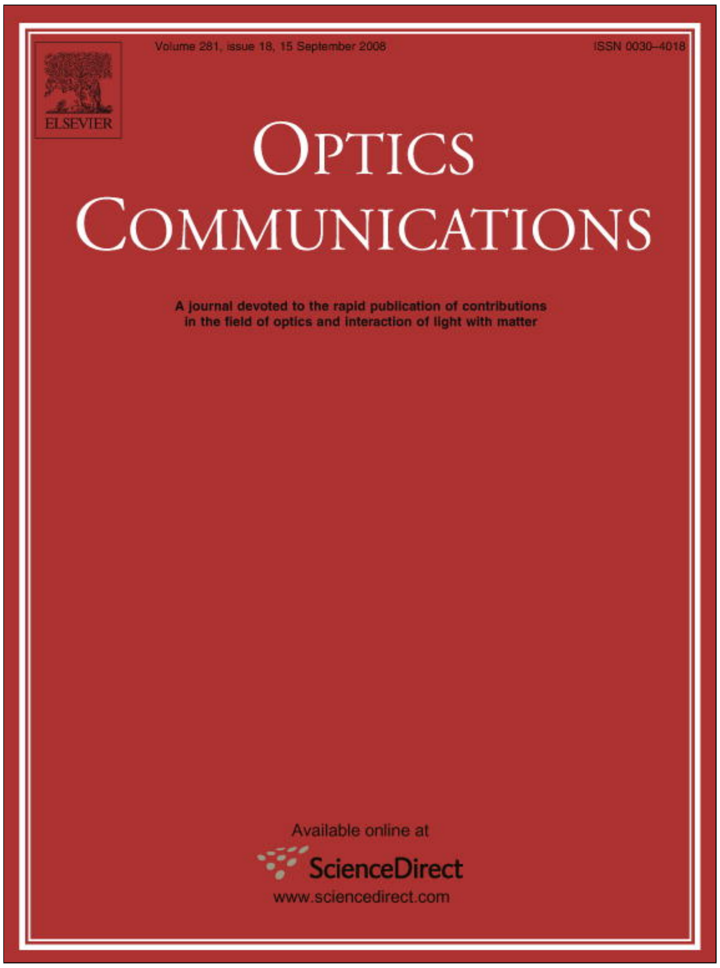
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Non-intrusive polarization dependent loss monitoring in fiber-optic transmission systems

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ABSTRACT

A method for non-intrusively monitoring the polarization dependent loss (PDL) of an installed fiber-optic transmission system is proposed using live dense wave division multiplexing (DWDM)-based traffic as the probing signal. The method extracts the statistical parameters of system PDL from the measured partial PDL data. Field measurements of PDL were performed on long-haul DWDM systems deployed in Sprint's network and the results validated our theoretical model.

1. Introduction

Polarization dependent loss (PDL) contributes to performance degradation in high-speed, long-haul optical fiber transmission systems [1], and can further degrade system performance when it interacts with polarization mode dispersion (PMD) [2]. The PDL in a system mainly comes from components such as optical amplifiers, couplers, isolators, multiplexers and de-multiplexers. However, even if the PDL of each individual component can be well-defined, the global PDL of the system may exhibit a random process which cannot be obtained by simply adding up the PDL of each component due to the random variation of relative orientations between various PDL elements [3–5]. In addition, the presence of PMD will further increase this uncertainty [6]. Due to its impact on the performance of optical communication systems, it is important to determine the time varying nature of PDL and its statistical distribution. Several PDL measurement methods have been proposed so far, such as the Mueller matrix method [7], Jones matrix method [8], polarization scanning method [9] and Poincare sphere method [10]. However, all these methods require the active control of the polarization state of the optical signal that couples into the system under test. This requirement prevented the application of these techniques to monitoring "in-service" optical systems because the source and the receiver of live optical networks are separated and usually are not accessible at the same time.

There is clearly a need for a more practical approach that supports a network provider's planning and route design process. Many network providers are planning to retrofit 10-Gb/s dense wave division multiplexing (DWDM) systems, both terrestrial and sub-marine, with 40 Gb/s (per λ) transmission equipment. These providers will want 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.

In this paper, we present (1) a novel method for non-intrusively monitoring the PDL of an installed DWDM system and (2) an analysis of the statistical nature of this measurement.

2. Statistical theory of PDL measurement

It is well-known that in the Poincare space, considering the optical signal passing through an optical system, the output Stokes vector $\vec{S}_{out} = (s_{out0}, s_{out1}, s_{out2}, s_{out3})$ and input Stokes vector $\vec{S}_{in} = (s_{in0}, s_{in1}, s_{in2}, s_{in3})$ can be linked with a Mueller matrix of the optical system as

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$$\begin{bmatrix} s_{\text{out0}} \\ s_{\text{out1}} \\ s_{\text{out2}} \\ s_{\text{out3}} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} s_{\text{in0}} \\ s_{\text{in1}} \\ s_{\text{in2}} \\ s_{\text{in3}} \end{bmatrix} \tag{1}$$

where $m_{i,j}$ (i,j = 1–4) are elements of the Mueller matrix which fully represent the characteristics of the optical system. Since the PDL measurement concerns only the optical power in the system output, only s_{out0} needs to be considered,

$$s_{\text{out0}} = m_{11}s_{\text{in0}} + m_{12}s_{\text{in1}} + m_{13}s_{\text{in2}} + m_{14}s_{\text{in3}} \tag{2}$$

The power transmission coefficient of the optical system can then be expressed as [9]

$$\begin{aligned} T &= \frac{s_{\text{out0}}}{s_{\text{in0}}} = m_{11} + \frac{s_{\text{in1}}}{s_{\text{in0}}}m_{12} + \frac{s_{\text{in2}}}{s_{\text{in0}}}m_{13} + \frac{s_{\text{in3}}}{s_{\text{in0}}}m_{14} \\ &= m_{11} + \text{DOP} \cdot [s_1m_{12} + s_2m_{13} + s_3m_{14}] = m_{11} + \text{DOP}(\vec{S} \cdot \vec{m}) \\ &= m_{11} + \text{DOP}|\vec{m}|\cos\theta \end{aligned} \tag{3}$$

where matrix elements m_{11} and $\vec{m} = (m_{12}, m_{13}, m_{14})$ are related to the PDL, $\vec{S} = (s_1, s_2, s_3)$ is the normalized input polarization vector with $s_j = s_{\text{in}j}/[s_{\text{in1}}^2 + s_{\text{in2}}^2 + s_{\text{in3}}^2]^{1/2} (j = 1, 2, 3)$, $\text{DOP} = [s_{\text{in1}}^2 + s_{\text{in2}}^2 + s_{\text{in3}}^2]^{1/2}/s_{\text{in0}}$ is the degree of polarization of input optical signal and θ is the angle between $\vec{m}$ and $\vec{S}$. In general, the input optical signal in a live optical system, which is usually provided by a laser diode, has a high degree of polarization and therefore we can assume DOP = 1, thus Eq. (3) is simplified as $T = m_{11} + |\vec{m}|\cos\theta$.

The power transmission coefficient T varies with time because of the random nature of the system PDL. However, corresponding to each PDL value, there exist a maximum $T_{\max} = m_{11} + |\vec{m}|$ and a minimum $T_{\min} = m_{11} - |\vec{m}|$ of the transmission coefficient. The system PDL can be described by a PDL vector $\vec{\Gamma}$ [3] where the amplitude of $\vec{\Gamma}$ is

$$\Gamma = \left|\frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}}\right| = \frac{|\vec{m}|}{|m_{11}|} = \frac{\sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}}{|m_{11}|} \tag{4}$$

The direction of the PDL vector is parallel to the polarization state vector $\vec{S}$ which corresponds to the direction of the maximum transmission coefficient. Eq. (3) indicates that the orientation of the PDL vector is determined by $\vec{m}$, and thus the global PDL vector can be defined by $\vec{\Gamma} = \vec{m}/m_{11}$. On the other hand, the traditional definition of PDL is $\rho = 10\log_{10}(T_{\max}/T_{\min})$, expressed in dB. The relationship between ρ and $\Gamma = |\vec{\Gamma}|$ is described by $\rho = 10\log_{10}[(1+\Gamma)/(1-\Gamma)]$. When Γ is small enough ($\Gamma \ll 1$), the following approximation is valid

$$\rho = 10\log_{10}\left[1 + \frac{2\Gamma}{1-\Gamma}\right] \approx 8.6859\Gamma \tag{5}$$

indicating that Γ is linearly proportional to ρ. It is generally accepted that ρ follows a Maxwellian distribution [11,12] and Γ should therefore also follow the same distribution. In the Mueller matrix, m_{11} represents a constant attenuation of the optical system since its effect on the system is independent of polarization parameters inherent to the input optical signal. Thus, each individual component m_{12}, m_{13}, m_{14} in the expression of the PDL vector $\vec{\Gamma}$ should follow a normal distribution with zero mean and equal variance q^2. The probability density distribution of $\vec{\Gamma}$ can then be expressed as

$$p(\Gamma) = \sqrt{\frac{2}{\pi}}\frac{\Gamma^2}{(q/m_{11})^3}\exp\left(-\frac{\Gamma^2}{2(q/m_{11})^2}\right) \tag{6}$$

$$\langle\Gamma\rangle = \sqrt{\frac{8}{\pi}}\frac{q}{m_{11}} \tag{7}$$

where $\langle\Gamma\rangle$ is the average value of Γ. Eq. (7) indicates that the system PDL can be fully determined by two parameters, m_{11} and q.

Without loss of generality, one can arbitrarily assume that the state of polarization (SOP) of the optical signal that is launched into the optical system is $\vec{S} = (1, 0, 0)$ and that rotation coordinate does not impact the transmission coefficient. Eq. (3) can then be simplified as

$$T = m_{11} + m_{12} \tag{8}$$

Since m_{11} is a constant, Eq. (8) clearly shows that T follows a normal distribution with m_{11} as the mean and q^2 as the variance. This indicates that in a practical optical system carrying live traffic, m_{11} and q^2 can be obtained by measuring the statistical distribution of T. It is worth noting that PDL is a system property which should be independent of the optical signal it carries. In a system with fixed input signal SOP, the optical signal may not necessarily see the worst-case PDL of the system and therefore T defined by Eq. (8) is only related to a partial PDL. In this case $|\vec{m}| = |m_{12}|$ and the part of the system PDL vector seen by the optical signal is $\Gamma_{\text{partial}} = |m_{12}|/m_{11}$, which follows a half-normal distribution.

3. Experiment setup and results

The PDL of a DWDM system may be measured by sampling the live-traffic carried in the system. A testing arrangement previously developed [13] is based on coherent detection and may be used to obtain the information for T, including the time-domain characteristics and the statistics. Fig. 1 shows the experimental setup, where a small portion of the optical signal is tapped from the DWDM transmission line. A tunable laser is used as the local oscillator (LO) for coherent heterodyne detection and channel selection. A programmable polarization controller is placed at the output of the LO to periodically scan the SOP of the LO. A 3-dB fiber coupler combines the received optical signal with the LO and a wideband photodiode (PD) is used to perform heterodyne detection with the intermediate frequency set at 20 GHz. A bandpass RF filter with a 1 GHz bandwidth is used to select a narrow slice of the amplified heterodyne spectrum, whose power is then measured by a detector. A data acquisition card reads the measured RF power and converts it into a voltage V_{out} for calculation,

$$V_{\text{out}} = \eta_D P_L P_s T\cos^2\frac{\phi}{2} + V_{\text{offset}} + V_N = kT\cos^2\frac{\phi}{2} + V_{\text{offset}} + V_N \tag{9}$$

where, η_D is a coefficient including the effects of the photodiode responsivity, the coupling coefficient of the fiber coupler, the RF amplifier, the RF filter, the RF detector and the data acquisition circuitry. P_s is the signal power launched into the optical system, P_L is the power of the LO and $k = \eta_D P_L P_s$. ϕ is the angle between the SOP vector of the input optical signal and that of the LO. V_{offset} is the voltage offset resulting from a non-ideal electronic circuit and V_N is the additive noise. In this system, since the receiver bandwidth

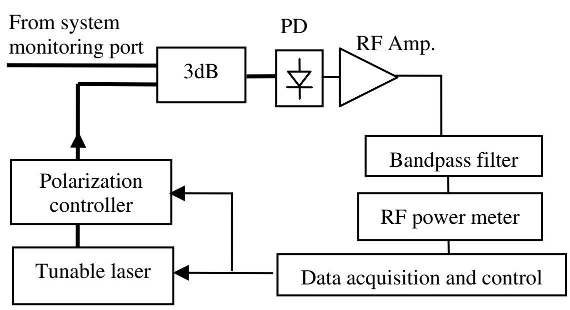

Fig. 1. Block diagram of PDL experiment setup.

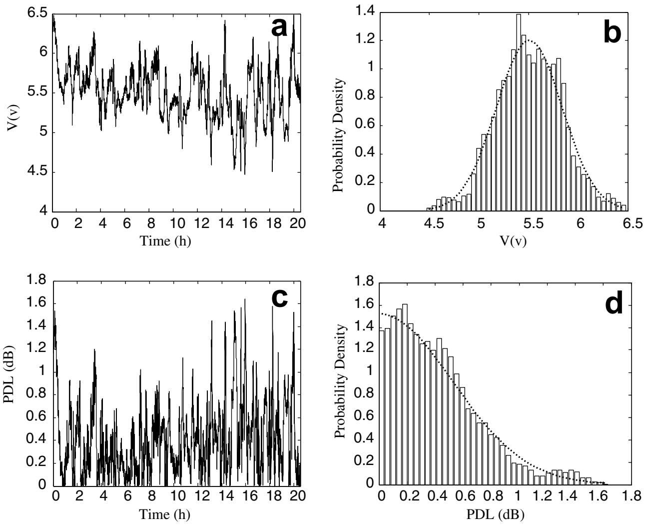

Fig. 2. (a) variation of V with time; (b) histogram of V; (c) variation of partial PDL in dB unit with time; (d) histogram of partial PDL. The dot line in (b) is the ideal normal distribution. The dash line in (d) is ideal half-normal distribution.

is only in the kilohertz range, the impact of shot noise and signal ASE noise in the coherent detection should be negligible. The major contribution to the receiver noise is believed to be additive which is primarily introduced by the electronic amplifiers.

In the coherent detection measurement, the SOP of the LO is periodically modulated, and thereby effectively scans the angle ϕ in Eq. (9). The scanning time to allow for the SOP of the LO to cover the entire Poincare sphere is less than 2 s. The system PDL vector is assumed to remain constant during each period of scanning. The maximum voltage in Eq. (9) is obtained when $\phi = 0$ so that

$$V_{\text{out-max}} = kT + V_{\text{offset}} + V_{N1} \tag{10}$$

while the minimum voltage corresponding to $\phi = \pi$ is

$$V_{\text{out-min}} = V_{\text{offset}} + V_{N2} \tag{11}$$

where V_{N1} and V_{N2} are random noises of zero mean and the same variance. The difference between $V_{\text{out-max}}$ and $V_{out-\text{min}}$ is

$$V = V_{\text{out-max}} - V_{\text{out-min}} = kT + V_{N3} \tag{12}$$

where $V_{N3} = V_{N1} - V_{N2}$ is also a random noise of zero mean and a variance of σ_{N3}^2. The mean value μ and the variance deviation σ^2 of V can be calculated from the measured data directly and are related to the parameters m_{11} and q^2 through T, consequently

$$\mu = km_{11} \tag{13}$$

$$\sigma^2 = k^2q^2 + \sigma_{N3}^2 \tag{14}$$

Since $|m_{12}| = |T - m_{11}|$, the partial PDL can be expressed as

$$\Gamma_{\text{partial}} = \frac{|m_{12}|}{m_{11}} = \frac{|T - \mu/k|}{\mu/k} = \left|\frac{V - V_{N3}}{\mu} - 1\right| \tag{15}$$

This partial PDL varies randomly in time and is in fact the PDL seen by the optical receiver.

Using the coherent PDL monitoring technique, we have carried out a number of field tests on installed DWDM systems. Fig. 2 shows an example of the measured results. The system is approximately 626 km long, connecting Washington DC and Hamlet, North Carolina, with 10 in-line optical amplifiers. Fig. 2a shows the measured V as a function of time, while Fig. 2b shows the histogram of V clearly following a normal distribution as predicted by our statistical analysis. Fig. 2c and d show the partial PDL, Γ_{partial}, as a function of time and its histogram which exhibits a half-normal distribution.

Although the measured partial PDL influences the transmission performance, the PDL of the optical system is also an important parameter which is often used as part of the system specification. The average PDL of an optical system can be evaluated based on Eq. (7) with the use of the measured parameters m_{11} and q^2 given by Eqs. (13) and (14), obtaining

$$\langle \Gamma \rangle = \sqrt{\frac{8}{\pi}} \frac{\sqrt{\sigma^2 - \sigma_{N3}^2}}{\mu} \tag{16}$$

According to the μ and σ values shown in Fig. 2, with a measured signal to noise ratio of 11.4 dB, the average system PDL value Γ is approximately 0.0926, which corresponds to a PDL, ρ, of 0.81 dB as defined by Eq. (5). It is worthwhile to point out that the measured PDL value may be affected by the noise contribution in the measurement system as indicated in Eq. (16). In our measurement, we have maintained the signal-to-noise-ratio of 11.4 dB, so that the measurement error in PDL should be less than ±0.04 dB. Since the measurement was conducted in a system which carries commercial traffic, it was not feasible to perform direct PDL measurement using traditional techniques which might interrupt the system operation. However, consider 10 in-line EDFAs used in the system with approximately 0.2 dB PDL per EDFA, plus the impact of the multiplexer in the transmitter side and the demultiplexer in the receiver side, the 0.81 dB overall PDL measured here is reasonable.

4. Conclusion

In conclusion, a PDL monitoring technique based on coherent detection and statistical analysis is proposed and demonstrated, which allows the accurate evaluation of PDL in installed fiber-optic transmission systems carrying live traffic. Field measurements of PDL were performed on terrestrial long-haul DWDM systems and the statistical distribution agrees with the theoretical prediction.

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