Investigation of the Fixed Analyzer Technique for Polarization Mode Dispersion Measurements on Optical Fibres

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Abstract—In this paper the fixed analyzer technique is employed to measure the polarization mode dispersion (PMD) of several different types of optical fibre. The data was analyzed using the extrema counting and mean-level crossing methods. Comparative PMD measurements were done using the Jones matrix eigenanalysis (JME) and interferometric PMD measurement techniques. The fixed analyzer PMD measurement results compared well with the PMD determined by the JME and interferometric techniques. It was however shown from error plots that the extrema counting analysis method has some limitations regarding its accuracy. A comparison between the extrema counting and mean-level crossing analysis methods are shown to agree well with one another. The bias in fixed analyzer measurements due to incorrect sampling is also briefly investigated and shown to be important in obtaining accurate results.

I. INTRODUCTION

INCREASE in the demand for higher bit rate and the rapid growth of fibre optic transmission systems implies that a greater understanding of polarization mode dispersion (PMD) is required. Currently PMD is regarded as one of the greatest limiting factors in high data bit rate transmission systems and plays a major role in causing pulse distortion in these systems. PMD stems from birefringence and mode coupling and poses a challenge to PMD compensation. It is a stochastic phenomenon which varies due to intrinsic, extrinsic factors and the number of mode coupling sites.

PMD measurements play a key role in characterizing and understanding system penalties in optical transmission systems caused by this dispersion effect. A variety of PMD measurement techniques, where each technique is based on a different principle, have been investigated. Routine characterization of optical fibre networks with respect to PMD requires a simple measurement technique. The fixed analyzer technique, also known as the wavelength scanning technique, fits this description well. An easy method to implement when analyzing data from fixed analyzer measurements is extrema (i.e. maxima and minima) counting which relies on the number of extrema counted in the transmission spectrum through a polarizer [1]. The method can be applied to both short and long fibres and to fibres with no and strong polarization mode coupling. Its counterpart is the mean-level crossing method which involves the counting of the number of times the transmission spectrum crosses the mean transmission [1].

This paper is organized as follows: A brief introduction to PMD is provided in section II. Section III concentrates on the fixed analyzer technique employed during this study. Equations for extrema counting and mean-level crossing methods will be presented. An equation for the sampling density reported by Williams and Wang [2] will also be discussed in conjunction with the need for correct sampling when using the fixed analyzer technique. In sections IV and V our experimental results will be presented and discussed.

II. POLARIZATION MODE DISPERSION

PMD occurs in optical fibre due to birefringence and polarization mode coupling. The propagation of a light pulse down an optical fibre may be modelled as two orthogonally polarized eigenmodes propagating with the same group velocity [3]. This is only true in the absence of birefringence which occurs from the asymmetry of the fibre core. Asymmetry of the fibre core is a result of imperfections in the fabrication process, mechanical stress and environmental conditions. Birefringence causes a difference between the group velocities of the orthogonally polarized modes, which results in pulse broadening.

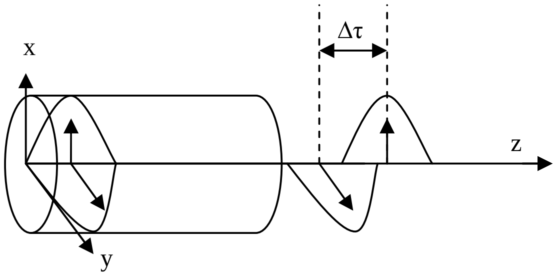

Figure 1. Schematic illustration of pulse broadening.

Figure 1 shows that due to the different propagation velocities of the orthogonal modes in the fast axis and in the slow axis there is a time delay Δτ. This resultant difference in propagation time is known as the differential group delay (DGD). The root mean square (RMS) DGD over the measured wavelength range is referred to as the PMD.

Mode coupling also plays a major role in defining the output PMD of a fibre. Mode coupling sites arise as a result of variations in fibre geometry caused during the fabrication process or some other form of stress induced on the fibre. A single mode optical fibre can be considered to consist of a concatenation of several birefringent sections with random birefringent axes. Figure 2 show that each fibre section may have its own fast and slow axis orientation.

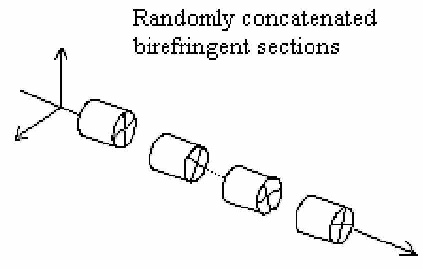

Figure 2. A model of concatenation of birefringent sections.

Mode coupling is defined as the process whereby the energy is recombined at the mode coupling sites between two adjacent segments. This recombination process may lower the PMD because some of the light travelling in the fast axis may be re-coupled into the slow axis or *visa-versa*.

III. FIXED ANALYZER TECHNIQUE

PMD measurement techniques operate either in the time domain or the frequency domain. Techniques which operate in the time domain sense the pulse delays between the modes propagating in the fast and slow axis, e.g. the interferometric technique. The interferometric PMD measurement technique is most suited for field measurements because it can perform rapid, accurate PMD measurements [4, 5]. Other techniques rely on changes of the polarization with frequency. The JME and the fixed analyzer method fall within the latter category. The JME technique can accurately determine the DGD as a function of wavelength [6, 7].

Figure 3 shows a general fixed analyzer setup. Light from a tunable laser source or a polarized broadband source is launched into the fibre under test (FUT). The transmission power through an output polarizer is measured as a function of wavelength with a detector, e.g. a power meter or an optical spectrum analyzer (OSA). The orientation of the polarizer and the analyzer are assumed to be random.

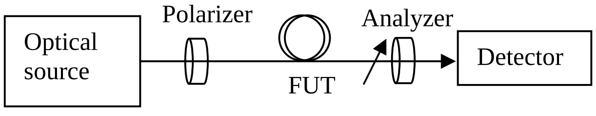

Figure 3. Illustration of a typical fixed analyzer setup.

The fixed analyzer measurement technique has been compared with several other PMD measurement techniques [8-11]. Its main advantage is the simplicity of the technique. In this article two methods for analyzing transmission spectra obtained from the fixed analyzer technique, namely extrema counting and mean-level crossing, will be discussed.

For both the extrema counting and mean-level crossing analysis the intensity spectrum from the detector is first normalized [12], in order to remove the spectral dependence of the measurement system components and the test fibre loss. This is done by obtaining the transmission spectrum both without and with the analyzer in place. The plot ratio is given by

$$T(\lambda) = \frac{P_A(\lambda)}{P_{TOT}(\lambda)} \tag{1}$$

where $P_A(\lambda)$ is the intensity spectrum transmitted through the analyzer and $P_{TOT}(\lambda)$ is the total transmitted power, in other words the intensity spectrum without the analyzer in place.

Reference [1] related the extrema density and the mean-level crossing density to the expected value of PMD. When using extrema counting and mean-level crossing analysis it is important to distinguish between the long length regime and the short length regime. When a fibre is scaling as √L (long length regime) then the derived equation relating the number of extrema counted from the transmission spectrum with the expected value for the PMD is

$$\begin{aligned} \langle \Delta\tau \rangle &= k\pi \frac{\langle N_e \rangle}{\Delta\omega} \\ &= \frac{k \langle N_e \rangle \lambda_1 \lambda_2}{2c(\lambda_2 - \lambda_1)}, \qquad \mathrm{L}/\mathrm{l_c} \to \infty \end{aligned} \tag{2}$$

where the PMD $<\Delta\tau>$ is equal to a constant multiplied by the ratio of the number of extrema $<N_e>$ and the angular optical frequency $\Delta\omega$. The starting and ending wavelength are denoted by λ_1 and λ_2 respectively. L denotes the length of the fibre and l_c is the coupling or correlation length. The mode coupling factor, k, reported in [1] is equal to 0.824 for fibres of high mode coupling sites and is equal to 1 for fibres with no mode coupling. Williams and Wang [2] reported a correction for the mode coupling factor, changing the previously accepted value from 0.824 to 0.805 with a 2% difference. This 2% difference has not been sufficiently verified experimentally [2]. The TAI/EIA FOTP-113 Standard [12] suggests that the value of 0.82 be used in PMD calculations.

The equation relating the mean-level crossing density to the expected value for PMD for high mode coupled fibre is as follows

$$\langle \Delta\tau \rangle = 4\frac{\langle N_m \rangle}{\Delta\omega} = \frac{2\langle \mathrm{N_m} \rangle \lambda_1 \lambda_2}{\pi c \Delta\lambda}, \qquad \mathrm{L}/\mathrm{l}_c \to \infty \tag{3}$$

where $<N_m>$ is the number of mean-level crossings which is the number of times that the transmission spectrum is expected to cross the mean transmission T. Hence the expected PMD is four times the mean-level crossing density for high mode coupled fibre.

For fibres scaling in the short length regime where the PMD scales linearly with length and is deterministic, the equations for the expected PMD reduce to

$$\Delta\tau = \frac{\pi N_e}{\Delta\omega} = \frac{\pi N_m}{\Delta\omega}, \qquad \mathrm{L}/\mathrm{l_c} \to 0 \qquad (4)$$

The length regime of the fibre is easily determined by using the ratio of the number of extrema to the number of mean-level crossings [1] as an indication of the length regime. For fibres scaling as long length

$$\frac{\langle N_e \rangle}{\langle N_m \rangle} = \frac{4}{0.824\pi} = 1.54, \qquad \mathrm{L}/\mathrm{l_c} \to \infty \qquad (5)$$

and the short regime

$$\frac{\langle N_e \rangle}{\langle N_m \rangle} = 1, \qquad \mathrm{L}/\mathrm{l_c} \to 0 \qquad (6)$$

Fixed analyzer measurement techniques are subject to bias in the PMD due to incorrect sampling and noise effects [2, 11]. Williams and Wang [2] investigated the effects of sampling by introducing the sampling density given by the formula

$$\eta = n_f \big/ \langle \Delta\tau \rangle \Delta\omega \qquad (7)$$

where η is the sampling density and n_f is the number of points sampled. From equation (7) it becomes evident that in order to keep the sampling density fixed for a fixed number of points, the frequency window will have to be made smaller with an increase in PMD. The contrary, as the PMD decreases the frequency needs to become larger, is also true. The correct sampling density can be chosen by using (7) and the problem of noise may be solved by introducing threshold techniques [2].

IV. EXPERIMENTAL MEASUREMENTS

All fixed analyzer results presented in this article were obtained from the setup as illustrated in Figure 3. An Agilent 86142B optical spectrum analyzer (OSA) was used as the detector and an EXFO M2100 polarized broadband (C band) source was used in all fixed analyzer measurements. We have developed a program in Labview to automate the data collection and calculation of PMD using equation (2). The program allows for various parameters on the OSA to be controlled via the computer. Measurements were made by initializing a session with the OSA and running a scan. In order to measure the PMD of a FUT two scans were run each time. The first scan was done without the analyzer in place and the second scan was run with the analyzer in place. The program normalized the transmission spectra using equation (1) and calculated the PMD by counting the number of extrema and by making use of equation (2).

Using the fixed analyzer setup illustrated in Figure 3, the transmission spectra of five different FUT were measured. The FUTs used were: fibre shipping spool (FSS), short (1 m) polarization maintaining fibre (PMF), long (30 m) PMF, emulator (EMU) and a 6 km long fibre optic cable. For each FUT ten measurements were made, the PMD was calculated using extrema counting and the half-range (error), i.e. the difference between the maximum and minimum divided by 2, was calculated. The same procedure was followed for the JME and the Generalized interferometric (GINTY) technique. The measurements for the three instruments were compared in terms of measured PMD value and error plots.

Using the density of mean-level crossings to determine the PMD should give the same value as that for extrema counting. This was verified by using the same transmission spectra of the FUT to determine the PMD value. Equations (3) and (4) were employed where appropriate.

Sampling density greatly influences the PMD result. Incorrect sampling may lead to an inaccurate PMD value. A basic emulator (EMU) consisting of highly birefringent PMF sections of length 1.5 m, 1.9 m, 0.8 m and 2.8 m was used to investigate the optimum sampling density. The wavelength window was changed in increments of 10 nm, ranging from 10 nm to 100 nm, while keeping the number of points fixed. The PMD for each transmission spectrum was calculated using extrema counting. The wavelength window for JME was also changed in steps of 10 nm and the measured PMD noted. A 70 nm wavelength window was measured using the JME and fixed analyzer method for wavelength range analysis.

V. RESULTS AND DISCUSSION

Figure 4 shows the transmission spectra of the four fibres tested. It is clear that each FUT transmission spectra has a unique signature depending on the birefringence and the number of mode coupling sites. An increase in birefringence implies more extrema over a given wavelength range. The number of mode coupling sites influences the periodicity of

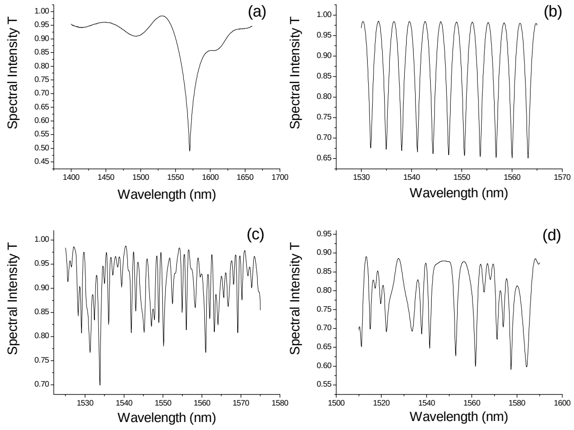

Figure 4. OSA transmission spectra of the FUT investigated: (a) FSS, (b) PMF, (c) EMU and (d) Fiber cable.

the transmission spectra. Many mode coupling sites imply a non-periodic signature. Since PMF has no mode coupling sites, the OSA transmission spectra for PMF is periodic as shown in Figure 4 (b). The transmission spectra of the emulator, shown in Figure 4 (c) indicate that it has a lot of mode coupling.

TABLE I
MEASURED PMD VALUE FOR SEVERAL FUT

		FIXED ANALYZER	GINTY	JME
FSS	<Δτ> (ps)	0.070	0.116	0.097
	Δ (ps)	0.012	0.004	0.007
	%Δ (%)	33.8	6.03	14.40
PMF (short)	<Δτ> (ps)	2.624	2.589	2.599
	Δ (ps)	< 0.001	0.002	0.0005
	%Δ (%)	< 0.04	0.15	0.04
PMF (long)	<Δτ> (ps)	30.132	30.314	30.136
	Δ (ps)	0.200	0.009	0.009
	%Δ (%)	1.33	0.056	0.06
EMU	<Δτ> (ps)	4.600	5.277	4.822
	Δ (ps)	< 0.001	0.099	0.005
	%Δ (%)	< 0.02	3.75	0.21
Fibre Cable	<Δτ> (ps)	1.366	1.348	1.266
	Δ (ps)	0.062	0.010	0.026
	%Δ (%)	9.07	1.48	4.03

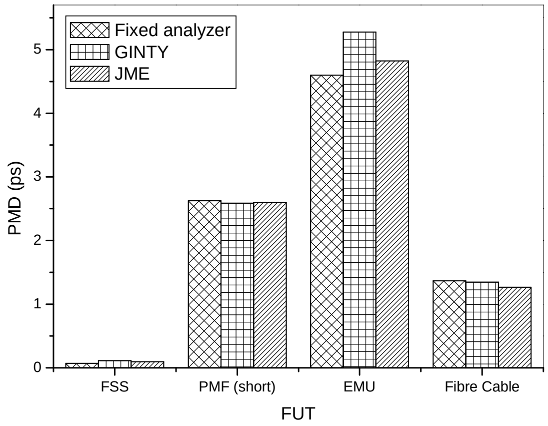

Figure 5. Comparison of the PMD of several FUT for different measurement techniques.

PMD results for several FUT using the fixed analyzer, JME and interferometric techniques are listed in Table 1. The fixed analyzer technique using the OSA as a detector is denoted as fixed analyzer and the interferometric technique as GINTY (Generalized interferometric technique). The highest PMD measured with the fixed analyzer technique was 30.132 ps for a 20 m long PMF and the lowest PMD measured was 0.07 ps for a 20 km long fibre shipping spool. As can be seen from Figure 5 the PMD results for the fixed analyzer technique compared extremely well with those of the JME and interferometric techniques.

Ten measurements were made for each FUT with each instrument, hence the half-range (Δ) and percentage range (%Δ) were calculated as shown in Table 1. From Table 1 it can be noted that the half-range for the fixed analyzer is either < 0.001 ps or greater than that for GINTY and JME. A half-range < 0.001 ps implies that the fixed analyzer technique is unable to detect such small changes in the PMD, which is verified by the fact that JME and GINTY do detect changes in the PMD value. This small change in the PMD detected by JME and GINTY may be attributed to changes in the SOPs due to fibre movement or due to instrumentation error. From equation (2) for extrema counting it is evident that the change in the PMD for the fixed analyzer depends on the change of the number of extrema (N_e). Thus the smallest PMD change that can be detected by the fixed analyzer technique in conjunction with the extrema counting method is the PMD calculated by n number of extrema followed by (n+1) extrema. Thus it is suggested that the technique would either be unable to realize the change or it may overestimate the PMD change. These effects are evident from percentage range plots shown in Figure 6. In Figure 6 (b) the fixed analyzer technique predicts an extremely low error for the short PMF and for the emulator, implying no change in PMD. Whereas Figure 6 (a) shows that the fixed analyzer technique has the largest error compared to the other two techniques.

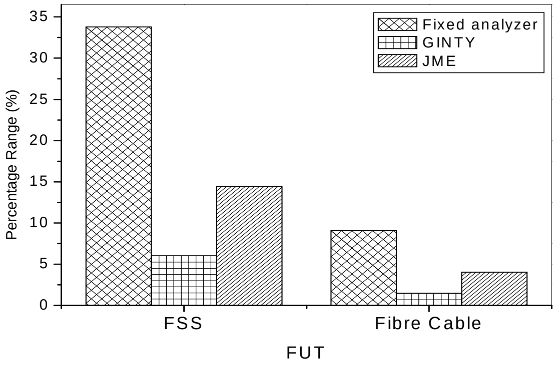

Figure 6. (a) PMD percentage range of FUT.

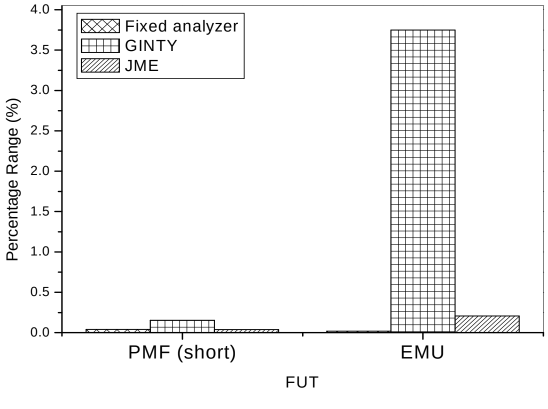

Figure 6. (b) PMD percentage range of FUT.

Having looked at the error analysis we now turn our focus to a comparison between extrema counting and mean-level crossing analysis methods. The data for various fibres was collected using the fixed analyzer technique and was analyzed using both the extrema counting and mean-level crossing methods. The results are indicated in Figure 7. As is evident form Figure 7 there is a very small difference in the PMD value predicted by these two methods which suggest that they are both suitable methods for determining the PMD.

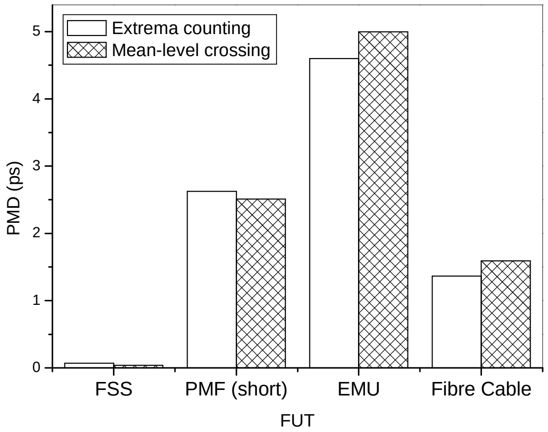

Figure 7. PMD calculated for an emulator using extrema counting and mean-level crossing.

Equations (5) and (6) indicate that the ratio of the number of extrema and the number of mean-level crossings give an indication of the fibres length regime [1]. If the ratio is close to or greater than 1.54 then the fibre is in the long length regime, implying that it has many mode coupling sites. A ratio of 1 indicates that the fibre is in the short length regime, i.e. no mode coupling. Table II shows this ratio for the FUT.

TABLE II
FUT LENGTH REGIME

FUT	No. Extrema (N_e)	No. Mean-level crossing (N_m)	N_e/N_m
FSS	5	2	2.5
PMF short	23	22	1.05
EMU	70	49	1.43
Fibre Cable	32	25	1.28

PMF has a periodic spectrum which is reflected by the ratio (N_e/N_m) of 1.05, hence it is in the short length regime with no mode coupling. This is quite evident from Figure 4 (b). The ratio for the emulator and the fibre optic cable are both close to 1.54 suggesting that both are in the long length regime with many mode coupling sites, which is indeed the case for both. The high ratio of 2.5 for the fibre shipping spool suggests that it may have many mode coupling sites. This is possibly due to the fact that when the fibre is wound around the shipping spool the fibre overlaps and mode coupling sites are formed at these points.

Sampling density has been identified as a significant factor when doing PMD measurements using the fixed analyzer technique [2, 11]. PMD measurements with the fixed analyzer technique may be biased due to incorrect sampling. This was investigated by making PMD measurements using transmission spectra of different wavelength windows. The minimum and maximum windows range from 10 nm to 100 nm. The window size was increased in steps of 10 nm. For each window the number of points was kept fixed at 1001. The increase in window size was done by spreading out from a central wavelength of 1530 nm. Hence the smallest scan range is 1525-1535 nm and the largest 1480-1580 nm. Figure 8 shows the results for the fixed analyzer technique. The same procedure was applied using the JME technique except the number of sampling points was not kept constant. Therefore the JME technique should predict the correct PMD value. The root mean square (RMS) DGD is represented. From Figure 8 it can be seen that windows from 10-40 nm and 90-100 nm give incorrect PMD values suggesting incorrect sampling. It is evident that under-sampling and over-sampling both gave incorrect measured PMD values. The windows from 50-80 nm agree well with the PMD determined by the JME technique. Using equation (7) and the expected value of the PMD for a sampling density of 4, the predicted size of the wavelength window is 70 nm.

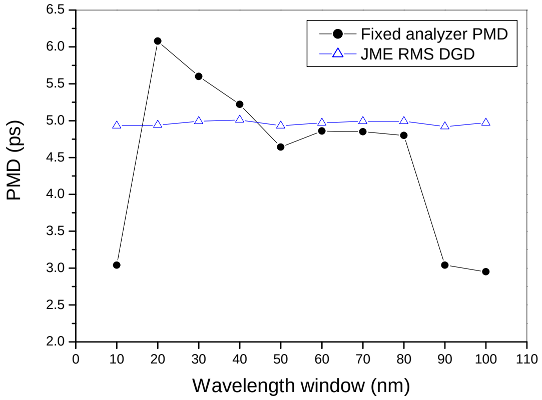

Figure 8. PMD of various wavelength windows for a fixed 1001 number of points. All windows were centred about λ = 1530. nm.

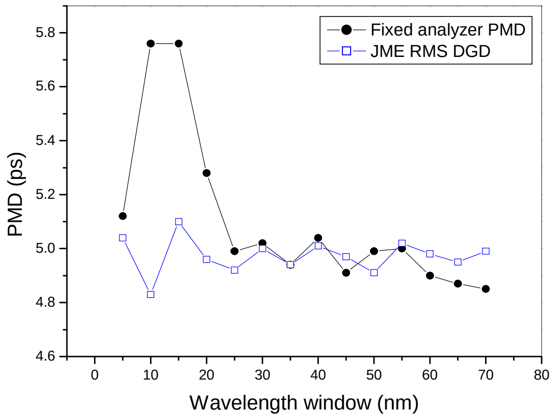

Figure 9. PMD calculated for different widths of a single wavelength window scan. The window was centred about λ = 1530 nm.

Figure 8 clearly shows that incorrect sampling can influence the PMD measurement accuracy. To investigate how the measured PMD value will fluctuate across a single transmission spectrum, a single OSA scan was made from 1495 nm to 1565 nm. The spectrum was divided up as before, but with a difference in the step size and the range used. The PMD was calculated using extrema counting. The minimum spectrum range was 5 nm and the maximum range 70 nm. Steps of 5 nm were used. The same procedure was applied to the JME technique. Figure 9 presents the results where the root mean square DGD is plotted for the JME technique. From Figure 9 it can be seen that the PMD changes when spreading out from the central wavelength at 1530 nm and increasing the wavelength window. This change is periodic and small for windows greater than 25 nm. This implies that the PMD calculated for a fixed spectrum, which was sampled correctly, is not affected much by the size of the selected wavelength window provided the window is not much smaller than the scan range. However it is quite evident by comparison with the JME spectrum that the PMD trend nears the true PMD value as the wavelength window approaches the full wavelength range of 70 nm.

VI. CONCLUSION

The fixed analyzer PMD measurement technique was assembled together and automated through a computer using Labview. It was successfully applied to the measurement of PMD on various optical fibres with a range of PMD values. Both the extrema counting and mean-level crossing methods were used and they agreed well with each other. A basic comparison between the fixed analyzer using extrema counting for data analysis, the JME and the interferometric technique for a range of large and small PMD values were conducted. Only a small difference in the measured PMD value was evident. Hence the fixed analyzer technique was shown to be a fairly accurate PMD measurement technique. Analysis of the error suggests that the fixed analyzer technique may not be suitable for investigating the statistical nature of PMD. Incorrect sampling was shown to give biased PMD values. Further work will involve making a comparison under different conditions between the fixed analyzer technique and interferometric techniques.

VII. ACKNOWLEDGEMENTS

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