

Experimental Demonstration of an Adaptive Poincaré sphere analysis and the Fixed Analyzer Polarization Mode Dispersion Measurement Techniques

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Abstract—Polarization mode dispersion (PMD) continues to mitigate the efficiency of optical networks. The link between the reduced bit transfer rates and increased presence of PMD in a fibre is well known. Technological advances spur new technologies which continue to demand faster data transfer rates, hence knowledge of PMD within optical networks becomes essential. In this paper the fixed analyzer (FA) and an adaptive Poincaré sphere analysis PMD measurement techniques are discussed, followed by experimental demonstrations. It is shown that the Poincaré sphere analysis (PSA) method presented in this paper is in principle equivalent to analysis methods presented before, but differs with respect to the method of analysis applied and the data required for analysis. The FA technique and PSA methods are compared, and the Jones matrix eigenanalysis (JME) method used as a reference technique. It is found that the FA and PSA methods yield the same average PMD value. The differential group delay (DGD) and the principle states of polarization (PSP) is valuable information given in addition by the PSA method.

Index Terms—Fixed analyzer (FA), Jones matrix eigenanalysis (JME), Poincaré sphere analysis (PSA), polarization mode dispersion (PMD).

I. INTRODUCTION

FUTURE technologies promise a great number of benefits but will require more bandwidth than what most networks are currently able to supply. This will necessitate more efficient use of current optical fibre networks and a thorough knowledge of the magnitude of pulse broadening optical effects such as polarization mode dispersion (PMD). Hence regular characterization of PMD in optical fibre links is required. This calls for easy to implement PMD measurement techniques.

PMD stems from birefringence and is complicated by mode coupling. Birefringence refers to the effect which causes a time delay between two orthogonal polarization modes. This time delay is referred to as the differential group delay. Mode coupling further complicates the effect of birefringence and is described as the process whereby the optical energy from two adjacent birefringent sections recouples into the new birefringent section. PMD is described as the average or root mean square (RMS) of the DGD.

The FA technique originally proposed by Poole and Favin involves measuring the intensity of light at the output of a polarizer over a specified wavelength range [1]. Features of the normalized intensity spectrum are then related to the average PMD. The FA technique is a reliable PMD measurement technique and is now considered to be a standard PMD measurement technique.

The PSA method was first proposed by Poole *et al.* in 1988 [2] and further refined by Cyr *et al.* [3]. Both techniques use the same experimental setup but differ in the data required for analysis. The PSA method as described by Poole *et al.* [2] requires three input states of polarization where one input state of polarization (SOP) should be circular. In reference [3], Cyr *et al.* shows that only linear input states of polarization (SOPs) are required in order to extract the full polarimetric data.

In this work the FA technique is compared to the PSA method. For the sake of accuracy the same source is passed through a fibre under test (FUT), split by a coupler and terminated at two polarimeters. One polarimeter measures the power over wavelength and the other records the SOP of a wavelength sweep. FA analysis and a self developed PSA method is performed on the appropriate collected data.

This paper is organized as follows. A brief description of PMD is undertaken followed by a thorough discussion of the FA technique. The developed PSA analysis method is then discussed in detail. This is followed by a description of the experiments carried out, a discussion of the results and conclusions of the work.

II. POLARIZATION MODE DISPERSION: A BRIEF DISCUSSION

As already mentioned previously PMD is a combination of birefringence and polarization mode coupling. A light wave may be modeled as two orthogonal polarization modes propagating with the same group velocity down an optical fibre [4]. This only occurs in the absence of birefringence which slows one of the orthogonal modes down relative to the other. Birefringence is a result of asymmetry within the fibre core which may be caused by the fabrication process, mechanical stress and environmental conditions. Birefringence has an overall pulse broadening effect on the input optical pulse. The time delay caused by birefringence in a birefringent fibre is known as the differential group delay (DGD). The root mean square (RMS) of the DGD is known as the PMD.

In the presence of mode coupling a length of fibre consists of several birefringent sections, each with its own birefringent axis. Each birefringent section has its own slow and fast axis orientation. Mode coupling is defined as the process whereby the optical energy recombines into the birefringent axis at mode coupling sites. Mode coupling

mainly arises as a result of variations in the fibre geometry caused by mechanical stress or handling of the fibre during the manufacturing process. During the recombination process at mode coupling sites light propagating in the fast axis may be re-coupled into the new slow axis and *vice-versa*.

III. FIXED ANALYZER PMD MEASUREMENT TECHNIQUE

The FA PMD measurement technique consist of a polarized source which is sent through a fibre or device under test and then through a linear polarizer after which the continuous wave is detected by a detector. A typical FA setup is illustrated in Fig. 1.

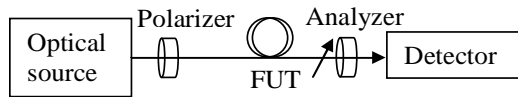


Fig. 1 Schematic of typical FA setup.

The source is either a broadband source or a tuneable laser in which case the detector would be either an optical spectrum analyzer or a power meter respectively. The detector records the intensity of the optical source passed through the FUT and a polarizer over wavelength.

The extrema density and the mean level crossing density have been related to the average PMD value [1]. Extrema density refers to the number of peaks and valleys per unit angular optical frequency and mean level crossing density to the number of times the intensity trace crosses the mean transmittance per unit angular optical frequency. When the fibre scales as the square root of length (long length regime) then the equation relating the number of extrema in the intensity spectra to the expected PMD is as follows

$$\langle \Delta \tau \rangle = k\pi \frac{\langle N_e \rangle}{\Delta \omega} = \frac{k \langle N_e \rangle \lambda_1 \lambda_2}{2c(\lambda_2 - \lambda_1)}, \quad L/l_c \rightarrow \infty. \quad (1)$$

In equation (1) the $\langle \Delta \tau \rangle$ is the PMD, k the mode coupling factor, $\langle N_e \rangle$ the number of extrema, $\Delta \omega$ the angular optical frequency, λ_1 and λ_2 the starting and ending wavelength. L denotes the length of the fibre and l_c is the coupling or correlation length. Originally the mode coupling factor k put forward was 0.824 [1] after which Williams and Wang suggested the value 0.805 [5]. In this work we make use of the mode coupling factor value of 0.82 recommended by the TAI/EIA FOTP-113 Standard [6]. In the presence of mode coupling the mean level crossing counting analysis equation is as follows:

$$\langle \Delta \tau \rangle = 4 \frac{\langle N_m \rangle}{\Delta \omega} = \frac{2 \langle N_m \rangle \lambda_1 \lambda_2}{\pi c(\lambda_2 - \lambda_1)}, \quad L/l_c \rightarrow \infty. \quad (2)$$

where $\langle N_m \rangle$ is the number of mean level crossings.

In the absence of mode coupling PMD scales linearly with length and the mode coupling factor takes the value one. The extrema density and mode coupling density analysis equations tend to be equal and have the form

$$\Delta \tau = \frac{\pi N_e}{\Delta \omega} = \frac{\pi N_m}{\Delta \omega}, \quad L/l_c \rightarrow 0. \quad (3)$$

IV. CUSTOM DEVELOPED PSA ANALYSIS METHOD

PSA methods require measurement of the SOP through a FUT over a specified wavelength range. The PSA method demonstrated by Poole *et al.* in 1988 [2] requires three input states of polarization of which one must be circularly polarized. Cyr *et al.* developed another PSA analysis method which requires three linearly polarized input SOPs and compared it to the JME technique [3]. Both these PSA analysis methods require three input polarization states. In this paper, the FA and PSA techniques are compared by using the same optical source, hence measuring the SOP and intensity at the same time. Thus only one input SOP must be used. This requires a different PSA analysis method. In this work we develop a PSA method which requires only one input SOP by applying the basic principle which states that the DGD is equal to the rate of rotation of the SOPs over angular optical frequency.

SOPs evolve over the Poincaré sphere when sweeping over a wavelength range. This evolution depends on the magnitude of birefringence and degree of mode coupling present in the FUT. High birefringence results in fast rotation of SOPs over wavelength and mode coupling changes the direction of rotation on the Poincaré sphere. Frequency domain techniques determine the DGD from the rate of rotation of the SOP about the principle states of polarization (PSP). This is described by the equation

$$\Delta \tau = \frac{\Delta \theta}{\Delta \omega} \quad (4)$$

where $\Delta \theta$ is the angle of rotation of the SOPs.

Suppose a wavelength sweep is performed and the SOPs trace a small arc, from point A to X to B, out on the Poincaré sphere as shown in Fig. 2.

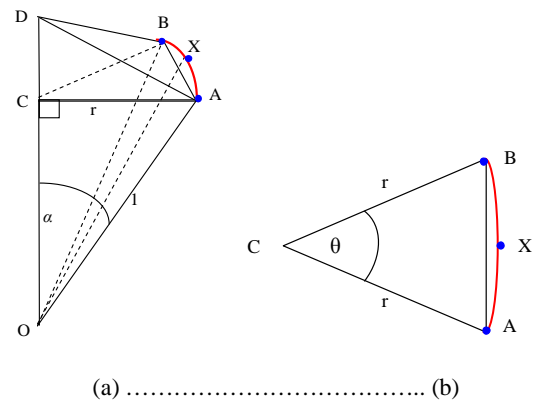


Fig. 2 (a) Schematic of an arc traced out on a Poincaré sphere and the corresponding SOP vectors. (b) Subsection of the schematic in (a).

If the SOPs continued about this path and formed a complete circle then the centre point of this circle would be the PSPs pointing in the direction of the PMD vector. Therefore the task is to determine θ . The developed

algorithm breaks this down into several tasks and θ is derived to be calculated as

$$\theta = \cos^{-1} \left(1 - \frac{(AB)^2}{2r^2} \right). \quad (5)$$

This algorithm was applied to determine the angle θ which is required to compute the DGD for a particular wavelength increment.

V. EXPERIMENTAL SETUP

The experimental setup applied in this work is illustrated in Fig. 3. For the FA technique the intensity over wavelength was recorded with polarimeter 1 and the SOP for the PSA method with polarimeter 2. A tuneable laser was swept from 1510 nm to 1570 nm with a step of 0.1 nm and polarization maintaining fibre was used as the fibre link.

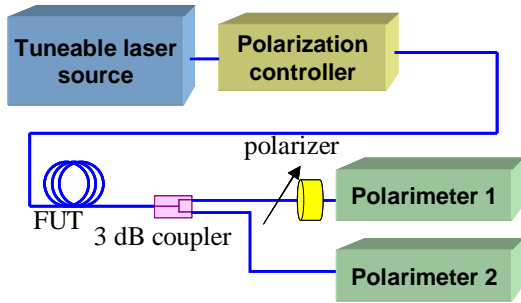


Fig. 3 Combination of conventional FA setup and the conventional PSA setup.

VI. RESULTS AND DISCUSSION

Fig. 4 shows an intensity spectrum from 1520 nm to 1530 nm for a 20 m long PMF section. Extrema counting analysis and mean level crossing analysis determined the PMD value to be 30.840 ps and 30.906 ps respectively.

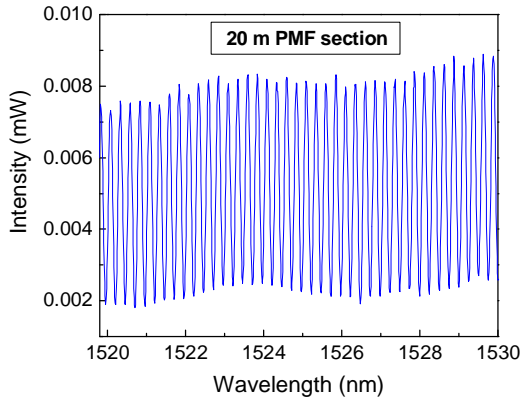


Fig. 4 Intensity spectrum of a 20 m long PMF section.

This is a result of the fact that the spectrum is more or less periodic because of the absence of mode coupling sites

hence the application of equation (3) gives an average PMD value which does not differ much.

The JME method determined the average PMD value to be 30.941 ps and the RMS PMD value as 30.941 ps giving a good comparison between FA and JME techniques.

From Fig. 5 it can be observed that the SOP through the polarizer remains fixed, hence the polarizer acts as a transform from SOP fluctuation to intensity fluctuation.

Polarimeter 2 recorded the SOP over a wavelength range from 1510 nm to 1570 nm. This data was analyzed using

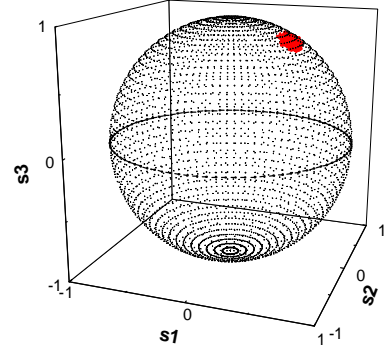


Fig. 5 Location of SOP through the linear polarizer on the Poincaré sphere.

equations (4) and (5). The DGD over wavelength was computed and is shown in Fig. 6. From Fig. 6 it can be observed that the PSA and JME analysis techniques give the same trend for the DGD over wavelength. The mean DGD given by the PSA method is 30.814 ps and the RMS DGD is 30.867 ps. The percentage difference between the PSA method and the FA method is 0.08 %.

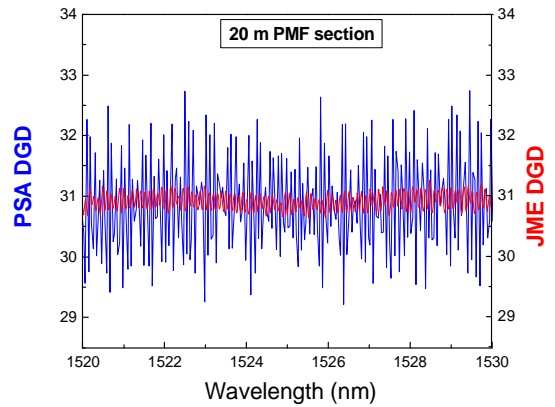


Fig. 6 DGD measurements using the PSA and JME techniques for a 20 m PMF section.

Note that the PSA method has the advantage of giving the PSP as well. In Fig. 7 the PSP as measured by the JME technique are shown. The orthogonal PSP is determined using the PSA method and is shown in Fig. 7. The fact that the PSP determined by the JME and PSA method are orthogonal confirms that the two techniques agree to a large extent.

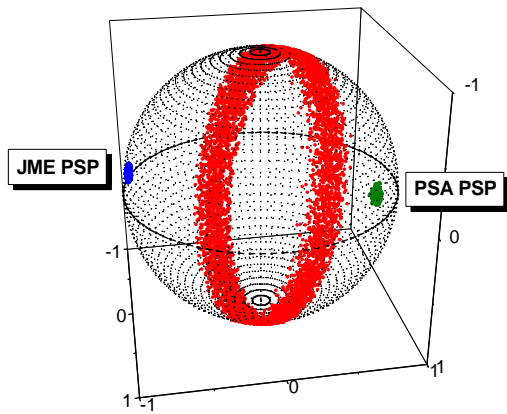


Fig. 7 PSA and JME DGD over wavelength for a 20 m PMF section.

VII. CONCLUSION

In this paper the FA technique is compared to the adaptive PSA method. It was found that the two techniques compare very well with a 0.08 % difference for the average PMD of a 20 m long PMF section. The PSA technique is able to further determine the DGD over wavelength and the PSPs as well. This is verified by comparing the DGD and PSP from the PSA method to that determined by the JME technique. The custom developed PSA technique shows very good agreement with the JME technique for both the DGD and PSPs. The developed PSP technique has the advantage of requiring only one input SOP for analysis.

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