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Calibration of a Polarisation State Analyser for Polarisation Mode Dispersion Measurements

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Abstract

This paper describes the calibration requirements for polarisation state analysers used to measure polarisation mode dispersion (PMD). The technique used at NPL to implement the calibration, and to ensure traceability to national standards, is outlined. The uncertainty limit on the measurement of PMD due to the calibration uncertainty of the polarisation state analyser will be described.

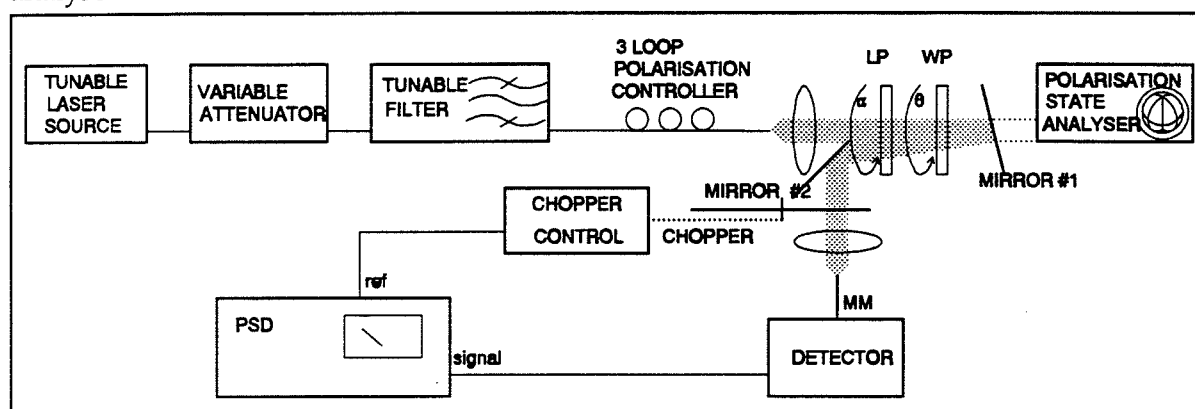


Figure 1 Polarisation State Analyser Calibration System

Introduction

The measurement of PMD using the Poincaré sphere method uses the measurement of the rotation of the output polarisation state around a principle state of polarisation (PSP) as a function of wavelength. The key requirements of the polarisation state analyser are to measure changes in polarisation state accurately while being independent of wavelength and power. Since only changes of polarisation state are required it is not necessary for absolute azimuth or ellipticity to be calibrated.

The approach taken was to calibrate the polarisation state analyser at one wavelength and one power over an evenly distributed sample of polarisation states and then to check the polarisation state analyser was independent of power and wavelength at one polarisation state. The primary traceability was provided through

the use of calibrated rotation stages.

Preparation of Known Polarisation States

The calibration system was set up as shown in Figure 1.

The linear polariser, LP, had been shown to have an extinction ratio $>50\text{dB}$. With mirror #1 in position, the optical beam performs a double pass of the linear polariser, LP, and quarter waveplate, WP, before illuminating the detector. The azimuth of the quarter waveplate, WP, was adjusted to give an extinction of the signal illuminating the detector. The wavelength of the tunable laser source and the tunable filter were adjusted in tandem to minimise the detected signal and give the greatest extinction ratio. This defines the operating wavelength at which the waveplate, WP, is exactly a quarter waveplate.

The azimuth of WP was changed from 90° to -90° in 15° steps. At each setting of WP the azimuth of the linear polariser, LP, was adjusted to give an extinction of the detected signal. The azimuth of LP was recorded and the detected signal noted. The azimuth of WP was rotated by 45° and the variable attenuator was adjusted to reduce the detected signal to that noted previously. The change in attenuation is the extinction ratio. The worst case extinction ratio, including the calibration of the attenuator, was found to be >45dB.

The uncertainty on the set Stokes parameters due to the non-ideal linear polariser and quarter waveplate is given

by $\sigma_E = \sqrt{10^{-\frac{E}{10}}}$, where E is the worst case extinction ratio between the linear polariser and the circular polarising system. $\sigma_E = 0.006$ for E = 45dB.

The variation of the difference between the azimuth of LP and that of WP at extinction was 5' (1σ) which suggests a setability/readability of 5' on the rotating mounts. This combined with the calibration uncertainty of the rotating mounts suggests an angular accuracy of 6' (1σ) was achieved. This gives an uncertainty on the calculated Stokes parameters, σ_θ , of, $\text{SIN}(2\theta) = 0.004$.

The effect of the non-normal incidence on mirror #1, on the reflected polarisation state was assessed using the polarisation state analyser. This suggested a Stokes parameter uncertainty of 0.003 for a 2° beam deviation. This is mainly due to changes in the phase of the parallel and perpendicular polarisations on reflection.

The Stokes parameter generated, at the polarisation state analyser with the mirror #1 removed, by the linear polariser, LP, at azimuth α and the quarter waveplate, WP, at azimuth θ is given by^[1]

$$\begin{pmatrix} s1 \\ s2 \\ s3 \end{pmatrix} = \begin{pmatrix} \cos(2\alpha)\cos(2\theta)^2 + \sin(2\alpha)\cos(2\theta)\sin(2\theta) \\ \cos(2\alpha)\cos(2\theta)\sin(2\theta) + \sin(2\alpha)\sin(2\theta)^2 \\ -\cos(2\alpha)\sin(2\theta) + \sin(2\alpha)\cos(2\theta) \end{pmatrix}$$

with uncertainty given by

$$\sqrt{\sigma_E^2 + 2\sigma_\theta^2 + \sigma_M^2} = 0.008.$$

The Stokes parameter generated will lie on the surface of the Poincaré sphere within a circle of radius 0.008 (1σ), centred on the calculated state.

Variation of Polarisation State Analyser versus Input State

The calibration set up of Figure 1 was used.

The angle θ of WP was set and with the mirror #1 in place the angle of LP, α , was adjusted to give an extinction of the signal illuminating the detector. The mirror #1 was removed allowing the beam to enter the polarisation state analyser. The attenuator was adjusted to give a signal of -20 dBm. The angle of WP, θ , was set from 90° to -90° in 15° steps. At each step the measured Stokes parameters were recorded from the polarisation state analyser. This was repeated with the LP angle adjusted for extinction with the WP angle set from -90° to 90° in 15° intervals, giving a total of 169 measurements.

From the measured Stokes parameters of the linear states the average offsets between the azimuth of LP, α , and WP, θ , and the polarisation state analyser were calculated. This offset arises as each of these angles has a different datum depending on the position of the elements within the rotating mounts. These angular offsets are used to calculate the effective azimuth of the LP and WP in the polarisation state analyser frame.

The Stokes parameters, s1, s2 and s3 of the theoretical input states were calculated. The deviation between the theoretical state and the measured state was calculated as

a distance across the surface of the Poincaré sphere. The theoretical states map the Poincaré sphere at 30° intervals giving 62 different states. All these states are repeated at least twice, circular and linear states more so. A weighting was given to each input state depending on the number of times it was repeated and the effective fraction of the surface area mapped on the Poincaré sphere by an surface arc of $\pm 15^\circ$.

The RMS weighted deviation of the measured state from the theoretical state on the surface of the Poincaré sphere was 0.011.

Variation of Polarisation State Analyser versus Input Power

This provides an overall linearity of the polarisation state analyser measurement system. A number of input states were tried (linear, circular ...) the worst case was found to occur for input states where $s_3 \sim 1/2$.

P (dBm)	s1	s2	s3	Deviation from -20 dBm
-6.41	0.7990	-0.0077	0.6010	0.0005
-10.00	0.7990	-0.0081	0.6010	0.0006
-15.01	0.7990	-0.0072	0.6010	0.0008
-20.03	0.7987	-0.0078	0.6014	-
-25.04	0.7990	-0.0068	0.6010	0.0011
-30.04	0.7990	-0.0058	0.6010	0.0021
-35.05	0.7990	-0.0053	0.6010	0.0026
-40.05	0.7992	-0.0050	0.6010	0.0029
-45.05	0.7981	-0.0075	0.6023	0.0011
-50.05	0.7991	-0.0056	0.6012	0.0022
-55.06	0.7986	-0.0053	0.6019	0.0026
-60.10	0.7938	-0.0121	0.6078	0.0091
-65.16	0.7841	-0.0257	0.6193	0.0292

A suitable input state was set by adjusting α and θ . The input power was varied by adjusting the attenuator. The Stokes parameter and power level were recorded for input powers -5 dBm to -65 dBm in 5 dBm steps. The deviation of the measured state from the state measured for -20 dBm was calculated.

An uncertainty on the measured Stokes parameters of 0.003 was assigned for input

powers in the range -5 dBm to -55 dBm.

Variation of Polarisation State Analyser versus Input Wavelength

In order to calculate the variation of the input set state with wavelength the exact thickness of the quarter waveplate WP is required. A wavelength scan of the extinction ratio was made using the set up of Figure 1 and replacing the tunable laser / filter with a white light source and the detector with an optical spectrum analyser. The wavelength of the signal nulls was used with the birefringent characteristic of quartz^[2] to calculate the order of the waveplate, this was found to be $4\frac{1}{4}$ at the operating wavelength. The exact quarter wavelength used as the operating wavelength earlier was used with the birefringent characteristics to calculate the exact physical plate thickness. This thickness is used to calculate the effective phase delay of the waveplate at all wavelengths.

The calibration set up of Figure 1 was reconfigured without the tunable filter. The LP azimuth, α , was set to 0° and the WP azimuth, θ , to 15° in the reference frame of the polarisation state analyser. For these settings of α and θ the Stokes parameters of the set input state are given by^[1]

$$\begin{pmatrix} s1 \\ s2 \\ s3 \end{pmatrix} = \begin{pmatrix} \frac{1}{4}(3 + \cos(\phi)) \\ -\frac{\sqrt{3}}{4}(1 - \cos(\phi)) \\ -\frac{1}{2}\sin(\phi) \end{pmatrix}$$

where ϕ is the phase delay of the waveplate at wavelength λ .

$$\phi = 2\pi \frac{B(\lambda)d}{\lambda}$$

where d is the actual plate thickness and $B(\lambda)$ is the birefringence^[2] $= n_e - n_o$, which is a function of wavelength.

The measured stokes parameters were recorded as a function of wavelength. The

RMS difference between the measured Stokes parameters and the theoretical input Stokes parameters was calculated as 0.021.

Uncertainty of Polarisation State Analyser

The uncertainty of the measured Stokes parameter is the combination of the following uncertainties:

Uncertainty of:	σ
Theoretical set state	0.008
Polarisation State Analyser over Poincaré Sphere	0.011
Polarisation State Analyser with Power	0.003
Polarisation State Analyser with Wavelength	0.021
Total	0.03

Thus the actual polarisation state lies on the Poincaré sphere within a circle of radius 0.03 (1σ) centred on the measured polarisation state.

Effect on PMD Measurements

At NPL the polarisation state analyser is used to measure PMD. The Stokes vector arc analysis method^{[3][4]} is used with 3 input states rotating around the principle state of polarisation (PSP). Consider the case where one of the input states is aligned with the PSP and the other 2 are orthogonal to the PSP. For a low mode coupled device where the wavelength step has been optimised the states will rotate by ~ 3 rad, the uncertainty on the rotation angle will be $(0.03 \cdot \sqrt{2}) / (\sqrt{2} \cdot \sqrt{2}) = 0.02$ (1σ) [This is the polarisation state analyser calibration uncertainty $\cdot \sqrt{2}$ for the two measurements at λ_1 and λ_2 , divided by $\sqrt{2}$ for the 2 rotating states and divided by $\sqrt{2}$ since the polarisation state analyser uncertainty has 2 degrees of freedom, it is an area of the surface of the Poincaré sphere.]. This would give an uncertainty of $< 1\%$ (1σ) on the PMD of a low mode coupled device. For a high mode coupled device the average rotation will be 0.6 rad, to ensure the statistical higher rotation rates do not exceed 3 rad, this will give an uncertainty of $\sim 4\%$ (1σ) on the PMD. This will not be significant to the overall uncertainty on the measurement of PMD which will be dominated by the

Maxwellian statistics^[5].

The best PMD resolution is given by a Stokes Vector rotation of 0.02 rad in the full wavelength range of the tunable laser source ~ 0.3 fs.

These uncertainties can be improved by increasing the number of input states.

Conclusions

In this paper I have outlined the requirements and techniques for the calibration of a polarisation state analyser used to make PMD measurements. The effect of this on the PMD measurement uncertainty has been described.

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