

Polarisation Mode Dispersion in Restricted Optical Bandwidth: An Evaluation of Measurement Techniques

Abstract

This report is intended to identify a technique for use in constructing a system to measure Polarisation Mode Dispersion (PMD) of Photonic components. Current methods have been reviewed.

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1. INTRODUCTION

Increasing consumer demand means that there is a requirement for higher rates of data transmission through fibre optic systems. Current capabilities are approximately 10 Gbits/s, and one of the limiting factors preventing higher rates is Polarisation Mode Dispersion (PMD).

PMD can be present in both optical fibre and fibre optic components, but investigations have previously been focused on optical fibre or systems as a whole. Now, as the contribution of Single Mode (SM) fibre to the system's PMD has been minimised through improved technology, PMD contributions from components are becoming more important. Components can be considered to be devices such as fibre Bragg gratings, isolators, circulators and Dense Wavelength Division Multiplexing (DWDM) devices. It is of particular interest to be able to quantify the PMD of DWDM devices as they present a way of increasing data rates using existing infrastructure.

The requirement is that devices manufactured for a system do not intolerably increase the system's PMD. As such manufacturers, including SMEs, are being given specifications for the PMD of their products, and so there is a demand for measurement of PMD in components.

As current techniques used were developed for the measurement of PMD in single mode fibre, their suitability for application to components needs to be considered. This report does this through literature-based investigations.

A figure of merit, FOM, will be assigned to each technique as an indicator of its fitness for purpose to measure component PMD. It is calculated from:

$$\text{Figure of Merit} = \frac{1}{\text{DGD [s]} \times \text{bandwidth [Hz]}} \quad (1)$$

where, 'bandwidth' is the spectral range needed to measure the associated DGD, Differential Group Delay. The higher the figure of merit the more suitable the technique.

1.1 Description of PMD

Physically, Polarisation Mode dispersion is the dispersion, or broadening, of a light signal travelling through an optical material due to the presence of two different refractive indices (birefringence [1]), which transmit polarised light at two different speeds.

Birefringence in components generally stems from either an element within the component that is intrinsically birefringent, or a piece of fibre within a device that is exhibiting birefringence [2]. There are many mechanisms that cause birefringence in fibre. The simple action of applying stress to, or tightly bending a single mode fibre induces birefringence, and Highly Birefringent (Hi-Bi) or Polarisation Maintaining (PM) fibre may have been engineered through geometrical asymmetries, for example.

In fibre, birefringence is manifested as two optical axes known as the fast and slow principal axes. Each axis has a Principal State of Polarisation (PSP) [3] associated with it, and these two polarisation states are orthogonal when no Polarisation Dependent Loss (polarisation sensitivity) is present.

When light is launched fully into a PSP, the output state is invariant for different wavelengths to first order, and the input state propagates unchanged provided no mode coupling occurs. Mode coupling occurs at a change in birefringence or at a junction between birefringent elements.

These concepts, along with Differential Group Delay, DGD, provide a physical basis for understanding PMD. DGD is the differential delay in arrival times between light from the PSPs. DGD is the maximum delay when there is no Polarisation Dependent Loss, but is not necessarily the maximum delay when the PSPs are not orthogonal [4, 5]. PMD is defined as an average of DGD values over a wavelength range, and can therefore be thought of as a statistical quantity.

2. REQUIREMENTS/DEFINITION OF THE PROBLEM

An example of a component that might be measured on the new system is a Dense Wavelength Division Multiplexer. It may have a specification of less than 100 fs PMD, and an optical bandwidth of 25 GHz, which limits the wavelength range to 0.2 nm when operated at 1550 nm.

These and other characteristics of components, detailed below [6], distinguish them from single mode fibre, and hence affect the choice of measurement method.

PDL

Components have PDL ranging from 0 to more than 10dB. If PDL is low (< 1 dB) then its effect on the PMD is to slightly increase the uncertainty and error. Whilst this does not present many measurement problems, a device such as a polariser, with a large PDL (> 10 dB) is likely to have unacceptably high PMD errors and should not be measured using techniques developed for fibre PMD measurement. In fact PDL is a more relevant parameter to measure here.

The Principal States of Polarisation are no longer orthogonal when PDL is present, and do not necessarily represent the fastest and slowest propagating pulses. Therefore the delay between the PSPs is not necessarily the maximum delay. Care should be taken with methods using these parameters in these circumstances.

Limited spectral range

The approximate spectral range of a device should be known, and it should be ensured that the wavelength range of the measurement does not exceed this. For components this range may be as narrow as 0.2 nm.

PMD level

This will vary from below 0.1 ps to above 2 ps dependant on the device.

Deterministic PMD

Mode coupling is likely to be finite or low, and the fast and slow polarisation modes, PSPs, may be relatively wavelength independent. PMD is likely to be deterministic due to fixed mode coupling

Birefringent elements

If there is more than one birefringent element then prior knowledge is needed of these elements in order to correctly interpret the results.

A component may have one or more birefringent element. Components with a simple single birefringent element, such as isolators or circulators, should be treated under the low mode coupling regime using the standard methods.

Reflections and multi-path dispersion

Multi-path dispersion may result from reflections from optical elements inside components. These may be PMD related, or polarisation-insensitive. It is necessary to distinguish between them and, in the latter case, eliminate the contribution to prevent recording an incorrect value of PMD.

Fibre Pigtailed

Fibre pigtailed may add to or subtract from the component's PMD. This means that the true device PMD is not being measured. The effect can be minimised by avoiding tight bends, and randomised through lead positioning if the leads are made of SM fibre, but the same is not true for pigtailed made of Hi-Bi fibre. In this case PMD measurements may be complicated.

Typical values of pigtail PMD are 0.005 ps per metre of SM fibre, and 0.5 to 2 ps per metre for Hi-Bi fibre.

These characteristics set out the criteria for deciding if it is appropriate to measure the PMD of a device, and also whether a technique is suitable for use for measuring components.

3. POSSIBLE SOLUTIONS

Four possible solutions will be considered for measuring Polarisation Mode Dispersion in components: the Interferometric, Fixed Analyser, and Stokes Parameter Evaluation techniques, which are usually used to measure PMD of single mode fibres, and the Phase Shift method, which is often associated with Chromatic Dispersion measurement of single mode fibres.

3.1 Interferometric Method

A basic measurement system for the Interferometric technique [7] is shown in Figure 1. Light from a broadband source goes through a polariser and then to the device under test. The output from the DUT is inputted to an interferometer – a standard Michelson type is shown in here – which is then received by a detector.

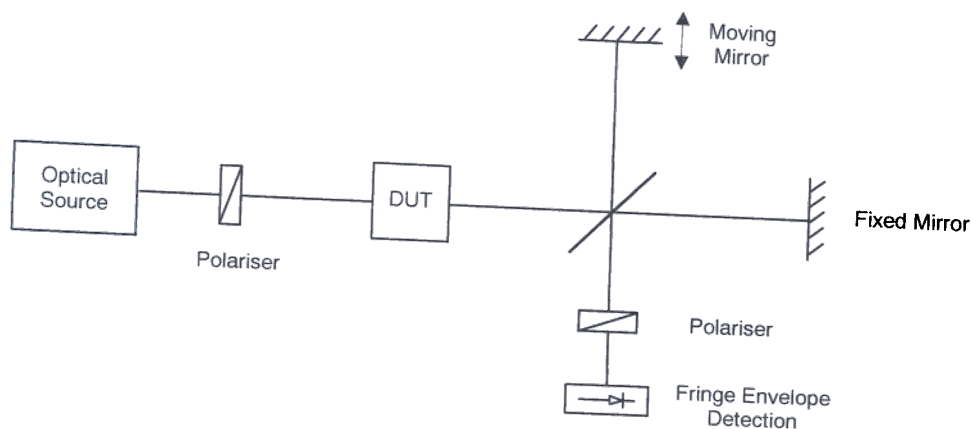


Figure 1: Interferometric PMD measurement system with a Michelson Interferometer.

The signal arriving at the detector is the autocorrelation of the electric field of the light, and in order to get good 'visibility', the polariser must be aligned midway between the fast and slow axes of the DUT so that half of the light travels down each axis.

If a component is made of a discrete birefringent element then the device will resolve the light into two orthogonally polarised beams. As little or no mode coupling occurs, these polarisation states will be maintained to the exit of the device, and light from the slow axis will arrive at a time $\Delta\tau$ later than from the fast.

The analyser axis, set midway between DUT's principal polarisation states, passes light from each arm of the interferometer to the detector.

In the interferometer, light from the fast axis will be split into two by the beamsplitter and travel in the fixed and movable arms, as will the light from the slow axis. For zero optical path difference, interference will occur between light from the two arms of the

interferometer. Interference will occur again between light from the fast and slow axes when light from the fast axis goes to the movable arm and is delayed by a time equivalent to the DGD, $\Delta\tau$, with the slow axis light in the fixed arm. Also, when light from the fast axis is in the fixed arm, the slow axis light must travel a shorter distance, hence shorter time compared with the fast axis light in the fixed arm, to interfere.

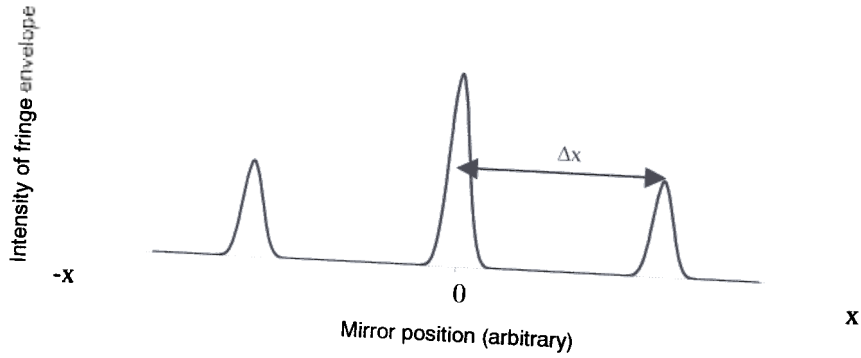


Figure 2: Diagram to illustrate the intensity of the fringe envelope from an interferometer for a single-element birefringent device.

If the envelope of the intensity of the signal on the detector is plotted against distance, three peaks will be seen (Figure 2). The central peak is at zero path difference, and the peaks either side of this are at a distance Δx away, which is equivalent to the DGD. $\Delta\tau$ is calculated using equation (2).

$$\Delta\tau = \frac{2\Delta x}{c} \quad (2)$$

where:

c is the velocity of light in free space.

The condition needed to measure PMD in this way is that the coherence time of the source is less than the PMD of the DUT [8], $\text{source } t_c < \text{PMD}$. The source coherence time is given by equation (3)

$$\text{source } t_c = \frac{\lambda_c^2}{\Delta\lambda c} \quad (3)$$

where:

λ_c is the central wavelength of the source,

$\Delta\lambda$ is the source spectral width, Full Width Half Maximum.

When there is more than one birefringent element in a device, additional peaks will be present on the plot. If any of these peaks are non-PMD related they must be excluded from calculations. They can be identified as those that do not change in amplitude as the input lead configuration or input polarisation state is changed.

3.1.1 System Configuration

There are many different variations of Interferometric system configurations. Some include placing the device under test before the interferometer, or using a different type of

interferometer, or placing polarisers or waveplates in the arms of the interferometer [7, 9, 10, 11].

For single mode fibre measurement, using polarisers is advantageous as it removes the central peak, facilitating curve-fitting. However, for components there is no advantage, as the central peak is not removed.

3.1.2 Capabilities and Limitations of the Interferometric Technique

Table 1 below shows the capabilities of the system. It can be seen that in order for the coherence time of the source to be less than the PMD of the device (100 fs), a source bandwidth of at least 80 nm is needed. When the bandwidth is reduced to 0.2 nm, the source coherence time increases to more than 40 ps.

Bandwidth $\Delta\lambda$	source t_c , and minimum PMD	Interferometer mirror movement Δx	Figure of Merit
0.2 nm	40 ps	6 mm	1
10 nm	0.8 ps	0.12 mm	
80 nm	0.1 ps	0.015 mm	1
100 nm	0.08 ps	0.012 mm	

Table 1: Evaluation of a Figure of Merit for the Interferometric Technique.
A centre wavelength of 1550 nm has been used.

3.1.3 Resolution

As the bandwidth of the source must not exceed the bandwidth of the device under test, this helps determine the minimum measurable PMD (40 ps here). The orthogonality of polarisation in the interferometer arms will also limit resolution.

Experimentally the resolution limit has been broken [12]. A DGD measurement of 10 fs was achieved, with a LED source of 100 fs coherence time for SM fibre.

3.1.4 Accuracy

Accuracy is given by the smallest mirror step Δx of the movable arm, approximately 15 ps for a Δx of 2.5 μm . Δx is taken here to be the smallest increment of a stepper motor driver for the mirror, for example 200th of a 1/2 mm thread. However, the accuracy may alternatively be defined by 1 fringe of the Helium Neon laser used in the interferometer if this is larger than the smallest mirror step.

3.1.5 Summary

The Interferometric technique is capable of measuring PMD of components. However, it relies on using a broadband source without ripples, which severely limits the techniques effectiveness in characterising PMD in components of restricted bandwidth. If a component has an operational bandwidth of just 0.2 nm then the coherence time of the source is such that the minimum PMD measurable is 40 ps. To reduce this PMD threshold the bandwidth would have to be larger. It is therefore very difficult to improve the figure of merit of this technique above 1.

An advantage of using the Interferometric technique is that it clearly distinguishes between birefringent elements and so the dependence upon prior knowledge of the internal structure of

a device is reduced. An additional advantage is its tolerance to movement of the optical test path during measurement.

3.2 Fixed Analyser

The Fixed Analyser, or wavelength scanning method measures PMD by scanning through different wavelengths, and looking at the intensity of the signal on a detector after it has passed through a fixed polariser, the device under test, and a further fixed polariser, the analyser [13, 14]. This setup is shown in Figure 3.

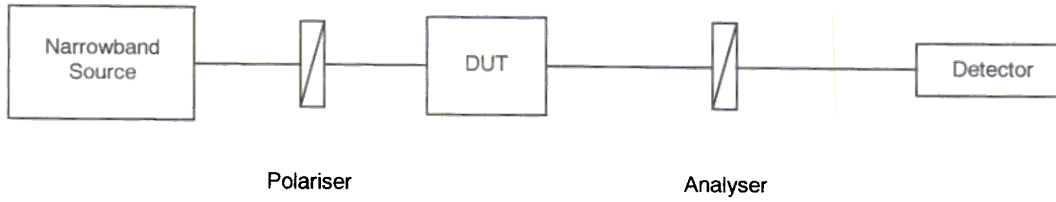


Figure 3: PMD Measurement system for the Fixed Analyser technique.

For each wavelength, light inputted to the fibre will be changed to an unknown polarisation state after having travelled down its length. At the fixed analyser only a fraction of the output light will pass through, according to the offset of this state with the analyser axis. A reference measurement is made with either the device removed or the analyser rotated by 90 degrees.

A ratio is then taken of the intensity of light with the analyser in place over the reference value, and plotted against wavelength. Peaks and troughs (extrema) are seen, which, for a discrete birefringent component, follow a sinusoidal pattern.

Determining the PMD involves either counting the number of extrema, N_e , for a given wavelength interval, or alternatively, carrying out a Fourier Transform of the intensity plot [15, 16]. Analysis using Extrema Counting (EC) or Fourier Transform gives the same result, and so the formulae in this report relate to Extrema Counting as they are more transparent.

PMD in components is found from equation (4) with the low mode coupling regime, $k = 1$

$$\langle \Delta\tau \rangle = \frac{kE\lambda_1\lambda_2}{2(\lambda_2 - \lambda_1)c} \quad (4)$$

(4) can alternatively be expressed in terms of optical frequency:

$$\langle \Delta\tau \rangle = \frac{\pi k E}{\Delta\omega} \quad (5)$$

where

$\Delta\omega$ optical frequency window of measurement in radians per second

3.2.1 System Configuration

Other implementations of the Fixed Analyser technique are to replace the analyser and detector with a polarimeter, or the detector alone with an optical spectrum analyser using a broadband source at the input [16].

A polarimeter might be used in preference to a detector as a polarimeter determines the three normalised Stokes parameters and hence gives a complete description of the polarisation state of light exiting the device. All three DGD's obtained can be used as they are independent measurements.

The polarimeter is also insensitive to power changes, and so the measurement is independent of received optical power.

3.2.2 Capabilities and Limitations of the Fixed Analyser Method

Due to the predictive evolution of intensity with wavelength, the minimum number of extrema needed to calculate component PMD is one peak and valley pair. The density of extrema is fairly unchangeable with different states of input polarisation, adding to the techniques robustness for this application. It might, however, be necessary to ensure that light is launched into both the fast and the slow axes of the DUT by rotating the polariser before measurement. This will affect the amplitude of the peaks.

In exploring the capabilities of this technique, the number of extrema was set to 2, and in order to facilitate estimating the PMD for different wavelength ranges, equation (4) was approximated to (6). A summary is seen in Table 2. For all of the calculations in Table 2, the central wavelength, λ_c , was kept constant, at 1550 nm.

$$\langle \Delta\tau \rangle = \frac{k E \lambda_c}{2(\lambda_2 - \lambda_1)c} \quad (6)$$

Wavelength range/extrema spacing	Bandwidth	PMD	Spectral Resolution, $\Delta\lambda$	Figure of Merit
80 nm	10 THz	0.1 ps	10 nm	1
8 nm	1 THz	1 ps	1 nm	
0.2 nm	25 GHz	40 ps	0.025 nm	1
0.08 nm	10 GHz	100 ps		1

It is apparent that lowering the PMD measured would mean an increase in the wavelength range scanned, as the extrema are further apart. As the PMD here is deterministic, the spacing between the peaks and troughs is fixed. A sufficient range must therefore be scanned to ensure that at least two extrema have been encompassed, which for a PMD of 0.1 ps means scanning over a minimum of 80 nm. This makes it impractical if the available bandwidth of the device is only 0.2 nm. Table 2 shows that the wavelength scanning method is limited to detecting a minimum PMD of 40 ps for a DUT with extrema separated by 0.2 nm, giving this technique a figure of merit of 1.

The fundamental limitations of the technique are the same whether analysis is carried out by Extrema Counting or Fourier Transform. However, a benefit of Fourier Transform is that a plot is obtained from this process, much like that from the Interferometric technique, which displays multiple peaks if more than one birefringent element is within the device. It distinguishes different sources of PMD.

3.2.3 Resolution

The spectral resolution is governed either by the spectral width of the instrument or the wavelength step size of the source for restricted bandwidth components. It is the point spacing needed to adequately define the transmission curve, and can be converted to temporal resolution via equation (4).

For adequate resolution, the following inequality must be obeyed.

$$\frac{\Delta\lambda}{\lambda} < \frac{1}{8\nu\Delta\tau} \quad (7)$$

where:

- $\Delta\lambda$ spectral width of the source / resolution bandwidth of the receiver,
- λ nominal measurement wavelength in m,
- ν optical frequency in Hz,
- $\Delta\tau$ differential group delay, DGD.

This can be expressed as (8) at 1550 nm

$$\text{At 1550 nm:} \quad \Delta\lambda(\text{nm}) < \frac{1}{\dots} \quad (8)$$

3.2.4 Accuracy

PMD is found from equation (4), which specifies a wavelength range for the extrema. A discrepancy could arise if this range is not precisely defined. Also, although a minimum of 2 extrema must be measured, the accuracy of this technique is improved by scanning over as many extrema as possible. As a guide, N_e is typically between 7 and 40, for single mode fibre.

Quantitatively, it is difficult to say what the accuracy of this technique is when applied to components. Poole and Favin [17] has an example of a Polarisation Maintaining fibre that is measured using two different EC techniques: Extrema Counting, and mean-level crossing (which is counting the number of times the normalised transmission curve crosses a line representing the mean transmission value). No uncertainty is quoted for the PMD values of

PM fibre, but they differ by 0.04 ps suggesting that there are quantifiable levels of uncertainties. Theoretically these two values should have been the same.

Poole and Favin also show that a PDL of up to 0.4 dB will not have a significant effect on the PMD when measured by extrema counting or mean-level crossing.

3.2.5 Summary

It is possible to measure the PMD of components using the Fixed Analyser technique. The technique has a figure of merit of 1, and although able to operate in a limited spectral range, would need to scan a large range to measure small PMDs. For a bandwidth of 0.2 nm, the minimum PMD detectable is 40 ps.

PMD is calculated from a ratio of DUT over reference transmission values, which is advantageous as it removes or reduces polarisation insensitive contributions from the device's PMD.

PMD can be calculated via Extrema Counting or Fourier Transform. Fourier Transform analysis, however, offers an advantage over Extrema Counting as it makes the distinction between different birefringent elements if more than one is present.

3.3 Stokes Parameter Evaluation

Stokes Parameter Evaluation is a generic term for the frequency domain measurement techniques of Jones Matrix Eigenanalysis (JME), State of Polarisation (SOP) and Poincaré Sphere Analysis (PSA). The basic principle common to all of these is that the Stokes parameters are used to directly determine the Differential Group Delay. The JME and PSA methods are equivalent, and the SOP is a simplified version of PSA.

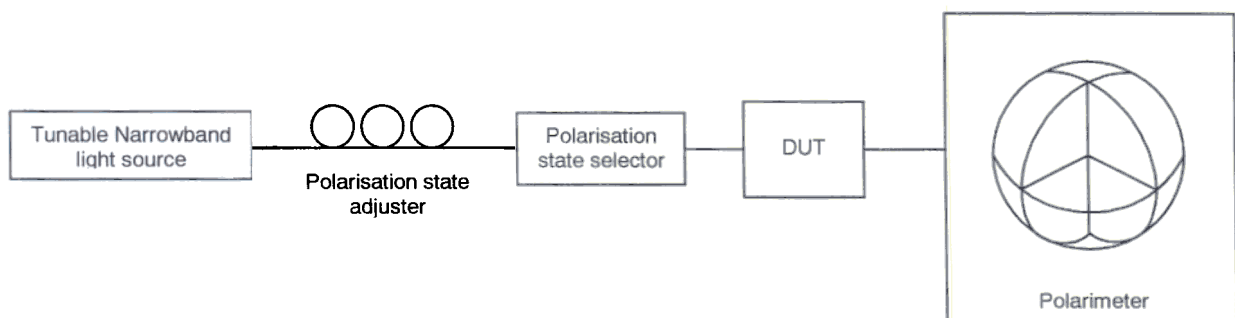


Figure 4: PMD Measurement system for Stokes Parameter Evaluation.

Figure 4 shows the experimental layout, which is the same for all three methods. A tuneable narrowband source, such as a laser, is used to provide light that remains polarised for all conditions. The polarisation state is defined using a polarisation state selector. For the JME and PSA methods, three linear states that are mutually orthogonal on the Poincaré sphere are launched in turn into the DUT at each wavelength point scanned, and for the SOP, one state is launched.

A polarimeter then determines the Stokes Parameters of the light exiting the device as the polarisation state of the light has been altered from its input state by the transmission properties of the fibre.

An output polarisation state is represented by a point on the Poincaré sphere. As the wavelength changes for a given input polarisation, the output polarisation state changes and moves to a different point on the sphere. For a discrete birefringent component, a circle is swept out on the sphere as the wavelength is incremented. The rate of change of polarisation state with optical frequency is an indication of the level of PMD. Small PMD's will cause a slower precession around the PSP axis than larger PMD's for an equivalent change in optical frequency. A separate circle is drawn out for each input polarisation state launched.

Analysis can be performed by Jones Matrix Eigenanalysis [18], in which the DGD is calculated from equation (9), and involves formulating a transmission Jones matrix from the Jones vectors of two adjacent wavelength points. This is only valid if there is no PDL present. The DGD is quoted at the midpoint of the wavelengths.

$$\Delta\tau = \left| \frac{\text{Arg}\left(\frac{\rho_1}{\rho_2}\right)}{\Delta\omega} \right| \quad (9)$$

where:

$\Delta\tau$ DGD,

ρ_1, ρ_2 complex eigenvalues of $\mathbf{T}(\omega+\Delta\omega) \mathbf{T}^{-1}(\omega)$,

$\mathbf{T}(\omega+\Delta\omega)$ Transmission Jones matrix, at the higher optical frequency,

$\mathbf{T}^{-1}(\omega)$ Inverse Jones matrix, at the lower optical frequency,

Arg denoted the argument function, that is $\text{Arg}(\eta e^{i\theta}) = \theta$,

$\Delta\omega$ optical frequency step, expressed in radians per second.

With Poincaré Sphere Analysis [15], DGD is also calculated using matrix algebra (10).

$$\frac{1}{\Delta\omega} \left[\arcsin\left(\frac{1}{2} \sqrt{\frac{1}{2} (\Delta\vec{h}^2 + \Delta\vec{q}^2 + \Delta\vec{c}^2)}\right) + \arcsin\left(\frac{1}{2} \sqrt{\frac{1}{2} (\Delta\vec{q}^2 + \Delta\vec{v}^2 + \Delta\vec{c}'^2)}\right) \right] \quad (10)$$

where:

Δ denotes a difference between two adjacent wavelength points,

$\vec{h}, \vec{v}, \vec{q}$ Stokes vectors, independent of input SOP,

$\vec{c}$ and $\vec{c}'$ vector products formed from the Stokes vectors.

For the State of Polarisation method, DGD is found from the phase difference of light exiting the DUT as a result of a frequency change of the optical source, and is given by the angle subtended on the Poincaré sphere. As SOP has the most transparent calculations of the three techniques its equations are used for numerical analysis in this report. It is, however, less robust than JME and PSA, and only works well when the change in output polarisation state is not rapid and random, which poses no problems for application to components. Equation (11) defines the DGD in terms of radians.

$$\Delta\tau = \frac{\Delta\theta}{\Delta\omega} \quad (11)$$

where

- $\Delta\tau$ differential group delay in seconds
 $\Delta\theta$ rotation about the principal states axis in radians
 ω radian optical frequency change

This is rewritten in terms of optical frequency and wavelength in equation (12) [19].

$$\Delta\tau = \frac{\Delta\theta}{2\pi} \frac{\lambda_1 \lambda_n}{c \Delta\lambda} = \frac{\Delta\theta}{2\pi} \frac{1}{\Delta f} \quad (12)$$

where:

- λ_1 wavelength at frequency f_1
 λ_n wavelength at frequency f_n
 Δf change in frequency,
 c speed of light in a vacuum

When the DGD for each wavelength pair has been calculated, a histogram is then plotted of the frequency of occurrence of each DGD value. For a component with discrete birefringence, this should be single valued. The delay corresponding to the peak value of a curve fitted to the distribution is defined as the PMD of the device.

3.3.1 Capabilities and Limitations of the Stokes Parameter Evaluation Methods

Stokes Parameter Evaluation is the Reference Test Method for measuring PMD in fibre, and can be used to provide a definitive answer when there are queries over results from the Fixed Analyser or Interferometric techniques.

It can also be said that the best DGD resolution reported, 50 attoseconds (50×10^{-18} s), was achieved by Heffner [20], using the JME method. Only two wavelength points, at 1304 nm and 1540 nm, were used in this calculation. However, this finite wavelength difference, and the necessity to avoid a 2π phase ambiguity, means that the maximum DGD measurable is 14.2 fs.

Table 3 shows the capabilities of the Stokes Parameter Evaluation methods as calculated from SOP analysis. Using a standard system configuration this method is able to detect a PMD as low as 191 fs if the phase resolution of the detector is 0.03 radians (a typical resolution for a polarimeter), and the wavelength range is 0.2 nm. This gives a figure of merit of 209. Unlike the Interferometric and Fixed Analyser methods, the figure of merit for the Stokes Parameter Evaluation is not constant. It can be increased whilst simultaneously reducing the PMD measurable by implementing a more sensitive detection of phase angle.

Phase angle, $\Delta\theta$		Wavelength step, $\Delta\lambda$	DGD $\Delta\tau$	Figure of Merit
radians	degrees			
0.016	0.9	0.2 nm	100 fs	400
0.03	1.7	0.38 nm	100 fs	200
0.03	1.7	0.2 nm	191 fs	200
0.03	1.7	0.1 nm	382 fs	200

Table 3: Evaluation of a Figure of Merit for the Stokes Parameter Evaluation Technique.

3.3.2 Resolution

A resolution limit is imposed by the phase resolution of the polarimeter and the bandwidth of the DUT. In order to measure a DGD of 100 fs, a bandwidth of 0.38 nm is needed if the phase resolution is 0.03 radians or a phase resolution of 0.016 radians is needed if the bandwidth is only 0.2 nm. If the wavelength step is reduced to enable lower PMD's to be measured, it has the effect of also reducing the accuracy of the measurement.

The upper limit of resolution is governed by the necessity to keep the rotation angle of the output state below 180° as the wavelength is changed from one point to the next. A rotation greater than this would cause an incorrect DGD to be registered. Equation (13) must be adhered to to prevent breaching the 'alias limit'.

$$\Delta\tau_{\max}\Delta\lambda \leq \frac{\lambda_c^2}{2c} \quad (13)$$

where:

$\Delta\tau_{\max}$ maximum expected DGD within the measurement wavelength range,
 $\Delta\lambda$ wavelength interval,
 λ_c central wavelength.

3.3.3 Accuracy

The accuracy of the Stokes Parameter Evaluation methods may be compromised if there is any movement of the test path during measurements. If, for example, the fibre pigtails of a device under test were to move, the output polarisation state of light travelling through the device might change. This change is not due to a change in optical frequency but has the same end result. As it is not possible to distinguish between these two sources that cause a change in polarisation state, the optical test path must remain motionless for the duration of the measurements.

Factors determining the accuracy of this method are the angular accuracy of the polarimeter ϵ , used to measure $\Delta\theta$ in equation (11), and the optical frequency uncertainty and interval used. If the wavelength step size is small, any uncertainty in the wavelength value may become dominant, and so a wavemeter may be needed to ensure wavelength accuracy. Also, as stated in section 3.3.2, the smaller the wavelength step, or frequency interval $\Delta\omega$, the less accurate this method becomes. The DGD, or temporal accuracy $\delta\tau$, can be summarised as (14) [21]

$$\delta\tau = \pm \frac{\epsilon}{\Delta\omega} \quad (14)$$

So, although the accuracy of the polarimeter is fixed, the wavelength interval can be selected to be as large as possible within the alias limit (13) to maximise the DGD accuracy. Generally, for the Stokes Parameter Evaluation methods, accuracy is approximately 2 % of DGD.

3.3.4 Summary

This technique is certainly capable of measuring PMD in components, and can measure low values in a restricted spectral range. For a bandwidth of 0.2 nm, and phase angle of 0.03

radians, the lower limit for PMD is 191 fs. This gives a figure of merit of 200. Ideally, this would be greater than 400.

Stokes Parameter Evaluation methods determine DGD by measuring the polarisation state of light at the output of a DUT, and PMD from the distribution of these DGD values. It is possible to identify if there is more than one birefringent element in a device using this method, although it is of limited use without prior knowledge of the device structure. Also, as normalised Stokes Parameters are measured, the sensitivity to spectral shape is removed. A further advantage of this technique is its ability to remove erroneous contributions to the components PMD of polarisation-insensitive and polarisation-sensitive origins.

The main disadvantage of this technique is that the accuracy decreases as measurement wavelength interval decreases. So, measurement of a narrowband device is possible, but at reduced accuracy.

3.4 Phase Shift Technique

The principle of this technique is to directly measure the group delay of light travelling through an artefact, having launched the light into its principle states of polarisation.

This technique can be implemented in two ways, one being the Modulation Phase Shift (MPS) Method and the other, the Differential Phase Shift (DPS) Method.

3.4.1 Modulation Phase Shift

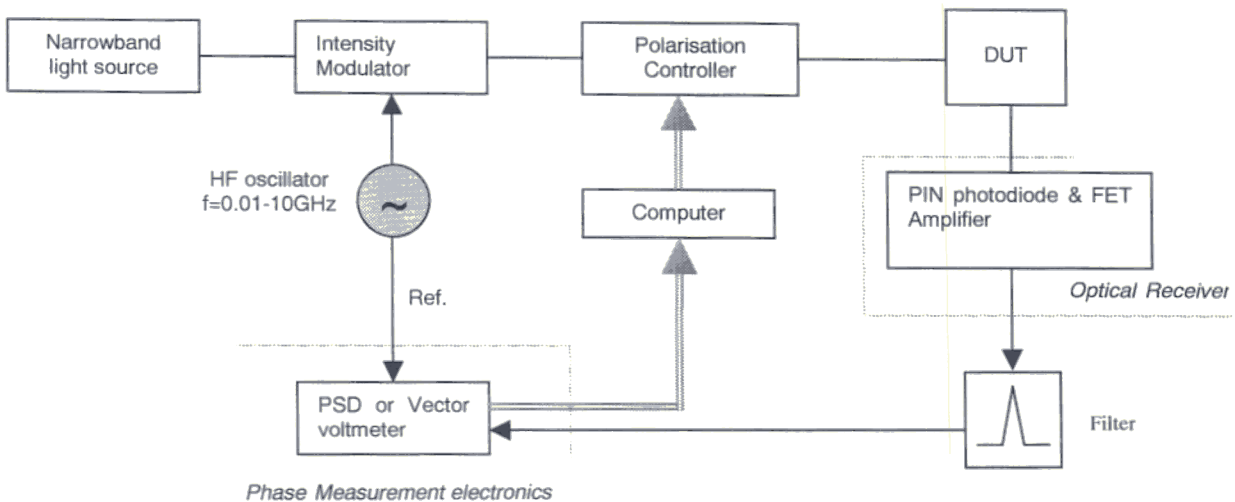


Figure 5: Modulation Phase Shift system for PMD measurement.

The basic layout of the system shown in Figure 5 is for the Modulation Phase Shift Technique [22, 23]. Polarised light from a narrowband source, such as a laser, which has been RF broadened, is intensity modulated by a Mach Zender modulator, and passed to a polarisation controller. The polarisation controller sets the polarisation state of the light, which is inputted to the device under test. The light will experience a group delay as it travels

down the fibre, and the magnitude of this group delay is shown by the phase shift of modulation of the light.

An optical detector, such as a PIN photodiode, and an amplifier, such as a FET amplifier, are placed after the DUT, and by filtering the detector signal at the modulation frequency, the information is retrieved. In order to determine the phase change of the light through the optical system, a phase sensitive detector or vector voltmeter compares the phase of the signal from the optical detector with the reference phase on the modulator.

DGD $\Delta\tau$ is found by launching light down the principal axes, and is given by equation (15). When the polarisation state is set to coincide with light being launched down the fast axis of the fibre, the phase shift ϕ_+ is a minimum, and for the polarisation state that causes light to travel down the slow axis, the phase shift ϕ_- is a maximum.

$$\Delta\tau = \frac{\phi_+ - \phi_-}{360^\circ f} \quad (15)$$

where:

f is the modulation frequency of the Mach Zender modulator.

One way of finding the fast and slow axes is to scan across all polarisation states and use this information to set the correct state. Once one PSP is found, the polarisation controller easily sets the other too, as it is orthogonal when no PDL is present.

Alternatively, it has been shown [24] that the DGD is deducible from 4 launched states which form a Muller set. A Muller set consists of 3 states that lie along a great circle and are spaced by 90° on the Poincaré sphere, and one state that lies along the axis of this great circle. This eliminates the need for the states to be launched down the PSP's to find the DGD. DGD is now calculated from (16), (17) and (18).

$$\Delta\tau = \frac{\delta_{rf}}{2\pi f}$$

where:

δ_{rf} in radians, is polarisation dependent phase offset, and is calculated from the phase values of the 4 launched states, $\phi_{RF,A}$, $\phi_{RF,B}$, $\phi_{RF,C}$ and $\phi_{RF,D}$.

$$\delta_{rf} = 2 \tan^{-1} \left[\{ \tan^2(\phi_{RF,A} - \Phi) + \tan^2(\phi_{RF,B} - \Phi) + \tan^2(\phi_{RF,D} - \Phi) \}^{1/2} \right]$$

where:

Φ is the polarisation independent phase offset.

$$\Phi = \frac{(\phi_{RF,A} + \phi_{RF,C})}{2}$$

where:

$\phi_{RF,A}$ and $\phi_{RF,C}$ represent orthogonal polarisation states.

3.4.2 Differential Phase Shift Method

For the Differential Phase Shift technique [22] the polarisation state is alternated between the fast and slow axes at a low frequency. To achieve this extra modulation a polarisation

switcher is added before the polarisation controller in the basic setup. It is activated by a low frequency oscillator.

A lock-in amplifier is connected to the low frequency oscillator and locks in to the output signal of the vector voltmeter or phase sensitive detector, hence measures the phase delay between the fast and slow modes directly. The amplitude of the signal is proportional to the DGD, defined by equation (19).

$$\text{DGD}(\lambda) = \frac{\Delta\phi(\lambda) - \Delta\phi'(\lambda)}{360f} \quad [\times 10^{12} \text{ for ps}] \quad (19)$$

where:

$\Delta\phi(\lambda)$ differential phase of the device, in degrees,

$\Delta\phi'(\lambda)$ differential phase of a calibration fibre, or phase offset of the system, in degrees,

λ wavelength, nm.

A reference fibre of known [22] DGD is measured to calibrate the system.

The differential technique could offer an advantage over MPS in improved DGD resolution, or a narrower bandwidth requirement.

3.4.3 Capabilities and Limitations of the Phase Shift Technique

Table 4 shows the capabilities of the Phase Shift Technique. Both phase angle and modulation frequency limit the DGD that can be measured. At a modulation frequency of 1.92 GHz, a phase angle of 0.1° defines a DGD of 145 fs. This leads to a figure of merit of 1800. A smaller phase angle will lower the detectable level of DGD, and in turn increase the FOM. A phase angle of 0.069° is required to achieve a DGD measurement of 100 fs. A modulation frequency of 2.8 GHz will also lower the detectable level of DGD, but does not increase the figure of merit as the measurement bandwidth, taken to be twice the modulation frequency, also increases. For a phase angle of 0.1° , a modulation frequency of 2.8 GHz is needed to detect levels down to 100 fs.

This system is capable of measuring DGD at a single wavelength point, and so can operate unhindered in restricted bandwidth conditions with both transmissive and reflective devices.

The bandwidth of the device, however, must be larger than the source spectral width and sidebands that occur at $\pm f$ away from central wavelength. So, for 1550 nm, with a modulation frequency of 1.92 GHz, there will be sidebands at 1549.985 nm and 1550.015 nm

Phase angle	Modulation frequency, f	DGD, $\Delta\tau$	Figure of Merit
0.069°	1.92 GHz	0.1 ps	2600
0.1°	2.8 GHz	0.1 ps	1800
0.1°	1.92 GHz	0.145ps	1800
1°	1.92 GHz	1.45 ps	180
10°	1.92 GHz	14.5 ps	18

Table 4: Evaluation of a Figure of Merit for the Phase Shift Technique.
Bandwidth is $2 \times$ modulation frequency.

3.4.4 Resolution

The phase detection unit limits the performance of the system as described previously. Typically the smallest phase angle is 0.1° .

Modulation frequency also affects the DGD resolution, and can be chosen to achieve the PMD required. To increase the DGD measurable, the modulation frequency must be lowered, and to decrease the DGD measurable, the frequency must be raised.

As the aim is to reduce the detectable level of DGD it would be beneficial to increase the frequency, but at the same time avoiding using too high a frequency which might cause a 2π phase ambiguity. The maximum frequency $f_{\max}$ can be calculated from equation (20).

$$f_{\max} = \frac{10^{12}}{\text{DGD}_{\max}} \quad (20)$$

where:

$\text{DGD}_{\max}$ is maximum DGD in ps,
 $f_{\max}$ is in Hertz.

Practically, the chosen modulation frequency may be determined by what is available for use.

3.4.5 Accuracy

If the Phase Shift Technique is implemented by scanning over all possible polarisation states to find the PSP (effectively, scanning the Poincaré sphere), the accuracy can be affected if the PSP's are not located correctly. If 300 states are launched, evenly distributed on the Poincaré sphere, then there is a possible misalignment in a PSP axis of 6° . This gives a systematic DGD error of less than 0.5 % [24].

3.4.6 Summary

The Phase shift method measures DGD by measuring the phase shift of light from one principal state of polarisation to the other. The PSPs can be found by sampling over the entire Poincaré sphere. An alternative is to launch states that form a Muller Set, which eliminates the need to find the PSPs measuring the DGD.

It is advantageous to use this method to measure the DGD of components with restricted bandwidths as DGD is found at a single wavelength point without the need to scan over a spectral range. The lowest DGD detectable, for a modulation frequency of 1.92 GHz and phase angle of 1° , is 145 fs. This leads to a figure of merit of 1800, where the bandwidth is taken as twice the modulation frequency due to the sideband that are created by modulation.

A further advantage of the Phase Shift technique is its removal of non-polarisation sensitive reflections. A disadvantage is that it does not remove polarisation sensitive reflections.

4. COMPARISON OF TECHNIQUES

The techniques that have been described in this report are compared in Table 5. The parameters used for the comparison, in the first column of the table, are explained in requirements/definition of the problem section (Section 2) as being those relevant to consider when choosing a technique to measure the polarisation mode dispersion of a component.

	Interferometric (Section 3.1)	Fixed Analyser (Section 3.2)		Stokes Parameter Evaluation* (Section 3.3)	Phase Shift, Modulation & Differential (Section 3.4)
		EC	FT	JME	
Figure of Merit	1		1	200	1800
Operate when PDL > 1 dB	x		x	x	x
PMD Level	Minimum 40 ps	Minimum 40 ps		Minimum 191 fs	Minimum 145 fs
Ability to Operate in a Limited Spectral Range	x needs broadband source (for low coherence)	x needs 2 extrema	✓ possible, but with increased uncertainty	✓ possible, but with increased uncertainty	✓
Deterministic PMD measurement	✓		✓	✓	✓
Distinguish between several birefringent elements	✓ multiple peaks on ratio plot	x must have prior knowledge of elements	✓ multiple peaks on plot, but could be complicated by intermodulation products	✓ but difficult without prior knowledge	x
Able to operate in the presence of reflections and multipath dispersions	x but can be overcome with effort	✓ due to source normalisation. Polarisation-insensitive only		✓ due to source normalisation. Polarisation sensitive and insensitive.	✓ due to differential phase shift. Polarisation- insensitive only.
Distinguish component PMD from Fibre pigtails	SM fibre	✓		✓	✓
	Hi- Bi or PM fibre	✓	x	✓	x

Table 5: Comparison techniques used to measure Polarisation Mode Dispersion against the requirements for component measurement.

*The SOP and PSA methods are not shown in the table as they have much the same qualities as the JME.

From Table 5 it is important to note that:

- The Phase Shift technique has the highest figure of merit of 1800, suggesting that it is a better technique than the other three to use for PMD measurement of components.

- None of the techniques are able to measure PMD in the presence of polarisation dependent loss. Therefore, it is important to know if a device has PDL, and if so, decide if it is appropriate to measure PMD.
- The Phase Shift method is the only method that is able to operate in a limited spectral range without being compromised.
- For a component with a bandwidth of 0.2 nm, only the Stokes Parameter Evaluation and Phase Shift Methods approach the target of measuring a PMD of 100 fs. The Phase Shift method should achieve the lowest measurable PMD of 145 fs.
- All of the techniques are able to measure PMD if it is deterministic, as may be the case for a component, as well as random, as is the case for single mode fibre.

If a component is made up of more than one birefringent element, the Interferometric method is the only method that could distinguish between the elements without difficulty.

- All techniques, except the Interferometric, are able to operate in the presence of polarisation insensitive reflections and multipath dispersions. However, the Stokes Parameter Evaluation alone can be used for those of polarisation sensitive origins.
- Fibre pigtails made from single mode fibre pose no problems to any of the techniques. If, however, the pigtails are made of highly birefringent or polarisation maintaining fibre, the Phase Shift and Fixed Analyser by Extrema Counting techniques are not able to distinguish the pigtails' from component PMD.

5. CONCLUSION

The aim of this report was to identify the requirements associated with measuring Polarisation Mode Dispersion in components and to identify a measurement technique that could be used effectively given the restrictions.

An assessment of the requirements showed that a device might have deterministic PMD, with one or more birefringent element, and that there may be reflections within the device between elements. The pigtails of the component may be single mode fibre or Hi-Bi or polarisation maintaining fibre, and may contribute to the PMD of the device. It could operate in a restricted bandwidth, and have a low level of PMD. Some devices may also have a characteristically high Polarisation Dependent Loss. It may be inappropriate to measure the PMD of devices with high PDL.

A literature-based evaluation was carried out of four systems: the Interferometric, Fixed Analyser, Stokes Parameter Evaluation, and Phase Shift systems.

It is recommended that a Phase Shift system be constructed to measure component PMD. Of primary importance is that, of the techniques evaluated, the Phase Shift technique can be used to measure the lowest PMD levels, with the possibilities of improvement with better electronics. Also, the Phase Shift technique requires only a single wavelength to make measurements, and so is well suited to components with narrow bandwidths. These two factors combine to give this technique a figure of merit of 1800, which is better than the other three techniques. Table 6 summarises these results.

	Figure of Merit	Lowest PMD for a 0.2 nm bandwidth
Interferometric	1	40 ps
Fixed Analyser	1	40 ps
Stokes Parameter Evaluation	200	0.19 ps
Phase Shift	1800	0.15 ps

Table 6: Summary of the Figure of Merit and lowest PMD levels measurable for four PMD measurement techniques.

The Stokes Parameter Evaluation techniques should also be capable of measuring PMD in components, but this may not be to such a low level or in such a restricted bandwidth as with the Phase Shift system. The advantage that the Stokes Parameter Evaluation technique has over the Phase Shift technique is that it is better able to distinguish between birefringent elements.

As a Stokes Parameter Evaluation system already exists at NPL, it can be used complementary to the Phase Shift system to measure PMD in components.

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