

REPORT

MEASUREMENT REQUIREMENTS AND METHODS FOR: OPTICAL FIBRE POLARISATION CONTROLLERS

David J Ives

April 2004

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Approved on behalf of Managing Director, NPL
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1. EXECUTIVE SUMMARY

Optical fibre polarisation controllers are widely used components with applications ranging from simple polarisation alignment to polarisation tracking and scrambling. Given the wide range of applications and uses there is a corresponding wide range of types and forms from simple manual Lefèvre loops to bulk optic rotating waveplates.

This report describes the types of polarisation controller available, the applications, the requirements of the applications and the suitability of the various types for particular applications. The report also describes the characteristics requiring measurement and assessment along with techniques for this assessment. A number of polarisation controllers were tested using the techniques described to illustrate the techniques and assess their suitability.

The report is written as part of the NMS Programme for Photonics Metrology GBBK/C/011/00005 as part of milestone 2.2.4.3.

2. OPTICAL FIBRE POLARISATION CONTROLLERS

2.1 Definition

Optical fibre polarisation controllers and scramblers are optical fibre components that allow the manipulation of the state of polarisation of the light that passes through them. They can be active or passive with either electronic or manually adjustment. This report will concentrate on single mode devices designed to work in the 1550 nm transmission window. Polarisation controllers allow the adjustment or setting of the state of polarisation of the light passing through them, while polarisation scramblers attempt to remove any degree of polarisation on a time average signal. The boundary between slow polarisation scramblers and electronically controlled polarisation controllers is blurred.

2.2 Types and Technology

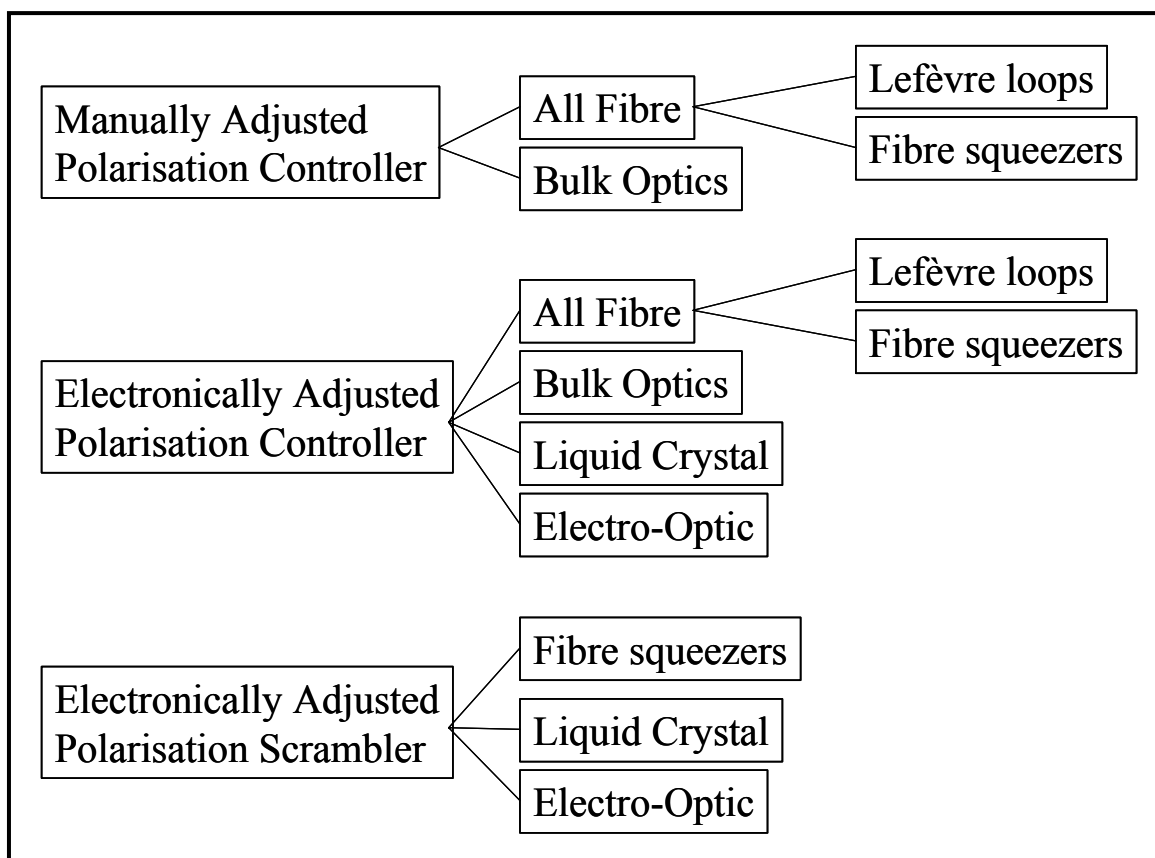


Figure 1 Types of Polarisation Controller.

We can break the technology into two basic types, electronically adjustable and manually adjustable.

Manually adjustable polarisation controllers can be broken into all fibre and bulk optics types. The bulk optics types consist of an expanded beam into which is typically placed a linear polariser followed by a quarter waveplate and finally a half waveplate. The all fibre devices use strain-induced birefringence in the fibre^[1], either in the form of Lefèvre loops^[2] or by squeezing the fibre. The fibre elements can be rotated to adjust the state of polarisation.

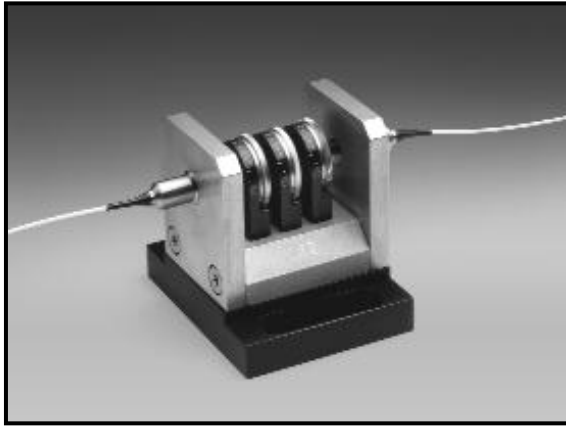


Figure 2 Manual Bulk Optic PC

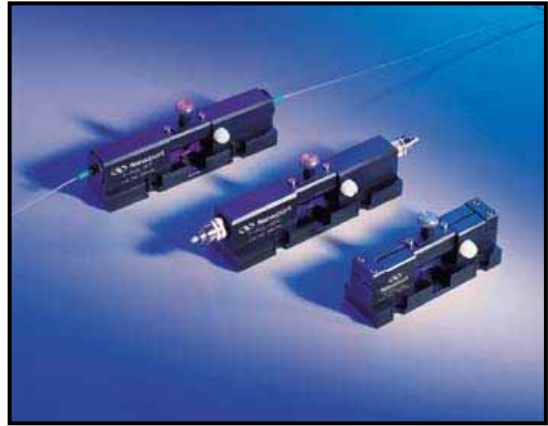


Figure 3 Manual Twist & Squeeze PC



Figure 4 Manual all fibre Lefèvre loop PC

Electronically adjustable polarisation controllers can be broken into those intended for polarisation adjustment and setting and those intended for reducing the time averaged degree of polarisation, polarisation scramblers.

Polarisation scramblers can be based on; all fibre technology with piezo or magnetic fibre squeezers, liquid crystal technology or electro-optic technology. These tend to be formed of three or four elements with their birefringent axis aligned at 45° and with the phase retardance of each element controlled. The speed and losses depend strongly on the technology used.

Electronically adjustable polarisation controllers can be based on all fibre technology with piezo squeezers or motorised Lefèvre loops, liquid crystal technology, electro-optic technology or bulk optic technology with motorised waveplates.

2.3 Typical Applications

There are a wide variety of applications for polarisation controllers. The basic task is to adjust an input polarisation state to an output polarisation state. An example is between a laser source and a modulator where the modulator is polarisation sensitive to align the optical signal for maximum transmission or modulation. In stable environments where the lengths of fibre are short manual polarisation controllers of the all fibre type are suitable for this application offering minimum insertion loss and a quick cheap solution. Where there may be some change in the input state of polarisation due to environmental conditions acting on long fibre lengths then electronically adjustable polarisation controllers that can track those changes are used.

Polarisation scramblers are used to reduce polarisation effects associated with optical fibre measuring equipment. They can be placed immediately prior to a power meter or on the output of an OTDR to reduce the polarisation dependence of the measurement. Such scramblers need to reduce the time-averaged degree of polarisation to zero while covering the whole of the Poincaré sphere. Depending on the measurement equipment the speed of scrambling will be important.

The measurement of PMD, PDL, PDR often requires the generation of known states of polarisation, requiring polarisation controllers with known and stable characteristics. The measurement of PDL by random scanning the polarisation state over the entire Poincaré sphere can make use of slow speed electronic adjusted polarisation controllers or manual PC that can provide good coverage of the entire Poincaré sphere while maintaining a constant insertion loss.

PMD compensation technology requires tracking of polarisation states and adjustment of PMD compensation elements. This requires reset free control of polarisation state so that tracking can be continuous without interruption. PMD emulation to test dynamic PMD compensation requires similar technology to PMD compensation in the form of polarisation controllers to adjust the coupling between DGD elements.

3. TYPICAL SPECIFICATIONS BY TYPE

3.1 Manually adjusted Polarisation Controllers

A survey of available manual adjustable polarisation controllers found the optical specifications shown in Table 1.

Manufacturer	FiberControl	FiberControl	FibrePro	FibrePro	FibrePro	General Photonics	OFR
Model	FPC	FPC-8CH	PC1000	PC1100	PC1200	PolaRITE	FiberBench
Type	3 Lefèvre loop	3 Lefèvre loop	3 Lefèvre loop	2 Fibre QP	3 adjust	Twist & Squeeze	LP QP HP
Insertion Loss (dB)	0.1	0.1	Negligible	0.5	0.5	0	
Insertion Loss Variation (dB)							
PDL (dB)	0.005	0.002					
Return Loss (dB)				60	40	69	
PER (dB)	33	36		20	30	40	
PMD (ps)							

Table 1 Survey of specifications of manual adjusted polarisation controllers (LP = Linear Polariser, QP = Quarter waveplate, HP = Half waveplate).

These relatively simple devices have few parameters beyond those traditionally specified for any fibre component; insertion loss, return loss and PDL. The only subtle difference is the specification of PER (Polarisation Extinction Ratio). In this instance the PER is defined as the ratio of the power in the principle polarisation to the power in the orthogonal polarisation. The difference from the usual PER definition is that the principle polarisation state is not restricted to the linear polarisation state aligned with the slow axis as for HiBi components but is defined so as to maximise the PER.

3.2 Electronically adjustable Polarisation Controllers

Tables 2 and 3 show the specification of a number of electronically adjusted polarisation controllers split into the slower all fibre and bulk waveplate types and the faster liquid crystal and electro-optic types.

Manufacturer	Agilent	Agilent	FiberControl	FibrePro	FibrePro	JDS Uniphase
Model	8169A	11896A	MPC1	PC1300	PC4000	PR Series
Type	LP QP HP	4 fibre QP	3 Lefèvre loop	2 Fibre QP	2 QP	LP QP HP
Control	Motor + Encoder	Motor + Encoder	Stepper	Stepper	Stepper	Stepper
Insertion Loss (dB)	1.5	1.5	1	0.5	0.5	1.5
Insertion Loss Variation (dB)	0.1	0.1		0.02	0.02	0.1
PDL (dB)			0.002			
Return Loss (dB)			60	60	60	45
PER (dB)	40	40	40	20	20	40
PMD (ps)						
Rotation resolution (°)	0.18	0.18	0.15	0.225	0.225	0.075
Rotation Speed (°/s)	3600	360	2880	1575	1350	144

Table 2 Survey of specifications of electronically adjusted polarisation controllers, all fibre and waveplate types (LP = Linear Polariser, QP = Quarter waveplate, HP = Half waveplate).

Here we still have the usual optical fibre component parameters of insertion loss, return loss, PDL and PER (with the subtle difference in definition). In addition to these a specification for insertion loss variation has been introduced. This is the variation of insertion loss as the polarisation controller is moved through all possible control positions. For the all fibre and waveplate type polarisation controllers we also have a specification for the angular resolution and speed of the drive mechanism. The faster liquid crystal and electro-optic type polarisation controllers include a response speed or bandwidth and a drive amplitude specification.

Manufacturer	JDS Uniphase	Lighthwaves2020	EO Space	E-TEK Dynamics
Model				FPCR-1B
Type	LiNbO ₃	Liquid Crystal	LiNbO ₃	Liquid Crystal
Control	8 Stage	3 or 4 stages	3 to 8 stage	4 stages
Insertion Loss (dB)	3.8		3	
Insertion Loss Variation (dB)				
PDL (dB)	0.5		0.2	
Return Loss (dB)	45		45	
PER (dB)				
PMD (ps)				
Rise / Fall time (ns)	100			
Bandwidth (MHz)			10	
V_{π} (V)	22		14	

Table 3 Survey of specifications of electronically adjusted polarisation controllers, faster types based on liquid crystals and electro-optic effects.

3.3 Active Polarisation Scramblers

Table 4 shows the specifications of a number of active polarisation scramblers.

Manufacturer	Advantest	EXFO	FiberControl	FiberControl	FibrePro	General Photonics	Sumitomo
Model	Q8163	IQS-5100B	PS-700	RCPS-600	PS3000	PolaRITE II	
Type	Scrambler	Fibre	Fibre	Resonant Coil	Fibre	Fibre	LiNbO ₃
Control			Piezo	Piezo	Piezo	4 Piezo	
Insertion Loss (dB)	3	0.1	0.75	1	1	0.05	6
Insertion Loss Variation (dB)	0.005	0.006	0.02			0.01	
PDL (dB)			0.05		0.05		
Return Loss (dB)	43	50	50	50	50	-69	
PER (dB)		40					
PMD (ps)					0.3	0.01	
Scrambling Frequency (Hz)	500	1	4.00E+06	1.00E+06	1.00E+06	6.00E+04	
DOP (%)			5	2	5		10
Sphere coverage (%)		98	95				

Table 4 Survey of specifications of active polarisation scramblers

Here we still have the usual optical fibre component parameters of insertion loss, return loss, PDL and PER (with the subtle difference in definition). In addition to these a specification for insertion loss variation has been introduced. The variation of insertion loss with polarisation control leads to a residual amplitude modulation on the transmitted signal. In addition the scrambling frequency, scrambled degree of polarisation and the coverage of the Poincaré sphere are also specified. It is possible to have a low DOP without complete coverage of the Poincaré sphere, for example if the output polarisation state circles the equator.

4. TYPICAL REQUIREMENTS BY APPLICATION

4.1 Polarisation State Adjustment

For both manually and actively adjusted polarisation controllers the typical application is to align the polarisation state from a laser source with an optical modulator. Such applications require low insertion loss, high return loss, high PER and the ability of the controller to take any input state and convert this to any output state i.e. full Poincaré sphere coverage to full Poincaré sphere coverage.

4.2 Polarisation State Generation

This application is involve with the repeatable generation of defined polarisation states, such as required to measure PMD, PDL, PDR etc. This requires the polarisation controller to be repeatable, ideally calculable with the output polarisation state being predicted from the control parameters. There may be an issue with speed and resolution of the control parameters.

4.3 Polarisation State Tracking

This application involves tracking an input polarisation state that may be varying due to environmental changes in the fibre transmission system and converting that input polarisation state to a time invariant output polarisation state. The controller will need the ability to take any input state and convert this to any output state i.e. full Poincaré sphere coverage to full Poincaré sphere coverage. There will also be a requirement on the adjustment speed and on endless tracking without resets.

4.4 Polarisation State Scrambling

Active polarisation scramblers produce a time varying state of polarisation such that the time average degree of polarisation is low. The important parameters are; the output degree of polarisation and any dependence on the input polarisation state, the time dependence of the degree of polarisation or how long before a specified DOP is achieved and the correlation time of the output polarisation state. For some measurement applications it is also important that the full Poincaré sphere is covered by the output polarisation state not just that the DOP is low. A measure of this is that the Eigenvalues of the covariance matrix of the polarisation states are $1/3$ ^[3].

4.5 PDL, PMD Measurements by defined States

This will require a polarisation controller to generate defined states of polarisation. In the case of a measurement of the PDL magnitude or PMD it is only necessary to know the relative positions of the polarisation states on the Poincaré sphere such that any rotation introduced by the fibre pigtailed is not important. For PDL measurement the insertion loss will also need to be repeatable for each control position as well as the polarisation state. For PMD it will be necessary to understand the variation of the output polarisation state with wavelength.

4.6 PDL, PMD Measurement by random scanning

This will require a polarisation state controller that can access all states across the Poincaré sphere. The speed will need to be sufficient to achieve a scan across all polarisation states in a reasonable time but slow enough to allow the measurement equipment time to record the transmitted power. For PDL measurements there is a strong requirement that the variation of insertion loss with control parameter is very low as this will likely limit the measurement accuracy. For PMD there is a requirement that the intrinsic PMD of the polarisation controller is very low.

4.7 PMD Compensation

This will require a polarisation state controller that can convert any input state of polarisation to the required output state. The polarisation controller needs to be sufficiently fast to follow the variations in the input state of polarisation and the control needs to be endless such that there is no need to reset control elements which might cause a brief interruption in the tracking.

5. CALIBRATION METHODS

5.1 Insertion Loss

Measuring the insertion loss of a polarisation controller is an identical measurement problem to that of measuring the insertion loss of any optical fibre component. There are two basic techniques available, the cut back technique and the substitution technique.

For polarisation controllers without connectors and long pigtail leads the cut back technique will provide the greatest accuracy. Such a measurement set up is shown in Figure 5. Light is launched into the input pigtail of the device under test and collected from the output pigtail. This first measurement records the output light intensity either at a fixed wavelength or over a wavelength range as specified. The input pigtail of the device is then cut and the light exiting the input pigtail collected and recorded. The insertion loss of the device under test is calculated from the measured input and output light intensities. This is the same experimental set up as used to measure the spectral attenuation of optical fibre and has a proven uncertainty of ± 0.03 dB (95% confidence level).

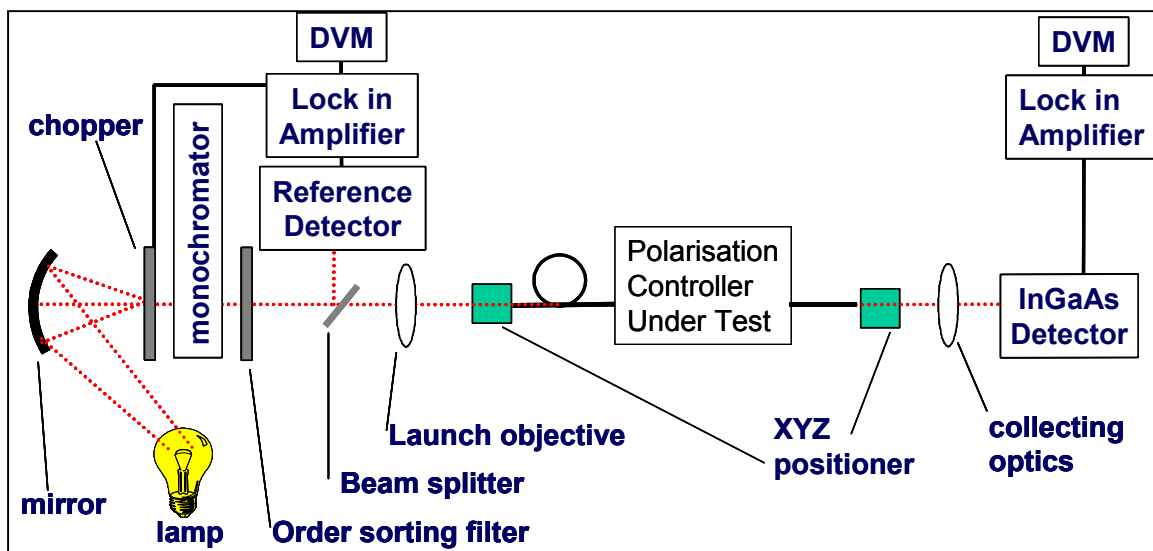


Figure 5 Layout of a traditional cut back spectral attenuation measurement.

The disadvantage is that the device input pigtail will be reduced in length by some 25m during the course of repeat measurements. It may be necessary to extend the initial pigtail by fusion splicing a length of similar fibre onto it. The actual loss of the fusion splice could be measured after measurements have been made on the device under test. For example if the pigtail were extended by 50m then following initial measurements of the insertion loss of the fusion splice and polarisation controller under test are measured the pigtail extension will be reduced to 25m leaving sufficient pigtail to measure the insertion loss of the splice, see Figure 6. The polarisation controller pigtail will be reduced by one small cut perhaps 0.5m. This will increase the uncertainty to 0.05 dB (95% confidence interval).

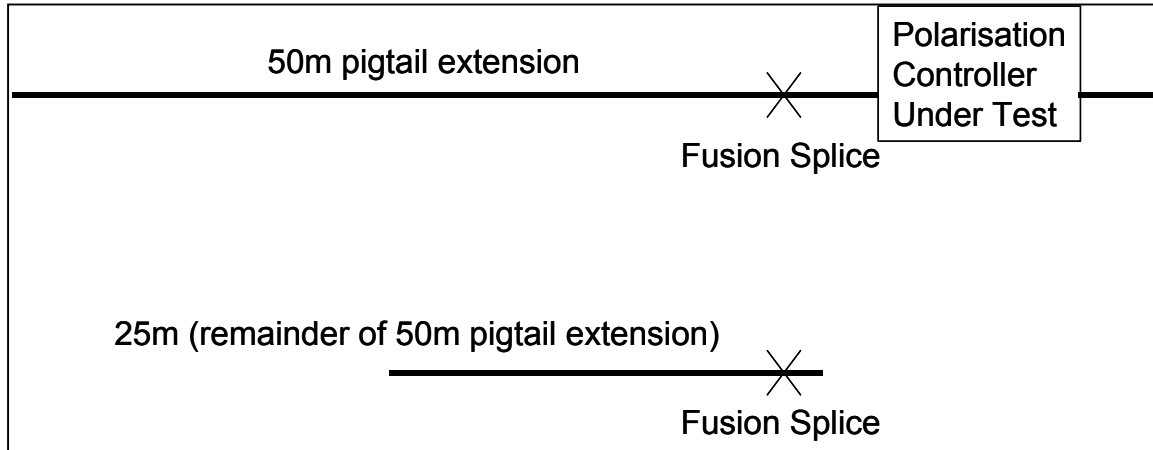


Figure 6 Layout of measurements with pigtail extension.

The substitution technique is suitable for connectorised devices. The transmission through the polarisation controller under test is compared with the transmission of a simple patch lead. In both cases there are an equal number of connector joints thus the insertion loss of the polarisation controller under test less its connectors is measured. The insertion loss is given by

$$\text{Insertion Loss} = 10 \text{ LOG} \left[\frac{P_{\text{REF}}}{P_{\text{DUT}}} \right] \quad (\text{dB}) \quad (1)$$

where P_{REF} and P_{DUT} are the measured optical power see Figure 7.

The uncertainties will be limited by the repeatability of connector joints. Previous trials have found that FC/UPC connectors have a repeatability of ± 0.4 dB (95% confidence interval) such that the insertion loss uncertainty could be as high as ± 0.8 dB (95% confidence interval).

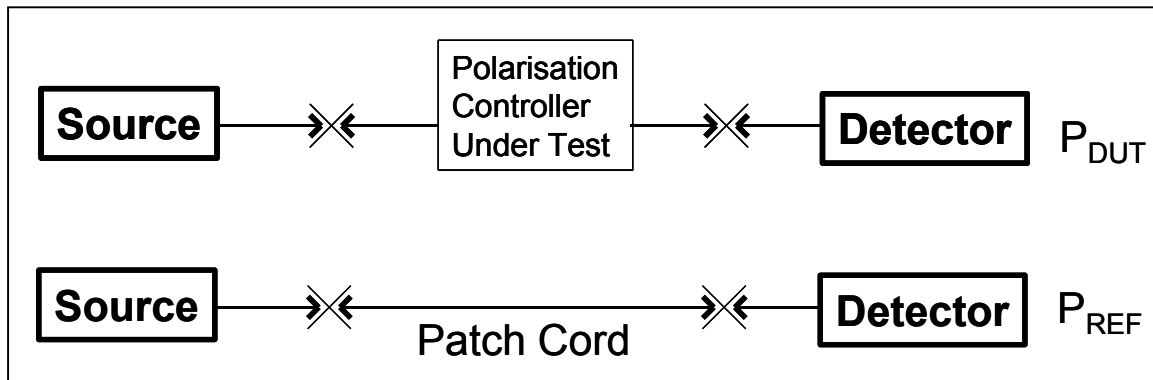


Figure 7 Layout of measurements for substitution technique.

5.2 Insertion Loss variation

The variation of the insertion loss with control parameter can be measured using a source and polarisation independent receiver. The layout is shown in Figure 8. For various polarisation input states generated by the programmable polarisation controller the transmitted power and reference power are recorded. For each input state the insertion loss variation (ILV) is defined as the maximum insertion loss less the minimum insertion loss.

$$ILV_{dB} = IL_{max} - IL_{min} = 10 \text{ LOG} \left[\frac{\left(\frac{P_{out}}{P_{ref}} \right)_{max}}{\left(\frac{P_{out}}{P_{ref}} \right)_{min}} \right] \quad (2)$$

where P_{out} is the measured output power and P_{ref} the measured reference power and the max and min refer to the maximum and minimum of the ratio. The maximum and minimum of the ratio is taken over each input polarisation state separately, the final ILV is given as the maximum ILV for all of the input polarisation states.

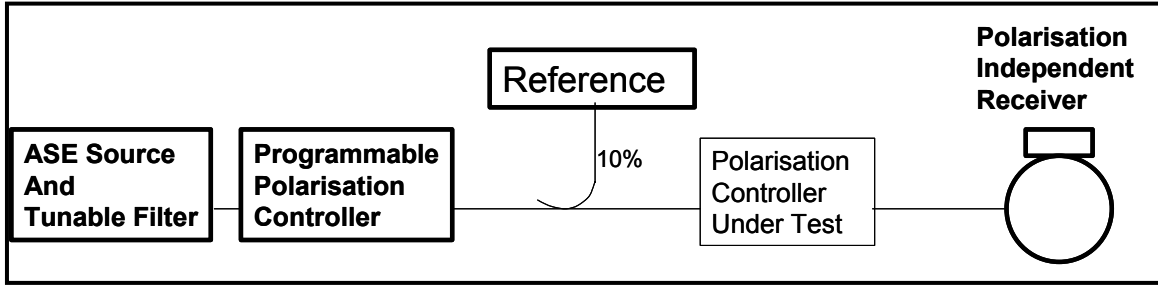


Figure 8 Layout of a possible experiment to measure insertion loss variation.

The uncertainty of the measurement is limited by the source stability over the time taken to vary over all control states and the receiver polarisation dependence. By using a filtered ASE source with a pick off detector the short term source stability could be as low as 0.1 % and by using an integrating sphere detector the PDR can be as low as 0.002 dB. This could result in a measurement uncertainty of 0.01 dB (95% confidence). Great care will need to be taken with manual polarisation controllers not to adversely affect the fibre pigtailed while controlling the polarisation state. With high-speed polarisation scramblers it will be necessary to find a polarisation independent receiver with suitable bandwidth.

5.3 Return Loss

Return loss is the effective loss experienced by the backward returned signal from the polarisation controller under test and is given by, RL (dB),

$$RL_{dB} = 10 \text{ LOG} \left[\frac{P_{Return}}{P_{Input}} \right] \quad (3)$$

where P_{Return} is the returned power and P_{Input} is the incident power. Typically the return loss does not include the connectors so the incident and return power should be those as measured in the polarisation controllers input fibre. The return loss can be measured using a calibrated return loss meter or a calibrated OTDR, in both instances a reference return loss will be required and this can be formed from a perpendicular air cleave or other standard.

For fibre pigtailed polarisation controllers the input pigtail is spliced to the return loss meter or the lead in fibre of the OTDR. The output fibre pigtail is wound around a small diameter mandrel, for example 20+ turns around 6 mm diameter, to remove any return signal from the output fibre end. The number of turns can be increased until the return loss reaches a maximum. In order to reference the measurement the polarisation controller input pigtail should be cleaved just after the fusion splice.

For connectorised polarisation controllers the return signal from the polarisation controller and that from the input connector pair must be separated. The output fibre is wound around a small diameter mandrel to remove any return signal from the output fibre end and the return signal measured. The input fibre is wound around a small diameter mandrel to remove any return signal from the polarisation controller and the return signal from the connector pair recorded. The return signal from the connector pair is removed from the return signal from the polarisation controller. In order to obtain a reference return loss the input connector pair is broken, this will provide a flat end face for FC/UPC type connectors otherwise a FC/UPC patchcord should be attached. The reference signal is returned from before the polarisation controller input fibre such that an additional uncertainty due to the loss of the connection will be introduced.

If the reference is an air cleave then the reference return signal is likely to be considerably larger than the measurement of the polarisation controller. Great care will be required to ensure that the measurement equipment is linear over this range.

5.4 PER

Polarisation extinction ratio can be measured using either a calibrated polarimeter or a calibrated polarisation extinction ratio meter. The slight difference in definition will require a slight modification to the measurement set up, see Figure 9.

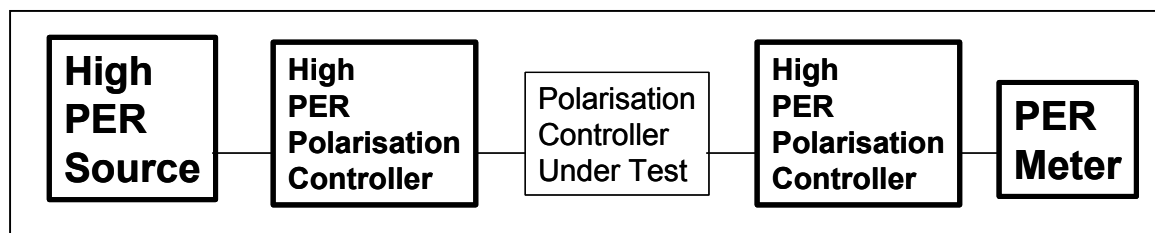


Figure 9 PER measurement set up.

A PER meter measures the polarisation extinction ratio by looking for the maximum transmission through a linear polariser and then measuring the transmission with the linear polariser rotated by 90° . The PER is given by the ratio of the maximum transmission through the linear polariser to the transmission of the linear polariser rotated by 90° to the maximum. In the case of polarisation controllers the PER refers to the ratio of the power in the principle polarisation to the power in the orthogonal polarisation and is not restricted to linear states of polarisation. Thus in order to use a commercial PER meter it is necessary to include a high PER polarisation controller to convert the polarisation state exiting the polarisation controller under test into a linear polarisation state for the PER meter. Thus the second high PER polarisation controller is adjusted to maximise the reading on the PER meter. Repeated measurements will be taken for different input states and for different control settings of the polarisation controller under test.

5.5 PDL

Polarisation dependent loss (PDL) is the variation in transmission of a polarisation controller for differing input states of polarisation while the polarisation controllers control elements remain fixed.

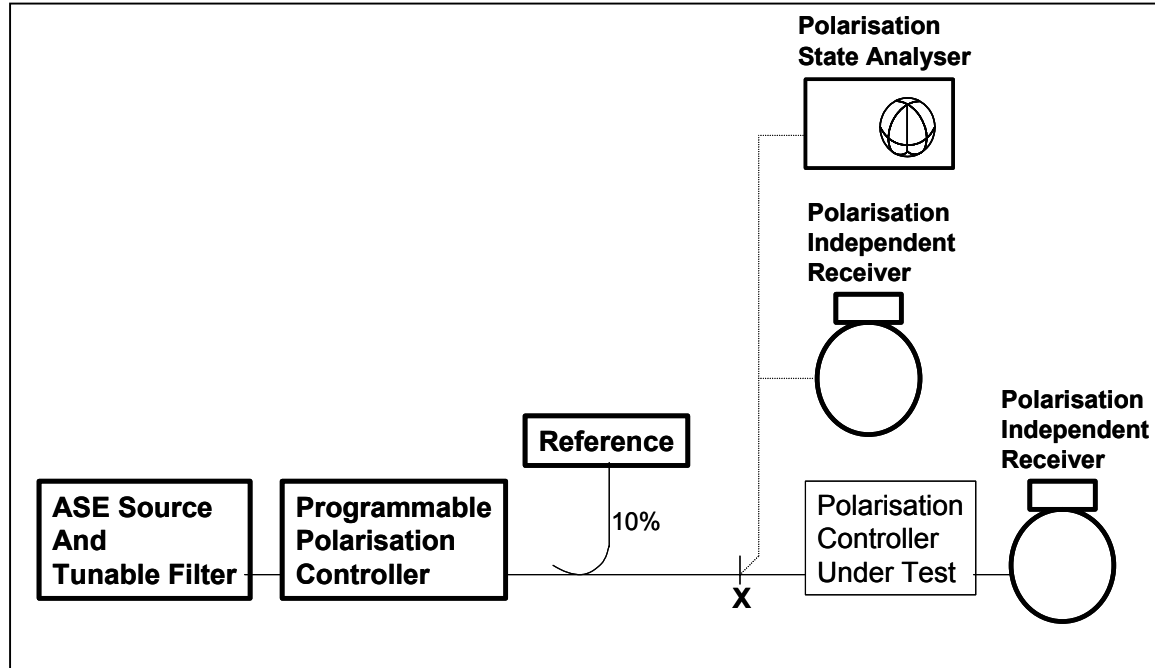


Figure 10 Experimental set up to measure PDL.

The experimental set up is shown in Figure 10 and consists of an ASE optical source and a programmable polarisation controller. The programmable polarisation controller is first connected to the polarisation state analyser and the quarter and half waveplate angles required to produce the desired polarisation states found. Six polarisation states are used; Linear Vertical (V), Linear Horizontal (H), Linear at 45° (+), Linear at -45° (-), Right hand circular (R) and left hand circular (L). Again, the exact states are not important only their relative positions on the Poincaré sphere. The programmable polarisation controller is then connected to the polarisation independent reference detector and the power for each of the six states recorded. The programmable polarisation controller is connected to the device under test and the output of the device under test connected to the polarisation independent reference detector. The power for each of the six states recorded. The relative transmission of the device under test for each input state is calculated and from this the PDL.

$$\text{PDL}_{\text{dB}} = 10 \text{LOG} \left[\frac{T_{\text{max}}}{T_{\text{min}}} \right] \quad (4)$$

where T is the relative transmission of the device under test.

The accuracy of the measurement is limited by the source stability and the polarisation dependence of the polarisation independent reference detector giving an uncertainty of approximately 0.01 dB (95% confidence interval).

5.6 PMD

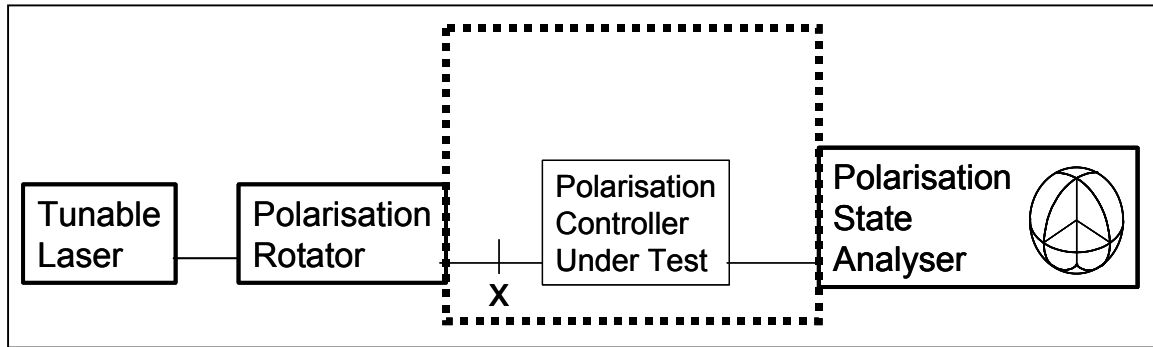


Figure 11 Experimental arrangement of PMD measurement at NPL.

The PMD of a polarisation controller can be measured in the same way as any other broadband component. The existing facilities at NPL are based on the measurement of the output polarisation state for a number of defined input polarisation states as a function of wavelength. The experimental arrangement is shown in Figure 11. Initially the polarisation state analyser is connected to the point X and the programmable polarisation controller adjusted in order to set the desired input polarisation states for each input wavelength. The device under test is then connected between X and the polarisation state analyser and the output polarisation state for each input polarisation state and each wavelength recorded.

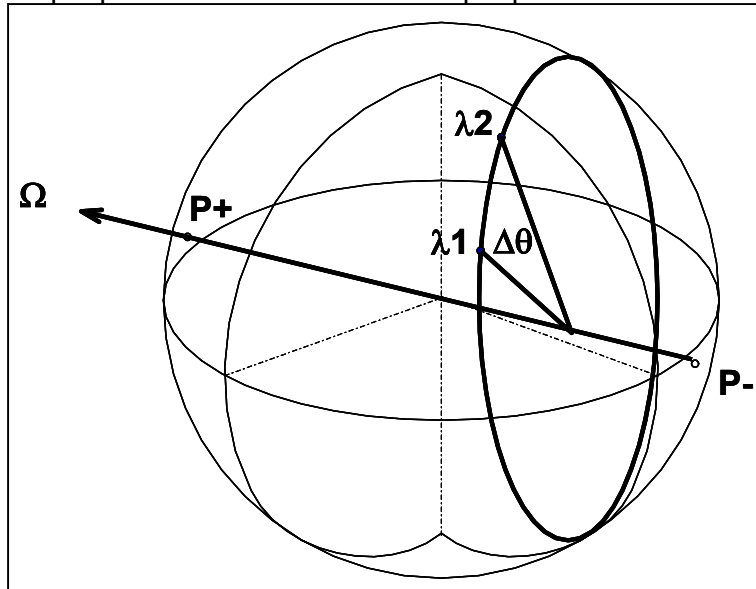


Figure 12

The data is analysed using the Stokes vector arc on the Poincaré sphere, see Figure 12. As the wavelength is changed from λ_1 to λ_2 the output polarisation state describes an arc of angle $\Delta\theta$ about the principle state of polarisation. The differential group delay, $\delta\tau$, is given by,

$$\delta\tau = \Delta\theta \frac{\lambda_1 \lambda_2}{2\pi c(\lambda_2 - \lambda_1)} \quad (5)$$

By using three input polarisation states, three arcs are described on the Poincaré sphere allowing the identification of the principle state of polarisation and a more accurate measure of the arc angle. This analysis leads to a measure of the full PMD vector and thus it is possible to calculate the change of this vector with wavelength and calculate the second order

PMD.

The accuracy of the existing system depends on the polarisation mode coupling characteristics of the device under test. For low polarisation mode coupled devices in the range 0.3 ps to 15 ps the accuracy is $\pm 2\%$ (95% confidence interval). For highly mode coupled devices such as all fibre devices the uncertainty will be limited by the statistics of the measurement, however for devices with near zero PMD (such as might exist with just a few metres of fibre) the uncertainty could be as low as ± 0.005 ps (95% confidence interval).

5.7 Sphere coverage

The primary use of many polarisation controllers is to convert any input polarisation state into any output polarisation state. A measurement set up capable of confirming this, based on a calibrated polarimeter, is shown in Figure 11.

Initially the polarimeter is connected to point X and the polarisation rotator adjusted to produce six polarisation states that cover the Poincaré sphere, for example Linear Vertical (V), Linear Horizontal (H), Linear at 45° (+), Linear at -45° (-), Right hand circular (R) and left hand circular (L).

The polarisation controller under test is connected between X and the polarimeter. For each input state the polarisation controller under test is adjusted to give six output polarisation states covering the Poincaré sphere as measured on the polarimeter, for example Linear Vertical (V), Linear Horizontal (H), Linear at 45° (+), Linear at -45° (-), Right hand circular (R) and left hand circular (L).

The maximum deviation of the set output state from the desired output state in radians for all the input and desired output polarisation states indicates the ability of the polarisation controller to transform polarisation states. This could also be expressed as a polarisation alignment penalty giving the losses associated with aligning a polarisation input state to a high extinction polariser. If the maximum deviation of the measured state from the required state is δ rads then the maximum penalty (dB) for alignment with a perfect polariser is given by

$$\text{Penalty}_{\text{dB}} = 10 \text{ LOG} \left[\cos^2 \left(\frac{\delta}{2} \right) \right] \quad (6)$$

5.8 Control Element Retardance and Azimuth

For polarisation controllers designed to generate define polarisation states the calibration of the retardance of the control elements and their relative azimuth angles is necessary. The retardance of each element may be fixed (e.g. waveplates) or variable (e.g. Liquid crystal or electro-optic elements). In each case the retardance as a function of wavelength may be required and for variable retardance elements the retardance as a function of control voltage. The azimuth angle between the elements may also be fixed or variable.

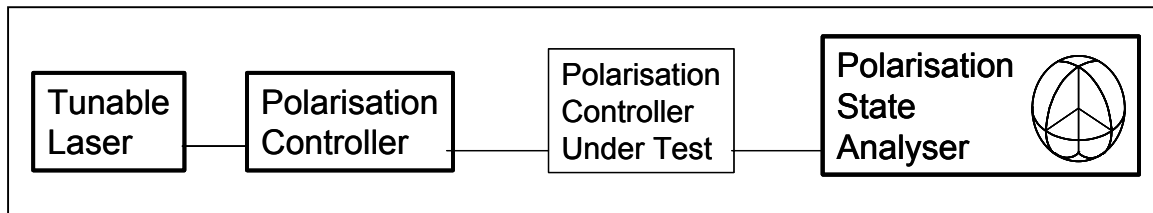


Figure 13 Experimental set up for measuring control element retardance and azimuth.

5.8.1 Fixed Retardance, Rotatable Azimuth Elements

The exact method will depend on whether the first element is a linear polariser or not. The basic technique will involve the measurement of the output polarisation state on a calibrated polarimeter as each plate in turn is rotated through 360° , see Figure 13. If the first element is a linear polariser such that a linear state of polarisation falls onto the first retarding element then as the retarding element is rotated a symmetric pattern is drawn on the surface of the Poincaré sphere, see Figure 14. The output polarisation state repeats every 180° and the pattern forms a figure of eight with the cross occurring when the axis of the plate are aligned with the linear input state of polarisation. It is thus possible to obtain the relative azimuth angles between the linear polariser and the linear retarding element. The angle between vectors drawn from the centre of the sphere to the two extremes of the pattern is equal to double the retardance phase.

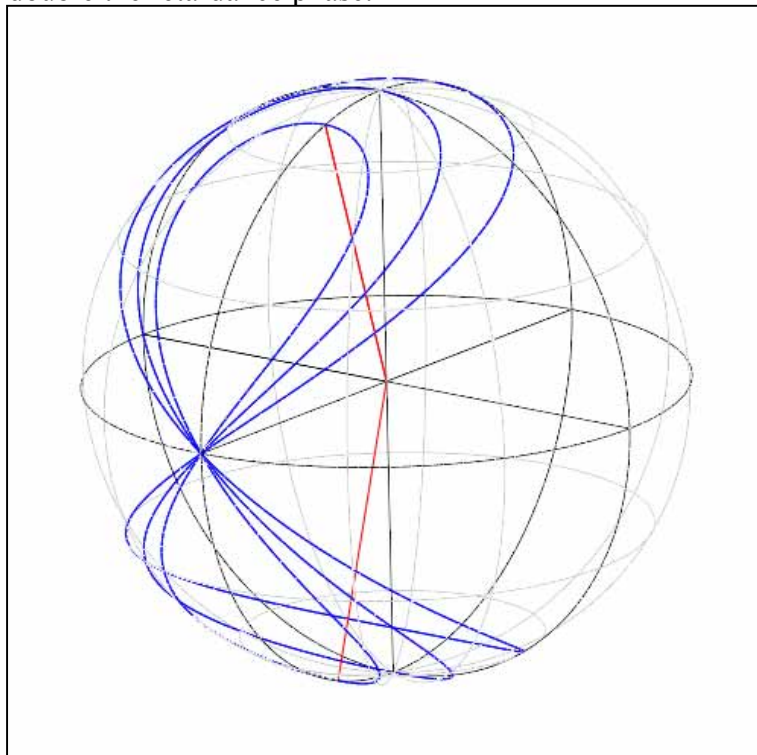


Figure 14 Showing the loci of the output polarisation state for a linear input polarisation state and three different retardances (1.27 rad, 1.57 rad and 1.87 rad) as they are rotated. The red vectors illustrate the extremes of the 1.27 rad retardance.

If the first element is not a linear polariser then the symmetry of pattern described on the surface of the Poincaré sphere depends on the input polarisation state falling onto the retarding element, see Figure 15. The angle between vectors drawn from the centre of the Poincaré sphere to the extremes is still equal to double the retardance. In order to locate the relative azimuth between the first and subsequent elements it will be necessary to adjust the

input polarisation state until it is a linear polarisation state by looking at the symmetry of the pattern.

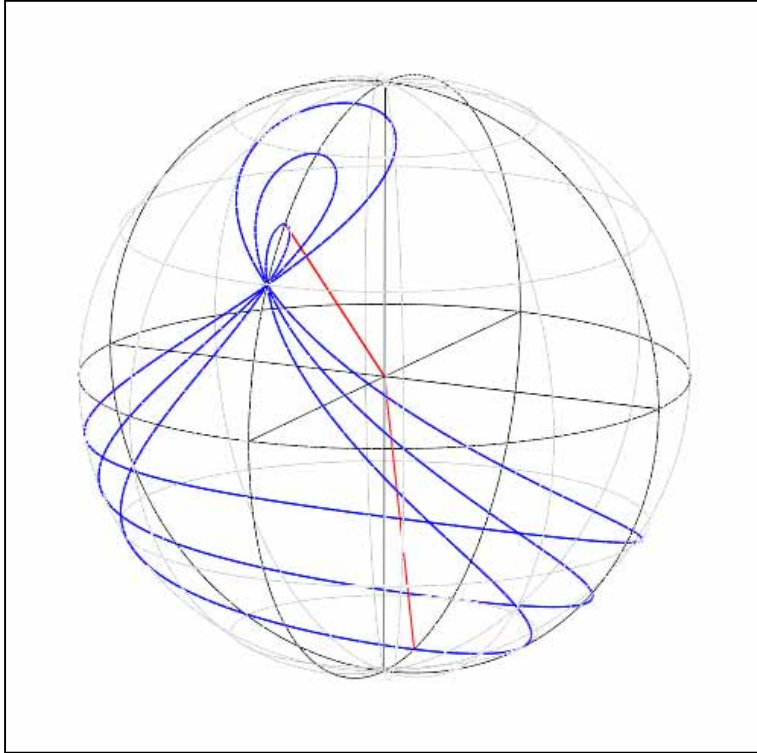


Figure 15 Showing the loci of the output polarisation state for a elliptical input polarisation state and three different retardances (1.27 rad, 1.57 rad and 1.87 rad) as they are rotated. The red vectors illustrate the extremes of the 1.27 rad retardance.

There will be an ambiguity between the fast and slow axis, and thus an ambiguity of 90° in the azimuth. There will also be an ambiguity for retardance greater than π rad, i.e. $\lambda/2$.

The loci of the polarisation vector on the surface of the sphere can be described by a curve $C(\{X_0, X_1, X_2, X_3, X_4\}, \theta)$ which is a function of the parameter θ and the fixed coefficients X_0 to X_4 . The fixed coefficients X_0 to X_4 describe a three axis rotation as the polarisation states are transformed in the fibre pigtail, the retardance of the element being rotated and the circular component of the light input to the retarding element.

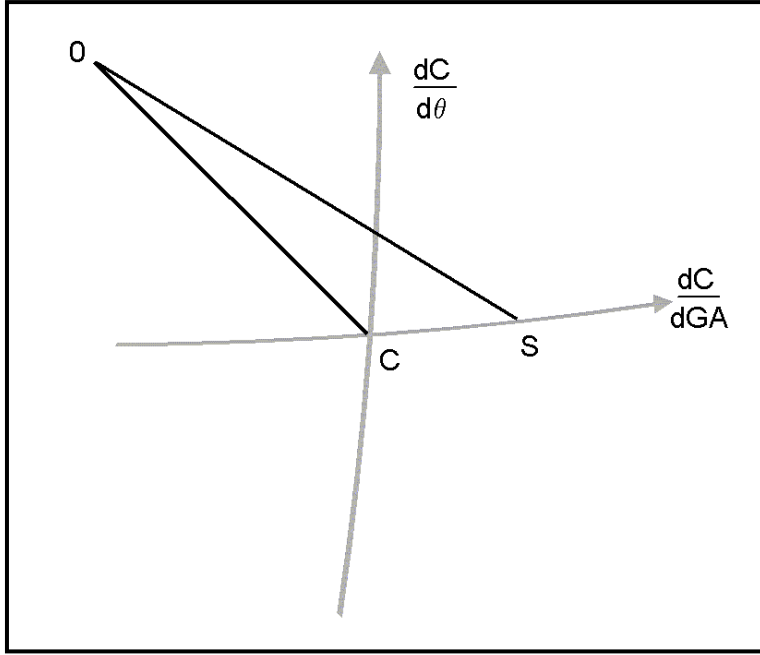


Figure 16 Vectors showing theoretical curve, C, measured polarisation, S and origin, 0.

In order to estimate the retardance of the plate the curve coefficients are optimised to fit the measured data. In order to optimise these coefficients an error between the measured point and the curve is required. In figure 16 the deviation of the measured point S from the curve C with a sign dependent as to whether the measured point S is to the left or right of the curve is used as the error deviation. For a point on the curve C and a measured point S the great arc joining these points has an axis along $C \times S$ and the vector pointing along the great arc dC/dGA is given by

$$\frac{dC}{dGA} = C \times (C \times S). \quad (7)$$

The vector pointing along the curve is $dC/d\theta$. The curve is closest to the measured point S when the vector pointing along the curve is at right angles to the vector pointing along the great arc linking C and S. This occurs when

$$\frac{dC}{dGA} \cdot \frac{dC}{d\theta} = 0 \quad (8)$$

which allows simple iteration to find θ and hence C. The angular deviation of the measured point S from the curve C is then calculated as

$$\delta C = (C \times S) \cdot \frac{dC}{d\theta} \left| \frac{d\theta}{dC} \right| \quad (9)$$

where the final terms provide the sign information.

Given this error deviation we can perform a non-linear least squares fit to optimise the curve coefficients, X_0 to X_4 . We first need good guess values for X_0 to X_4 that are obtained by visual adjustment. Then we calculate the design matrix A given by

$$A = \begin{bmatrix} \frac{\partial \delta C_1}{\partial X_0} & \frac{\partial \delta C_1}{\partial X_1} & \frac{\partial \delta C_1}{\partial X_2} & \frac{\partial \delta C_1}{\partial X_3} & \frac{\partial \delta C_1}{\partial X_4} \\ \frac{\partial \delta C_2}{\partial X_0} & \frac{\partial \delta C_2}{\partial X_1} & \frac{\partial \delta C_2}{\partial X_2} & \frac{\partial \delta C_2}{\partial X_3} & \frac{\partial \delta C_2}{\partial X_4} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial \delta C_n}{\partial X_0} & \frac{\partial \delta C_n}{\partial X_1} & \frac{\partial \delta C_n}{\partial X_2} & \frac{\partial \delta C_n}{\partial X_3} & \frac{\partial \delta C_n}{\partial X_4} \end{bmatrix} \quad (10)$$

and then perform a non-linear least squares fit giving

$$\delta X = [A^T A]^{-1} [A^T \delta C] \quad (11)$$

where δC is a column vector of the error deviation for all the measured points and δX are the estimated corrections to the guessed coefficients X . The process is iterated with the new corrected X values replacing the original guesses until δX is small. The optimum parameter θ , for each measured point is found for the optimum coefficients X and this allows the offset angle of the first point and the apparent angular step to be estimated. The offset angle gives the azimuth difference between the angle of the linear retardance axis of the first measured point and the linear component of the input polarised light.

5.8.2 Variable Retardance, Fixed Azimuth Elements

The output polarisation state is measured as each element in turn is varied. The output polarisation state will describe a circle on the surface of the Poincaré sphere, see Figure 17. The radius of the circle will depend on the polarisation state arriving at the input to the element. The output polarisation state will rotate once around the axis for each increase in retardance of 2π , and thus retardance versus control voltage can be measured. The axis of the circle is the axis of the element modified by the rotation of subsequent elements. Finding the relative angle between the azimuths of the elements can only be done if the subsequent elements can have their retardance set to $2n\pi$. The angle between vectors drawn from the centre of the Poincaré sphere and the axis of the circle is then twice the difference in the azimuths.

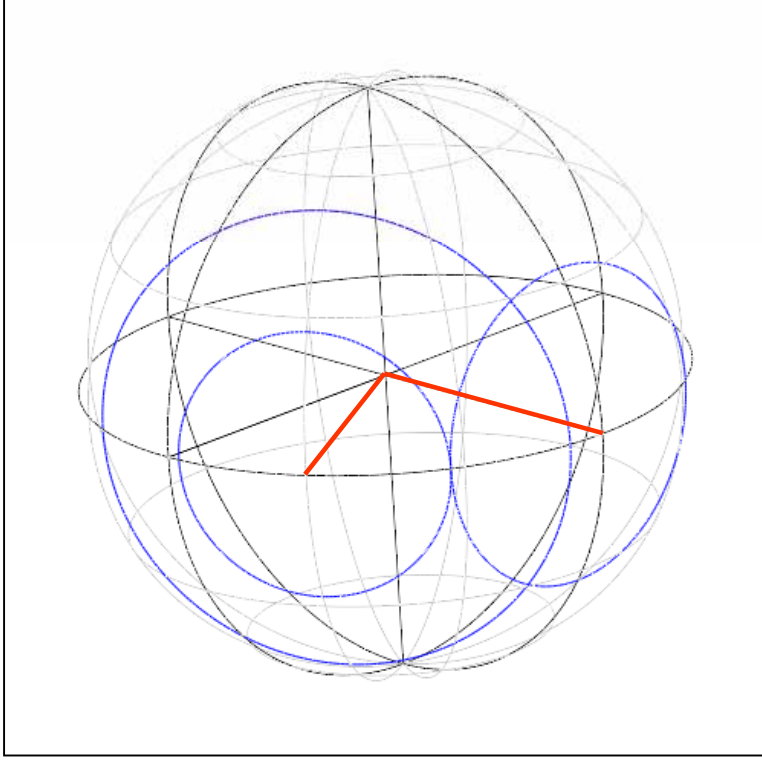


Figure 17 Showing the loci of the output polarisation state for two variable retarders, the output variation (diameter of circle) from the second retarder depends on the setting of the first. The axis of the circle depends on subsequent retarders. The red vectors show the axis of the two retarding elements, the angle between these is twice the difference in azimuth provided the following retardance elements are set with $2n\pi$ retardance.

The axis of the circle can be found using least squares. The points lie in a plane, the normal to this plane points in the direction of the circle axis. A plane is defined by,

$$c_1x + c_2y + c_3z = 1 \quad . \quad (12)$$

Thus in matrix form we have,

$$\begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_n & y_n & z_n \end{bmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = A \cdot c = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} \quad . \quad (13)$$

If we replace x, y, z with s_1, s_2 and s_3 , of the points forming the circle, then c can be found by simple linear least squares regression,

$$c = (A^T A)^{-1} (A^T I) \quad . \quad (14)$$

The normal to the plane is in the direction of the vector c and thus the normalised axis of the circle, P , can be found as $c/|c|$. The change in retardance, $\delta\beta_{a-b}$, that results in the output polarisation state rotating from s_a to s_b is calculated as,

$$\delta\beta_{a-b} = 2 \arctan \left(\frac{|s_b - s_a|}{\sqrt{(s_b + s_a)^2 - ((s_b + s_a) \cdot P)^2}} \right) \quad . \quad (15)$$

Thus within a constant offset the retardance as a function of control can be found by summation.

5.9 Scrambler DOP, Sphere Coverage and Speed

These parameters can be measured using a polarimeter and recording the polarisation state as a function of time with the scrambler running. The difficulty is that the polarimeter will need to be faster than the scrambler such that the instantaneous DOP is high. In the absence of a high speed polarimeter a low speed polarimeter can be used to measure the average DOP only.

The DOP as a function of averaging time can be calculated using

$$\text{DOP}(t) = \sqrt{\langle s_1 \rangle_t^2 + \langle s_2 \rangle_t^2 + \langle s_3 \rangle_t^2} \quad (16)$$

where $\langle s_i \rangle_t$ correspond to the linear mean of s_i over a time interval, t . The scrambling time can then be defined as the time for the DOP to reach $1/e[1-\text{DOP}(\infty)] + \text{DOP}(\infty)$ where $\text{DOP}(\infty)$ is the long term average DOP.

A measure of the sphere coverage is that the Eigenvalues of the covariance matrix of the polarisation states is $1/3$.

$$\text{cov}[s(t)] = \begin{bmatrix} \varepsilon\{(s_1(t) - \mu_1)^2\} & \varepsilon\{(s_1(t) - \mu_1)(s_2(t) - \mu_2)\} & \varepsilon\{(s_1(t) - \mu_1)(s_3(t) - \mu_3)\} \\ \varepsilon\{(s_2(t) - \mu_2)(s_1(t) - \mu_1)\} & \varepsilon\{(s_2(t) - \mu_2)^2\} & \varepsilon\{(s_2(t) - \mu_2)(s_3(t) - \mu_3)\} \\ \varepsilon\{(s_3(t) - \mu_3)(s_1(t) - \mu_1)\} & \varepsilon\{(s_3(t) - \mu_3)(s_2(t) - \mu_2)\} & \varepsilon\{(s_3(t) - \mu_3)^2\} \end{bmatrix}$$

where $\varepsilon\{x\}$ is the expectation value of x and μ_i is the mean of $s_i(t)$.

6. CALIBRATION RESULTS

6.1 Manual Twist and Squeeze

Type: All fibre Soleil Babinet Compensator
Connectors: FC/APC

6.1.1 Polarisation Dependent Loss

The Polarisation Dependent Loss (PDL) was measured using the technique described in section 5.5. The PDL was measured as 0.006 dB at 1550 nm. This might be due to the FC/APC connectors attached to the device.

6.1.2 Insertion Loss Variation with Control Parameter

The Insertion Loss Variation (ILV) was measured using the technique described in section 5.2 using a filtered ASE source and an integrating sphere detector as the polarisation independent detector. Six input states were used that were orthogonal on the Poincaré sphere.

Operating Wavelength = 1550 nm

Input Polarisation State			Insertion Loss Variation (dB)
S_1	S_2	S_3	
1	0	0	0.032
-1	0	0	0.032
0	1	0	0.035
0	-1	0	0.040
0	0	1	0.027
0	0	-1	0.047

Thus the insertion loss variation is 0.047 dB.

6.1.3 Sphere Coverage and Transformation Ability

The ability of the polarisation controller to convert any input polarisation state to any output polarisation state was assessed as described in section 5.7. The angle and pressure on the fibre was manually adjusted. The pressure was recorded in terms of turns of the screw where zero is the maximum pressure defined by a stop and turns are counted as the pressure is released. The angle is measured as shown in Figure 18.

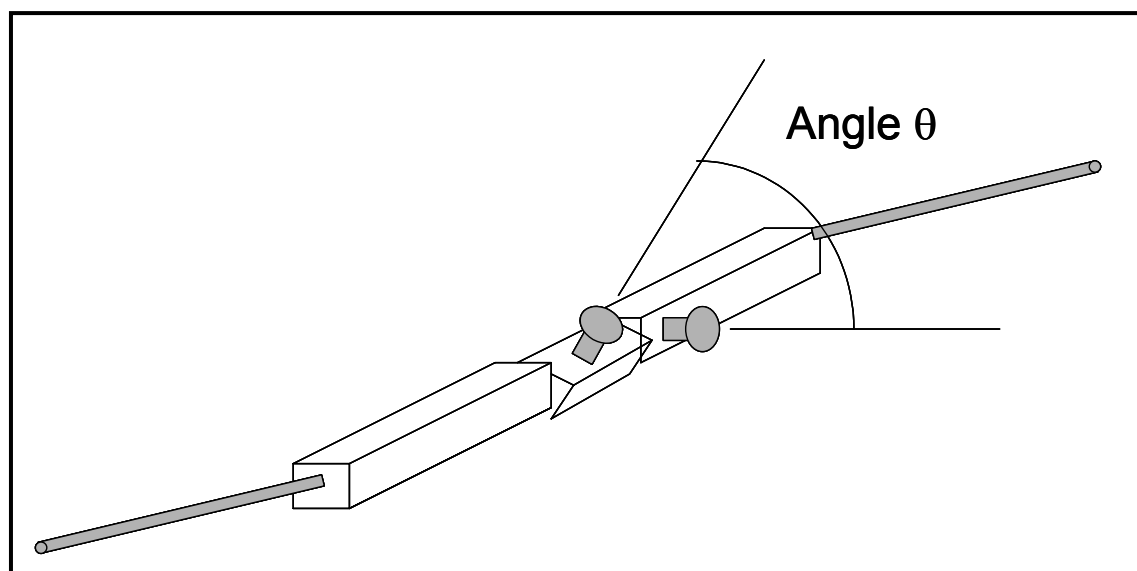


Figure 18 Definition of angle with respect to Twist and Squeeze polarisation controller.

Operating Wavelength = 1540 nm

Input State set to (1,0,0)

Output Polarsition State			Control Parameters	
S_1	S_2	S_3	Twist Angle θ °	Squeeze (Turns)
1.000	0.008	-0.013	180	5.00
-1.000	0.011	-0.001	110	1.63
-0.003	1.000	-0.005	90	0.25
-0.009	-1.000	0.005	135	1.38
0.011	-0.006	1.000	210	2.25
0.002	-0.006	-1.000	0	5.13

Input State set to (0,1,0)

Output Polarsition State			Control Parameters	
S_1	S_2	S_3	Twist Angle θ °	Squeeze (Turns)
1.000	0.007	0.005	140	1.75
-1.000	0.005	-0.004	95	1.63
-0.004	1.000	0.007	170	0.75
-0.006	-1.000	-0.002	20	3.25
-0.003	0.006	1.000	170	4.25
-0.007	0.007	-1.000	45	3.25

Input State set to (0,0,1)

Output Polarsition State			Control Parameters	
S_1	S_2	S_3	Twist Angle θ °	Squeeze (Turns)
1.000	0.002	0.012	20	2.38
-1.000	-0.002	-0.008	110	5.38
-0.010	1.000	0.010	60	3.50
0.006	-1.000	-0.004	170	4.50
0.006	0.012	1.000	135	1.75
-0.002	0.001	-1.000	30	6.13

Input State set to $(-1,0,0)$

Output Polarsition State			Control Parameters	
S_1	S_2	S_3	Twist Angle θ°	Squeeze (Turns)
1.000	-0.002	-0.010	110	1.63
-1.000	-0.007	-0.004	180	5.25
-0.018	1.000	0.008	135	1.25
0.000	-1.000	0.000	90	0.13
0.001	0.002	1.000	90	4.88
0.003	0.008	-1.000	20	2.50

Input State set to $(0,-1,0)$

Output Polarsition State			Control Parameters	
S_1	S_2	S_3	Twist Angle θ°	Squeeze (Turns)
1.000	-0.008	0.004	90	1.88
-1.000	-0.002	-0.002	135	2.00
-0.003	1.000	-0.002	20	3.00
0.001	-1.000	0.010	160	1.00
0.001	0.008	1.000	45	3.00
-0.001	-0.008	-1.000	180	4.13

Input State set to $(0,0,-1)$

Output Polarsition State			Control Parameters	
S_1	S_2	S_3	Twist Angle θ°	Squeeze (Turns)
1.000	-0.001	0.002	110	5.25
-1.000	0.001	0.001	20	2.38
-0.003	1.000	-0.002	170	4.25
-0.001	-1.000	0.006	60	3.38
0.002	0.004	1.000	30	5.75
-0.002	-0.002	-1.000	120	1.75

Thus for each of six input states evenly spaced on the Poincaré sphere the polarisation controller was able to transform the input polarisation state to six different output polarisation states which covered the whole Poincaré sphere. The worst deviation of the output polarisation state from the desired state is 0.018 rad, mainly due to the accuracy of the manual adjustment and is much less than the uncertainty of the polarimeter at 0.03 rad (1σ). This would give a polarisation alignment penalty better than 0.0004 dB.

6.1.4 Control Element

The retardance of the polarisation control element as the fibre is squeezed was measured using a polarimeter. The output polarisation state was measured for differing screw pressures. The output polarisation state describes an arc on the Poincaré sphere

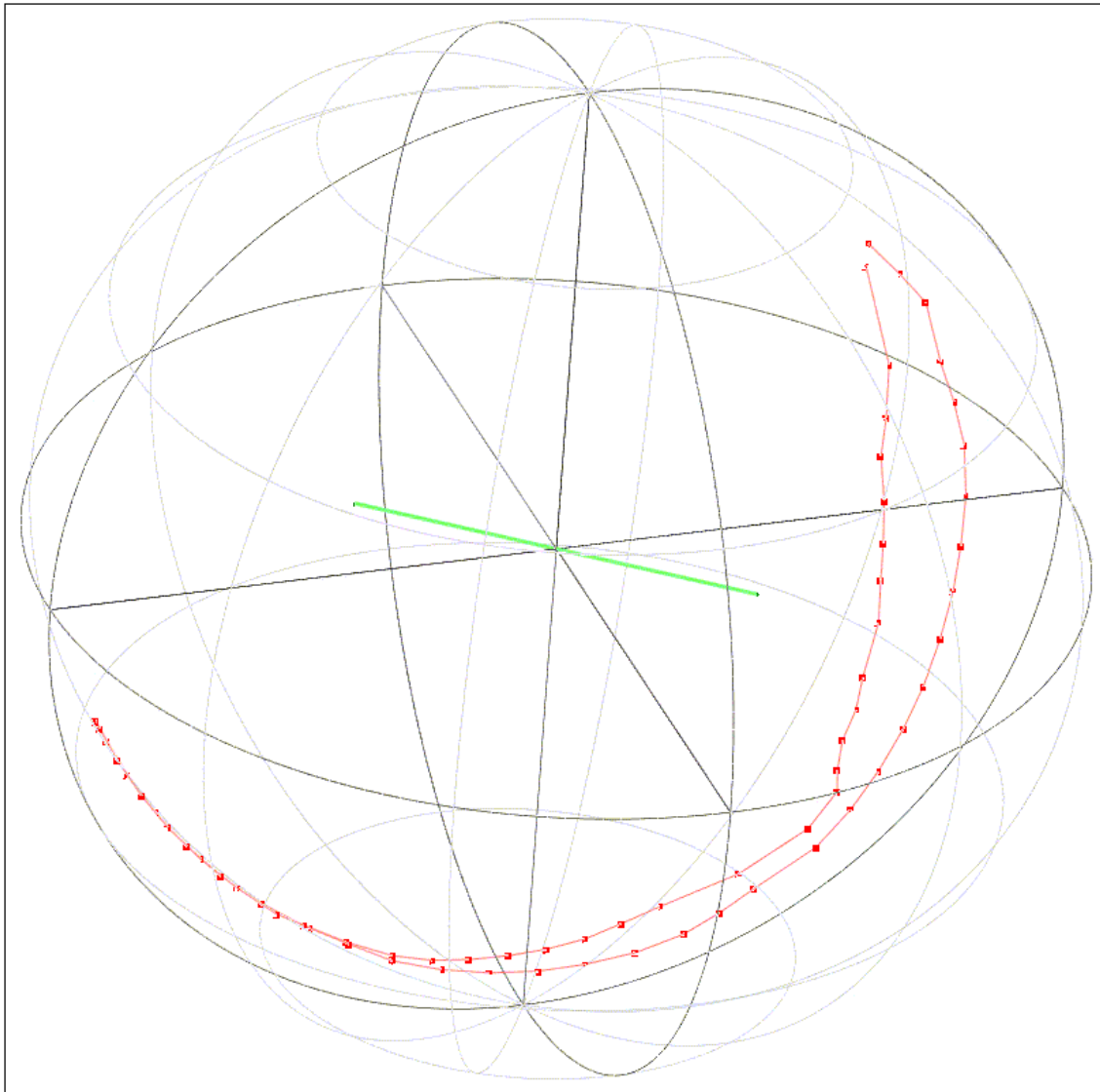


Figure 19 Output polarisation state as fibre is squeezed and released. The green line shows the axis of the SOP path.

The measurements shown in Figure 19 were analysed, as described in section 5.8.2, to produce the retardance angle vs squeeze (in turns) shown in Figure 20. The absolute retardance was found from subsequent measurements shown in Figure 20. This shows that the element can be varied from zero to a half wave plate allowing full control of the polarisation state. The device showed some hysteresis particularly when the screw was loosened. Good linearity was observed as the squeeze screw was tightened. There fibre showed some intrinsic birefringence that is observed when the screw is fully loosened.

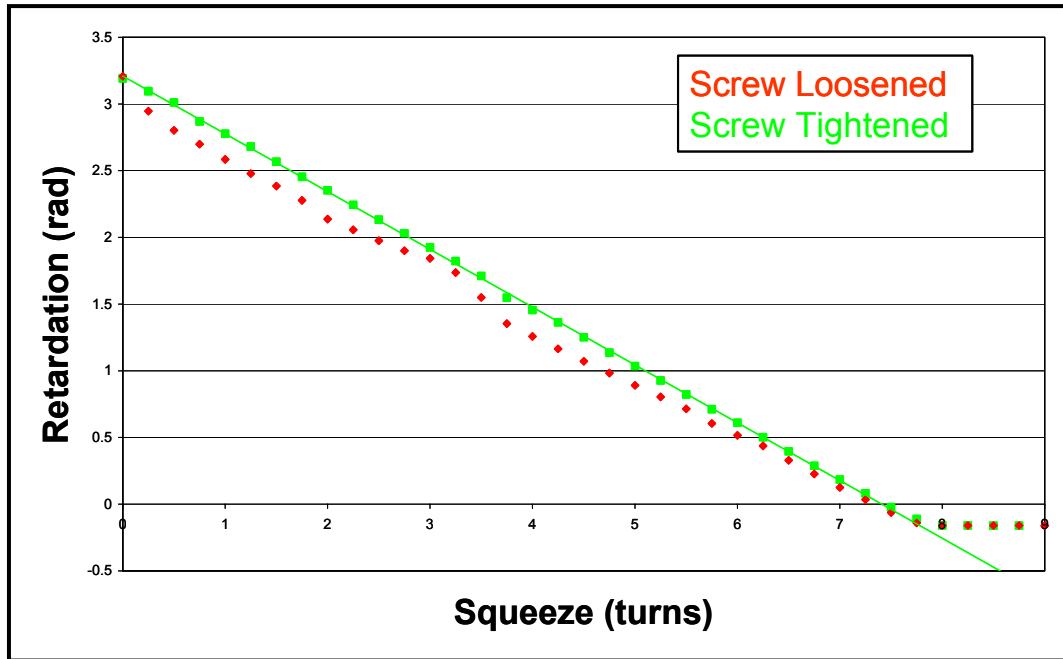


Figure 20 Retardance of the polarisation controller vs squeeze (turns of screw). Points are measured, line is fitted to linear portion only.

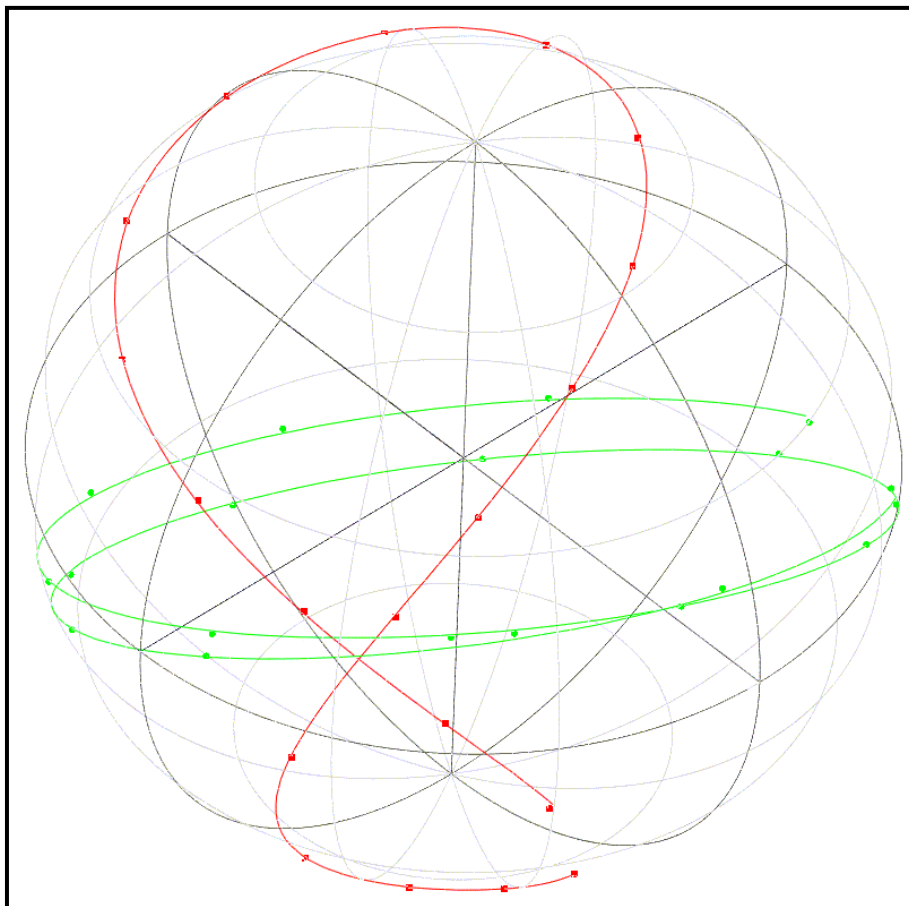


Figure 21 Loci of the output state of polarisation as the angle, θ , is changed from 180° to 0° for two fixed squeeze amounts. The squeeze corresponds to approximately $\frac{1}{4}$ waveplate (red) and approximately $\frac{1}{2}$ waveplate (green). The figure shows the measured points and the fitted loci.

Figure 21 shows the output polarisation state for two fixed squeeze amounts with the angle of the squeeze element, θ , changed from 180° to 0° . The squeeze was set to 0 turns for the green loci and 3.75 turns for the red loci. It should be noted that for both loci the end points do not meet suggesting that the output state of polarisation for 180° and 0° are not identical, this is due to the twisting circular birefringence introduced into the fibre on either side of the squeeze element. Following the analysis of section 5.8.1 the retardance with the squeeze set to 0 turns was found to be either 3.08 or 3.21 rad and that with the squeeze set to 3.75 turns was 1.55 rad. Taking the retardance at 0 turns as 3.21 rad is consistent with the measurements shown in figure 20 and the retardance for 3.75 turns of 1.55 rad.

6.2 Manual Lefèvre Loop

Type: 3 loops each 4 turns of SMF28™ type fibre.
Connectors: FC/UPC

6.2.1 Polarisation Dependent Loss

The Polarisation Dependent Loss (PDL) was measured using the technique described in section 5.5. The PDL was measured as 0.002 dB at 1550 nm.

6.2.2 Insertion Loss Variation with Control Parameter

The Insertion Loss Variation (ILV) was measured using the technique described in section 5.2 using a filtered ASE source and an integrating sphere detector as the polarisation independent detector. Six input states were used that were orthogonal on the Poincaré sphere.

Operating Wavelength = 1550 nm

Input Polarisation State			Insertion Loss Variation (dB)
s_1	s_2	s_3	
1	0	0	0.0039
-1	0	0	0.0042
0	1	0	0.0036
0	-1	0	0.0032
0	0	1	0.0039
0	0	-1	0.0028

Thus the insertion loss variation is 0.0042 dB.

6.2.3 Sphere Coverage and Transformation Ability

The ability of the polarisation controller to convert any input polarisation state to any output polarisation state was assessed as described in section 5.7. The angle of each element was manually adjusted. Figure 22 shows the definition of the angle for each loop element.

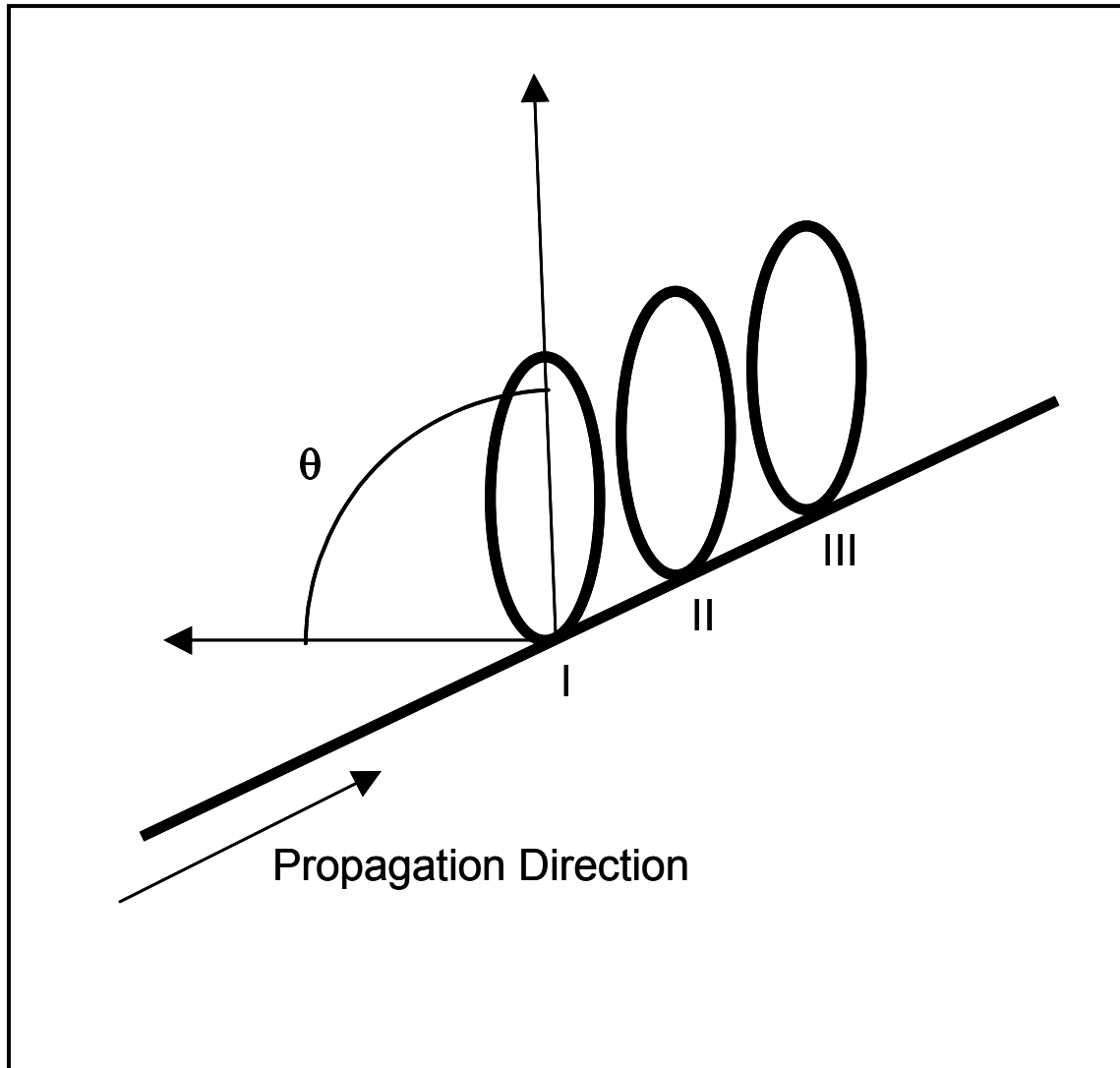


Figure 22 Angle definition used with Lefèvre loop polarisation controller.

Operating Wavelength = 1540 nm

Input State set to (1,0,0)

Output Polarsition State			Control Parameters Angle θ°		
s_1	s_2	s_3	Loop I	Loop II	Loop III
1.000	-0.002	0.002	125	99	90
-1.000	-0.004	-0.003	46	78	90
0.002	1.000	-0.003	22	42	90
-0.002	-1.000	0.006	92	72	90
-0.001	-0.001	1.000	130	57	90
-0.002	0.004	-1.000	137	135	90

Input State set to (0,1,0)

Output Polarsition State			Control Parameters Angle θ°		
S ₁	S ₂	S ₃	Loop I	Loop II	Loop III
1.000	0.003	0.002	61	0	90
-1.000	-0.002	-0.002	~-10	138	90
0.000	1.000	0.003	148	140	90
0.006	-1.000	0.006	25	162	90
0.002	0.004	1.000	117	96	90
-0.006	0.001	-1.000	133	172	90

Input State set to (0,0,1)

Output Polarsition State			Control Parameters Angle θ°		
S ₁	S ₂	S ₃	Loop I	Loop II	Loop III
1.000	0.000	0.003	133	170	90
-1.000	-0.004	0.005	132	55	90
0.001	1.000	0.003	67	146	90
0.005	-1.000	0.005	8	~205	90
0.006	-0.004	1.000	91	132	90
-0.006	-0.001	-1.000	89	50	90

Input State set to (-1,0,0)

Output Polarsition State			Control Parameters Angle θ°		
S ₁	S ₂	S ₃	Loop I	Loop II	Loop III
1.000	-0.001	0.002	46	78	90
-1.000	0.002	0.005	125	99	90
-0.002	1.000	0.002	93	73	90
0.003	-1.000	-0.001	22	41	90
0.000	0.005	1.000	137	136	90
-0.005	-0.005	-1.000	131	58	90

Input State set to (0,-1,0)

Output Polarsition State			Control Parameters Angle θ°		
S ₁	S ₂	S ₃	Loop I	Loop II	Loop III
1.000	0.002	-0.003	~-10	138	90
-1.000	-0.003	0.000	59	0	90
-0.001	1.000	0.001	25	163	90
0.006	-1.000	-0.004	147	139	90
-0.002	-0.003	1.000	133	171	90
0.004	0.000	-1.000	116	96	90

Input State set to (0,0,-1)

Output Polarsition State			Control Parameters Angle θ°		
S ₁	S ₂	S ₃	Loop I	Loop II	Loop III
1.000	0.005	-0.004	132	54	90
-1.000	-0.003	0.001	134	170	90
0.004	1.000	-0.001	17	~200	90
-0.002	-1.000	0.000	86	160	90
-0.002	0.003	1.000	88	49	90
-0.004	-0.004	-1.000	91	133	90

Thus for each of six input states evenly spaced on the Poincaré sphere the polarisation

controller was able to transform the input polarisation state to six different output polarisation states which covered the whole Poincaré sphere. It is noted that two of the loops were sufficient to perform the transformation. The worst deviation of the output polarisation state from the desired state is 0.009 rad that is mainly due to the accuracy of the manual adjustment and is much less than the uncertainty of the polarimeter at 0.03 rad (1σ). This would give a polarisation alignment penalty better than 0.0001 dB.

6.2.4 Control Element

The retardance of each loop was measured using a polarimeter as described in section 5.8.1. The output polarisation state was measured for differing angles of each loop as defined in figure 22. The input state was set to give approximately linear polarisation to the first loop by looking at the symmetry of the pattern described on the Poincaré sphere. Figure 23 and 24 show the measured data and fitted results for loops I and III.

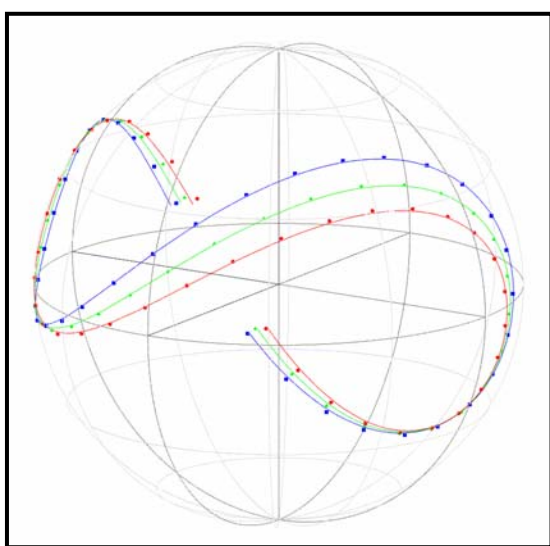


Figure 23 Loci of output polarisation state as loop I azimuth is changed from 0° to 180°. red = 1540 nm, green = 1500 nm and blue = 1460 nm. Points are measured, lines are fitted.

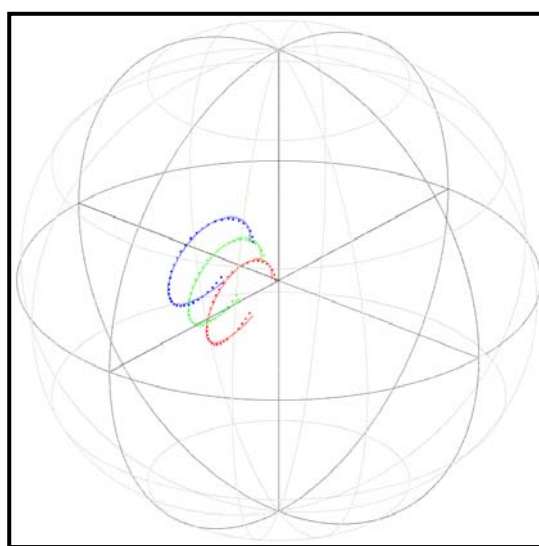


Figure 24 Loci of output polarisation state as loop III azimuth is changed from 0° to 180°. red = 1540 nm, green = 1500 nm and blue = 1460 nm. Points are measured, lines are fitted.

Wavelength (nm)	Linear Retardance		
	Loop I (rad)	Loop II (rad)	Loop III (rad)
1460	1.566	1.699	0.210
1500	1.520	1.644	0.200
1540	1.477	1.589	0.192

The loci of the output polarisation state do not form closed circuits for a change in azimuth of 180° since the rotation of the loops causes some twisting in the interconnecting fibre which causes circular birefringence and this reduces the effective change in azimuth by approximately 10%. The birefringence is approximately inversely proportional to wavelength. It is seen that loop III shows considerably less linear retardance despite having the same mechanical characteristics. This does not affect the transformation performance of the device since the first two loops are sufficient.

6.3 Bulk Optic Polarisation Rotator

Type: Linear Polariser, Quarter Waveplate and Half Waveplate.
Connectors: FC/UPC

6.3.1 Polarisation Dependent Loss

This is not a relevant parameter since only polarisation states aligned with the input linear polariser are transmitted.

6.3.2 Insertion Loss Variation with Control Parameter

The Insertion Loss Variation (ILV) was measured using the technique described in section 5.2 using a filtered ASE source and an integrating sphere detector as the polarisation independent detector. Only one input states was used that was aligned with the input linear polariser. Only the quarter and half waveplates were moved during the test.

Operating Wavelength = 1550 nm

Input Polarisation State			Insertion Loss Variation (dB)
S_1	S_2	S_3	
1	0	0	1.1

Thus the insertion loss variation is 1.1 dB.

6.3.3 Control Element

The retardance of the nominal quarter waveplate and half waveplate was measured using a polarimeter as described in section 5.8.1. The linear polariser was set to zero azimuth. For the half waveplate measurements the quarter waveplate was set to -0.4° in an attempt to offset the azimuth offset. Figure 25 and 26 show the measured polarisation loci and the fitted lines.

Wavelength (nm)	Measured Zero Azimuth Offset (deg)	
	Quarter Waveplate	Half Waveplate
1550	0.5	-18.1
1625	0.7	-15.9

As the quarter waveplate azimuth was not fully aligned with the linear polariser (a difference of 0.1° and 0.3° at 1550 nm and 1625 nm respectively), the actual azimuth offset of the half waveplate is -18.2° and -16.2° at 1550 nm and 1625 nm respectively. The variation in this azimuth with wavelength may be due to circular birefringence within the waveplate that would not be detected by this measurement technique.

Wavelength (nm)	Retardance (rad)	
	Quarter Waveplate	Half Waveplate
1550	1.504	3.076
1625	1.489	3.086

The waveplates were specifically designed to be achromatic based on polymer technology. There is ambiguity in the half waveplate retardance in that it could be 3.20 or 3.08.

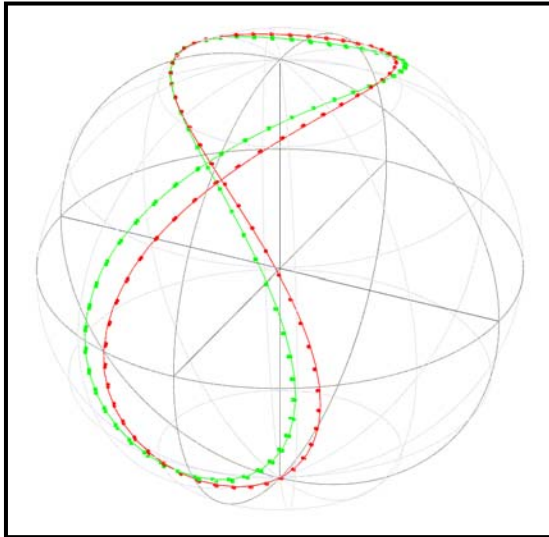


Figure 25 Loci of output polarisation state as the quarter waveplate azimuth is changed through 360°. red = 1625 nm and green = 1550 nm. Points are measured, lines are fitted

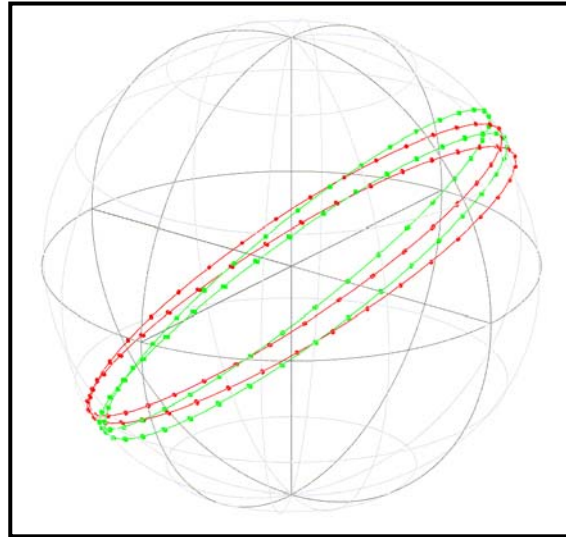


Figure 26 Loci of output polarisation state as the half waveplate azimuth is changed through 360°. red = 1625 nm and green = 1550 nm. Points are measured, lines are fitted

6.4 Liquid Crystal Polarisation Controller

Type: Four liquid crystal elements
Connectors: FC/APC

6.4.1 Polarisation Dependent Loss

The Polarisation Dependent Loss (PDL) was measured using the technique described in section 5.5. The PDL was measured as 0.099 dB at 1550 nm.

6.4.2 Insertion Loss Variation with Control Parameter

The Insertion Loss Variation (ILV) was measured using the technique described in section 5.2 using a filtered ASE source and an integrating sphere detector as the polarisation independent detector. Six input states were used that were orthogonal on the Poincaré sphere.

Operating Wavelength = 1550 nm

Input Polarisation State			Insertion Loss Variation (dB)
S_1	S_2	S_3	
1	0	0	0.13
-1	0	0	0.13
0	1	0	0.13
0	-1	0	0.14
0	0	1	0.13
0	0	-1	0.13

Thus the insertion loss variation is 0.14 dB.

6.4.3 Sphere Coverage and Transformation Ability

The ability of the polarisation controller to convert any input polarisation state to any output polarisation state was assessed as described in section 5.7. The cell voltages were manually adjusted.

Operating Wavelength = 1540 nm

Input State set to (1,0,0)

Output State			Control Voltage (V)			
S ₁	S ₂	S ₃	Cell 1	Cell 2	Cell 3	Cell 4
1.000	0.002	0.003	5.890	10.000	6.000	3.870
-1.000	0.003	0.004	5.640	10.000	6.000	7.270
0.001	1.000	0.002	4.140	4.020	6.000	3.020
-0.003	-1.000	-0.004	3.990	10.000	6.000	7.100
-0.013	-0.015	1.000	5.440	10.000	6.000	5.020
0.016	-0.008	-1.000	6.210	10.000	6.000	3.110

Input State set to (0,1,0)

Output State			Control Voltage (V)			
S ₁	S ₂	S ₃	Cell 1	Cell 2	Cell 3	Cell 4
1.000	0.002	0.003	2.700	4.400	5.700	2.940
-1.000	0.014	0.006	4.130	4.000	6.000	2.910
0.000	1.000	-0.007	3.160	3.820	6.420	4.100
-0.003	-1.000	0.009	2.680	4.300	2.610	2.680
0.006	0.013	1.000	2.480	3.540	6.420	3.680
0.003	0.007	-1.000	2.760	3.420	7.100	2.000

Input State set to (0,0,1)

Output State			Control Voltage (V)			
S ₁	S ₂	S ₃	Cell 1	Cell 2	Cell 3	Cell 4
1.000	0.006	0.003	2.630	4.120	2.600	2.700
-1.000	-0.009	0.012	4.400	3.070	2.920	2.700
0.006	1.000	0.002	3.000	4.450	5.540	4.900
-0.003	-1.000	-0.010	3.000	2.850	5.540	2.640
-0.003	-0.002	1.000	4.210	3.880	2.800	2.650
0.003	-0.002	-1.000	4.400	2.650	5.460	2.640

Input State set to (-1,0,0)

Output State			Control Voltage (V)			
S ₁	S ₂	S ₃	Cell 1	Cell 2	Cell 3	Cell 4
1.000	0.010	-0.004	2.960	11.690	5.540	4.940
-1.000	0.008	0.000	2.960	2.970	5.540	3.150
0.006	1.000	-0.006	2.860	3.550	5.140	4.200
-0.001	-1.000	0.005	2.860	2.100	7.480	3.730
0.003	0.002	1.000	2.960	5.560	5.540	4.900
0.001	0.002	-1.000	2.960	2.860	5.540	3.870

Input State set to (0,-1,0)

Output State			Control Voltage (V)			
S ₁	S ₂	S ₃	Cell 1	Cell 2	Cell 3	Cell 4
1.000	0.005	-0.001	5.610	4.380	7.560	3.690
-1.000	0.004	0.007	5.610	2.830	7.560	3.420
-0.008	1.000	-0.008	3.300	2.070	7.560	3.270
0.002	-1.000	0.009	5.710	2.180	7.560	3.420
-0.001	0.001	1.000	4.240	2.100	7.560	3.420
0.004	0.005	-1.000	2.710	2.000	7.600	3.370

Input State set to (0,0,-1)

Output State			Control Voltage (V)			
s_1	s_2	s_3	Cell 1	Cell 2	Cell 3	Cell 4
1.000	-0.009	0.002	5.610	3.080	8.560	4.390
-1.000	0.006	0.000	4.910	5.600	8.560	3.140
-0.004	1.000	0.002	3.280	2.900	6.660	3.540
0.000	-1.000	0.006	5.610	5.600	8.560	4.400
0.009	0.008	1.000	3.980	2.600	5.850	2.790
0.006	0.002	-1.000	3.780	2.690	5.800	4.360

Thus for each of six input states evenly spaced on the Poincaré sphere the polarisation controller was able to transform the input polarisation state to six different output polarisation states which covered the whole Poincaré sphere. The RMS deviation of the output polarisation state from the desired state is 0.009 rad that is mainly due to the accuracy of the manual adjustment and is much less than the uncertainty of the polarimeter at 0.03 rad (1σ). This would give a polarisation alignment penalty better than 0.0001 dB.

6.4.4 Control Element

The relative retardance of each control cell was measured as a function of control voltage by measuring the output state of polarisation on the Poincaré sphere. The measurements were made at 1550 nm. The data was analysed as described in section 5.8.2. Figure 27 shows the measured output polarisation state for each cell controlled in turn with uncontrolled cells set to 2V. Figure 28 shows the retardance relative to the retardance at 2V control.

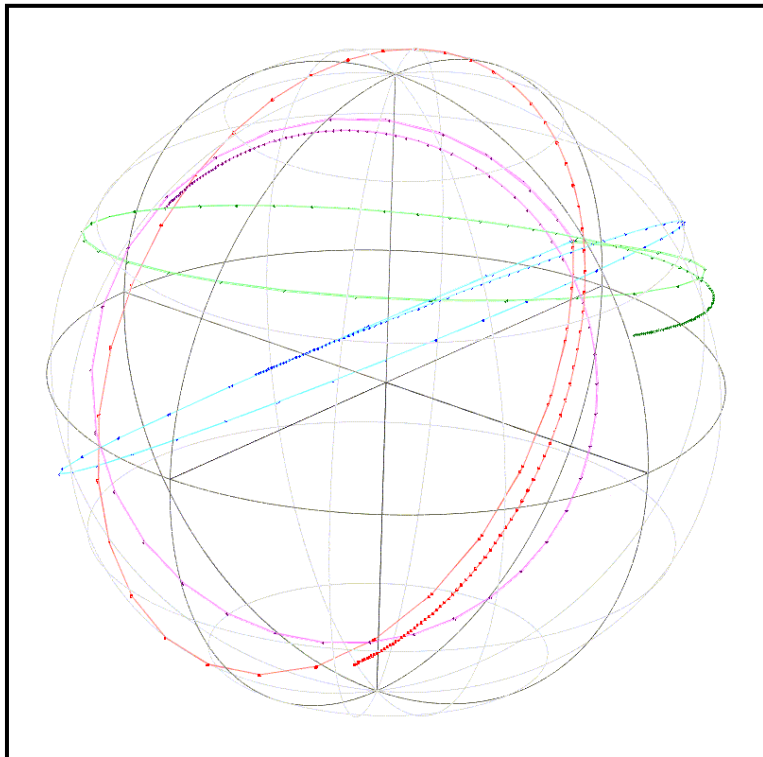


Figure 27 Loci of output state of polarisation for each cell controlled in turn.

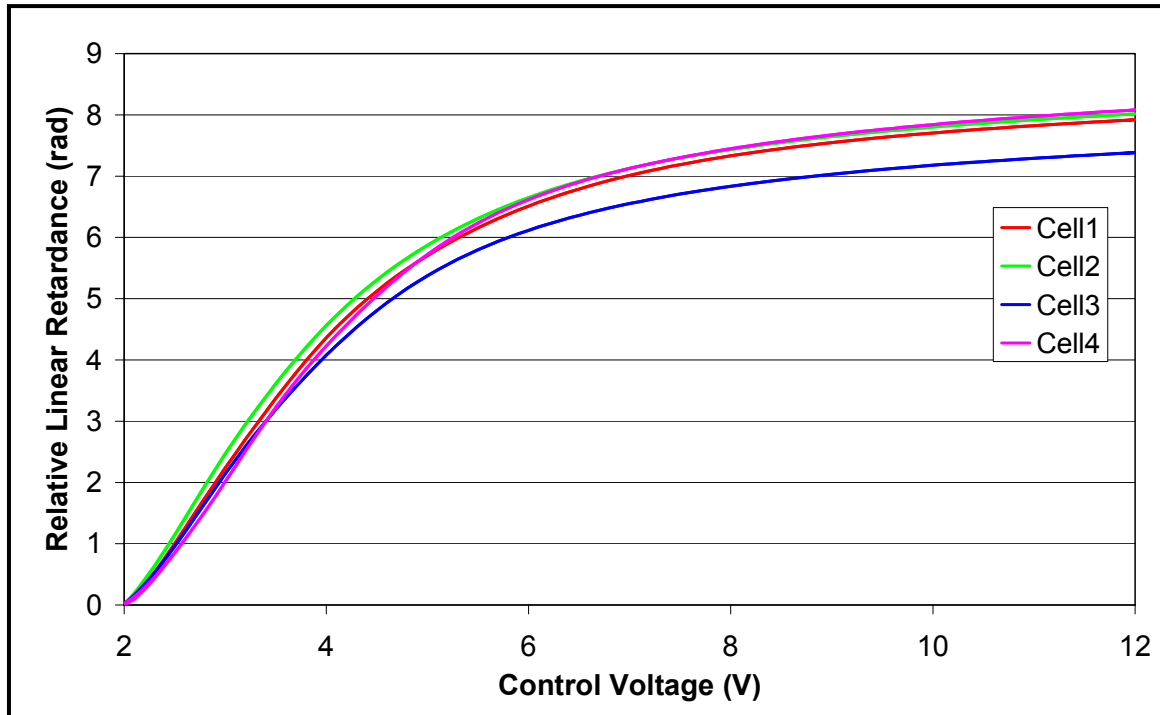


Figure 28 Relative linear retardance vs control voltage. With other cells at 2V

This shows that each cell can vary its retardance over a full wavelength. The relative axis of the four elements are bound in the axis of the circles described on the Poincaré sphere however the axis of cell3 is modified by the rotation of cell4 while that of cell2 is modified by the rotations of cell3 and cell4 etc... In order to neglect the rotation of subsequent cells it would be necessary to set the retardance of all the following cells to a full wavelength (ie 2π rad) so that the rotation of the following cells was zero.

6.4.5 Tracking Ability

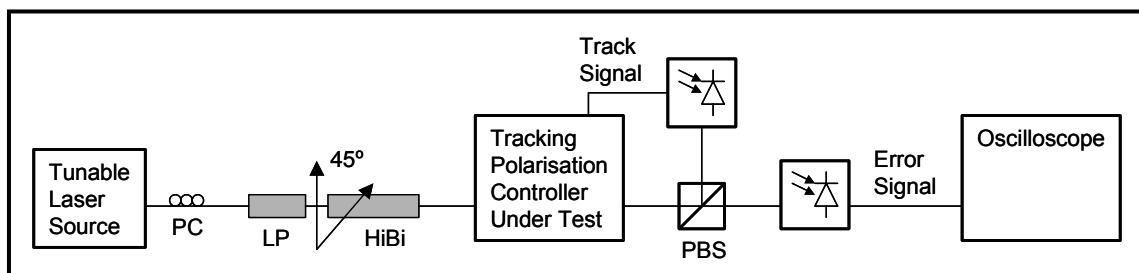


Figure 29 Set up to test tracking ability.

The optical set up described in Figure 29 was used. The output of the high extinction ratio polariser was aligned at 45° to the axis of the HiBi fibre so that the output state followed a great arc from left to right hand circular states as the wavelength of the source is incremented. The output state from the HiBi fibre described one complete circle for a wavelength shift of 3.87 nm. Thus the rate of rotation of the state of polarisation can be controlled from the rate of change of the wavelength of the source. A source wavelength change of 0.1 nm.s^{-1} being equivalent to a rate of rotation of 0.16 rad.s^{-1} on the Poincaré sphere.

The output of the polarisation controller passed to a polarising beam splitter, one arm forms the polarisation signal for the tracking while the other gives an error signal used to monitor the angle between the actual state of polarisation and the desired state of polarisation. The error signal is converted to an error angle on the Poincaré sphere by normalisation from the maximum and minimum values when the polarisation controller was run in random scanning mode.

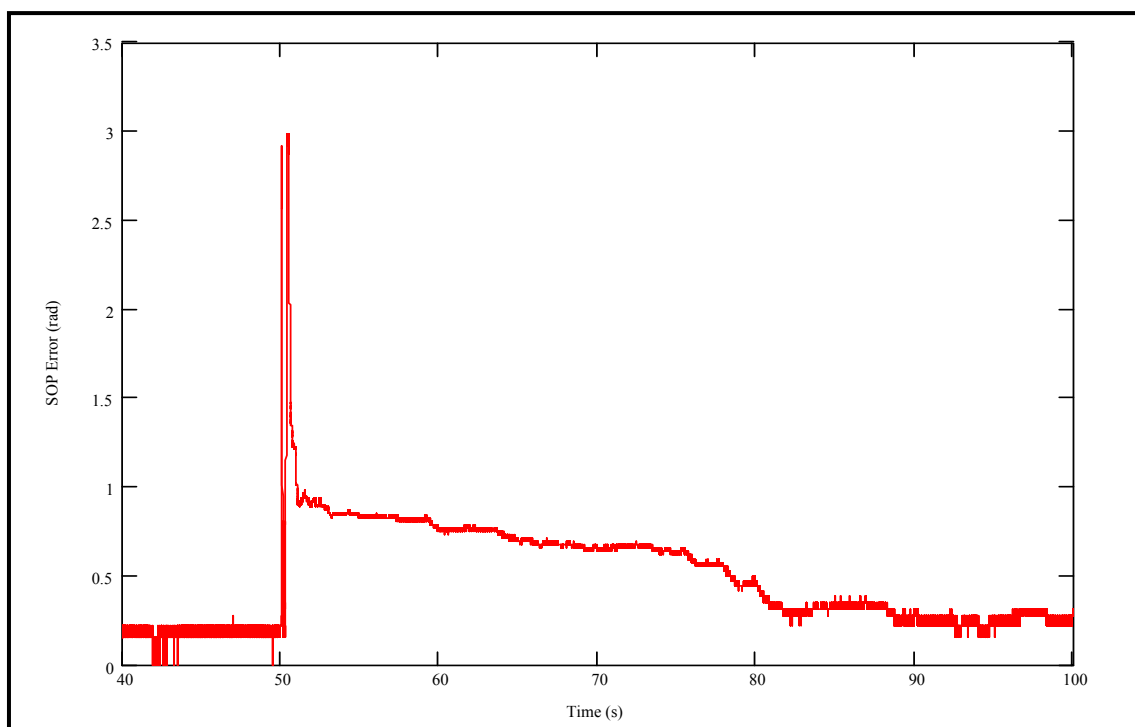


Figure 30 State of polarisation error for a step change in input state of polarisation.

Figure 30 shows the error signal in radians with time when the wavelength was changed by 1.94 nm (corresponding to a shift of π radians on the Poincaré sphere, ie a switch between orthogonal states.). This shows a quick partial recovery of the polarisation track within 1 s but it then takes a further 30 to 40 s to regain normal tracking. The average error in the angle of the state of polarisation on the Poincaré sphere was 0.2 rad during normal tracking.

Figure 31 shows the average error angle as the laser wavelength was ramped at different rates. The trend is an increase in average error angle the faster the input state of polarisation is rotated. (Note the maximum average error angle is $\pi/2 = 1.57$, when the tracking is not operating). It was observed that for many of the tracking runs that polarisation tracking was almost complete except for one excursion see Figure 32. This may have been due to the reset of the elements when they have reached there maximal extent.

Figure 33 shows the error angle vs input SOP rotation speed when the occasional excursions are removed from the calculation. This shows that the tracking system can track changes in input SOP up to approximately 0.08 rad.s^{-1} on the Poincaré sphere.

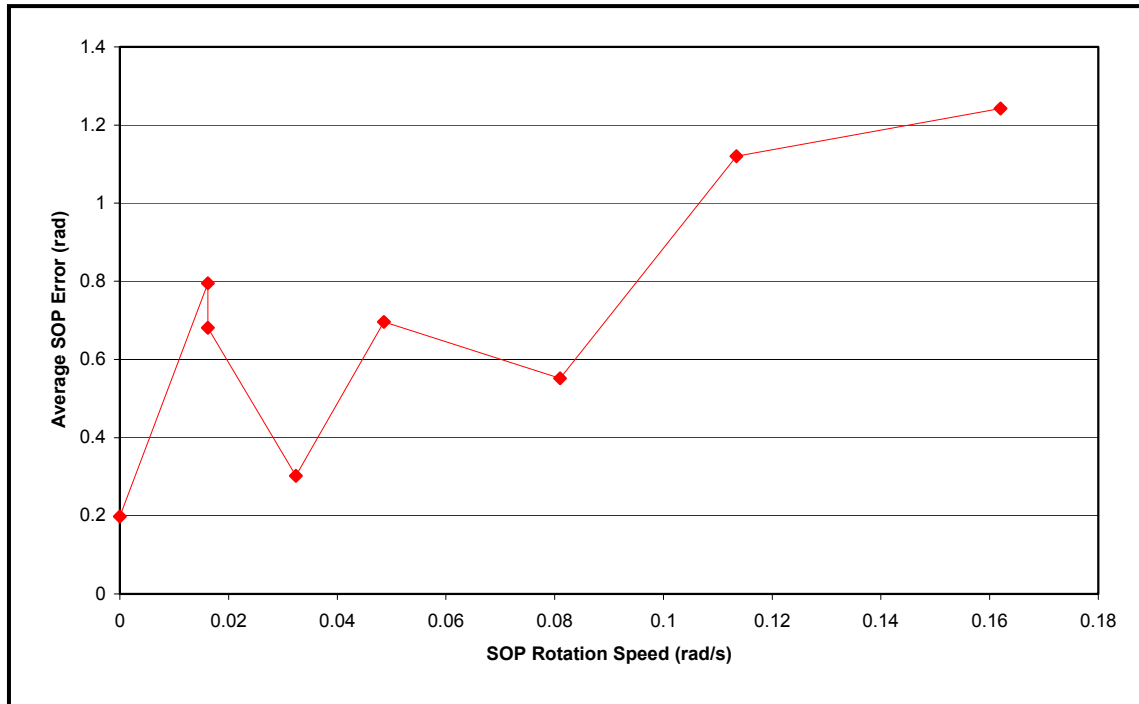


Figure 31 Average SOP error in radians for various rates of rotation of input SOP.

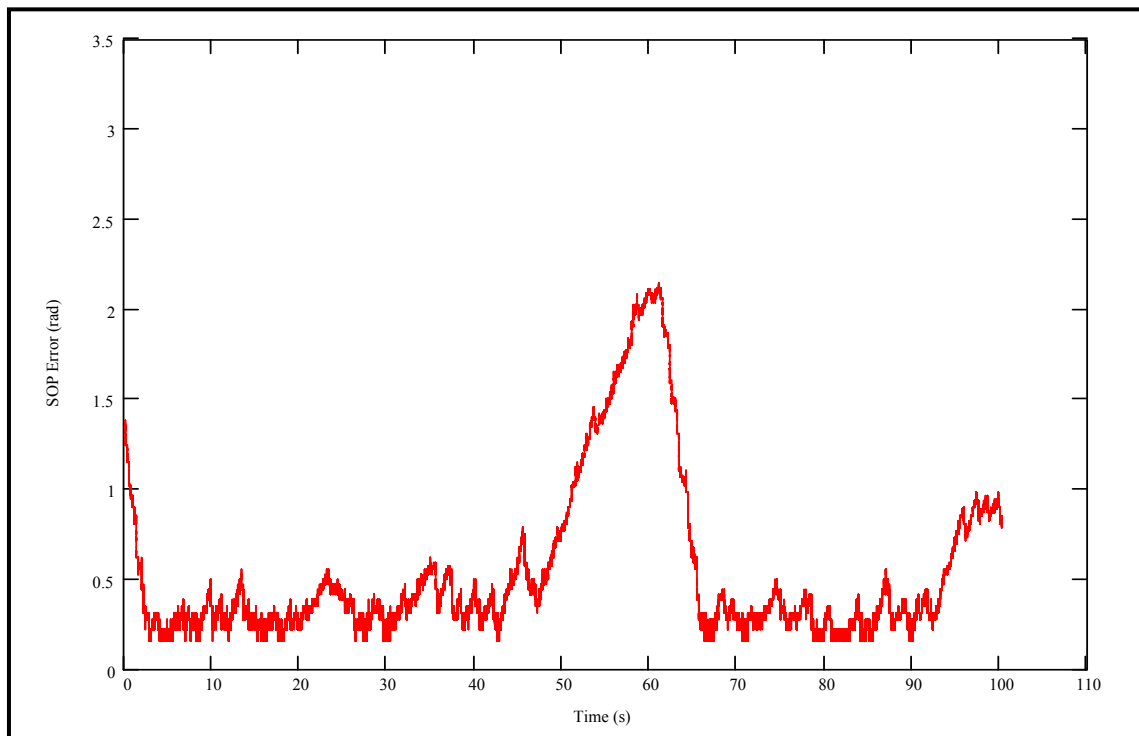


Figure 32 SOP error angle vs time for an input SOP rotation of 0.08 rad.s^{-1} .

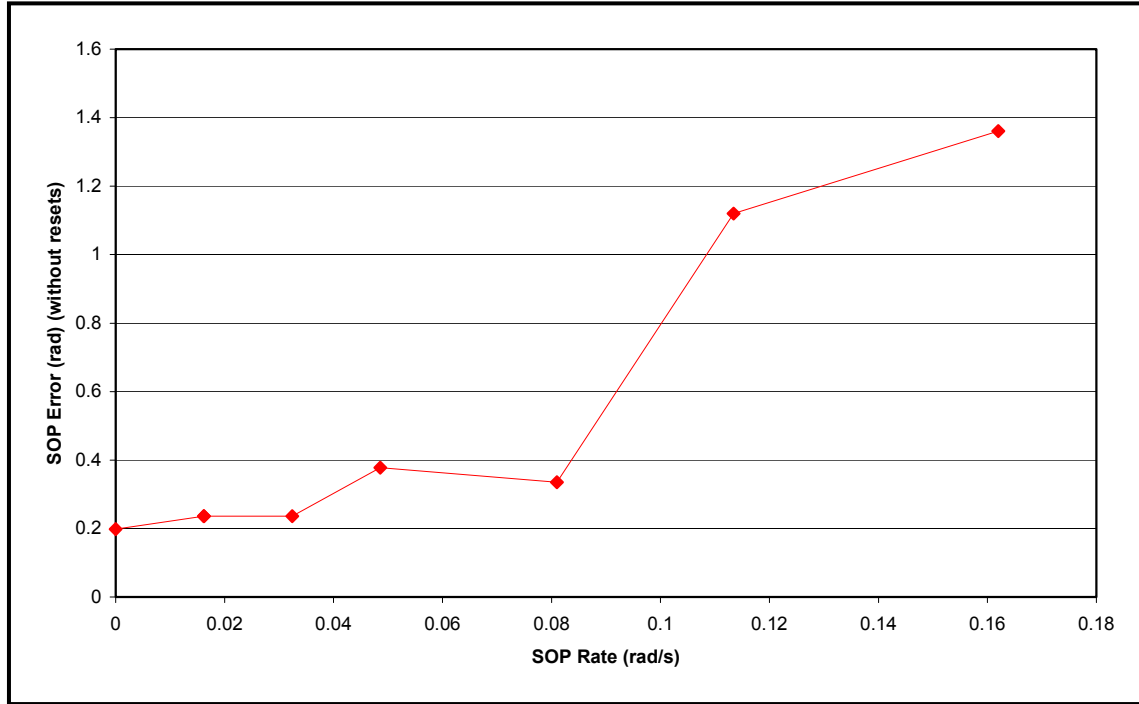


Figure 33 Output SOP error angle vs input SOP rotation rate.

These results show that in principle a system based on this technique can probe a polarisation tracking controller at various input SOP rotation rates. The difficulty, in terms of an accurate characterisation of the maximum tracking speed or tracking bandwidth, is in the determination of the average SOP error away from SOP errors that occur due to poor tracking and resets for slowly varying input states.

6.4.6 Polarisation Scrambling Ability

Measurements were performed to assess the ability of the polarisation controller to uniformly scramble the input polarisation state. Since the polarisation controller is relatively slow the output polarisation state was monitored directly using the polarimeter. The polarisation controller was set to its slowest rate with its cell rates set to 1, 2, 3 and 4 respectively. The output polarisation state was monitored for six different input states covering the full Poincaré sphere.

The DOP of the time-averaged output was calculated for a given averaging time as

$$\text{DOP}(t) = \sqrt{\langle s_1 \rangle_t^2 + \langle s_2 \rangle_t^2 + \langle s_3 \rangle_t^2} \quad (17)$$

where $\langle s_1 \rangle_t$ correspond to the linear mean of s_1 over a time interval, t . The long term DOP showed some variation with input state with orthogonal input states giving similar DOP see Figure 34. The average DOP averaged over input state has a time average trend that is well modelled by, see Figure 35

$$\text{DOP}(t) = 0.137 + 0.613e^{\frac{-t}{0.4}} + 0.25e^{\frac{-t}{4}} \quad (18)$$

This shows a short term rapid decrease in the degree of polarisation followed by a longer term slower reduction.

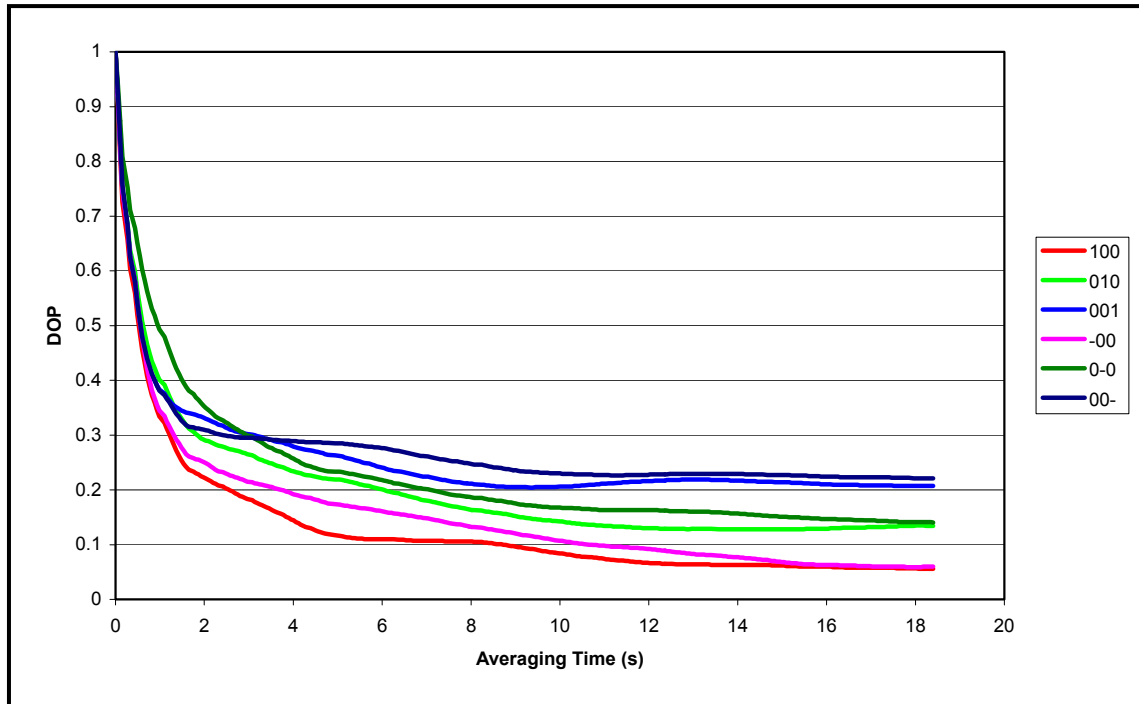


Figure 34 DOP vs Averaging Time, for various input states; (100) = linear horizontal, (-00) = linear vertical.

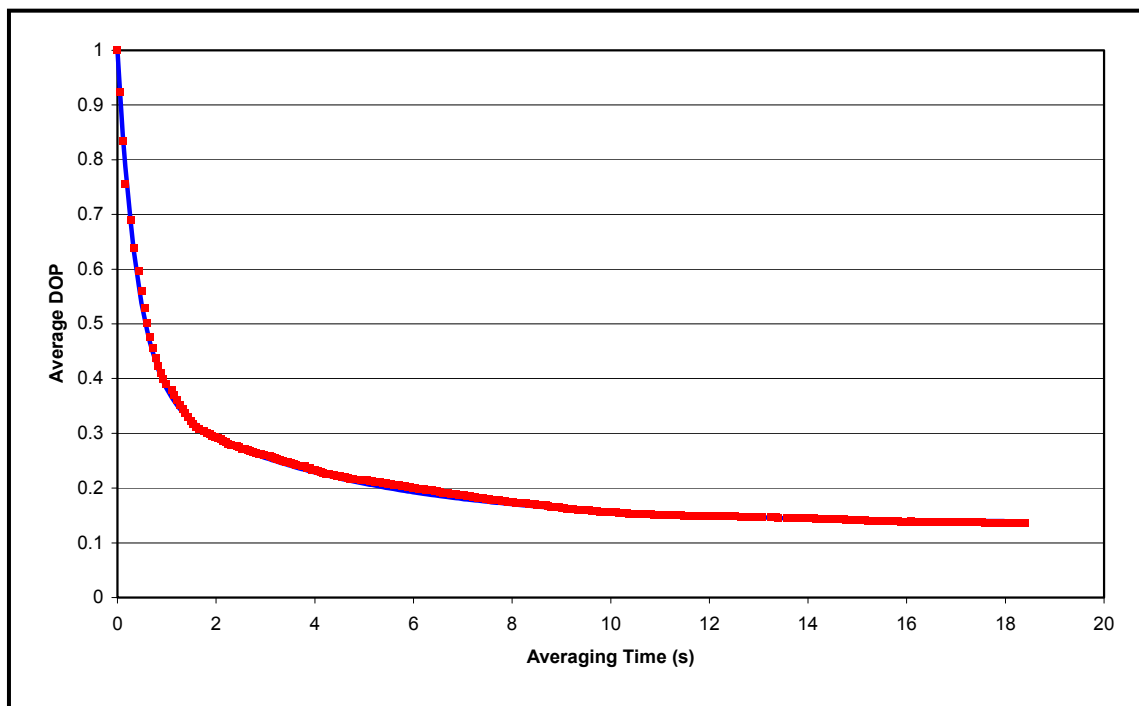


Figure 35 Average DOP (over input states) with Averaging Time. Red = Measured, Blue = Trend Equation (18).

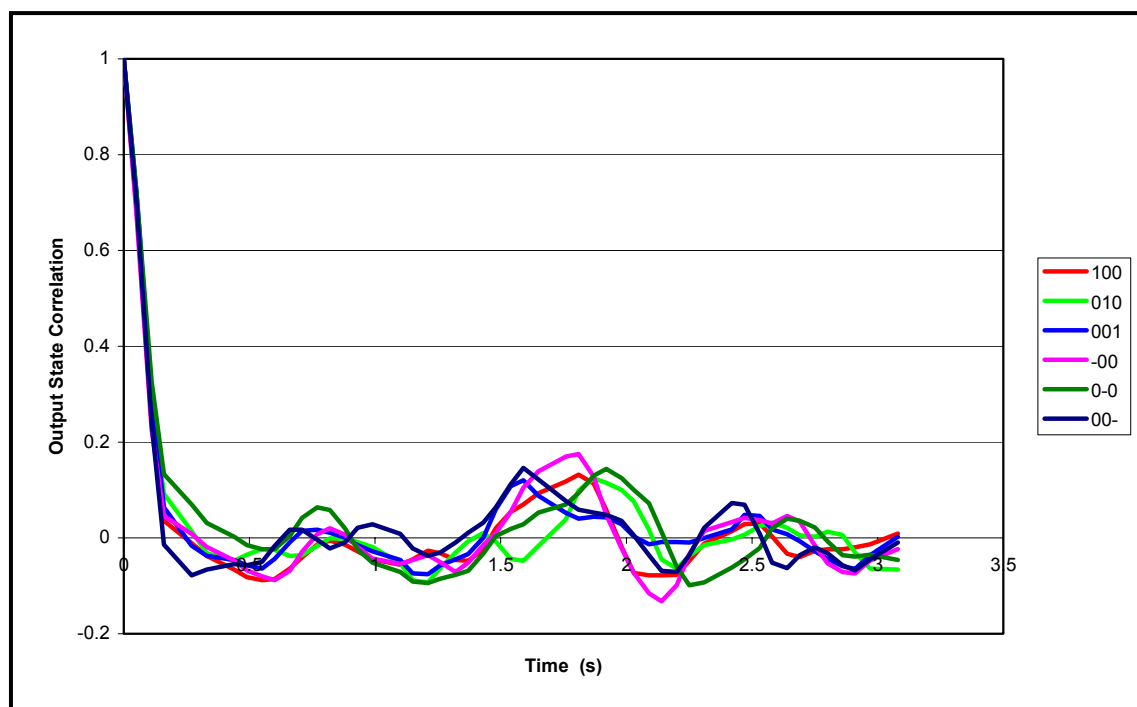


Figure 36 Correlation of the output state of polarisation with time.

Figure 36 shows the correlation function for the output state of polarisation and suggests a decorrelation time of approximately 0.2 s. This would suggest that the output state revolves once around the Poincaré sphere every 0.8 s and this would give the fast reduction in DOP observed.

Input State	Eigenvalues of Covariance Matrix	Long Term DOP
(1, 0, 0)	(0.27, 0.31, 0.42)	0.06
(0, 1, 0)	(0.29, 0.32, 0.37)	0.13
(0, 0, 1)	(0.26, 0.33, 0.36)	0.23
(-1, 0, 0)	(0.27, 0.31, 0.41)	0.07
(0, -1, 0)	(0.27, 0.34, 0.37)	0.13
(0, 0, -1)	(0.26, 0.33, 0.37)	0.21

The long term DOP was calculated as the average DOP over the monitoring time of approximate 32 s.

Since the eigenvalues of the covariance matrix are not 0.33 there is not an even coverage of the entire sphere and this is probably reflected in the long term DOP being >0 .

APPENDIX A REFERENCES

- [1] S C RASHLEIGH, “Origins and Control of Polarization Effects in Single-Mode Fibers”, *J. of Light. Tech.*, **Vol LT-1 No 2**, June 1983, pp 312 –331.
- [2] H C LEFEVRE, “Single-Mode Fibre Fractional Wave Devices and Polarisation Controllers”, *Electron. Lett.*, **Vol 16 No 20**, September 1980, pp778 – 780.
- [3] V MIRVODA, D SANDEL, F WUST, R NOE, “Optimized Polarization Scramblers for PMD Detection” *ECOC 2002*, **P3.5**.