PMD Measurements on Undeployed and Deployed Aerial Optical Fibre Cables using the Interferometric Technique

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Abstract— Polarization mode dispersion (PMD) is one of the major factors limiting high data transmission rates (10 Gb/s and above) in optical transmission systems. PMD originates from birefringence and mode coupling and is affected by the environment where the optical fibre cable is deployed. In this study, PMD was measured on undeployed and deployed aerial optical fibre cables using the interferometry based PMD analyzer. The effect of environmental conditions (temperature and wind speed) on PMD was investigated on the deployed aerial cable. We found that the PMD fluctuates more rapidly on deployed aerial cable than on undeployed cable, because of the faster changes on environmental condition. On the other hand, the PMD of the deployed aerial cable measured without polarization scrambling showed significant correlation with its environment, namely a change in the temperature and the wind speed.

Index Terms—Optical fibre cable, polarization mode dispersion, Interferometry technique, polarization scrambling

I. INTRODUCTION

POLARIZATION mode dispersion (PMD) is a fundamental property of non-ideal single mode optical fibre and optical components [1], and is the major limitation on high data transmission rates (≥10 Gb/s) long haul systems. PMD in optical fibres is caused by birefringence and is complicated by mode coupling. Environmental conditions such as temperature and wind causes the fibre PMD to vary randomly in time, making PMD particularly difficult to manage. This is an especially important factor on aerial optical cables.

Birefringence in a fibre causes one of the two orthogonal polarization modes of an optical signal to travel faster than the other resulting in differential group delay-DGD ($\Delta\tau$), as shown in Fig. 1. It is caused by both intrinsic and extrinsic factors. The intrinsic factors include non-circular core, cladding eccentricity, elliptical fibre and stress introduced during the manufacturing process. Birefringence on spooled, cabled, or deployed fibre can be introduced by different extrinsic factors, such as bending, twisting of fibres, and pressure during installation and operation. As the external environment of the fibre changes, a birefringence of the fibre changes resulting in the alteration of extrinsic factors.

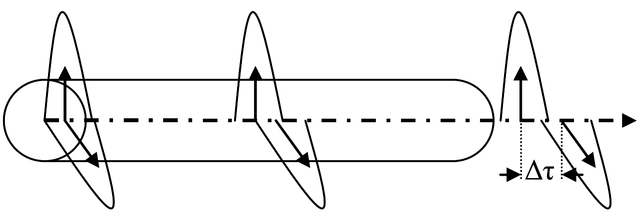

Fig. 1. Schematic illustration of the broadening of the optical pulse through an optical fibre resulting in differential group delay ($\Delta\tau$) [2].

Long fibres are treated as a concatenation of birefringence sections with birefringent axes that change randomly throughout the fibre length as shown in Fig. 2. Random variation of birefringence axes along the fibre results in random polarization mode coupling between polarization modes, where there is an exchange of energy. This will reduce the PMD of the fibre. Polarization mode coupling results from variations in the fibre drawing process, intentional fibre “spinning” during drawing, localized stress during spooling, cabling or deployment, and from splices and components [3].

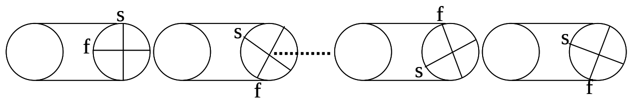

Fig. 2 A concatenation of birefringent sections, where f is the fast axis and s is the slow axis at each birefringence section.

The environment where optical cables are installed (submarine, buried, aerial and in ducts) influences the fluctuation of PMD and state of polarization (SOP) of light propagating through the fibre. Buried and submarine cables are located in a very static environment (stable PMD [4] and SOP [5]), whereas aerial cables are exposed directly to a dynamic environment and experiences great strain under wind and temperature fluctuations. If there are no vibrations that disturb the fibre environment, the stress on a buried fibre remains constant. In an aerial cable, the SOP and PMD changes on a short time scale because the fibre is in a dynamic state. To understand how the environmental conditions play a role in determining the quality of the signal, PMD should be addressed in terms of environmental changes.

II. POLARIZATION MODE DISPERSION MEASUREMENT TECHNIQUES

The need to accurately characterize and asses the impact of PMD in optical fibres has led to the development of many measurement methods. These PMD measurement methods

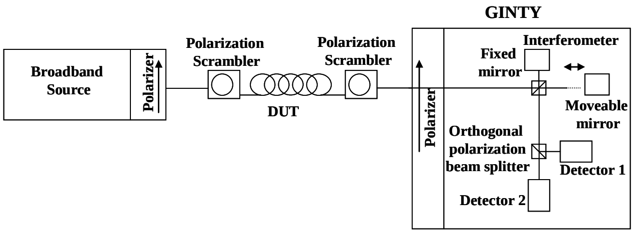

Fig. 3 Block diagram of the experimental set-up: polarized broadband source covering the C- and L-bands (1530-1625 nm), device under test and a PMD analyzer using the GINTY technique.

can be classified as frequency or time domain techniques. The frequency domain techniques (e.g. fixed analyzer [6], Jones matrix eigenanalysis [7], and Poincaré arc method [8]) determine PMD by detecting the changes of the output polarization state as a function of frequency, whilst the time domain technique (interferometry technique [9], and modulation phase shift techniques [10]) determines PMD by measuring the delay between the two orthogonal polarization modes of the pulse. This paper will concentrate on the interferometry technique since it is tolerant of movement along the fibre path during measurement and is not time consuming.

III. THE INTERFEROMETRY TECHNIQUE

The interferometry technique is based on the Michelson interferometer and is the most commonly used method to determine PMD of deployed fibre. There are different variations of interferometry techniques used to determine PMD: the Traditional Interferometry technique (TINTY) [11] and the improved Generalized Interferometry technique (GINTY) [9, 12]. In this study the PMD analyzer used is based on the latter.

The measured PMD as given by the instrument depends on the input and output (I/O) SOP of the light to and from the fibre. When the input and output SOPs are changed intentionally, there are fluctuations on PMD readings about the mean [4]. These fluctuations of PMD readings are due to different SOPs being used, and are not from a change of the fibre PMD. If the output SOP is aligned orthogonally to the analyzer axis there will be no signal detected. Furthermore, if the I/O SOPs are not changed, not all segments of the device under test (DUT) contribute to the measured PMD and no additional information can be obtained even when several measurements are taken with the same I/O SOPs. To get a more reliable PMD value and to reduce the uncertainty associated with performing a single measurement using only one I/O SOP pair [9], many combinations of SOPs must be analyzed. For a stable DUT, the SOP can be randomly or continuously changed by polarization scramblers, one at the DUT input and one at the output. The uncertainty associated with a single measurement is given by [9]:

$$\sigma_{sm} = PMD \cdot \sqrt{\left(1 - \frac{8}{3\pi}\right) \cdot \sqrt{\frac{1}{1 + \frac{1}{4}\left(\frac{PMD}{\sigma_A}\right)^2}}} \qquad (1)$$

where σ_A is the autocorrelation of the source. The uncertainty given by (1) is encountered if there is no I/O SOP scrambling performed intentionally and if the DUT is stable (no SOP fluctuations). It was shown in Ref. [4], that there is a high degree of fluctuation on PMD, when either input, output or I/O scrambling is performed. The SOPs of buried cable change slowly (of the order of hours) since they are in a static environment [5], whereas for aerial cable there are fast SOP fluctuations [5,14] due to cable movement resulting from wind and temperature changes. The changes in SOPs here result from both a topological effect (Berry Phase) [15] as well as from changes in fibre birefringence and mode coupling. The latter will cause PMD variations in the cable.

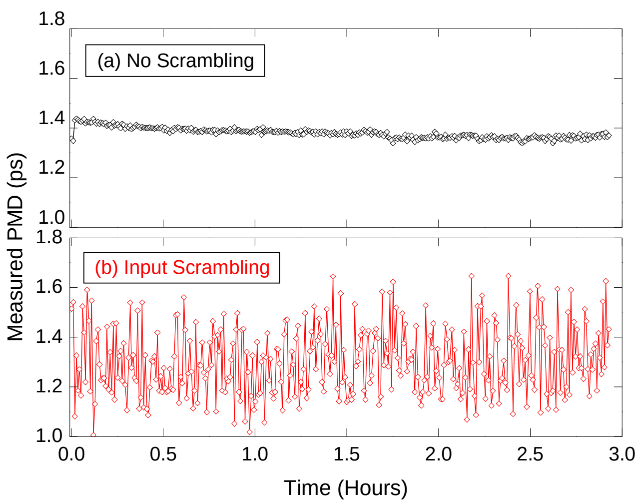

Fig. 4 PMD measured using GINTY from a cable on a shipping drum with (a) no polarization scrambling and (b) input polarization scrambling.

IV. EXPERIMENTAL CONDITIONS

Fig. 3 shows the block diagram of the experimental set-up used to measure PMD using GINTY [12] on undeployed and deployed aerial cables. The setup consists of a polarized broadband source covering the C- and L-bands (1530-1625 nm), the DUT, and a PMD analyzer using the GINTY technique. When polarization scrambling was required, a automatic polarization scrambler (EXFO- IQS 5100B) was inserted at the beginning of the fibre link. Since PMD fluctuates about a mean with either input or output polarization scrambling [4], the results presented here were only for input polarization scrambling. Where required, the states of polarization were changed continuously during measurements. PMD measurements were made on: (A) undeployed 6 km short span loose tube aerial cable consisting of 24 single mode fibres (SMF) on a 1.3 m diameter shipping drum, and (B) deployed 7.1 km loose tube aerial cable linking St Albans and Rocklands, outside Port Elizabeth, consisting of 24 SMF.

V. RESULTS

A. *Undeployed Aerial Cable on a Shipping Drum*

Two optical fibres were selected from a cable on a shipping drum stored in our laboratory. They were looped to give a 12 km link. The PMD of the link was monitored over

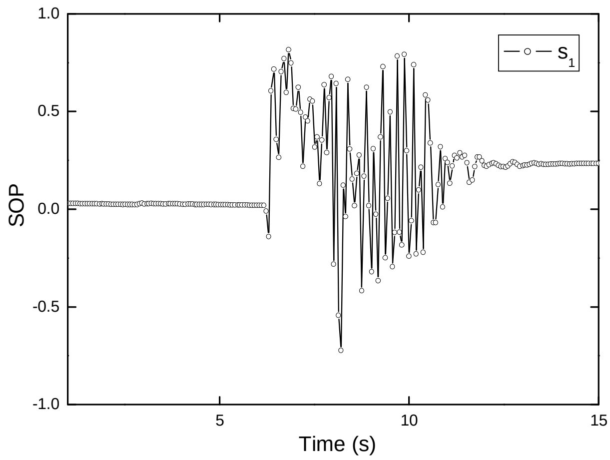

Fig. 5 The fluctuation of SOP, showing one of the Stokes parameters, resulting from a patchcord disturbance.

an extended period with the following polarization scrambling conditions: (a) no polarization scrambling, and (b) input polarization scrambling. Fig. 4 shows the PMD values measured over time using the setup shown in Fig. 3. In Fig. 4 (a) where no intentional polarization scrambling was performed, the PMD readings observed are very stable during the monitoring period and only slight deviations from the mean PMD are observed. The small fluctuations of PMD are likely due to minor changes in the birefringence and mode coupling of the fibres. This is attributed to slight temperature changes in the laboratory environment. The rapid change in PMD at the beginning of the measurement was due to the patchcord being disturbed. The fluctuations of SOP resulting from the shaking of a patchcord are shown in Fig. 5. The change in the SOPs is due to a topological effect [14], and not from a change in the birefringence. When the SOPs changes, the PMD measured using the interferometry technique will also change.

To increase the accuracy of the PMD measurement, input polarization scrambling was performed (Fig. 4 (b)). Input polarization scrambling has a large effect on the scattering of PMD, as compared to Fig. 4 (a). The scattering of PMD is due to the changing input SOPs and not from a change in

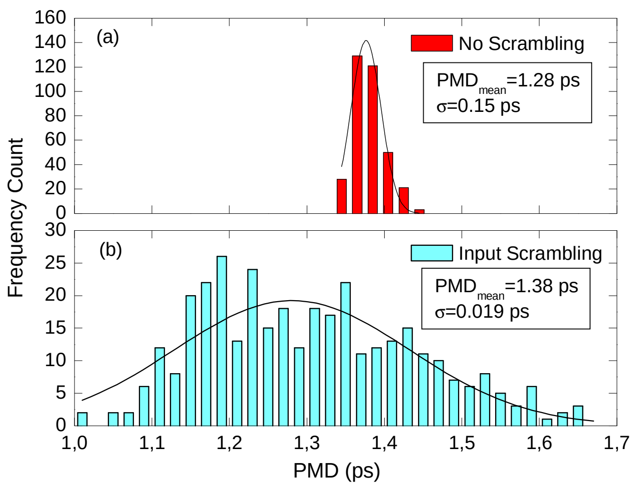

Fig. 6 Gaussian distribution for PMD reading on undeployed aerial optical fibre cable with (a) no polarization scrambling and (b) with input polarization scrambling.

environmental conditions or the change in the fibre properties as will be seen in Section V (B).

Fig. 6 (a) and (b) shows the distribution of measured PMD on undeployed cable with no polarization scrambling and input polarization scrambling, respectively. The solid lines represent the Gaussian fit to the measured data. The PMD measured without polarization scrambling show a small spread of the PMD readings (Fig. 6 (a)), about PMD_{mean}=1.38 ps. The standard deviation estimated from the Gaussian fit was 0.019 ps, and the σ_{sm} calculated from (2) was 0.19 ps. The difference between the σ and σ_{sm}, implies that the PMD obtained does not reflect the true PMD of the fibre due to sampling with incomplete SOPs.

When input polarization scrambling is performed, the results scattered more about PMD_{mean}=1.28 ps and the distribution of PMD is broader. This PMD_{mean} is more reliable than with no polarization scrambling, since it is sampled across all possible SOPs. The non ideal Gaussian fit in Fig. 6 (b) is due to the insufficient number of data sample collected. If more data was collected the "dip" around the mean would have been populated and the histogram would have a closer Gaussian fit. When input polarization scrambling is performed, the standard deviation is 0.15 ps which shows that the mean PMD is closer to the true PMD of the DUT. Shifts in the mean PMD observed for each scrambling condition are attributed to sampling with incomplete SOPs (without I/O scrambling) and the fact that the temperature where the cable was stored is not constant.

B. Deployed Aerial Optical Fibre Cable

PMD was measured on a 7.1 km deployed aerial optical cable extending from St Albans to Rocklands outside Port Elizabeth. Two optical fibres from the cable were looped to form a link of 14.2 km, and the PMD was measured using the setup shown in Fig. 3. Weather data was obtained from the South African Weather Station situated at the Port Elizabeth airport, which is 30 km away from St Albans. Consequently, the temperature and wind data given here may deviate slightly from the actual conditions experienced by the aerial cable.

Fig. 7 (a) and (b) shows measured PMD over time, and the temperature and wind speed monitored over the same period, respectively. During the first 2 hours, a general

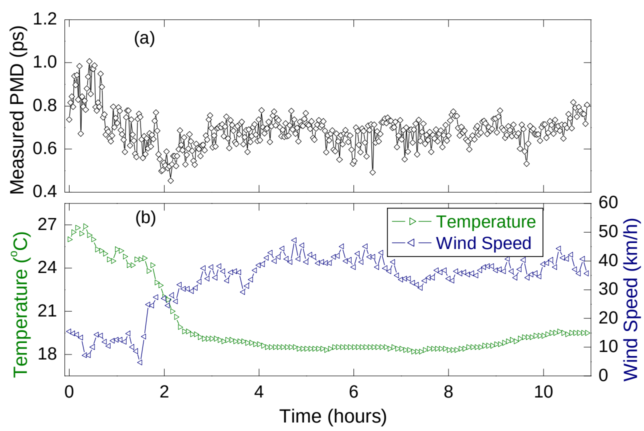

Fig. 7 (a) PMD measurements with no polarization scrambling, and (b) weather data (temperature and wind speed) obtained from the SA Weather Station at Port Elizabeth.

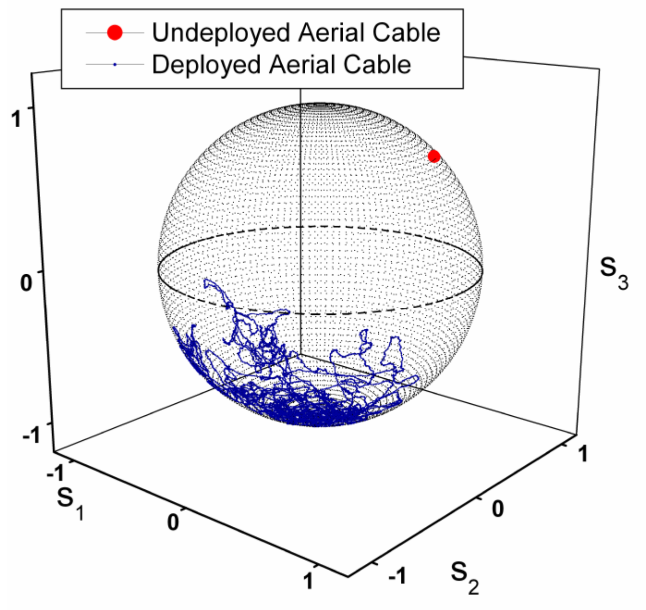

Fig. 8 The fluctuations of SOPs on undeployed and deployed aerial cable collected over a period of 3.5 seconds.

decrease in the PMD can be observed. This correlates rather well with the change in temperature seen in Fig. 7 (b). Note that the wind speed is relatively low and remained rather constant during the first two hours. At low wind speed, the contribution of the wind speed to the change in birefringence and mode coupling is rather low. The stress caused by the movement of the cable is likely to be very small compared to the stress caused by the rapid change in temperature. The change in temperature has a stronger influence on the birefringence and mode coupling along the fibre link, and is likely to be the major cause of the PMD decrease.

Fig. 7 (b) shows that after the initial temperature drop over 2½ hours, there were slow changes in temperature for the rest of the measurement period (Min 18°C and Max 20°C), however the wind speed was very high and more or less constant. Since there are small changes in temperature, its effect on PMD is likely to be small. At high wind speed, the wind causes the fibre to move (gallop) [16]. At such wind speeds there is a rapid oscillation of the cable between the poles that will introduce more tension (stress) on the fibre. The birefringence and mode coupling of the fibre changes due to stress induced by the oscillation of the optical fibre cable. Consequently, the fluctuation of PMD is largely due to the changes in birefringence and mode coupling resulting from stress of the cable.

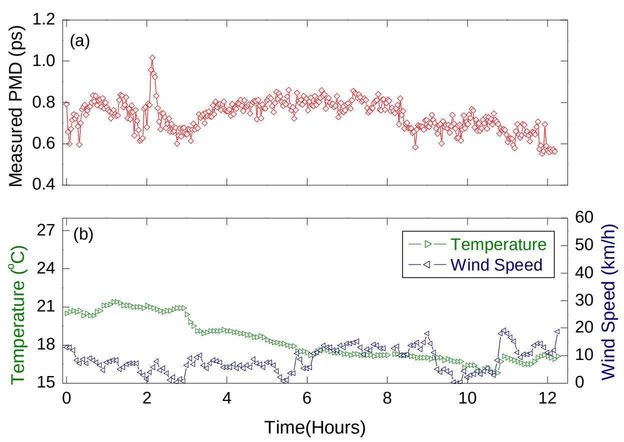

Fig. 9 (a) PMD measurements of the deployed aerial cable with input polarization scrambling, and (b) weather data (temperature and wind speed) obtained from the SA Weather Station at Port Elizabeth.

Fig. 7 (a) shows that there is a high degree of scattering of the PMD within the first two hours of the measurement, while the PMD is less scattered after the initial period. During the first 2 hours, the wind conditions are rather calm, but pick up speed after 2.5 hours and then remain more or less constant during the first two hours. It is suggested that each of the PMD readings in the graph is not from a single I/O SOP pair, but is an average of several SOP pairs. The measured PMD thus approaches that of the true PMD when more SOPs are averaged.

The time taken for the PMD analyzer to obtain a measurement is between 3-5 seconds. During this measurement period, the SOPs can vary rapidly. This is illustrated in Fig. 8 above, which shows a rapid change of SOPs in the deployed aerial cable over a period of only 3.5 seconds. Under high wind conditions, where there is a high number of galloping oscillations, there will be more rapid SOP variations from the topological phase effect [14] than under light breeze conditions.

Fig. 9 (a) and (b) shows the PMD measured on the same aerial cable with intentional scrambling at the fibre link input, and the temperature and wind speed monitored over an extended period, respectively. Fig. 9 (b) shows that there are only small changes in the wind speed (Min 0 km/h and Max 20 km/h) and temperature (Min 15.5 °C and 21.5 °C) over the period monitored. Fig. 9 shows that the change in environmental factors (wind speed and temperature) has a minor effect on the fluctuation of PMD as compared to Fig. 7. There may be small changes in birefringence and mode coupling of the fibre due to stress induced by the wind and change in temperature. The fluctuation of the PMD measured in Fig. 9 (a) is due to the changes in the input SOPs. There is no observed correlation between the environmental factors (temperature and wind speed) and the measured PMD.

Comparing Fig. 6 and Fig. 10 of undeployed and deployed aerial cables, the distribution of the measured PMD with no polarization scrambling on the deployed cable

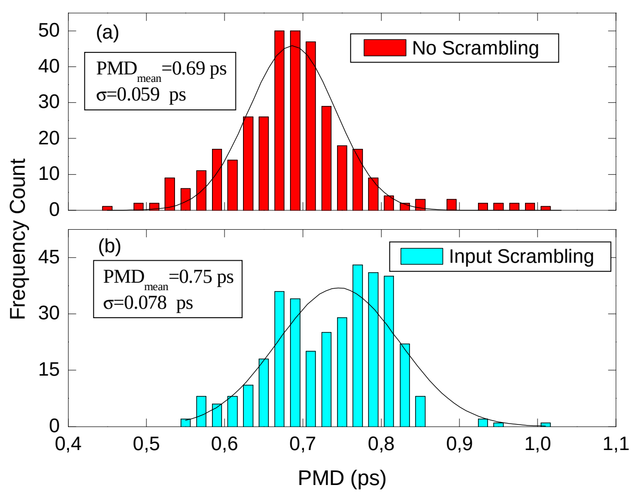

Fig. 10 Gaussian distribution of measured PMD on aerial optical fibre cable with (a) no polarization scrambling and (b) input polarization scrambling.

is slightly broader than the undeployed cable. For the deployed cable, the measured PMD with no polarization scrambling is more scattered (see Fig. 7 (a)) and there is a broader distribution (Fig. 10 (a)), about the PMD_{mean}=0.69 ps, as compared to PMD measured on buried fibre [4] and undeployed cable (see Fig. 6 (a)). This may be due to the unintentional self scrambling resulting from a topological effect [14] and the change in the birefringence and mode coupling of the fibre.

When input polarization scrambling is performed, the distribution of PMD is broader than when no polarization scrambling is performed. This is expected since the sample distribution must improve (Fig. 10 (b)). The change in the standard deviation shows that, to improve the accuracy of the measured PMD value, intentional polarization scrambling is necessary. The observed shifts in the mean PMD are attributed to the changes in the fibre birefringence and mode coupling due to the changes in the environmental conditions (temperature and wind speed).

VI. Conclusions

The PMD of undeployed cable remains stable when monitored without polarization scrambling over a period of time (hours). When input polarization scrambling is performed the measured PMD is more scattered around the mean, and the value obtained is more reliable. For aerial cable the PMD is more scattered even with no polarization scrambling is performed, this is the result of self scrambling of the aerial cable due to environmental changes (temperature and wind speed). We were able to distinguish between temperature and the wind effects on the PMD of deployed aerial cable under certain conditions. At low wind speed, PMD observed seems to “track” the change in temperature. When there are small changes in temperature at high wind speed, PMD fluctuates about the mean. To fully understand the effect of the environmental condition on PMD, PMD must be measured with both input and output polarization scrambling, over a longer period. Long term monitoring of SOP fluctuation in a aerial cable is also required.

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