Essence of Re-Calibrating Optical Instruments:

Analysis of the Digital Delay Line

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Abstract

In this work a digital delay line (DDL) from Oz Optics was used. The DDL introduces a delay in optical paths between the fast and slow orthogonal polarizations by adjusting the relative travel distance of the two orthogonal modes. The insertion loss of the DDL is 1.5 dB. A Labview programme was used to write and read from the DDL. The DDL was adjusted from 0 to 60 ps and the observed first order polarization mode dispersion (FO-PMD) was measured. With 1018 random values between 0 and 60 ps, written to the DDL to adjust it, the resulting FO-PMD values give a histogram approaching the Maxwellian distribution, although not well populated on the tail. This therefore means the DDL alone can be controlled to generate a distribution approximating the Maxwellian distribution over a large sample size as would be expected theoretically.

Keywords: Digital Delay Line (DDL), First Order Polarization Mode Dispersion (FO-PMD), Second Order Polarization Mode Dispersion (SO-PMD), Polarization Maintaining Fibre (PMF), General interferometry technique (GINTY)

I. INTRODUCTION

Polarization mode dispersion (PMD) emulation is the first vital step to undertake in order to analytically understand the complex behaviour of PMD under the laboratory environment over a short time frame. Emulation is also known to be the key to the effective design of adaptive PMD compensators. PMD emulators can be further used in testing for system tolerance, diagnosing system impairments, as calibrators in instruments used for accurate characterisation and measurement of PMD, and as models for deployed fibre links. Therefore, PMD emulation is a novel approach essential in the move towards a cost-effective optical network upgrade through system analysis within the laboratory before field testing.

There are certain conditions emulators should meet in order to accurately reproduce PMD in deployed networks. Below is an overview of these conditions. These vary depending on the expected outcome and properties of the emulator design.

When the autocorrelation function (ACF) is averaged over an ensemble of fibre realisations, the background autocorrelation (BAC) should tend towards zero outside the limited frequency range. The presence of second order polarization mode dispersion (SO-PMD) has been seen to affect the symmetry of the first order polarization mode dispersion (FO-PMD) ACF central peak [1]. For a good PMD emulator the ACF peak should be centred at zero, however, in a combined FO- and higher-order PMD emulator this might not be achievable.

The FO-PMD should be Maxwellian-distributed over an ensemble of fibre realisations at any fixed optical wavelength and over a wide wavelength spectrum [2]. However, some fibre links do not approach the Maxwellian-distribution [3]. Emulators constructed to mimic the PMD behaviour in these fibres do not need to have FO-PMD distributions which are Maxwellian. Therefore, a PMD emulator should accurately reproduce the FO-PMD statistics of a particular or given deployed fibre link or fibre plant.

The emulator should be able to produce accurate higher-order PMD (i.e. SO-PMD and above) statistics and should be able to reach any combination of first and higher-order PMD values [2]. Just as for FO-PMD, SO-PMD emulators should accurately mimic the SO-PMD statistics of the fibre link under investigation. Some researchers have

maintained either FO-PMD fixed and varied SO-PMD or vice versa [3],[4]. Other emulators can have either FO- or SO-PMD null as one parameter is investigated [5].

Stability should be achievable over a measurement period, which may last from minutes to hours [2]. This solely depends on how the properties of the emulator components behave under certain laboratory environments i.e. stable temperature, high tolerance to vibrations or movements during experimental measurements. Stability ensures emulator repeatability or reproducibility [6], which ensures the emulator, is applicable for important sampling (IS).

The emulator should have low insertion loss and exhibit negligible polarization dependent loss. The presence of PDL distorts PMD statistics away from theoretical distributions even in the presence of infinite random mode coupling [7].

Implementation of the emulator should be easily controllable from one emulator state to the other [2]. This can be achieved either through programming or manual control. Simplicity makes the emulator user friendly and marketable.

A PMD emulator is designed from a combination of different components. These components are configured to ensure a desired PMD statistical outcome is achieved. These components are grouped into two groups namely: optical delay and polarization orientation control components. For this paper, the emphasis will be on optical delay components.

II. TUNEABLE DELAY ELEMENT

Delay lines are modules that are meant to induce a delay time in one of the two orthogonal polarization modes of light. This results in the disparity in arrival times of the two orthogonal modes at the receiver end. These two orthogonal modes belong to the same pulse. The delay represents the FO-PMD in optical networks, which means a delay line is a PMD emulator module. There are different types of delay lines with different control mechanisms which are all designed to induce an adjustable FO-PMD. Some of these variable delay lines are manufactured by Oz Optics Limited, ThorLabs and General Photonics Corporation. This section gives emphasis to the delay line manufactured by Oz Optics Limited (Figure 1) since it was used in this study for this paper. This delay line is referred to as the variable polarization digital delay line (DDL).

Figure 1: Photograph of the DDL from OZ Optics in the NMMU Fibre Optics laboratory.

The DDL by Oz Optics is an electrically controlled, reflector-style, variable device. It consists of an input fibre collimator, output fibre coupler and polarization beam splitting optics. The optics are mounted and aligned to produce a fixed gap between collimators for one orthogonal polarization and a variable gap for the other orthogonal polarization. The collimator projects light into free space and the coupler collects it into the output fibre. The difference in path travelled by the two orthogonal polarizations is the FO-PMD. The difference in the optical paths is precisely controlled by reflecting the light off a moveable reflector. Most if not all delay lines are equipped with a microprocessor to enable remote communication through an electrical device or personal computer. The DDL used in this study covers over ± 65 ps delay range with a resolution of 0.0017 ps and insertion loss of the DDL is 1.5 dB.

This type of emulator adjusts the PMD without changing the number of fibre sections. This is achieved by changing the birefringence of the material, i.e. a fibre can be subjected to temperature changes which change the birefringence hence changing the PMD [8]. Unlike the delay induction used by Hauer *et al.* [8], in this study, the DDL introduces a delay in optical paths between the fast and slow orthogonal polarizations by adjusting the relative travel distance of the two orthogonal modes.

III. RESULTS AND DISCUSSIONS

A Labview programme was used to write and read from the DDL. The DDL was adjusted from 0 to 60 ps and the observed FO-PMDs were measured. The set FO-PMD

($\tau_{\text{set-DDL}}$) of the DDL was compared to the observed FO-PMD ($\tau_{\text{obs-DDL}}$) and is shown in Figure 2 (c). The gradient of the slope is 0.99 and y-intercept is 0.19 (close to zero) which shows there is a negligible difference between $\tau_{\text{set-DDL}}$ and $\tau_{\text{obs-DDL}}$. Thus, $\tau_{\text{set-DDL}}$ and $\tau_{\text{obs-DDL}}$ are equivalent and will be referred to as the DDL FO-PMD (τ_{DDL}). The observed FO-PMD is wavelength-independent (Figure 2 (a)) due to finite mode coupling, while SO-PMD is stochastic (Figure 2 (b)) over a small range which is likely due to principal states of polarization (PSP) rotations enhanced by internal mechanical changes occurring in the DDL.

Figure 2: ((a) and (b)) FO- and SO-PMD at different DDL FO-PMD settings ($\tau_{\text{set-DDL}}$). (c) DDL characteristics in terms of the observed FO-PMD ($\tau_{\text{obs-DDL}}$) and the mean SO-PMD ($\langle \tau_{\omega} \rangle$) when $\tau_{\text{set-DDL}}$ is adjusted. The average- $\langle \tau_{\omega} \rangle$ ($\langle \tau_{\omega} \rangle_{\text{avg}}$) over $20 \text{ ps} \leq \tau_{\text{set-DDL}} \leq 60 \text{ ps}$ is $0.24 \pm 0.07 \text{ ps}^2$. The JME was used to measure both FO- and SO-PMD. The SO-PMD spectra in (b) were offset for clarity.

Figure 2 (c) shows that the DDL has low residual SO-PMD (residual- τ_{ω}) present. This is similar to what would be obtained in a single PMF section of arbitrary FO-PMD magnitude. The low SO-PMD is ascribed due to finite mode coupling. Though low, the behaviour of the SO-PMD of the DDL is important in this study due to its application in the design of the PMD emulator. The residual mean SO-PMD (residual- $\langle \tau_{\omega} \rangle$) was non-uniform for $\tau_{\text{DDL}} \leq 18 \text{ ps}$, while the residual- $\langle \tau_{\omega} \rangle$ remains fairly constant at $0.24 \pm 0.07 \text{ ps}^2$ for $20 \text{ ps} \leq \tau_{\text{DDL}} \leq 60 \text{ ps}$. This non-uniformity in SO-PMD is likely due to the manufacturing imperfections of the DDL. It should be noted that the behaviour of residual SO-PMD in other delay lines does not necessarily follow this trend.

Figure 3: The statistical distribution of the DDL observed FO-PMD after randomly generating 1018 DDL set FO-PMD ($\tau_{set-DDL}$) values. The solid line in (b) is the Maxwellian distribution fit. GINTY was used to measure the FO-PMD.

In this study, 1018 values between 0 and 60 ps were randomly generated using Labview to give a variation similar to that in Figure 3 (a). These 1018 random values were written to the DDL to adjust it and the resulting FO-PMD values are those shown in Figure 3 (a). These FO-PMD values were measured using GINTY. The FO-PMD variation in Figure 3 (a) gives a histogram approaching Maxwellian (Figure 6.13 (b)), although not well populated on the tail. This therefore means the DDL alone can be controlled to generate a distribution approximating the Maxwellian distribution over a

large sample size. Take note that the FO-PMD values generated by the DDL are independent of wavelength as illustrated in Figure 2 (a).

IV. CONCLUSIONS

The FO-PMD of the digital delay line (DDL) is wavelength-independent and so is its FO-PMD vector. The residual SO-PMD of the DDL is very small though it is uneven in the region ≤ 18 ps, this is likely due to manufacturing imperfections. The DDL was controlled to generating stochastic FO-PMD statistics that approach the Maxwellian distribution. Concatenating several of these types of DDL will make the FO-PMD wavelength-dependent and will result in SO-PMD.

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