PMD and PDL monitoring of traffic-carrying transatlantic fibre-optic system

J. Jiang, D. Richards, S. Oliva, P. Green and R. Hui

For the first time the direct monitoring of polarisation mode dispersion (PMD) and polarisation-dependent loss (PDL) in a traffic-carrying transatlantic fibre-optic system without the requirement of looping-back is reported. The impact of transmitter polarisation scrambling in the measured results is analysed and verified by the measured results.

Introduction: Polarisation mode dispersion (PMD) is an important factor in the performance of long-distance high speed optical transmission systems. There is clearly a need for a practical approach that supports the network provider's planning and route design process for possible capacity upgrading in existing fibre plants, such as to retrofit 10 Gbit/s dense wave division multiplexing (DWDM) systems with 40 Gbit/s per wavelength. A comprehensive characterisation of fibre system properties has to be performed before upgrading, but this often has to be done without disrupting customer traffic. Traditional PMD and polarisation-dependent loss (PDL) measurement techniques, such as the Jones matrix and Mueller matrix methods [1], require access to both ends of the fibre, which is not feasible when the transmitter and the receiver are far apart, except by using loop-back techniques. These techniques are also intrusive because of the need for a probe optical signal to make the measurement. We have recently demonstrated a non-intrusive method to directly measure the first-order differential group delay (DGD) and PDL in traffic-carrying terrestrial optical systems using coherent detection and RF signal processing [2, 3]. In this Letter, we report the measurement of PMD and PDL on wavelengths of the transatlantic fibre-optic system known as TAT-14. One segment of this submarine fibre-optic system runs from Manasquan, NJ, USA, to Blaabjerg, Denmark, a path that is approximately 7500 km long, employing 147 erbium doped fibre amplifiers (EDFA). A chirped return-to-zero (RZ) modulation format is used in the DWDM transmitters, and intra-bit polarisation scrambling is used to suppress the effects of polarisation-hole burning [4] and other nonlinear waveform distortions such as four-wave mixing and cross-phase modulation [5]. Since our measurement utilises live traffic as the probe signal, the high-speed polarisation scrambling in the transmitter complicates the measurement of PMD and PDL compared to the previously reported methods, and a modified algorithm is used to analyse the results.

Principle of operation: The measurement setup is similar to that reported in [2]. A small portion of the optical signal is tapped off from the transmission line for analysis, and a tunable laser is used as a local oscillator (LO) for coherent heterodyne detection. A polarisation controller is placed at the output of the LO to randomly scramble its state of polarisation (SOP). After coherent detection, the heterodyne IF spectrum is amplified and two narrowband RF filters with 10 GHz frequency separation are used to select two different frequency components of the IF spectrum. By measuring polarisation walk-off, $\Delta\alpha$, between the two frequency components, the first-order DGD experienced by the optical signal can be evaluated with $\tau_S = \Delta\alpha/\Delta\omega$, where $\Delta\omega$ is the frequency separation [3]. In terrestrial fibre-optical systems, the SOP of the optical signal from the transmitter is fixed, and the DGD seen by the receiver was found to have a Rayleigh distribution [3]. However, if the SOP of the transmitter is scrambled, the statistical distribution of the measured DGD would be different.

The equivalent optical circuit for polarisation scrambling can be regarded as a phase modulator in concatenation with a fixed birefringent element [4, 5]. When the SOP of the laser source is placed midway between the fast and the slow axes of the birefringent element, the optical phase modulation can be converted into polarisation modulation at the output of the birefringent element. In Poincare space, the angle between the SOP of the laser $\boldsymbol{S}$ and the PMD vector of the birefringent element Ω_D, is orthogonal as shown in Fig. 1. Under this Cartesian coordinator, we can decompose the PMD vector $\vec{\Omega}$ of the transmission fibre into three independent orthogonal components Ω_1, Ω_2 and Ω_3, also shown in Fig. 1. Each of these orthogonal components follows a normal distribution with the mean of zero and the variance of q^2. Since Ω_3 is parallel to the SOP vector $\boldsymbol{S}$ of the laser, it does not introduce DGD at the coherent PMD monitor. In fact the PMD components which can be seen by the coherent monitor are $\Omega_1' = \Omega_1 + \Omega_D$ and Ω_2 shown in Fig. 1. The measured DGD τ_s will be [3],

$$\tau_s = \sqrt{(\Omega_1')^2 + \Omega_2^2} \tag{1}$$

If μ_p is the fixed DGD value of the birefringent element in the transmitter, Ω_1' will follow a normal distribution with the mean of μ_p and the same variance of q^2 as Ω_1. Based on (1), τ_s should follow a Rice distribution with the probability density function,

$$f(\tau_s) = \frac{\tau_s}{q^2}\exp\left(-\frac{\tau_s^2 + \mu_p^2}{2q^2}\right) I_0\left(\frac{\mu_p \tau_s}{q^2}\right) \tag{2}$$

where $I_0(\ )$ is the 0th-order modified Bessel function of the first kind. Although there are three parameters, μ_p, q and τ_s required to determine the probability density function in (2), since τ_s is not independent, being related to μ_p and q, there are only two independent parameters. In practice, if we can precisely measure the probability distribution of τ_s, the values of μ_p and q can be easily obtained through curve fitting. This technique does not even require the knowledge of the exact DGD value, Ω_D, of the birefringent element in the transmitter, which in this case is on the opposite side of the Atlantic Ocean.

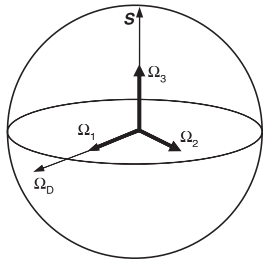


Fig. 1 *Poincare representation of source laser SOP, $\boldsymbol{S}$, DGD of birefringence element Ω_D in transmitter, and decomposed PMD vector of transmission fibre [Ω_1, Ω_2, Ω_3]*

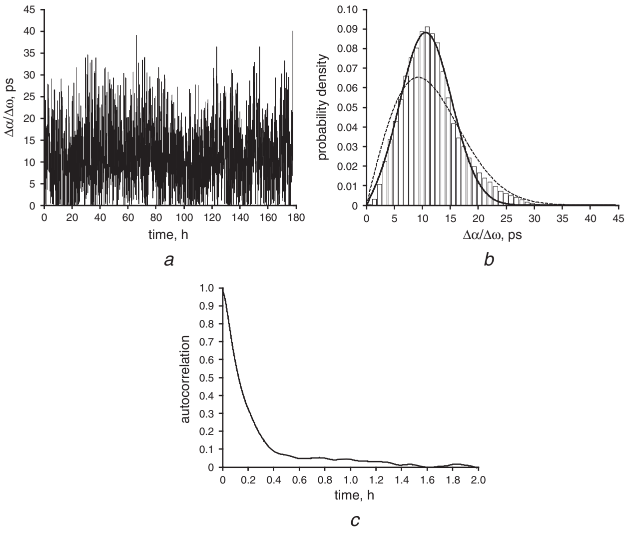


Fig. 2 *Measured DGD, τ_s. (a) against time, (b) normalised statistic distribution of τ_s, (c) autocorrelation function*

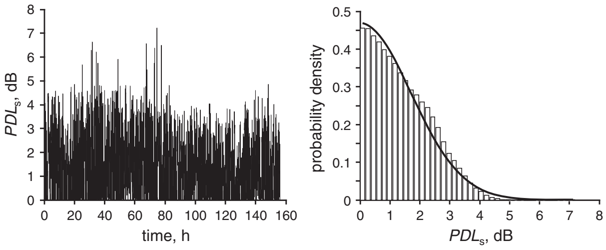
Solid and dashed lines in (b) represent Rician and Rayleigh distribution, respectively

Result of field test: A field test was carried out at the TAT-14 terminal station in Manasquan, NJ, USA. The 7500 km transatlantic fibre-optic system carries DWDM traffic at 10 Gbit/s per wavelength. Fig. 2*a* shows the measured first-order DGD, τ_s, against time over 178 h, while Fig. 2*b* is its statistical distribution which has approximately 402 000 data points. The measured correlation time of this fibre link is about 0.13 h as indicated in Fig. 2*c*, so that 178 h of monitoring is equivalent to 1370 uncorrelated samples. The solid line in Fig. 2*b* is the best fit using the Rice distribution of (2) with $\mu_P = 9.6$ ps and $q = 4.87$ ps. It is important to note that the measured DGD, τ_s, using the coherent detection technique is the DGD experienced by the optical signal. The actual fibre PMD parameter, which is the DGD between the fast and slow axes of the fibre, can be calculated as $\mu_1 = q\sqrt{8/\pi} = 7.76$ ps. In the previously reported DGD measurements in terrestrial optical systems in which the SOP of the transmitters were not scrambled, the DGD followed a Rayleigh distribution [3]. Shown as the dashed line in Fig. 2*b*, it is obvious that a Rayleigh distribution does not fit to this submarine system, which has a polarisation-scrambled transmitter.

Another useful system parameter that this coherent monitoring system can provide is the PDL seen by the receiver, which can be found from the output voltage $V(t)$ of either RF detector [6],

$$PDL_s = 10\log_{10}\left|(1+\Gamma_s)/(1-\Gamma_s)\right| \qquad (3)$$

where $\Gamma_s = \left|V(t)/V_m - 1\right|$ is related to the PDL seen by the optical receiver, and V_m is the mean value of $V(t)$. Fig. 3*a* shows the measured PDL against time using the procedure described in [6], while Fig. 3*b* provides the statistic distribution of PDL_s. However, in order to obtain the mean PDL of the fibre system itself, Γ_s has to be replaced by $\Gamma = \sqrt{8/\pi}\sigma/V_m$ in (3), where σ is the standard deviation of $V(t)$. Using this approach, the system PDL can be found as approximately 2.6 dB. The impact of PDL in the PMD measurement is estimated to be less than 3%.



a *b*

Fig. 3 *Measured PDL_s in dB unit (a) with time (b) its histogram*

Solid line in (b) is ideal half normal distribution

Conclusion: We have characterised the PMD and PDL of the TAT-14 transatlantic fibre-optic system while it carries live DWDM traffic. To the best of our knowledge, this is the first field test of its kind that does not requiring looping-back and interrupting the system operation. Polarisation scrambling in the transmitter alters the probability distribution of the DGD seen by the receiver, which exhibits Rician statistics.

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