PMD monitoring in traffic-carrying optical systems and its statistical analysis

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Abstract: Differential group delay (DGD) experienced by the optical signal in in-service terrestrial optical fiber systems has been monitored for the first time without the requirement of looping-back, in which the live traffic carried in the fiber was used as the probing signal. The relationship between the measured DGD using this technique and the actual fiber PMD parameter is formulated and verified by field experiments.

OCIS codes: (060. 2330) Fiber optics communications; (260.5430) Polarization.

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1. Introduction

In high speed optical fiber communication systems, polarization mode dispersion (PMD) is one of the most important factors of performance degradation. Traditionally the PMD parameter of a fiber can be measured by a number of techniques, such as Jones Matrix Eigen-analysis, Poincare Sphere Analysis and Mueller Matrix method [1-3]. Fig. 1 shows the Poincare sphere representation of signal polarization vector. With the frequency change of the optical signal which propagates through an optical fiber, the output state of polarization (SOP)

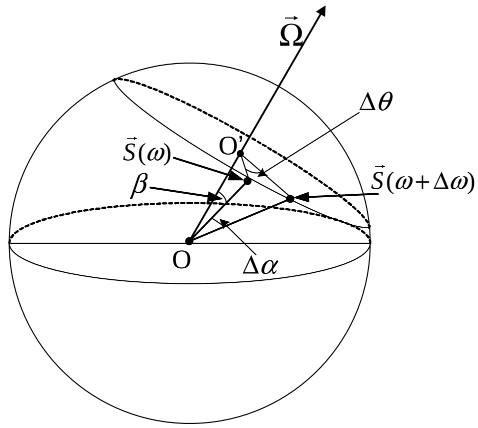

Fig. 1. Poincare sphere representation of polarization vectors and output SOP rotation with optical frequency change

rotates on the Poincare sphere around the principle state of polarization (PSP) vector $\vec{\Omega}$. For the polarization states $\vec{S}(\omega)$ and $\vec{S}(\omega+\Delta\omega)$ of two the frequency components selected from the optical signal shown in Fig. 1, if the separation between their azimuth angles is $\Delta\theta$, the DGD of the fiber can be found as $\tau_f = \Delta\theta/\Delta\omega$, where $\Delta\omega$ is the frequency difference between these two components. Obviously, $\Delta\theta$ has to be small enough so that this linearization is valid for the measurement of the 1st-order PMD. In practice, in order to measure $\Delta\theta$, several different SOP settings of the input optical signal have to be used to complete a Jones matrix or a Mueller matrix. In addition, both the Jones matrix and the Mueller matrix techniques require the synchronization between the PSP settings of the input optical signal and the polarimeter measurement at the output side. As the consequence, these traditional PMD measurement techniques require the accesses to both ends of the fiber, which prevents their application from monitoring in-service optical systems since the source and the receiver of live optical networks are at distance and usually are not accessible at the same time. However, there is clearly a need for a more practical approach that supports a network provider's planning and route design process for possible capacity upgrading and the system characterization has to be done without disrupting customer traffic.

Recently, several techniques were proposed for in-situ evaluation of PMD utilizing the optical signal carried in the fiber as the probe signal. A heterodyne polarimeter with an RF spectrum analyzer was used to estimate the PMD-induced system penalty by measuring the state of polarization 'string' length in a nonintrusive way [4]. A similar technique with a higher measurement speed was proposed in [5], which uses direct detection with a high resolution optical spectrum analyzer consisting of an InGaAs line-scan camera and a virtually imaged phase array. We have proposed a simplified method to directly measure the DGD in traffic-carrying optical links using coherent detection and RF signal processing [6]. For all these non-intrusive PMD monitoring techniques, the SOP of the input optical signal is not adjustable and the measurement of $\Delta\theta$ in Fig. 1 is therefore not feasible. In fact, the core angle $\Delta\alpha$ shown in Fig. 1 is usually measured in these in-service monitoring techniques, because it only depends on the relative polarization walk-off between two frequency

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components within the optical spectrum of the probe. However, since it is $\Delta\theta$ instead of $\Delta\alpha$ which represents the DGD between the fast and the slow axis of the fiber, it is important to find the relationship between them. $\Delta\alpha$ is generally smaller than $\Delta\theta$ and $\tau_p = \Delta\alpha/\Delta\omega$ represents the actual DGD seen by the probing signal. In order to correctly interpret the results obtained by the in-service PMD monitoring technique, it is important to rigorously examine the relationship between the PMD parameter of the fiber and the DGD measured by the technique demonstrated in references [6] and [7].

2. Theoretical analysis

Figure 1 indicates that $\Delta\alpha$ is related to $\Delta\theta$ by,

$$\sin(\frac{\Delta\alpha}{2}) = \sin(\frac{\Delta\theta}{2})\sin\beta \tag{1}$$

where, β represents the angle between point *A* and the PMD vector $\vec{\Omega}$. When $\Delta\theta$ is small enough, which can be ensured by choosing appropriate frequency difference $\Delta\omega$, Eq.(1) can be simplified to,

$$\Delta\alpha = \Delta\theta\sin\beta \tag{2}$$

In Stokes space, the well-known PSP model indicates that a long fiber can be regarded as a wave plate with the time retardation equals to the modulus of the PMD vector in the fiber, while the principle axis of the wave plate is aligned with the slow axis of the PMD vector. Thus, the angle between the input polarization state of the signal $\vec{S}_{in}$ and the fiber PMD-vector is also equal to β and therefore,

$$\cos\beta = \frac{\vec{\Omega}\cdot\vec{S}_{in}}{\left|\vec{\Omega}\right|\left|\vec{S}_{in}\right|} \tag{3}$$

In a Cartesian coordinator, the PMD vector can be decomposed into three orthogonal components, $\vec{\Omega} = \vec{a}_x\Omega_1 + \vec{a}_y\Omega_2 + \vec{a}_z\Omega_3$, where $\vec{a}_x$, $\vec{a}_y$ and $\vec{a}_z$ are unit vectors, and thus $\left|\vec{\Omega}\right| = \sqrt{\Omega_1^2 + \Omega_2^2 + \Omega_3^2}$. When each of the three orthogonal components Ω_1, Ω_2 and Ω_3 follows an independent Gaussian distribution with zero mean and the same standard deviation *q*, the statistics of PMD vector will exhibit a Maxwellian distribution [8],

$$p_3(\tau_f) = \sqrt{\frac{2}{\pi}}\frac{\tau_f^{\;2}}{q^3}e^{-\frac{\tau_f^{\;2}}{2q^2}} \tag{4}$$

In general, the fiber PMD parameter is regarded as its mean DGD which is related to the parameter *q* by,

$$\langle\tau_f\rangle = q\sqrt{8/\pi} \tag{5}$$

where, the mean DGD $\langle\tau_f\rangle$ is the average value of the Maxwellian distribution shown in Eq. (4). In practice, using the live traffic carried in the fiber as the probing signal is critical for the in-service monitoring of live optical systems. Since the SOP of the input optical signal is determined by the laser in the transmitter, it is relatively stable. Without losing generality, one can arbitrarily assume that the SOP of the input optical signal is $\vec{S}_{in}$ = (1, 0, 0), then

$$\left|\vec{\Omega}\right|\cos\beta = \Omega_1 \tag{6}$$

The combination of Eqs. (2) and (6) yields,

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$$\tau_p = \frac{\Delta\alpha}{\Delta\omega} = \left|\vec{\Omega}\right|\sin\beta = \sqrt{\Omega_2^2 + \Omega_3^2} \tag{7}$$

Note that, a Maxwellian distribution is referred to as a *Chi* distribution with 3 degrees of freedom because it is related to three independent components Ω_1, Ω_2 and Ω_3. In our case, Eq. (7) indicates that τ_p is only related to two of the three independent orthogonal components, and therefore, it should follow a *Chi* distribution with 2 degrees of freedom, which is also known as Rayleigh distribution and its probability density function can be expressed as [9],

$$p_2(\tau_p) = \frac{\tau_p}{q^2} e^{-\frac{\tau_p{}^2}{2q^2}} \tag{8}$$

The mean value of this distribution is

$$\left\langle \tau_p \right\rangle = q\sqrt{\pi/2} \tag{9}$$

From Eq. (5) and (9), the relationship between $\left\langle \tau_f \right\rangle$ and $\left\langle \tau_p \right\rangle$ can be easily found as,

$$\left\langle \tau_f \right\rangle = 4\left\langle \tau_p \right\rangle / \pi \tag{10}$$

It is worth noting that quantity τ_p in eq.(7) is a "partial" DGD, which is in fact the projection of the fiber PMD vector perpendicular to the signal SOP direction. However, the mean and the statistic distribution of the actual fiber DGD can be derived from the measured τ_p, and it is sufficient for most of the practical applications since it is directly related to system eye-closure penalty [10, 11].

In practical fiber-optic systems, polarization-depend loss (PDL) may exist in addition to PMD. When PDL is taken into accounted, the output polarization state $\vec{S}$ will vary with optical frequency as [12],

$$\frac{\partial\vec{S}}{\partial\omega} = \vec{\Omega}\times\vec{S} - (\vec{\Lambda}\times\vec{S})\times\vec{S} \tag{11}$$

where, $\vec{\Lambda}$ is the differential attenuation slope (DAS) vector which is related to PDL vector $\vec{\Gamma}$. Λ can be decomposed into three orthogonal and independent random Gaussian components with the same standard deviation q' when PDL is small enough: $\vec{\Lambda} = \vec{a}_x\Lambda_1 + \vec{a}_y\Lambda_2 + \vec{a}_z\Lambda_3$. Again, let $\vec{S} = (1,0,0)$,

$$\begin{aligned}\left(\frac{\Delta\alpha}{\Delta\omega}\right)^2 &= \left|\vec{\Omega}\times\vec{S}\right|^2 + \left|(\vec{\Lambda}\times\vec{S})\times\vec{S}\right|^2 + 2\left|\vec{\Omega}\times\vec{S}\right|\left|(\vec{\Lambda}\times\vec{S})\times\vec{S}\right|\cos\varphi \\ &= (\Omega_2 + \Lambda_3)^2 + (\Omega_3 - \Lambda_2)^2\end{aligned} \tag{12}$$

Where, φ is the angle between the vectors $\vec{\Omega}\times\vec{S}$ and $(\vec{\Lambda}\times\vec{S})\times\vec{S}$. Equation (12) indicates that the distribution of $\Delta\alpha/\Delta\omega$ still follows Rayleigh statistics and its mean value is,

$$\left\langle \frac{\Delta\alpha}{\Delta\omega} \right\rangle = \sqrt{\frac{\pi(1+L)}{2}}q \tag{13}$$

Where,

$$L = (q'/q)^2 \tag{14}$$

Under the small PDL assumption, the relationship between PMD, PDL and DAS vectors is,

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$$\left\langle \left|\vec{\Lambda}\right| \right\rangle = \sqrt{\frac{\pi}{8}} \left\langle \left|\vec{\Omega}\right| \right\rangle \cdot \left\langle \left|\vec{\Gamma}\right| \right\rangle \tag{15}$$

As an example, with a 2dB PDL, the value of L will be 0.021 and the difference between the mean values of τ_p with and without PDL is only 1.03%. Therefore one can generally conclude that the impact of PDL on PMD measurement is negligible when system PDL is less than 2 dB.

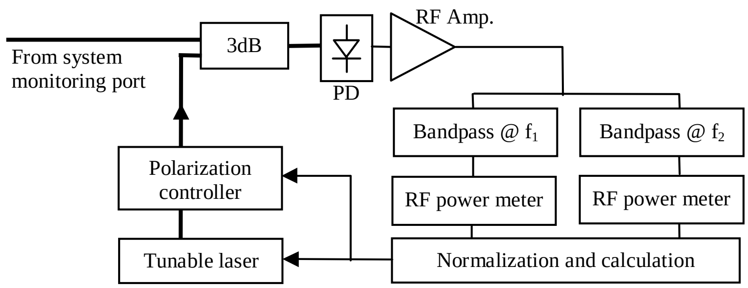

Fig. 2. Block diagram of the coherent PMD monitor

3. Experimental setup and results

We have assembled an experimental setup for in-service PMD monitoring using coherent detection [6] as schematically shown in Fig. 2, where a small portion of the optical signal is tapped from the transmission link for the measurement. A tunable laser is used as a local oscillator (LO) for coherent heterodyne detection and transmission channel selection. A polarization controller is placed at the output of the local oscillator to randomly scramble the SOP of the local oscillator. When the SOP of the LO is aligned with the received optical signal at the frequency component ω, the relative angular walk-off $\Delta\alpha$ between $\vec{S}(\omega)$ and $\vec{S}(\omega+\Delta\omega)$ will be equal to the angle between $\vec{S}(\omega+\Delta\omega)$ and the SOP of LO. Under this condition the angle can obtained through the measured IF intensity $I(\omega+\Delta\omega)$, which is proportional to $P_L P_s \cos(\Delta\alpha)$, where P_{L} and P_{s} are the optical powers of the signal and the LO [7]. After the heterodyne IF spectrum is amplified, two RF filters with 1GHz bandwidth are used to select two different frequency components of the signal and their central frequency difference is 10 GHz. The measurement is relatively independent of modulation format of the optical signal since the signal average power is used for measurement. The two frequency components selected by the RF bandpass filters can be any part within the modulated signal spectrum. By measuring the differential polarization walk-off between the two frequency components, the first-order DGD experienced by the optical signal can be evaluated. The accuracy of the PMD measurement in the laboratory environment was verified by using a PMD emulator and setting $\beta = 90^\circ$ [6]. The smallest DGD that can be measured by the current setup is about 0.3 ps which was verified in a system without DGD. This measurement error is believed to be mainly caused by electrical circuit noise. In a previous field trial, we have also demonstrated that the system Q margin was inversely proportional to the instantaneous DGD measured by this technique [7].

In the current measurement apparatus, since polarization scrambling is used for LO, the variation of signal SOP at the fiber output cannot be monitored. If the signal SOP needs to be measured, one can programmatically switch the SOP of the LO between three orthogonal polarization states on the Poincare sphere and performing Stokes parameter analysis of the detected IF signal.

In order to verify the statistical distribution predicted by our analysis, we have recently carried out a number of field trials in various long-distance terrestrial fiber-optic systems

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carrying DWDM traffics at 10Gb/s data rate with non-return-to-zero (NRZ) modulation. Fig. 3 shows the results of DGD measurements at Sprint's Kansas City switch site and -20dBm of signal optical power was tapped to perform the measurement. Figure 3(a) shows the result of 268-hour continuous measurement of partial DGD, τ_p as the function of time for a fiber link between Kansas City and Chicago which is approximately 900 km, while Fig.3(b) shows the statistical distribution of τ_p which is composed of approximately 480,000 data points. The correlation time of this link is about 0.5 h as shown in the inset of Fig. 3(b). Our 268 hours of monitoring is equivalent to 536 uncorrelated samples, which is reasonably sufficient to reconstruct a statistic distribution. The solid line in Fig. 3(b) is a Rayleigh distribution which fits well to the measured partial DGD, while as a comparison the dotted line in the same figure shows a Maxwellian distribution which is obviously not a good fit. It is noticed that Fig. 3(b) looks very similar to Fig. 1 in [13] where the statistics of PMD-induced system impairments was numerically simulated. Since the eye-closure penalty in the receiver depends on the alignment between the SOP of the optical signal and the PSP of the optical fiber [14, 15], a Rayleigh distribution was expected. From in-service system monitoring point of view, our coherent detection technique evaluates τ_p which has a mean value of $\langle \tau_p \rangle$. Eq.(10) can be used to convert this result to the more traditionally defined mean DGD of the fiber, $\langle \tau_f \rangle$. The PDL of this system was estimated to be approximately 0.997dB through another measurement, therefore the impact of PDL in the PMD measurement is only about 0.26% and is negligible. To the best of our knowledge, this is the first PMD measurement reported in commercial DWDM systems carrying live traffic and without the requirement of looping-back.

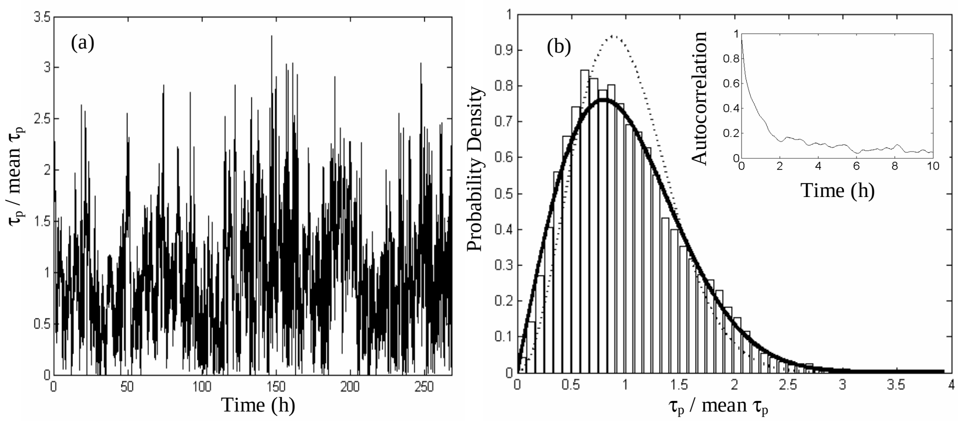

Fig. 3. (a) Normalized partial DGD versus time measured over a 900km link; (b) normalized statistic distribution of (a). Solid lines in (b): Rayleigh distribution, dotted lines: Maxwellian distribution with the same mean value. Inset in (b) is the autocorrelation function.

4. Conclusion

In conclusion, PMD monitoring in traffic-carrying DWDM optical fiber systems is reported for the first time without the requirement of looping-back. The simple relationship between the partial DGD measured with the coherent detection technique and the actual PMD parameter of the fiber is theoretically derived and verified, which allows the accurate evaluation of the PMD parameter in installed fiber systems without disturbing the commercial traffic. The measured partial DGD statistics fits well with a Rayleigh distribution as predicted by the theory.

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