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A polarization mode dispersion (PMD) emulator with tuneable first-order PMD and constant second-order PMD

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ABSTRACT

We design a polarization mode dispersion (PMD) emulator with fixed second-order polarization mode dispersion (SO-PMD) but varying first-order PMD (FO-PMD). The emulator constitutes of an optical delay line (ODL), a polarization controller (PC) and a fixed number of randomly concatenated polarization maintaining fibre (PMF) segments. An understanding of the SO-PMD equation is the first vital step to consider before designing such an emulator. The control of the differential group delay (DGD) statistics with wavelength proves to be the key measure for this design. Results show that the mean DGD (or the mean magnitude of the FO-PMD vector ($\vec{\tau}$)) of the emulator is biased towards the dominant wavelength-independent $\vec{\tau}$ of the ODL. This is provided the dominant $\vec{\tau}$ is by far greater than FO-PMD contributions from the other cascaded sections. Experimentally it is shown that when the DGD ($\Delta\tau$) is wavelength-independent due to the absence of mode coupling, or when the wavelength-dependent DGD spectra do not change with time due to fixed mode coupling, there is negligible influence on the SO-PMD. The PC angle is controlled at an angle θ to ensure that the sub-emulator $\vec{\tau}$ is always parallel to the ODL $\vec{\tau}$. Thus by rotating the mode coupling angle θ, we change the wavelength-dependent DGD spectra thereby ensuring SO-PMD variation.

1. Introduction

The phenomenon of polarization mode dispersion (PMD) is one of the key factors limiting signal transmission speed in optical network systems [1,2]. This phenomenon is of concern because of current and future increases in bit-rate transmission from 10 Gbit/s and beyond. PMD is defined to first-order (FO) as the differential group delay (DGD) between the fast and slow principal states of polarization (PSPs) along an invariant unit Stokes vector [3], and to second-order (SO) as the variation of DGD ($\Delta\tau$) and rotation of PSPs as a function of optical frequency [4]. Thus the variation of DGD and rotation of PSPs with frequency correspond to the two components of the SO-PMD vector, the polarization-dependent chromatic dispersion (PCD) and PSP-depolarization, respectively. PCD causes pulse compression and broadening [5] and PSP-depolarization results in the reduction in the degree of polarization (DOP) of propagating signals [6]. In order to understand PMD behaviour and its implications in deployed optical fibres, it is vital to perform PMD emulation under a controlled environment.

PMD emulators exhibiting both FO-PMD and SO-PMD have been designed and implemented [7–9]. These types of emulators were found to be necessary due to the coexistence of FO-PMD and SO-PMD in optical network links [2,10]. Due to the interaction between these two effects, the impact of SO-PMD on FO-PMD has been investigated [10,11].

By definition, SO-PMD is dependent on the magnitude of the FO-PMD vector ($\vec{\tau}$), represented as $\Delta\tau$ [4]. The impact of FO-PMD on SO-PMD should therefore also be looked into experimentally. In this paper, we design a PMD emulator with a fixed mean SO-PMD but varying mean-DGD to investigate this phenomenon. This PMD emulator is designed from a combination of an optical delay line, a polarization controller and a fixed number of concatenated polarization maintaining fibre (PMF) segments. The concatenated PMF segments were used to generate DGD and SO-PMD changes with wavelength. Ideally, the DGD statistics should follow the Maxwellian distribution [12] and SO-PMD statistics follow the theoretical distribution proposed by Foschini et al. [13]. However, these distributions are valid only in the presence of infinite random mode coupling.

The advantage of our PMD emulator design is that SO-PMD or DGD behaviour can be set as stochastic or not depending on the emulator configuration. This means predetermined SO-PMD can be generated by controlling the mode coupling; the ODL will only adjust the DGD. Thus this design can be experimentally used in cases where there is a need to investigate which of the two, either DGD, SO-PMD or both, has more profound signal degradation effects on propagating light signals. Furthermore such a design could be implemented in designing, investigating or improving PMD compensators.

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This paper will also show that an understanding of the SO-PMD components [4] and the PMD concatenation rule provide an easy guide for the design of any desired type of combined FO-PMD and SO-PMD emulator. The question as to whether the DGD has an impact around the mean penalty induced by SO-PMD will be answered experimentally.

2. Design considerations for the PMD emulator

We give an overview of how the PMD emulator is designed, how it operates and its background. The emulator comprises of a sub-emulator (made up of cascaded PMF segments), a computer controlled polarization controller (PC) and an optical delay line (ODL) as shown in Fig. 1. The sub-emulator has a fixed number of PMF segments (8 segments), with random birefringence and mode coupling distribution. The length of each PMF segment lies within 20% standard deviation (Gaussian distribution) of the mean length ($\sim$4 m) of the sub-emulator, in accordance with other PMD emulator designs [14,15]. The DGD values of the 8 segments are: 4.35, 6.6, 4.95, 5.4, 6.3, 5.7, 7.1 and 7.8 ps in order set. These PMF segments were fusion spliced together without any intentional alignment of the birefringent axes, leading to the assumption that the mode coupling angles are randomly distributed. The PC is computer adjusted till an angle θ is found that ensures the angle β between the sub-emulator and the ODL FO-PMD vectors is equal to 0°. This means the FO-PMD vectors of the sub-emulator and the ODL are parallel.

The choice of the angle $\beta = 0°$ emanated from the concatenation equation (see below). The total emulator FO- and SO-PMD can be expressed in vector form by the concatenation equations:

$$\vec{\tau}_{\text{tot}} = \vec{\tau}_{\text{ODL}} + \mathbf{R}_{\text{ODL}}\vec{\tau}_{\text{sub}} \quad (1)$$

$$\vec{\tau}_{\omega\_\text{tot}} = \vec{\tau}_{\omega\_\text{ODL}} + \mathbf{R}_{\text{ODL}}\vec{\tau}_{\omega\_\text{sub}} + \vec{\tau}_{\text{ODL}} \times \vec{\tau}_{\text{tot}} \quad (2)$$

where $\vec{\tau}_{\text{ODL}}$ and $\vec{\tau}_{\text{sub}}$ are the FO-PMD vectors of the ODL and the sub-emulator, respectively, $\mathbf{R}_{\text{ODL}}$ is the rotational matrix of the ODL, $\vec{\tau}_{\omega\_\text{ODL}}$ and $\vec{\tau}_{\omega\_\text{sub}}$ are the SO-PMD vectors for the ODL and the sub-emulator, respectively. So in order to make the overall SO-PMD of the emulator independent of the ODL DGD, $\vec{\tau}_{\text{ODL}} \times \vec{\tau}_{\text{tot}}$ should be null. This is achievable if $\vec{\tau}_{\text{ODL}}$ and $\vec{\tau}_{\text{tot}}$ are collinear (either the vectors are parallel or anti-parallel). This is deduced from the cross product defined as $\vec{\tau}_{\text{ODL}} \times \vec{\tau}_{\text{tot}} = |\vec{\tau}_{\text{ODL}}||\vec{\tau}_{\text{tot}}| \sin\psi\hat{n}$, where | | denotes the magnitude of the vectors, ψ ($0 \leqslant \psi \leqslant 180°$) is the angle separating the vectors and $\hat{n}$ is a unit vector (vector with magnitude = 1) perpendicular to the plane containing $\vec{\tau}_{\text{ODL}}$ and $\vec{\tau}_{\text{tot}}$. These two vectors in this case are collinear if ψ is 0 or 180° (resulting in a null vector). This leads to the choice of $\beta = 0°$ which means $\vec{\tau}_{\text{sub}}$ is parallel to $\vec{\tau}_{\text{ODL}}$. Eq. (1) reduces to $\vec{\tau}_{\text{tot}} \sim \vec{\tau}_{\text{ODL}}$ considering the ODL to being the emulator's dominant FO-PMD vector contributor. In summary, to make the SO-PMD independent of the ODL DGD, β has to be 0°. Since the PMD at each wavelength is represented by a unique vector, the PC needs to be adjusted for each wavelength to ensure the angle $\beta = 0°$ (obeying the condition $\vec{\tau}_{\text{ODL}} \times \vec{\tau}_{\text{tot}} = 0$) for that wavelength.

Fig. 2 provides an insight into the behaviour of the DGD $\Delta\tau$ and SO-PMD $\vec{\tau}_{\omega}$ of the emulator when the PC angle is altered enabling β to rotate between 0° and 180°. There is a minimum SO-PMD output, close to that of the sub-emulator, when $\beta = 0°$ or 180° and maximum when $\beta = 90°$. The DGD is always fairly constant at

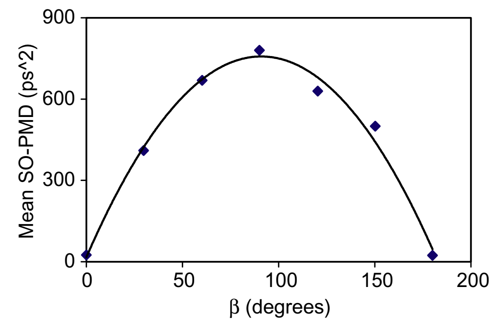

Fig. 2. The SO-PMD of the emulator when the β is varied from 0° to 180°. The solid line is a guide to the SO-PMD trend. The ODL DGD is fixed at 26 ps, resulting in the emulator mean DGD remaining fairly uniform at 38.8 ± 0.8 ps. PC stands for polarization controller.

38.8 ± 0.8 ps^2 due to the dominant ODL FO-PMD vector. Adjusting the ODL DGD whilst β is at 0° will always give a SO-PMD outcome almost equivalent that of the sub-emulator alone and the mean DGD approximates the ODL DGD setting. Thus controlling the PC angle changes the SO-PMD statistics and the nature of the DGD spectrum but still maintains a fairly uniform mean DGD.

An adjustment of the ODL gives an increase or decrease in $\Delta\tau$ only, although there is a low residual SO-PMD present. This is equivalent to a single PMF segment of any $\Delta\tau$ value up to the maximum $\Delta\tau$ determined by the ODL, known to only possess $\vec{\tau}$ [7,8]. Two concatenated PMF segments result only in $\vec{\tau}$ and $\vec{\tau}_{\omega}$ coexisting. When the numbers of PMF segments are greater than two, FO-, SO- and higher-order PMD vectors are all present. The DGD between the PSPs will show strong wavelength-dependence when the number of PMF segments are high [16], as shown in Fig. 3a, indicating that the PSPs are wavelength sensitive.

Although the main aim of this experiment was to monitor the mean PMD values, the PMD statistics of the emulator cannot be ignored. The emulator can also be used as a statistical emulator which scans PMD conditions whilst changing wavelength or the polarization controller. Fig. 3b illustrates the histogram (occurrence) of the sub-emulator DGD, which is extracted from the stochastic DGD characteristics in Fig. 3a. The sub-emulator DGD histogram, with a mean DGD ($\langle\Delta\tau\rangle$) = 18.1 ps, seems to approximate the Maxwellian distribution. The corresponding SO-PMD statistics of the sub-emulator (see Fig. 3c), with a mean SO-PMD ($\langle\tau_{\omega}\rangle$) of 21.4 ps^2, does not approach the SO-PMD theoretical distribution [13] well as compared to that of an installed fibre (refer to Fig. 3d) although they almost have similar mean DGD values. This is evident through Fig. 3c that is not populated with enough SO-PMD data than that of Fig. 3d.

Failure of the sub-emulator to approximate PMD theoretical distributions is most likely due to the limited amount of randomly distributed birefringent segments (8 segments only) as compared to the 84 km long deployed buried fibre that we suspect constitutes hundreds if not thousands of randomly distributed birefringent elements. In addition, the degree of random mode coupling in deployed fibres far exceeds that of our emulator, although not infinite. However not all deployed fibre PMD statistics approach the ideal theoretical distributions. Therefore further additions of random birefringence segments and mode coupling on the sub-emulator will result in its PMD statistics approaching the well known ideal PMD theoretical distributions. The limitation imposed by these factors (mode coupling and number of birefringent elements), leads to a lower than expected amount of sub-emulator SO-PMD as compared to the SO-PMD of a deployed fibre with the same mean DGD value ($\sim$18 ps). Lizé et al. [17] designed an emulator going as far as 25 (with mean DGD $\sim$ 0.8 ps and mean SO-PMD $\sim$ 0.4 ps^2) PMF sections, respectively.

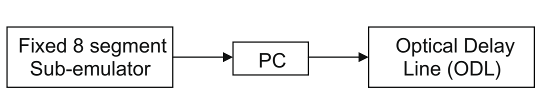

Fig. 1. Block diagram for fixed SO-PMD but varying FO-PMD emulator. The polarization controller (PC) angle θ alters to always ensure β is always equal to 0° as wavelength changes.