The Design and Operation of an Optical Post-Transmission Polarization Mode Dispersion Compensator

Tim Gibbon, Ann Conibear, Andrew Leitch

Abstract – In this paper we outline the operation of an optical post-transmission PMD compensator currently under construction. Experimental and simulated results are used to illustrate the manner in which the monitoring of the degree of polarization of a scrambled signal can be used as a control parameter in PMD compensators of this type.

Index Terms – Polarization mode dispersion, PMD compensation, degree of polarization

I. INTRODUCTION

Polarization mode dispersion (PMD) poses a major challenge in the successful implementation of modern telecommunication systems operating at bit rates of 10 Gb/s and above. PMD itself is a birefringence-related phenomenon that results in the dispersive broadening of an optical pulse as it propagates along the length of an optical fibre. Should the PMD exceed 10% of the bit slot, the outage probability increases above the acceptable threshold of 10^{-7}, which translates to a network downtime in excess of three seconds per year [1]. In practice this means that the total PMD of the link should not exceed 10 ps and 2.5 ps for systems operating at 10 Gb/s and 40 Gb/s respectively.

PMD compensation is particularly challenging for a number of reasons. The first of these is that the PMD of a given fibre is not fixed. Instead, the PMD fluctuates with time under the influence of environmental factors such as vibrations and temperature variations, which affect the birefringence and mode coupling properties of the fibre [2]. For this reason PMD measurements extending over a period of time are best treated statistically [3]. The timescale on which significant changes occur may vary from the order of milliseconds in aerial cables, to days in seemingly dormant buried cables [4] [5]. Furthermore, PMD varies not only with time, but also as a function of wavelength giving rise to second order and higher order PMD.

In order to overcome these challenges, the PMD compensator should meet a number of criteria. Due to the random statistical nature of PMD, the compensator must accurately monitor the changes in PMD and adapt accordingly. This needs to take place within an acceptable response time relative to the timescale of the PMD fluctuations. Ideally, the operation of the compensator should also be independent of the bit rate and modulation format.

II. APPROACHES TO PMD COMPENSATION

PMD compensation can broadly be divided into two categories, namely electrical compensation and optical compensation. In electrical compensation, use is made of photodetectors, transverse filters and decision feedback equalizers to correct for PMD. This however proves to be both difficult and costly at 40 Gb/s and beyond [6]. Furthermore, since electrical compensation does not contribute to a transparent transmission system, optical compensation is often the preferred option.

Before presenting a brief overview of the strategies behind optical PMD compensation, it is useful to review the concepts of *principal states of polarization* and *differential group delay*. In 1986 Poole and Wagner established that, at each wavelength within an optical fibre, there exists a unique pair of orthogonal input states of polarization for which the output state of polarization remains independent of small changes in the wavelength of the transmitted light [7]. These input states of polarization are referred to as the principal states of polarization (PSPs). Due to birefringence, there is a difference between the propagation times of light traveling in each of the PSPs. This propagation time difference, referred to as the differential group delay (DGD), is ultimately what gives rise to the broadening of the optical pulse. The PMD value itself is defined as the root mean square of the DGDs over the wavelength range of interest. In deployed optical fibre both the PSPs and the DGD tend to vary significantly with wavelength due to mode coupling. A complete classification of the PMD thus requires the knowledge of both the DGD and PSPs at all wavelengths within the transmission window.

Optical PMD compensation can broadly be divided into two categories, namely pre-transmission and post-transmission compensation. Pre-transmission compensation involves ensuring that the transmitted light is launched exclusively into either of the PSPs. Information regarding orientation of the changing PSPs is continuously fed from the fibre output to a polarization controller at the fibre input. The polarization controller is then used to align the launched light with one of the input PSPs. Compensation will fail should the PSPs vary on a shorter timescale than the total time taken to determine

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the PSPs, transmit this information from the fibre output to the fibre input, and align the input light with one of the PSPs. Pre-transmission PMD compensation thus tends to be ineffective in situations where the PSPs vary rapidly with time, such as in aerial cables.

Post-transmission compensation overcomes the limitations of pre-transmission compensation in terms of response time, by confining the compensation process entirely to the fibre output. Light exiting the fibre enters a PMD compensator device used to cancel the PMD. This eliminates the need for information to be sent from the fibre output to the fibre input during each compensation step.

Two conditions must be met in order for the PMD compensator to successfully cancel the PMD of the link. Firstly, the magnitude of the compensator DGD must equal that of the fibre link. Since the DGD of the link will vary with time, this requires that the compensator contain an adaptive birefringent element. The second condition for compensation is that the alignment of the fast PSP of the compensator must correspond to the slow PSP of the fibre link, and vice versa. A polarization controller is generally used to achieve this.

III. PMD COMPENSATOR DESIGN

The adaptive birefringent element is the principal component of the compensator and can take on many forms. These include opto-mechanical delay lines, concatenations of polarization maintaining (PM) fibre separated by polarization controllers, and non-linearly chirped PM fibre Bragg gratings [8]. The PMD compensator we have chosen to construct is closely based on the 160 Gb/s compensator designed and constructed by Kieckbusch et al [9] [10]. Instead of a cascade of birefringent crystals separated by Faraday rotators, we make use of birefringent PM fibre segments separated by adjustable half wave-plates (HWPs) as shown in Fig. 1. The electrically adjustable HWPs to be used have a response time of 10 ms, and may be set to any rotation angle between 0º and 180º by applying a control voltage of up to 4 volts.

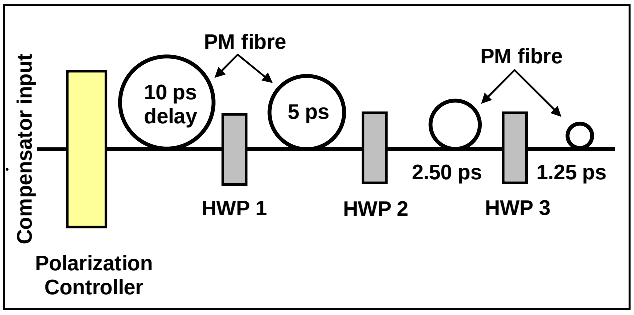

Fig. 1: PMD compensator consisting of PM fibre segments separated by adjustable half wave-plates.

In this design, adjustable HWPs effectively function as switches between the individual birefringent PM fibre segments. By adjusting the orientations of the HWPs, the compensator DGD can be adjusted to match that of the fibre link. The polarization controller serves to align the fast PSP of the link with the slow PSP of the compensator, and vice versa.

With reference to Fig. 1, consider the case where the principal axes of each of the PM fibre segments are aligned and the rotation angle of each of the HWPs is set to 0º. Under these conditions the nett DGD of the compensator is 18.25 ps, the sum of the DGDs of the individual PM fibre segments. Rotating a HWP through θ degrees rotates the plane of polarization of the light through 2θ degrees. Should HWP 3 subsequently be set to 45º then the nett DGD of the compensator would be 16.25 ps, since the contribution of the fibre segment following HWP 3 would be -1.25 ps. Similarly, the DGD of the compensator can be set to any value between 1.25 ps and 18.75 ps in increments of 2.50 ps by setting the individual HWPs as shown in Table 1.

	Half wave-plate settings			
State	**HWP 1**	**HWP 2**	**HWP 3**	**Compensator DGD (ps)**
1	0º	0º	0º	18.75
2	0º	0º	45º	16.25
3	0º	45º	45º	13.75
4	0º	45º	0º	11.25
5	45º	45º	0º	8.75
6	45º	45º	45º	6.25
7	45º	0º	45º	3.75
8	45º	0º	0º	1.25

Table 1: PMD compensator settings.

Compensators containing a number of PM fibre segments separated by polarization controllers are notorious for having complex control algorithms due to their many degrees of freedom. A major benefit of this compensation scheme is its elegance. During switching between two states, only a single HWP is rotated at a time, while the remaining HWPs are either positioned at 0º or 45º. This greatly reduces the complexity in finding the optimum states during the compensation process.

The design is general in the sense that it may be adapted in order to compensate at any bit rate. The DGD of the smallest birefringent segment should be 5% of the bit slot. Every additional birefringent element thereafter should have a DGD of twice the previous element. This ensures that the compensator can be set to a state where the nett DGD of the compensated link will not exceed 10% of the bit slot. The design shown in Fig. 1 caters for PMD compensation in a 40 Gb/s transmission system with a maximum DGD of 18.75 ps at the transmission wavelength. The compensator can easily be modified for links with higher PMD simply by adding PM fibre segments separated by adjustable half wave-plates.

Fig. 2 shows the DGD of the compensator as a function of wavelength during switching from state 4 to 5. These simulated results were generated using Jones-Matrix-Eigenanalysis [11].

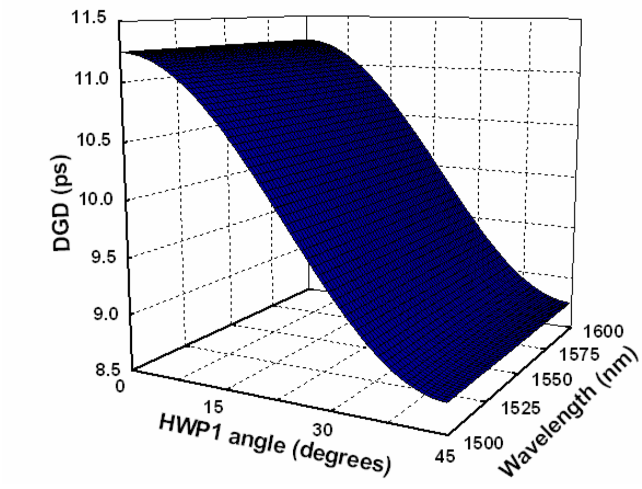

Fig. 2: DGD of the compensator during switching from state 4 to 5.

It is evident that the operation of the compensator remains uncomplicated by second order PMD in the sense that during switching the DGD is practically independent of wavelength. Furthermore, the operating point of the compensator need not be confined to the eight states of Table 1. Instead the HWP involved in switching could be set to an intermediate angle between 0° and 45° in order to totally cancel the DGD of the link.

IV. DEGREE OF POLARIZATION AS A PMD MONITORING AND CONTROL TECHNIQUE

All forms of PMD compensation require a technique by which the compensation process can be controlled and monitored. Such a technique should not only provide the compensator with real-time information regarding PMD fluctuations, but should do so at a rate which allows the compensator to adjust within an adequate response time. PMD in an optical fibre has the effect of depolarizing transmitted light, where the extent of depolarization depends on the input polarization state. As a consequence of this, the depolarization of light transmitted through the fibre serves as an ideal control and monitoring parameter for PMD compensation. A polarization scrambler is used to sample over a range of input polarization states.

The *degree of polarization* (DOP) of light is defined as the ratio of the intensity of the polarized light to the total light intensity. The Poincaré sphere proves most useful when dealing with polarized or partially polarized light [12]. The Poincaré sphere itself is a mathematical construct for representing states of polarization (SOPs) in three-dimensional Stokes space. For completely polarized light, different SOPs correspond to unique points on the surface of the sphere. Points lying within the sphere represent depolarized light, where the degree of polarization is proportional to the distance of the point from the centre of the sphere.

In order to explain how PMD causes the depolarization of light, consider the transmission of a polarized optical pulse of finite spectral width through an optical fibre. Should the input SOP correspond to any SOP other than one of the two PSPs, each wavelength within the spectral source packet will have a slightly different output SOP. This leads to depolarization of the output light, corresponding to a point lying within the Poincaré sphere. For a given DGD, the depolarization will be at a maximum for an input SOP midway between the PSPs. On the other hand, should the input SOP correspond to one of the PSPs, the output SOP will be independent of wavelength. Under such conditions the output light will hence be completely polarized, corresponding to a point lying on the surface of the Poincaré sphere.

Results illustrating the depolarization by PMD of scrambled polarized input light will now be presented. The experimental setup is shown in Fig. 3, where a length of PM fibre with a DGD of 2.30 ps is used to emulate a link with PMD.

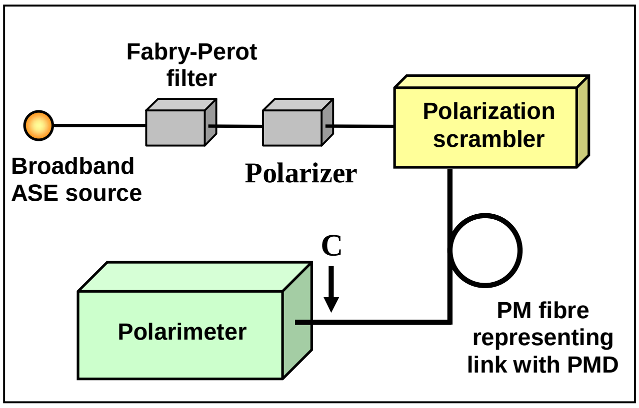

Fig. 3: Experimental setup used to illustrate the depolarization of light by PMD. Point C indicates the position at which a PMD compensator would be inserted.

An amplified stimulated emission (ASE) source together with a Fabry-Perot filter were used to provide a 1.2 nm FWHM Gaussian wave packet centered about the wavelength of 1530 nm. The light was then polarized, before a high-speed lithium niobate scrambler was used to scramble the SOP. A sample of the scrambled light at the fibre input is shown in Fig. 4, where 256 random SOPs were realized within a period of approximately 50 ms.

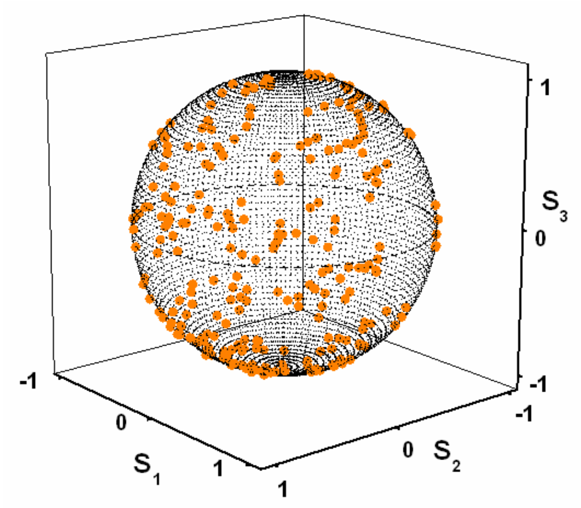

Fig. 4: Scrambled states of polarization at the PM fibre input.

The resultant output after transmission through the PM fibre is the polarization ellipsoid appearing in Fig. 5. The orientation of the ellipsoid within the Poincaré sphere depends on the PSPs of the fibre at the transmission wavelength. The PSPs correspond to the two SOPs which undergo no depolarization, and hence lie on the surface of the Poincaré sphere. All other SOPs undergo some degree of depolarization, and thus lie within the Poincaré sphere. The mean DOP of the points forming the ellipsoid, or conceptually the minor axis of the ellipsoid, depends on the magnitude of the DGD. In the absence of DGD the ellipsoid reduces to a sphere, with a mean DOP of unity.

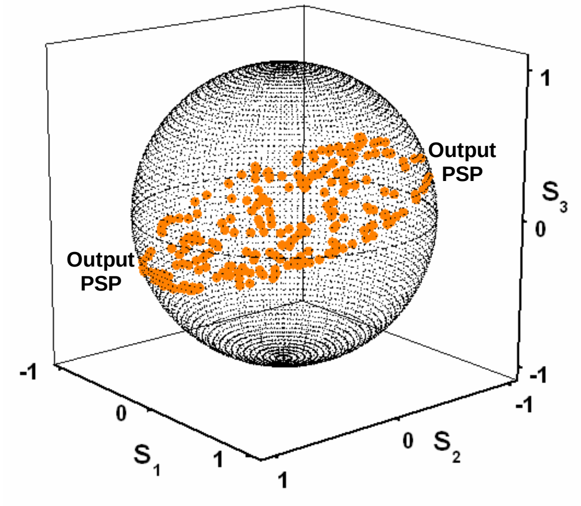

Fig. 5: Depolarization of the scrambled states of polarization by PM fibre with a DGD of 2.30 ps.

In a separate investigation to determine the relationship between the mean DOP and the DGD, the length of PM fibre in Fig. 3 was replaced by a variable opto-mechanical delay line. This experimental result, along with a simulated result appears in Fig. 6. It is clear that a maximum mean DOP is achieved when the DGD, and thus the PMD, is zero.

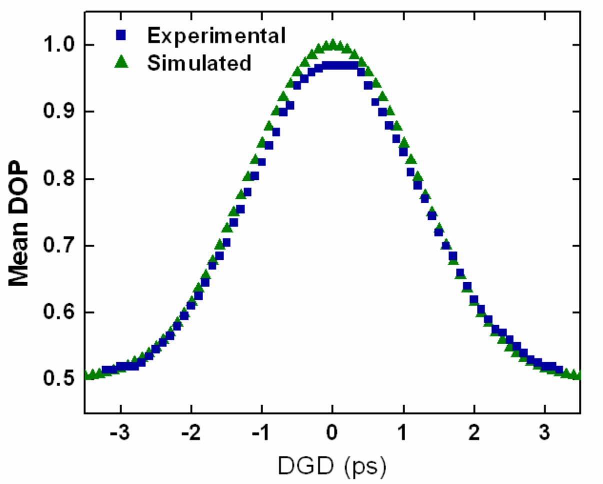

Fig. 6: The relationship between DGD and the resultant mean DOP.

There is excellent agreement between the experimental and simulated results. The only minor discrepancy is that, with the DGD of the delay line set to zero, the mean experimental DOP reaches a maximum of 0.97 instead of unity as expected. This may be attributed to depolarization of the light by factors other than PMD. It should be noted that the mean degree of polarization is not only a function of DGD, but also depends on the width of the Fabry-Perot filter.

We have shown that the DGD of the fibre may be related to the mean DOP of the transmitted light. A maximum mean DOP is achieved when the DGD is zero. A typical arrangement for compensating the PMD of the fibre would be that shown in Fig. 3, with the compensator inserted between the fibre and polarimeter at point C. During compensation, the state of the compensator is adjusted in order to ensure that the mean DOP of the light passing through the fibre link and compensator is maximized. This ensures that the effective DGD at the transmitted wavelength is zero. The time taken to scramble the input SOP and adjust a wave-plate is in the order of only 60 ms, which facilitates adaptive PMD compensation.

V. CONCLUSIONS

The design and operation of an optical post-transmission PMD compensator capable of high-speed, adaptive compensation has been presented. Furthermore, it has been shown how the depolarization of a scrambled input may be used as a control and monitoring parameter for PMD compensation.

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BIOGRAPHY

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