation point was calculated. The compensation was based on either a variable DGD element (3DOF) or compensation with 6DOF. Figure 19 and 20 shows the PMD and 2nd order PMD magnitude as a function of frequency offset. For the PMD it was found that for compensation with 3DOF and with 6DOF the compensated PMD within 386 GHz was found to be lower than the original uncompensated PMD but further away there is degradation as the PMD compensation acts to increase the total system PMD. The compensated PMD with 6DOF was lower than that with 3DOF within this

bandwidth. Similar simulation for an uncompensated system PMD of 0.5 ps gave a crossing at 687 GHz suggesting a bandwidth for improved PMD of approx $\sim 0.35/\text{PMD}$. Thus the compensated PMD bandwidth appears to be related to the uncompensated PMD. The 2nd order PMD magnitude shows immediate degradation for 3 DOF compensation but shows improvement for 6 DOF compensation within a bandwidth of $\sim 0.15/\text{PMD}$. Higher order PMD effects may show narrower bandwidths.

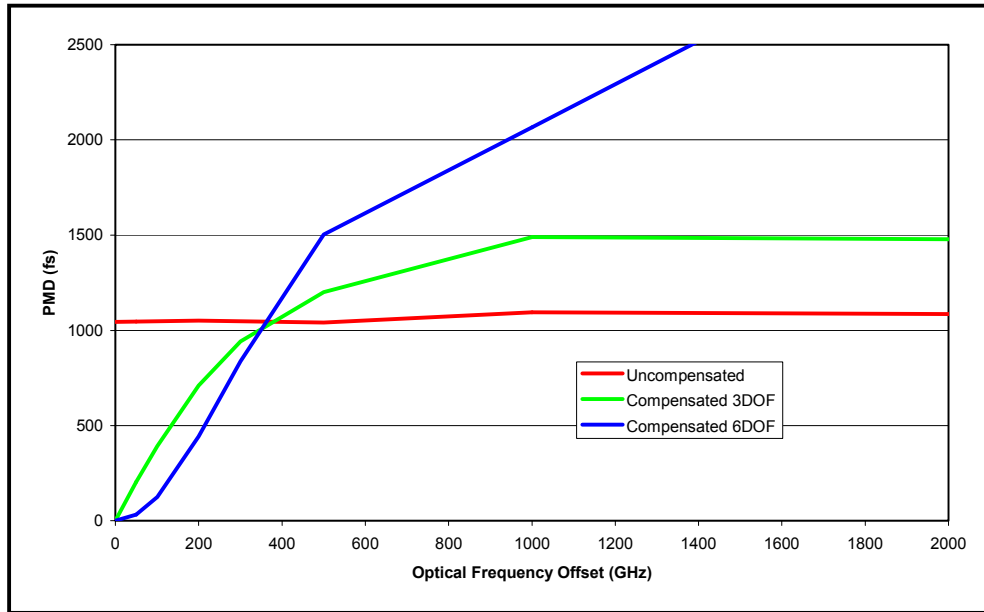


Figure 19 Effect of PMD compensation on first order PMD.

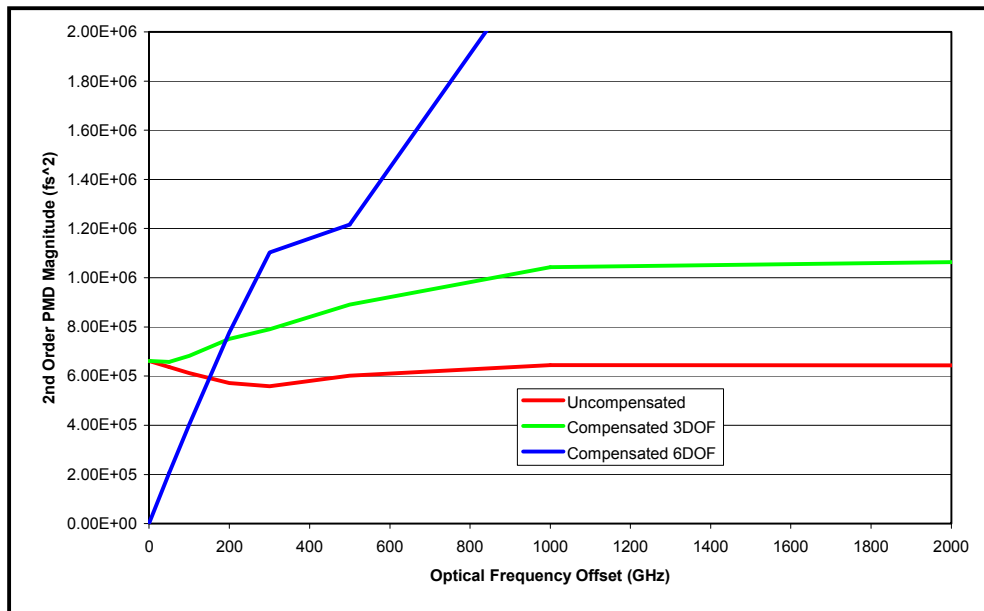


Figure 20 Effect of PMD compensation on 2nd order PMD magnitude.

4.5 Compensation Advantage

Following the work by Frank Bruyère^[4] the worst case penalty due to first and second order PMD is given by

$$P(\text{dB}) = 10 \frac{|\Omega|^2}{T_{bit}^2} + 408 C_0 \frac{|\Omega \omega|}{T_{bit}^2} \quad (21)$$

where C_0 is the normalised chromatic dispersion, see equation 17.

For an arbitrary outage probability of 1 second / day (10^{-5}) we have the maximum DGD equal to 2.9 times the PMD and the maximum 2nd order PMD magnitude equal to 5.3 time the RMS 2nd order PMD magnitude. Taking the worst case that both these maxima occur together we can find the PMD that will give a 1 dB penalty for the various compensation schemes, for a normalised chromatic dispersion of 0.08, see table 1.

PMD Compensation	Maximum Uncompensated PMD (UI)
None	0.09
Fixed DGD, 2DOF	0.10
Variable DGD, 3DOF	0.13
Two fixed DGD, 4 DOF	0.16

Table 1

While the exact PMD values rely on worst case statistics and the work of F Bruyère^[4] the trend suggests that in order for PMD compensation to provide any real improvement high order compensation will be required and that even then the original system PMD maxima is only doubled.

5. PMD COMPENSATION SPECIFICATIONS

5.1 Specifications

An extensive search has revealed just one PMD compensation unit available as a full product. This was the Yafo10 a PMD compensator for 10 Gbit/s systems. Unfortunately the company has since ceased trading.

The following specifications are copied from Yafo literature

Parameter	Specification
Maximum DGD	100 ps
Response Time	500 Hz
Wavelength Coverage	C & L Bands
Insertion Loss	< 6 dB
Input Optical Power Range	-9.5 to 2.5 dBm
Power Requirements	-40 to -57.5 V DC
Environmental Requirements	-5 to +55°C, 5 to 85% relative humidity
Dimensions	23" x 12" x 22.75"

Considering the optical parameters specified the requirement for standard measurements might include the DGD, the speed of response, and the insertion loss.

5.2 System Measurements

System design engineers require parameters that characterise the system performance of PMD compensators. Parameters that characterise the effects both good and bad of using a PMD compensation module within an optical system. Such parameters include the:

- 1) Bit Error Rate power penalty (BER Penalty) or Q factor penalty for the PMD compensation module back-back where there is no actual system PMD. This is the increase in launch power required to overcome the residual effects of the PMD compensator.
- 2) The maximum system PMD that can be compensated for a given BER or Q Penalty. That is an optical system degraded by PMD after compensation appears to be a zero PMD system with a small increased loss. How much PMD can be compensated in the degraded system and for what increase in loss.

5.3 Optical Specification

Detailed optical parameters relating specifically to PMD compensation modules might include:

- 1) Residual or back-back PMD
- 2) Maximum first, second and higher-order DGD and relationship between first and higher order DGD capability.
- 3) Compensated first and higher-order DGD
- 4) Tracking speed for time varying system PMD
- 5) Compensated optical bandwidth

These optical parameters will be in addition to the more usual component optical parameters for example:

- 1) Insertion Loss
- 2) Return Loss
- 3) Polarisation Dependent Loss

6. PMD COMPENSATION MEASUREMENT METHODS

This report will concentrate on the measurements of the physical optical properties that relate specifically to PMD compensators. The measurements of the more general optical component parameters are well established.

6.1 Measurement Methods for PMD

There are a number of established methods for measuring PMD in optical fibres. The difficulty associated with measuring PMD in compensated systems stems from the dynamic nature of the compensation and the restricted optical bandwidth associated with the compensated channel. The well established methods include interferometric, fixed analyser, phase shift, and polarimetric based methods.

Measurement Method	Suitable for Dynamic Systems	Suitable for Restricted Optical Bandwidths	Higher-Order PMD Capability
Interferometer ^{[14][15]}	Ideal	No	No
Fixed Analyser ^{[16][17]}	Yes	No	No
Phase Shift ^{[18][19]}	No	Ideal	No
Polarimeter ^{[20][21][22][23]}	No	Yes	Yes

As can be seen from the table above there is no ideal measurement method for this situation. The Interferometric methods which are fast and ideal for the dynamic situation but the restricted bandwidth of one channel will lead to a limited DGD resolution, a 50 GHz optical bandwidth will lead to a 20 ps resolution. The phase shift techniques are ideal for giving the highest resolution in restricted optical bandwidths but the involve measurements of phase shift for a number of differing polarisation input states which will take time such that the dynamic compensation may compensate any measurement signal. The only techniques capable of measuring the higher-order PMD effects, in particular the PSP rotation, are the polarimetric based techniques using either Muller Matrix or State of Polarisation analysis. The technique involves the measurement of the output state of polarisation for a number of input states for a number of optical frequencies. Again the dynamic nature of the PMD compensation may compensate the measurement signal however the technique is capable of giving 0.1 ps resolution in 50 GHz bandwidth and can calculate both DGD, PSP and their variations with optical frequency.

6.2 Measurement of Specific PMD Parameters

6.2.1 Residual or Back-Back PMD

The PMD compensation unit will be manually set to its minimum value. The tracking system will have to be turned off. Thence the PMD can be measured within the optical bandwidth as required.

6.2.2 Maximum First and Higher-Order PMD

The PMD compensation unit will be manually set. The tracking system will have to be turned

off. Thence the PMD can be measured within the optical bandwidth as required. In order to assess the PMD compensation capability it will be necessary to measure the maximum DGD, the maximum higher order DGD and also the maximum higher order DGD while set to the maximum first order DGD etc... The exact nature of the tests will depend on the type of PMD compensation and the number of DOF available within the compensation network.

6.2.3 Compensated First and Higher-Order PMD

This will require a suitable system transmission test bed such that the PMD compensation unit may operate in its design mode. A selection of PMD emulators with realistic first and higher order PMD are added into the test bed. The PMD compensation unit will be allowed to track and optimise the PMD compensation before the compensated PMD can be measured. Depending on the exact PMD measurement technique it is likely that the PMD compensation tracking will need to be isolated for the duration of the measurement.

In order to understand the statistical nature of these parameters it will be necessary to repeat the measurements with different emulators of nominally the same PMD. This can be achieved with real high mode coupled fibre by recording measurements at different temperatures. With fixed PMD emulators it may be possible by operating at different wavelengths, while with dynamic emulators it will be possible to make small adjustments. Accurate characterisation of the PMD emulators used will be required.

6.2.4 Compensated Optical Bandwidth

The compensated optical bandwidth can be calculated from the measurements made in section 6.2.3. It will depend on the residual compensated higher-order PMD. There is a requirement for an exact definition. Perhaps this might be the optical bandwidth over which the compensated PMD is less than the uncompensated PMD. A system based definition might be the optical bandwidth over which the penalty due to the residual PMD is less than 1dB.

6.3 Assessment of Tracking Speed

The PMD of real systems evolves with time and because of this the PMD compensator will need to track these changes. For buried systems the time constant of such changes is hours while for aerial systems it is much faster, changing in seconds.

There are two possible methods for testing the tracking speed of PMD compensators

- 1) Using a well characterised dynamic PMD emulator
- 2) Using a fixed emulator and tracking the operation wavelength

In both cases a known dynamic PMD will be produced. The PMD compensation error signal could then be used to monitor the residual PMD. The dynamic PMD would be changed at various speeds and the error signal recorded. The tracking speed will need formal definition but might be the speed where the error signal reaches half its maximum or a system based definition relating to PMD penalty.

6.3.1 Fixed Emulator

A suitable fixed emulator for tracking speed assessment of PSP changes might be two pieces

of HiBi fibre with their axes misaligned to give a PSP rotation with wavelength. By taking HiBi pieces with DGD equal to 2τ and τ with their axes aligned at 60° , see Figure 21, then the PMD vector looking at the output from the shorter length is given by

$$\Omega = \begin{bmatrix} 0 \\ \sqrt{3}\tau \cos(\omega\tau) \\ \sqrt{3}\tau \sin(\omega\tau) \end{bmatrix} \quad (22)$$

where ω is the optical frequency rad.s^{-1} . Thus the PMD vector has a fixed DGD equal to $\sqrt{3}\tau$ while the PSP rotates about the s_1 axis.

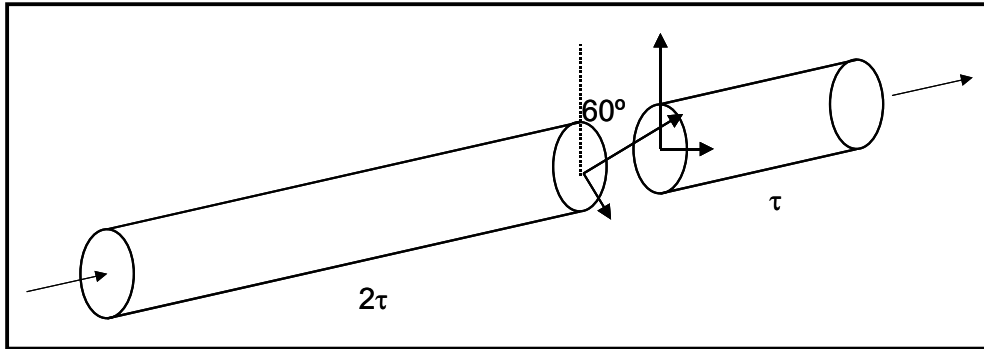


Figure 21 Possible emulator to evaluate PSP rotation tracking speed.

More complex structures will allow the DGD and PSP to change.

7. PMD COMPENSATION MEASUREMENTS

In the absence of a commercial PMD compensation system and in order to assess some of the techniques and measurements a manual PMD compensation scheme was developed. A fibre system based on 24 km of dispersion shifted fibre giving a total PMD of approximately 450 fs was compensated using a fixed length of HiBi fibre (with DGD of 325 fs) and a manual polarisation controller of the Lefèvre loop type, see figure 22. The HiBi fibre was aligned to compensate the system PMD by maximising the output degree of polarisation. In order to give a significant change to the degree of polarisation the source was changed to a 3nm wide for this alignment operation, equivalent to a bit rate of 250 Gbit.s^{-1} , such that the PMD was $\sim 0.1 \text{ UI}$.

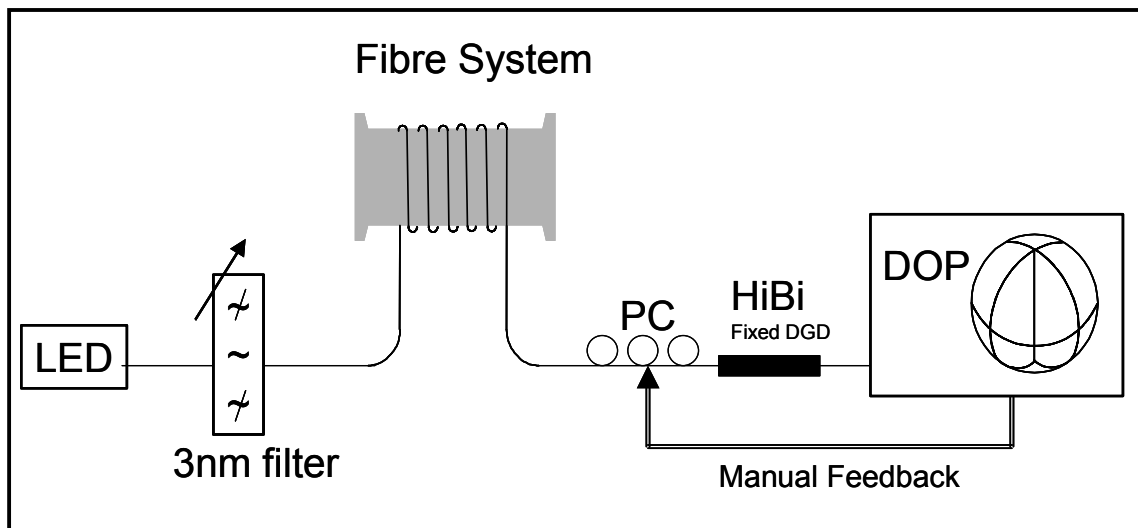


Figure 22 System to manually compensate fibre system.

The compensated system was then measured for PMD using the NPL PMD measurement system. This is based on a polarimeter with SOP analysis, see figure 23. In order to increase the number of statistical measurements the fibre system was compensated at four different wavelengths by tuning the optical filter and measurements repeated at two different temperatures.

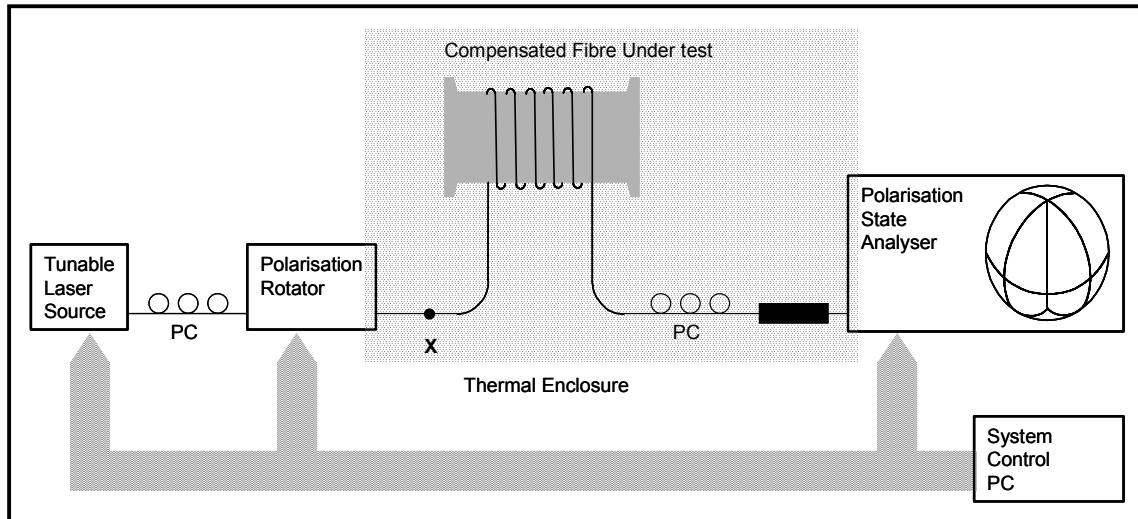


Figure 23 Diagram of PMD measurement system at NPL.

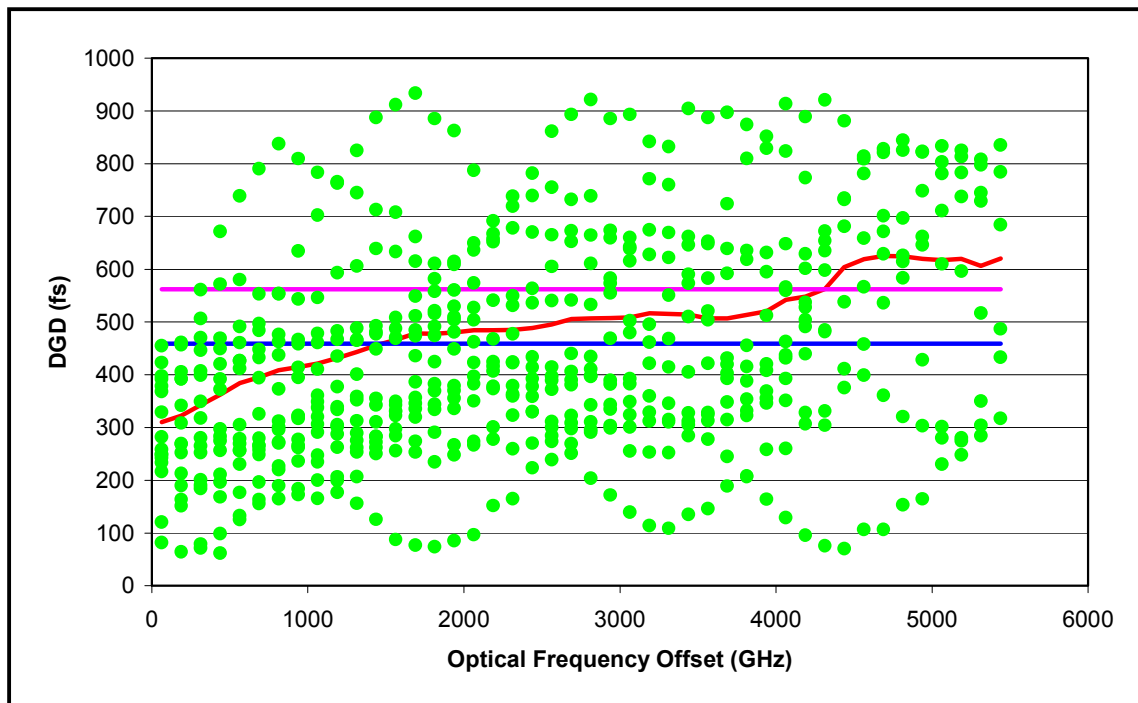


Figure 24 Measured of fixed DGD compensated fibre system.

Figure 24 shows the measured DGD versus offset from the compensated frequency as green points while the red line is the RMS DGD based on the sixteen measurements at each offset frequency. The blue line shows the uncompensated PMD while the pink line the compensated PMD at optical frequencies well away from the compensation optical frequency. The compensated PMD appears to be about 300 fs, which is larger than the theoretical 200 fs for this fibre system. The less than perfect compensation is probably due to the manual adjustment to maximise the DOP. The maximum DOP varied from 98 to 99.5%. The compensated bandwidth of about 1400 GHz is almost double that from the simulation which predict 750 GHz.

8. CONCLUSIONS

The degrading effects of PMD have been widely studied however the exact power penalty for 1st and 2nd order PMD effects is unclear and depends on the exact system type. The studying of the system power penalty is based on PMD emulators and the emulators ability to provide 1st, 2nd and higher order PMD in the correct proportions and directions is critical to the proper assessment of the effects of PMD.

The studies that have been carried out suggest that the higher order PMD effects are considerably more degrading than 1st order DGD. Thus in order to compensate for PMD complex high order compensation is required to have any significant effect. The compensated optical bandwidth appears to be limited by the uncompensated system PMD and thus for very high PMD fibres it may not be possible with even the most complex of PMD compensation to compensate sufficient bandwidth for the fastest data rates.

In terms of specific optical parameters the PMD compensation ability (ie the compensated PMD) and the tracking speed are most significant. In order to correctly assess the PMD compensation ability correct PMD emulation is required. Tracking speed will require either dynamic PMD emulation or a fixed PMD emulator and taking advantage of the wavelength dependence by tracking the operating wavelength.

Of the currently available PMD measurement techniques none are ideal due to the narrow band nature of the compensated system and the dynamic aspect of the compensation. It is likely that the PMD compensation will need to be frozen for the duration of any measurements. This leads to the polarimeter based measurement techniques as the most favoured due to their ability to measure higher order PMD.

In conclusion optical PMD compensation requires significant complexity in order to make any real impact on system performance. The fundamental measurement techniques are available but considerable attention to the detail of PMD emulators is required to accurately assess the impact of PMD and PMD compensation.

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