First- and Second-Order PMD Characterization of a 265 km Dispersion Managed Link by means of Jones Matrix Method

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Polarization mode dispersion (PMD) in optical fiber has become the most important limitation at bit rates exceeding 10 Gbit/s. PMD is a stochastic, dynamically changing process and consists besides zero-order DGD of higher order effects. Both the Differential Group Delay (DGD) and Principal States of Polarization (PSPs) vary randomly with the wavelength, temperature and stress along the fiber. Furthermore, they also drift randomly in time. This work reports the characterization of PMD up to second-order of a link of True Wave Reduced Slope (TWRS) fiber using the Jones matrix method. The total length of the link was 265 km and included dispersion compensating fiber modules and loss compensating optical amplifiers (EDFAs). For a range of 10 nm (1540-1550 nm), we have measured an average DGD value of 0.6 ps, and for the second-order PMD components, an average Polarization-Dependent Chromatic-Dispersion (PDCD) and depolarization of 0.1 ps/nm and 0.5 ps^2, respectively.

Introduction

Polarization is a property of light related to the direction of its vibrations, horizontally and vertically. This means the light can vibrate in two principal polarization modes; the fast and the slow mode. The effect causing a difference in the arrival times of the two modes, the DGD, is part of the PMD. The DGD is caused by random optical birefringence along the fiber. For long distances the DGD increases with the square root of the fiber length. The first-order PMD of a fiber is characterized by the DGD. The second-order PMD of a fiber is characterized by the variation of the PSPs of the fiber with respect to the wavelength. Recently, the PMD appears to be an important limitation in high-speed fiber communication systems because it leads to pulse distortion and system penalties when bit rates exceed 10 Gbit/s, even in dispersion managed systems. For high bit rate, for instance 160 Gbit/s OTDM systems, high-order PMD produces other distorting effects which are comparable to effects from the chromatic dispersion. Thus, high-order PMD becomes the major limiting factor to the bandwidth and linearity of optical systems. The effect of the high-order PMD in the Return to Zero (RZ) format is stronger than the Non-Return to Zero (NRZ) format due to the larger bandwidth in RZ format.

It is possible to determine the DGD for different fiber configurations using measuring equipment. Recently, several methods have been developed to evaluate the second- and higher order PMD of a fiber [1]-[4]. In this paper we apply an expansion of the Jones matrix method to characterize the fiber up to the second-order of the PMD [5],[6]. We have developed a simple algorithm to determine the DGD and the rotation of one PSP of the fiber in order to calculate the depolarization of the optical signal. The

measurements are carried out over distances of 85 km and 265 km of TWRS fiber. The link includes dispersion compensating fiber modules and loss compensating optical Erbium-Doped Fiber Amplifiers (EDFAs). With these experiments we obtain more information about the link and the potential deterioration of systems due to PMD can be evaluated in order to perform appropriate PMD compensation. The measurements confirm the theory developed in [7] because they show that the depolarization component of the total polarization equals $8/9^{th}$ of the total value of the second-order PMD. Furthermore, the Jones analysis used here offers advantages by its simplicity and by the high accuracy for low values of PMD compared to other methods, for instance, the Stokes parameters method.

Theoretical background and experimental results

The setup shown in Figure 1 is used to measure the transmission Jones matrix $\boldsymbol{T}$. The matrix $\boldsymbol{T}$ is given by

$$\boldsymbol{T} = \beta \begin{pmatrix} k_1 k_4 & k_2 \\ k_4 & 1 \end{pmatrix},$$

where β is a complex constant, k_1 proceeds from the ratio between the x and y components of the output Jones vector when the electric vector of the incident linearly polarized light is parallel to the x-axis. Similarly, k_2 is the same ratio when the electrical vector of the incident linearly polarized light is parallel to y-axis. Finally, $k_4 = (k_3 - k_2)/(k_1 - k_3)$, where k_3 is the ratio between the output Jones vector components when the incident light with a linear polarization is parallel to the bisector of the angle between the positive x- and y-axes [8].
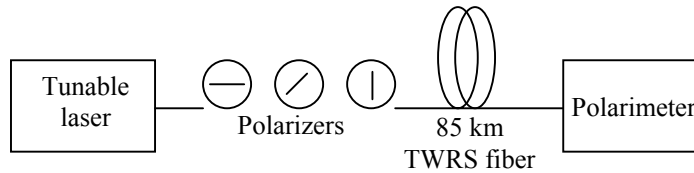

Figure 1. Experimental set up to measure the transmission Jones matrix.

With the polarimeter, we measured the coefficients of the matrix $\boldsymbol{T}$ for a piece of TWRS fiber of 85 km for a wavelength range of 1500 to 1560 nm using step size of 2 nm. We calculated the DGD at every step using the eigenvalues ρ_1 and ρ_2 of the product $\boldsymbol{T}' \boldsymbol{T}^{-1}$ according to

$$\Delta\tau = \left| \frac{Arg(\rho_1 / \rho_2)}{\Delta\omega} \right|,$$

where $\Delta\tau$ is the DGD, Arg denotes the argument function and $\Delta\omega$ is the step size in terms of angular frequency [9]. First-order PMD is determined by the dispersion vector $\vec{\Omega} = \Delta\tau\, \hat{q}$, where $\hat{q}$ is the unitary vector in the Stokes vector space, aligned with one of the PSPs. Second-order PMD is composed by two components, PDCD and depolarization, as described by the derivative $\vec{\Omega}_\omega = \Delta\tau_\omega \hat{q} + \Delta\tau\, \hat{q}_\omega$, with subscript ω indicating differentiation with respect to the angular frequency.

The PSPs of the fiber are obtained from the eigenvectors of the product $T'\,T^1$. The depolarization is a result of the rotation of the PSPs, as described by $\hat{q}_{\omega}$, the derivative of the $\hat{q}$ vector. The PDCD is calculated from the derivative of the DGD with respect to the angular frequency. We have developed an algorithm to estimate the variation of one of the PSPs with respect to the frequency. Thus, each of the two components of the second-order PMD can be calculated. Figure 2 shows the rotation of the PSP and the $\hat{q}$ vector in the Stokes vector space.
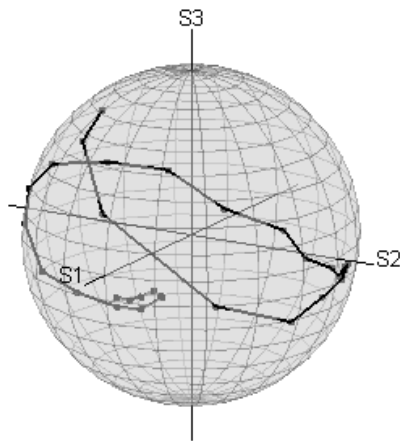

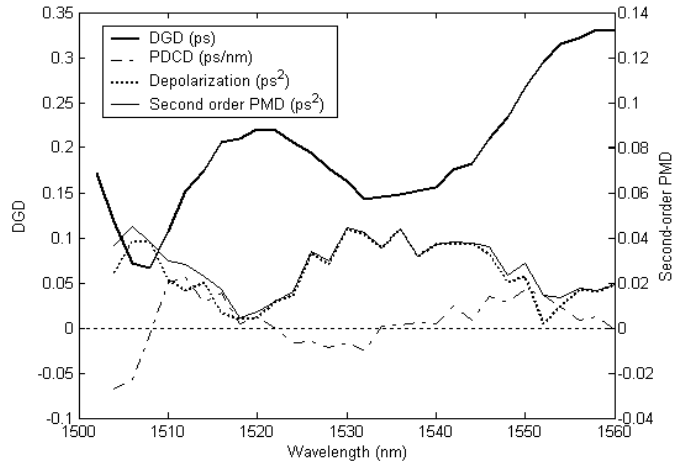Figure 2. Vector $\hat{q}$ and PSP rotation for 85 km of TWRS fiber.

Figure 3. PMD measurements for 85 km of TWRS fiber. Thick solid curve shows the DGD (left scale). Thin solid curve shows the second-order PMD. Dash-dotted and dotted curves show the components or second-order PMD (right scale).
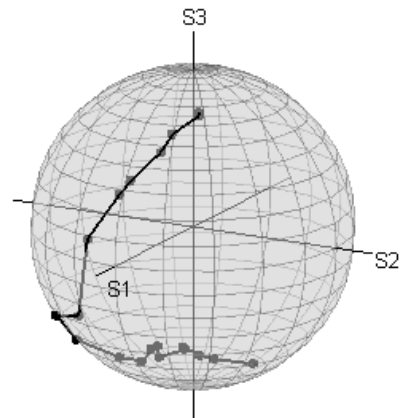

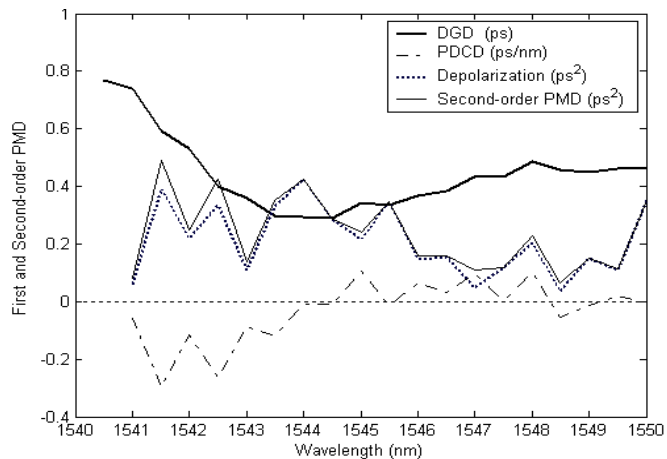Figure 4. Vector $\hat{q}$ and PSP rotation for 265 km of TWRS fiber.

Figure 5. PMD measurements for 265 km of TWRS fiber. Thick solid curve shows the DGD. Thin solid curve shows the second-order PMD. Dash-dotted and dotted curves show the components or second-order PMD.

From Figure 3, it can be seen that the average DGD is 0.19 and the PMD coefficient of 0.021 ps/$\sqrt{\text{km}}$ which approximates fiber specifications. The calculated average second-order PMD is 0.02 ps^2 for this fiber length.

The same procedure is applied to the link of 265 km for a wavelength range of 1540 to 1550 nm using a step size of 0.5 nm. We decreased the range compared to the first measurements to avoid wavelengths being outside the bands of the optical amplifiers. Figure 4 shows the rotations of one PSP and its corresponding $\hat{q}$ vector over the Stokes vector space. Figure 5 shows the PMD parameters calculated by Jones analysis to characterize the 256 km link. The average value measured for the DGD is 0.44 ps, but for several measurements in different conditions this value became as much as 0.6 ps. The average calculated second-order PMD is 0.3 ps^2 and the maximum value is 0.5 ps^2 for certain wavelengths. In this figure it is confirmed that depolarization component governs the second-order PMD with a ratio of 8/9 and the inverse relationship between the DGD and the second-order PMD. This is because for a small resultant PMD vector, a small change in frequency strongly affects the overall PMD vector direction and this causes a large rotation rate of the PSPs.

Acknowledgements

Conclusions

We have characterized a 256 km dispersion managed link up to second-order PMD by means of Jones matrix method. The obtained results confirm the high accuracy of this method even for the small PMD parameters of a TWRS fiber. Low resources and simple processing algorithms are required for this method to characterize the PMD of the fiber.

References

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