Making reliable PMD measurements: The importance of polarization scrambling

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Abstract— Polarization mode dispersion (PMD) is a major impediment towards high speed data transmission in fibre optic networks. Accurate and reliable PMD measurements are required when conducting feasibility studies and budgeting for network outages. We conduct an investigation into the reliability of PMD readings obtained from the commonly used interferometry-based PMD analyzers. This study shows that there is a large uncertainty associated with taking only a few readings and not performing polarization scrambling. It will be shown that scrambling is necessary for an accurate determination of the PMD in a fibre.

Index Terms—optical fibre, polarization scrambling, polarization mode dispersion.

I. INTRODUCTION

OPTICAL fibres are the backbone to telecommunication networks. To meet the growing demand on bandwidth, higher data transmission through optical fibres become necessary and with it, the increasing deleterious influence of polarization mode dispersion (PMD), which induces system penalties through signal distortion. Fibre imperfections resulting from the manufacturing process, random mechanical stresses as well as environmental factors, including temperature variation and local stresses, all contribute to the quantity known as PMD. This effect is described statistically, due to the deployed fibre's changing environment.

At the current data transmission rate of 2.5 Gb/s in South Africa, the effect of PMD is minor. However, it can become a major issue in the upcoming network upgrade to 10 Gb/s, where the tolerable PMD limit is set at 0.5 ps/km$^{1/2}$. With the evolution of specialized manufacturing methods, PMD in present-day telecommunication grade fibre is kept very low, typically < 0.1 ps/km$^{1/2}$ for undeployed cables. Yet, the South African fibre network consists of many legacy fibres, deployed at a time when PMD was not even considered to be a problem. Our field tests have measured PMD of up to 4 ps/km$^{1/2}$ [1], which is far above the specifications for 10 Gb/s networks. PMD is an even greater predicament for 40 Gb/s and beyond. In order to for system designers to properly budget for network outages, accurate PMD values must be provided. It is thus imperative that the measured PMD of these fibres be reliable.

II. MEASURING PMD: THE INTERFEROMETRIC TECHNIQUE

The most commonly used field instrument for determining fibre PMD is based on the Michelson interferometer. The Traditional Interferometry technique (TINTY) uses only a single detector [2], whereas the improved Generalized Interferometry method (GINTY) employs two detectors that analyses the two orthogonal components of the interferogram [3]. The interferograms in the earlier version of the PMD analyzer contains a prominent autocorrelation peak, which can lead to inaccurate PMD measurements; in addition, it is based on certain unrealisable assumptions such as infinite random mode coupling. The GINTY technique, on the other hand, eliminates the autocorrelation peak and removes these assumptions. The reader is referred to N. Cyr's paper for further details [3].

In both the interferometric instruments, a vital component is the analyzer, which possess a fixed polarization axis. If the state of polarization (SOP) of the incoming signal is orthogonal to the analyzer axis, no signal will be detected. Consequently, the measured PMD from these methods are very much dependent on the fibre output SOP. This would also apply to the measurement of PMD using the fixed analyzer method. As shall be discussed below, movement from connecting patchcords can also affect these results. The favoured method by field technicians of conducting only 10 consecutive readings can therefore result in substantial inaccuracies.

III. INFLUENCE OF THE STATE OF POLARIZATION ON THE MEASURED PMD

When light with a certain SOP propagate through a length of optical fibre that is not co-planar, the output SOP is changed as a result of the rotation of the polarization state about an axis through the fibre [4]. Any fibre movement can thus alter the SOP and consequently, can influence PMD readings determined from the fixed analyzer method and interferometric techniques. If the input SOP to the fibre is fixed, not all segments of the fibre contribute to the measured PMD. Again, if the output SOP is fixed, and since the analyzer is also fixed, there is a possibility that the fibre output SOP is aligned at exactly orthogonal to the analyzer orientation. Here, no signal is detected and

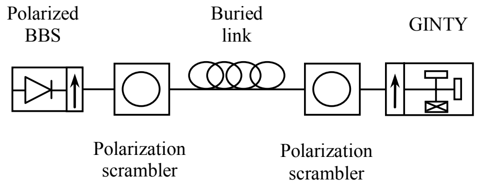

Fig.1. Diagram showing the interferometry-based setup for measuring PMD.

consequently, a zero PMD reading is given.

To fully characterize the PMD of a fibre, it is therefore necessary to sample across all possible states of polarization. Incomplete sampling of the SOP ensemble gives rise to an uncertainty due to using only a single input/output (I/O) SOP pair (see section IV).

It should be noted that PMD determined using Jones Matrix Eigenanalysis and related methods do not encounter these problems, because they are based on a different approach. However, they are not suitable for field measurements because of sensitivity to fibre movement and slow measurement speed.

IV. THEORETICAL SINGLE-SCAN UNCERTAINTY AND PMD STATISTICS

There is an uncertainty, σ_{sm}, associated with performing a single scan using only one I/O SOP pair, which has been theoretically determined as [5, 6]

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

where σ_A is the autocorrelation of the source.

This uncertainty has a Gaussian distribution and is related to the incomplete sampling of the SOP ensemble during PMD measurements where methods such as the fixed analyzer or interferometry-based techniques are used. This should not be confused with the statistical PMD uncertainty. The latter is described by a Maxwellian distribution [7].

By conducting polarization scrambling to the fibre input and output, the uncertainty associated with using only a single I/O SOP pair can be minimized. The uncertainty for the mean PMD so determined is then $\sigma_{sm}/\sqrt{N}$, where N is the number of I/O SOP pairs.

The intention of this paper is to perform a systematic study of whether polarization scrambling is necessary, and if so, under what conditions and whether it is only required for low PMD fibres, high PMD fibres or in all instances.

V. EXPERIMENTAL CONDITIONS

Two optical fibre links were selected from the same buried cable, 28.8 km long, situated in an optical fibre network located in Port Elizabeth. One link has a low PMD of about 2.5 ps (PMD coefficient of 0.5 ps/km$^{1/2}$) which we label L-PMD, while another link is looped in such a way that it has a much higher resulting PMD of ~13 ps (PMD coefficient of 2.4 ps/km$^{1/2}$) and is labelled H-PMD. The PMD of these links were then monitored as a function of time. The system setup is shown in Fig. 1. It consists of a polarized broadband source covering the C- and L-band (1530-1625 nm) and a PMD analyzer using the GINTY technique [3]. When polarization scrambling was required, automatic polarization scramblers (Adaptif A3200) were inserted before and/or after the fibre link. The state of polarization was changed randomly every 5 seconds.

The L-PMD and H-PMD fibre links were monitored over an extended period for the following polarization scrambling combinations, each with 333 data points: (a) no scrambling, (b) scrambling at the fibre input only, (c) scrambling at the fibre output only, and (d) scrambling at both the fibre input and output.

VI. FIELD MEASUREMENTS

The PMD of one of the two links (H-PMD) are shown in Fig. 2 for the four polarization scrambling conditions. Similar results are seen for the L-PMD link and are not shown here. Histograms of the measured PMD distribution are shown in Fig. 3 and 4 for low PMD and high PMD links, respectively. The solid lines are Gaussian fits to the data and the standard deviation σ estimated from such fits are listed in Table 1, along with a summary of the mean PMD for the four scrambling options conducted on the two buried fibre links.

Shifts in the mean PMD observed for each scrambling condition are attributed to incomplete SOP sampling of the fibre as a result of a fixed input SOP, or a fixed analyzer axis. For the instances of input scrambling in Fig. 3(b) and Fig. 4(b), each scrambling data set were collected over different days; it is therefore likely that the fibre-measurement system may have experienced some temporary mode coupling event, either between the patchcord connectors coupling the instruments to the buried link

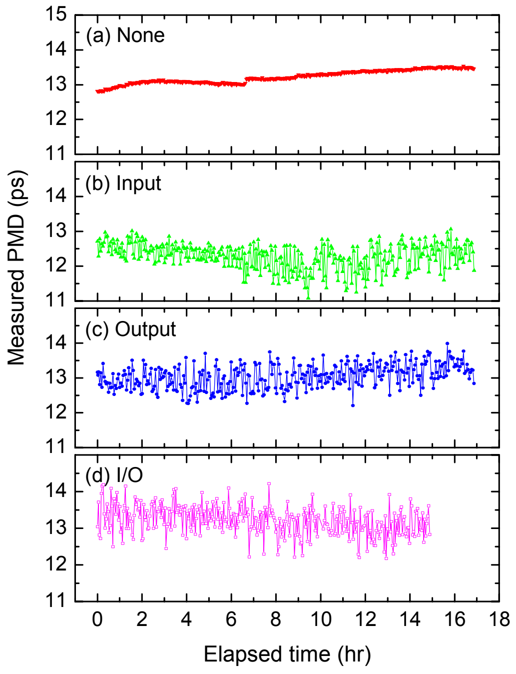

Fig.2. PMD of a buried H-PMD fibre link for (a) no scrambling, (b) input scrambling, (c) output scrambling, and (d) input/output scrambling.

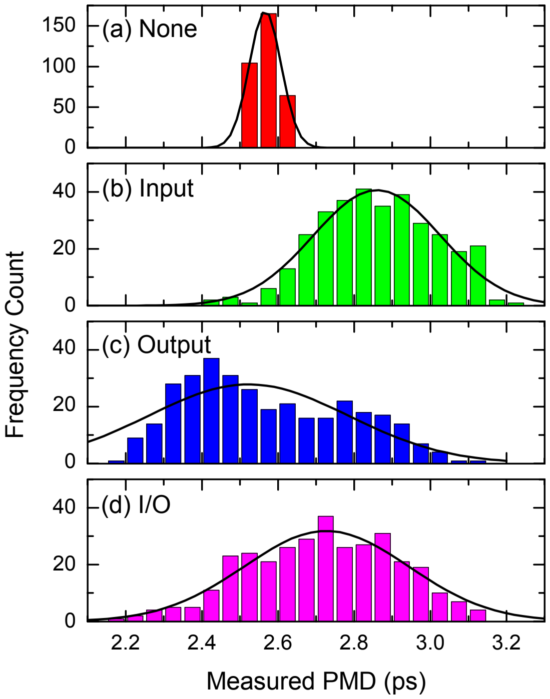

Fig.3. Distributions of the measured PMD on a low PMD (L-PMD) fibre link in Port Elizabeth. Bin size = 0.05 ps.

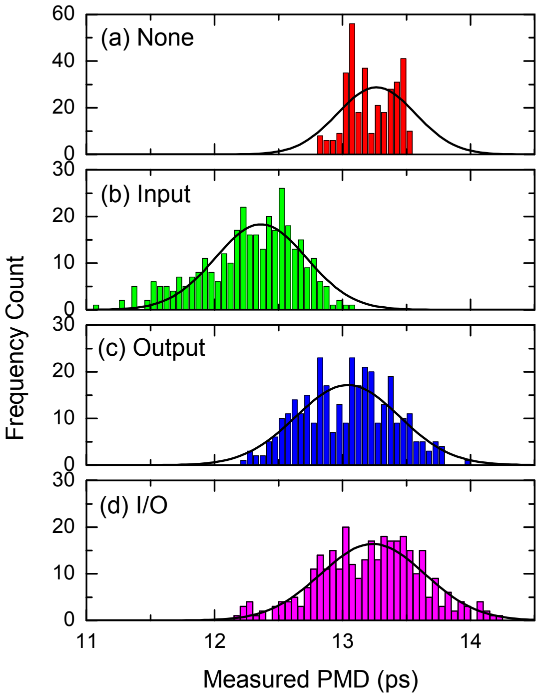

Fig.4. Distributions of the measured PMD on a high PMD (H-PMD) fibre link in Port Elizabeth. Bin size = 0.05 ps.

(unlikely), or experienced stress from the patchcord looped at the other end of the link (more likely). Nevertheless, the spread or distribution of the PMD is the main concern here.

When no scrambling on the fibre is implemented, the PMD readings are observed to evolve slowly with time and rarely contain any fluctuations. In Fig. 2(a), a sudden jump in the PMD value of ~0.2 ps after 6.6 hours of monitoring can be seen. This sudden change is most likely due to the movement of a patchcord connecting the fibre under test to PMD analyzer or light source. The disturbance of the patchcord changed the SOP either at the input or the output from the fibre link.

The corresponding histograms in Fig. 3(a) and 4(a) for L-PMD and H-PMD links show very little spreading of the PMD readings, creating the illusion that the mean PMD determined here is highly reliable, with a standard deviation of only 1.6% and 2.3%, respectively. On the contrary, the reality is that the uncertainty associated with using a single I/O pair for L-PMD and H-PMD is 0.27 ps (~10%) and 0.59 ps (~4.5%), respectively, where the single-scan uncertainty σ_{sm} is calculated using (1). It is seen that polarization scrambling is especially important where the fibres have low PMD. Under these circumstances, the percentage uncertainty associated with conducting a single I/O measurement is much higher than fibres with high PMD and is of more consequence.

If only either input or output polarization scrambling is performed, one notices more scatter in the measured PMD and a broader distribution. Here, the mean PMD is more reliable than without scrambling. The standard deviations for the two links are larger and closer to the theoretically determined values.

Polarization scrambling on both ends should result in an even broader distribution, and more reliable mean PMD. This is not what we have found in our study. It can be seen from Table 1 that scrambling on both ends adds little or no value to when only output scrambling is considered. This is attributed to the insufficient number of sample data collected, and a bad Gaussian fit in the case of Fig. 3(c). If more data were collected in Fig. 3(c), the "dip" in the histogram at around 2.65 ps would have been populated, and the distribution approach a Gaussian curve with a narrower σ. For a sufficiently large sample size, all the histograms should approach a Gaussian distribution. Nevertheless, scrambling on both input and output ends is theoretically sound and is strongly recommended.

VII. CONCLUSIONS

When designing systems that take into account the effect of PMD, accurate PMD measurements is required. This systematic study has found that the there is a large

TABLE I

SUMMARY OF POLARIZATION SCRAMBLING RESULTS FOR LOW PMD AND HIGH PMD BURIED FIBRE LINKS. THE THEORETICAL UNCERTAINTY σ_{SM}, CALCULATED USING (1) FOR L-PMD AND H-PMD ARE 0.27 PS AND 0.59 PS, RESPECTIVELY.

	Scrambling	Mean PMD (ps)	σ (ps)	%σ
L-PMD	None	2.57	0.04	1.6
	Input	2.86	0.17	5.9
	Output	2.52	0.26	10.3
	I/O	2.73	0.22	8.1
H-PMD	None	13.26	0.31	2.3
	Input	12.36	0.36	2.9
	Output	13.04	0.40	3.1
	I/O	13.24	0.41	3.1

uncertainty associated with using only a single pair of I/O SOP when conducting field PMD measurements using the interferometry-based technique. Polarization scrambling at both the input and output to the fibre is therefore necessary to completely sample all possible SOPs and to provide a more reliable fibre PMD value. The percentage uncertainty for low PMD links are larger than high PMD links and so the uncertainty from the use of a single I/O SOP pair is of more significance in low PMD links than high PMD links.

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