PMD Monitoring in Traffic-carrying Optical Systems

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Abstract

DGD was monitored in in-service terrestrial optical fiber systems for the first time without the requirement of looping-back. The relationship between the measured DGD and the actual fiber PMD parameter is formulated and verified.

Introduction

Traditional polarization-mode dispersion PMD measurements usually require the accesses to both ends of the fiber, which prevents their application from monitoring in-service optical systems without looping-back [1, 2]. Recently, we have proposed a novel method to evaluate the effect of differential group delay (DGD) in traffic-carrying optical links using live traffic as the probe signal [3]. As shown in Fig.1, in this setup a tunable laser is used as a local oscillator for coherent heterodyne detection. A polarization controller is placed at the output of the local oscillator to randomly scramble the state of polarization (SOP) of the local oscillator. After the heterodyne RF spectrum is amplified, two narrowband RF filters are used to select two different frequency components of the signal. By measuring the differential polarization walk-off between the two frequency components, the first-order DGD experienced by the optical signal can be evaluated.

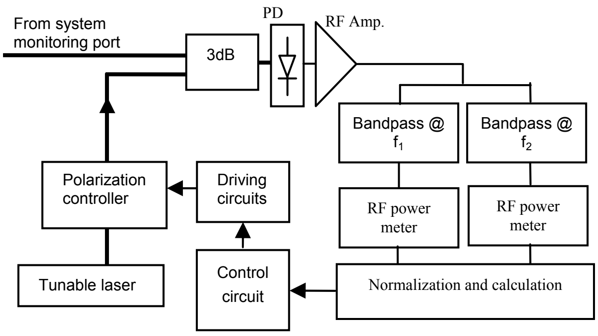

Fig. 1: Block diagram of coherent PMD monitor

In a previous field verification test, we have demonstrated that the system *Q* margin was inversely proportional to the instantaneous DGD measured by this technique [4]. It is important to notice that the DGD value obtained by this method is a partial DGD, which is in fact the DGD seen by optical signal, rather than the actual PMD parameter of fibers. In this paper, we explain how to obtain the fiber PMD parameter from the measured partial DGD. Field experiments in 700km and 900km in-service terrestrial optical systems are reported and the results agree reasonably well with our theoretical predictions. Currently, many network providers are planning to retrofit 10-Gb/s DWDM systems, both terrestrial and sub-marine, with 40 Gb/s (per λ) transmission equipment. These providers need a simple system characterization of PMD and PDL for qualification and design purposes in order to minimize disruptions in customer traffic and reduce labor and coordination efforts.

Theoretical analysis and field trials

As illustrated in Fig.1, the dependence of output SOP on PMD in a fiber can be described by a PMD vector $\vec{\Omega}$. The output SOP of an optical signal will rotate when its optical frequency changes, with $\vec{\Omega}$ as the rotation axis. The rotation rate $\Delta\theta/\Delta\omega$ is defined as the DGD, which equals to the modulus of $\vec{\Omega}$, where $\Delta\theta$ is the change in the rotation angle and $\Delta\omega$ is the corresponding frequency change. DGD value of the fiber can be evaluated if the rotation angle $\Delta\theta$ is known between two frequency components shown as point A and B in Fig.2.

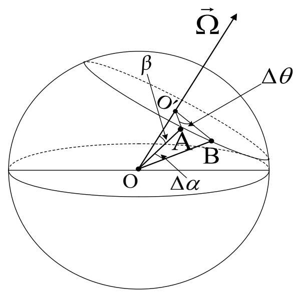

Fig. 2: PMD vector and output polarization state rotation with optical frequency change

However the calculation of $\Delta\theta$ is usually complicated and the evaluation of fiber PMD requires several different SOPs of the input optical signal to complete a Jones matrix or Mueller matrix. On the other hand, the angle $\Delta\alpha$ shown in Fig.2 is relatively easier to obtain and our monitoring technique described above is based on measuring $\Delta\alpha$. In fact, when $\Delta\theta$ is small enough, the relationship between $\Delta\alpha$ and $\Delta\theta$ is simple and can

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be expressed as, $\Delta\alpha = \Delta\theta \sin\beta$, Where, β represents the angle between point *A* and the PMD vector shown in Fig.2. The relationship is ensured in our system by choosing frequency difference of the two RF filters as 10 GHz.

In the Stokes space, the principle polarization state 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 and the fiber PMD-vector is also equal to β and therefore, $\cos\beta = (\vec{\Omega} \cdot \vec{S}_{in}) \big/ (|\vec{\Omega}||\vec{S}_{in}|)$. In a Cartesian coordinator, the PMD vector can be decomposed into three orthogonal components, each of the three components follows a Gaussian distribution and therefore the statistics of PMD vector exhibit a Maxwellian distribution [5], $p_1(x) = (\sqrt{\tfrac{2}{\pi}} x^2 e^{-x^2/2q^2}) \big/ q^3$, where the parameter *q* is related to the mean DGD by $\mu_1 = q\sqrt{8/\pi}$. Note that, a Maxwellian distribution is also referred to as a *Chi* distribution with 3 degrees of freedom. In practice, using the digital optical signal itself as the source is critical for the realization of the measurement of live system. Since the SOP of the input signal is determined by the laser in the transmitter, it is relatively stable. One can arbitrarily assume that the SOP of the input optical signal is $\vec{S}_{in}$ = (1, 0, 0) and $\Delta\alpha / \Delta\omega = (\Delta\theta / \Delta\omega)\sin\beta = \sqrt{\Omega_2^2 + \Omega_3^2}$. This indicates that $\Delta\alpha / \Delta\omega$ follows a *Chi*-distribution with 2 degrees of freedom, which is also known as Rayleigh distribution. Its probability density function is $p_2(x) = (xe^{-x^2/2q^2}) \big/ q^2$ and its mean value is $\mu_2 = q\sqrt{\pi/2}$. The relationship between μ_1 and μ_2 can be found simply as $\mu_1 = 4\mu_2/\pi$. Since the coherent detection technique evaluates μ_2 from the monitoring of $\Delta\alpha$, we can obtain the fiber PMD value from this simple relationship.

We have recently carried out a number of field trials in various long-distance terrestrial fiber-optic systems carrying DWDM traffics at 10Gb/s data rate. Fig.3 shows the results of DGD measurements at Sprint's Rialto switch site in California. Fig.3 (a) shows the result of 24-hour continuous measurement of DGD versus time for a fiber link from Stockton to Rialto which is approximately 750km, while Fig.3(b) shows the statistical distribution of the DGD. The solid line in Fig.3(b) is a Rayleigh distribution which fits to the measured DGD reasonably well, as a comparison, the dotted line shows the Maxwellian distribution. Similarly Fig.3 (c) and (d) show the measured results for another link between Phoenix to Rialto which is approximately 550km. The results look very similar to Fig.1 in [6] where the statistics of PMD-induced system impairments was numerically simulated.

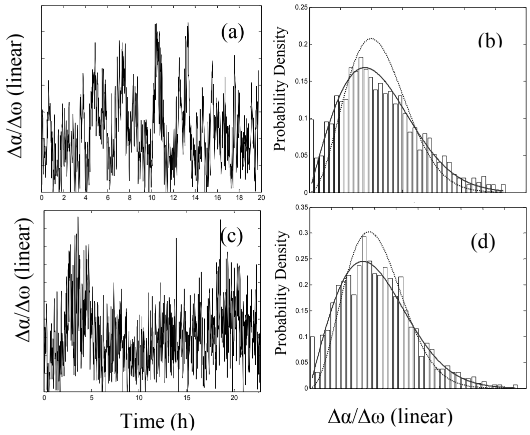

Fig. 3: (a) Partial DGD versus time for a 750km link; (b) normalized statistic distribution of (a); (c) Partial DGD versus time for a 550km link; (d) normalized statistic distribution of (c). Solid lines in (b) and (d) are Rayleigh distribution, dotted lines are Maxwellian distribution with the same mean value.

Conclusions

We have derived a simple relation between the DGD measured using a coherent detection technique and the actual PMD parameter in the fiber. This allows the accurate evaluation of fiber parameter in installed fiber systems which carry live traffic. Field measurements of DGD were performed on in-service long distance terrestrial fiber-optic systems and the DGD statistics fits will by a Rayleigh distribution as predicted by the theory.

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