Simultaneous Monitoring of Both Optical Signal-to-Noise Ratio and Polarization-Mode Dispersion Using Polarization Scrambling and Polarization Beam Splitting

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***Abstract*—This paper proposes a simple method to monitor both optical signal-to-noise ratio (OSNR) and polarization-mode dispersion (PMD) simultaneously using a polarization-scrambling module followed by polarization beam splitting. OSNR and PMD are obtained from interaction terms between two orthogonal polarization arms. Monitored OSNR and PMD are independent of each other. Experimental results are demonstrated in a 10-Gb/s nonreturn-to-zero (NRZ) system with OSNR from 18 to 36 dB and PMD from 0 to 70 ps.**

***Index Terms*—Degree of polarization, optical communications, optical polarization, optical signal-to-noise ratio (OSNR), polarization-mode dispersion (PMD).**

I. INTRODUCTION

A key challenge for future deployment of high-performance optical networks is that many systemic issues are not static and tend to vary with time, including the following: 1) temperature changes; 2) reconfigurable optical networking; 3) wavelength drifts; and 4) periodic repair and maintenance. These changes will cause variations in several signal-quality-related parameters, such as optical signal-to-noise ratio (OSNR) and polarization-mode dispersion (PMD). Therefore, performance monitoring of signal quality may be required in order to manage, diagnose, and repair a network. A key feature of performance monitoring would be the isolation of the specific parameter being affected, rather than a simple alarm that monitors the overall degradation of the signal.

In particular, we consider the performance monitoring of OSNR and PMD. OSNR degradation can occur due to any signal power fluctuations or changes in optical-amplifier-noise characteristics. PMD effects are stochastic, time varying, and temperature dependent. Moreover, the degradation may also change rapidly due to the fiber's nonlinear birefringence.

If there were a desire to monitor both OSNR and PMD, the typical solution would be to have two different and distinct monitoring implementations. It would be advantageous to have one module that could monitor both OSNR and PMD in a straightforward fashion. Different approaches to monitoring OSNR and PMD individually has been reported in the literature [1]–[13]. Traditional OSNR monitoring using a high-resolution spectrum analyzer is costly, inconvenient, and sometimes inaccurate [2]. The bit error rate (BER) can be correlated to the OSNR only within a certain range [3]. The degree of polarization (DOP) has been used to monitor not only PMD [4]–[6], but also OSNR [7], [8]. However, the OSNR and PMD (depolarization) monitoring affect each other significantly [7], [8]. PMD-insensitive OSNR monitor schemes that use either precise polarization control or narrow-band optical filtering have been proposed [9], [13]. Very recently, a scheme that can monitor both PMD and OSNR information has been demonstrated using enhanced radio-frequency (RF) spectral dip analysis assisted with a local large differential group delay (DGD) element [14].

In this paper, a simple configuration that provides both OSNR and PMD information simultaneously using polarization scrambling and orthogonal polarization detection is proposed and demonstrated. A narrow-band optical filter is inserted in one optical path. By measuring the power fluctuation of the two orthogonal polarization channels, optical noise and depolarization effects can be decoupled and, therefore, the contribution of amplified spontaneous emission (ASE) and PMD or nonlinear birefringence can be obtained at the same time. Using a 10-Gb/s nonreturn-to-zero (NRZ) transmission system, it is shown that monitored OSNR from 18 to 36 dB is not sensitive to PMD. Meanwhile, the monitored PMD from 0 to 70 ps is also independent of OSNR.

II. POLARIZATION-BASED OSNR MONITOR

In a typical transmission system, compared to the polarized signal, optical noise is depolarized, thus, by measuring the optical power of polarized signal and unpolarized noise background, we can obtain the DOP of the signal and the

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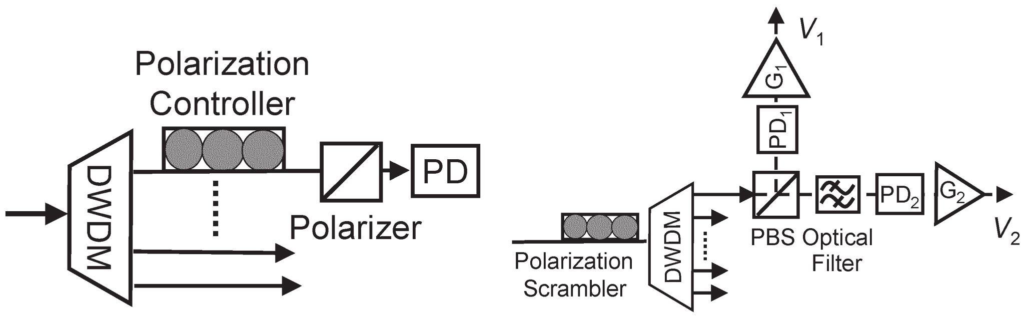


(a) (b)

Fig. 1. Configurations of OSNR/PMD monitor. (a) Simple approach with OSNR and PMD dependent to each other. (b) Proposed approach consists of one polarization scrambler, one polarization beam splitter (PBS), two photodiodes (PD_1 and PD_2) and two electrical operational amplifiers (G_1 and G_2).

relative OSNR information by the relationship as $\mathrm{OSNR} = \mathrm{DOP}/(1 - \mathrm{DOP})$, as shown in Fig. 1(a). The polarization controller is used to find the minimum and maximum optical power by aligning to either the state of polarization (SOP) of the signal or its orthogonal state to the polarizer. Note that the demultiplexer [dense-wavelength-division multiplexing (DWDM)] here works as a series of optical filters with a certain bandwidth, and the monitored OSNR depends on this bandwidth value. Since the DOP of the signal after transmission may also vary with the PMD of the link, the derived OSNR will be affected by the PMD accordingly.

In order to decouple the effect and monitor both the OSNR and PMD simultaneously, we propose a new configuration as shown in Fig. 1(b). Only one polarization scrambler that can scramble the input polarization state to cover the Poincare sphere is shared by many wavelength-division-multiplexing (WDM) channels, while previous approaches need one polarization controller (or polarization stabilizer) for each channel. After the demultiplexer, the desired channel will be split into two arms using a polarization beam splitter (PBS). In one arm, there will be an optical bandpass filter with a bandwidth narrower than the channel spacing used to further reduce the effects of optical noise. One photodiode is used in each arm to detect the power fluctuations. After optical–electrical (O/E) conversion, additional electrical operational amplifiers with different gain factors (G_1 and G_2) are used to increase the sensitivity and provide the corresponding voltage outputs (V_1 and V_2).

Assuming the power contributions of the signal and noise are P_S and P_N and that the depolarization factor along the link introduced by PMD and nonlinear birefringence is δ, we then can write the power fluctuations of the two arms as

$$V_1^{\max} = G_1\left[P_S(1-\delta) + 0.5P_N\right] \tag{1}$$

$$V_1^{\min} = G_1[P_S\delta + 0.5P_N] \tag{2}$$

$$V_2^{\max} = G_2\left[P_S(1-\delta) + 0.5\alpha P_N\right] \tag{3}$$

$$V_2^{\min} = G_2[P_S\delta + 0.5\alpha P_N] \tag{4}$$

where α is the noise power filtering factor of the narrow-band optical filter. We can easily get

$$(1)+(2):\quad V_1^{\max} + V_1^{\min} = G_1(P_S + P_N) \tag{5}$$

$$(1)-(2):\quad V_1^{\max} - V_1^{\min} = G_1\left[P_S(1-2\delta)\right] \tag{6}$$

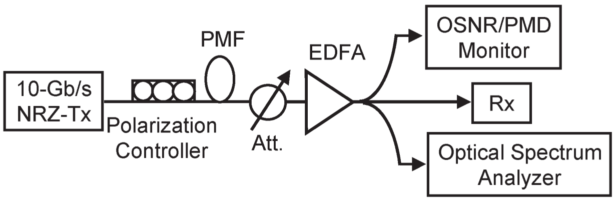


Fig. 2. Experimental setup for OSNR and PMD monitoring. Att.: optical attenuator.

$$(3)+(4):\quad V_2^{\max} + V_2^{\min} = G_2(P_S + \alpha P_N) \tag{7}$$

$$(3)-(4):\quad V_2^{\max} - V_2^{\min} = G_2 P_S(1-2\delta). \tag{8}$$

Furthermore, $G_2 * (5) - G_1 * (7)$ produces

$$P_N = \frac{1}{1-\alpha}\left[\frac{V_1^{\max} + V_1^{\min}}{G_1} - \frac{V_2^{\max} + V_2^{\min}}{G_2}\right] \tag{9}$$

then from (5) and (9), we can get

$$P_S = \frac{1}{1-\alpha}\left[\frac{V_2^{\max} + V_2^{\min}}{G_2} - \frac{\alpha}{G_1}\left(V_1^{\max} + V_1^{\min}\right)\right]. \tag{10}$$

Thus, the OSNR is

$$\frac{S}{N} = \frac{P_S}{P_N} = \frac{G_1\left(V_2^{\max} + V_2^{\min}\right) - \alpha G_2\left(V_1^{\max} + V_1^{\min}\right)}{G_2\left(V_1^{\max} + V_1^{\min}\right) - G_1\left(V_2^{\max} + V_2^{\min}\right)}. \tag{11}$$

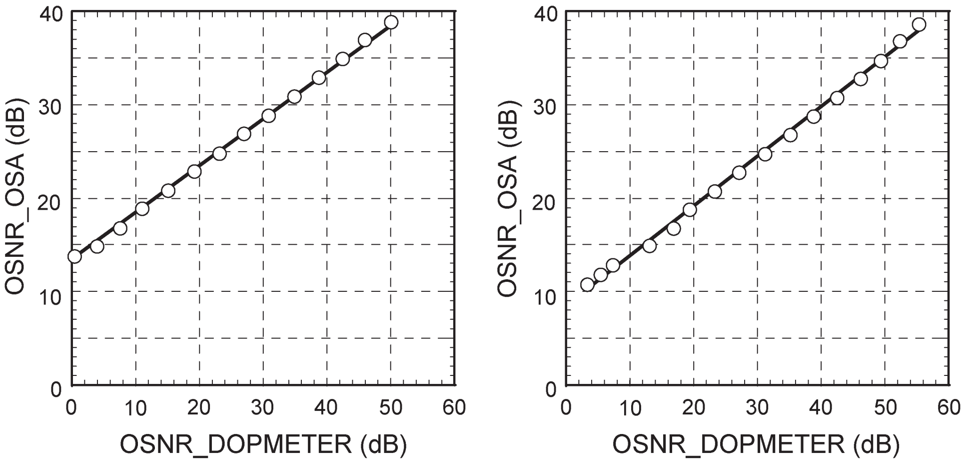
Let $\overline{V_1} = (1/2)(V_1^{\max} + V_1^{\min})$ and $\overline{V_2} = (1/2)(V_2^{\max} + V_2^{\min})$, and the OSNR changes to

$$\frac{S}{N} = \frac{G_1\overline{V_2} - \alpha G_2\overline{V_1}}{G_2\overline{V_1} - G_1\overline{V_2}}. \tag{12}$$

This signal-to-noise ratio (SNR) only depends on the average value of V_1 and V_2. It is excluded from all the effects of PMD, nonlinear birefringence, and the imperfection of PBS.

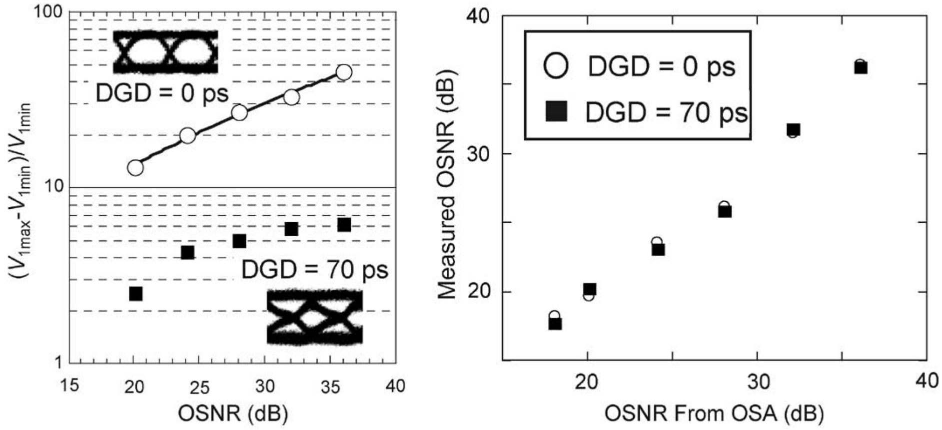
From (6), (9), and (10), we can calculate the depolarization term δ as

$$\delta = \frac{1}{2}\left[1 - \frac{(1-\alpha)\left(V_1^{\max} - V_1^{\min}\right)}{2\left(\frac{G_1}{G_2}\overline{V_2} - \alpha\overline{V_1}\right)}\right]. \tag{13}$$



(a) (b)

Fig. 3. Measurement results (OSNR only) using the simple approach described in Fig. 1(a) where the filter has a 3-dB bandwidth of (a) 1.0 nm and (b) 0.5 nm.



(a) (b)

Fig. 4. Comparison between PMD-dependent OSNR monitoring approach and the new approach. (a) Monitoring results using only one polarizer (i.e., one arm of the PBS); PMD has a significant effect on the OSNR monitoring results. (b) OSNR monitoring results of the proposed approach using polarization beam-splitting approach (PMD independent).

One may always adjust the amplification gain so that $(G_1 = G_2)$. Therefore, we can get the simplified expression

$$\frac{S}{N} = \frac{\overline{V_2} - \alpha\overline{V_1}}{\overline{V_1} - \overline{V_2}} \tag{14}$$

$$\delta = \frac{1}{2}\left[1 - \frac{(1-\alpha)\left(V_1^{\max} - V_1^{\min}\right)}{2(\overline{V_2} - \alpha\overline{V_1})}\right]. \tag{15}$$

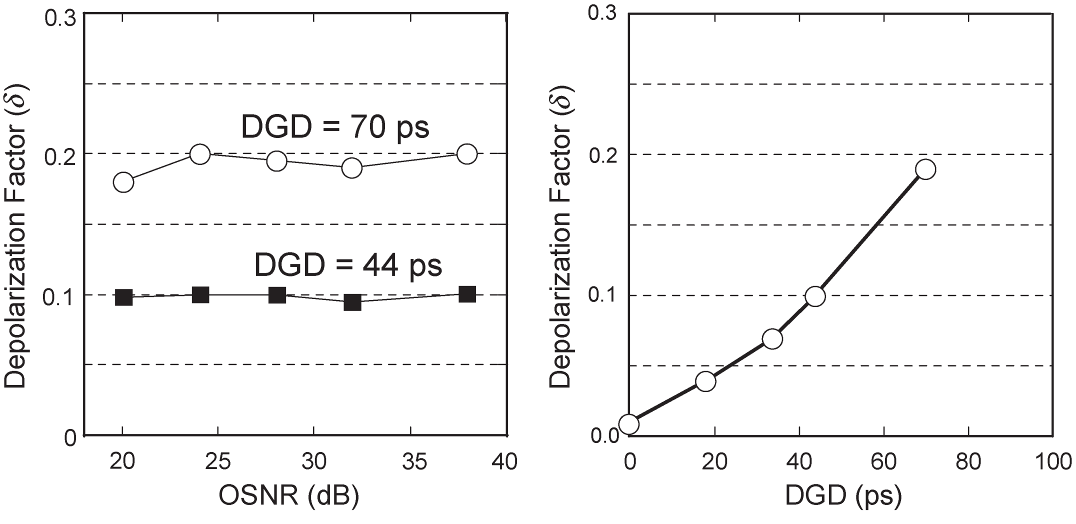
This depolarization factor can be used to monitor the PMD effect along the transmission link.

III. EXPERIMENTAL RESULTS

To show the effectiveness of our approach, we put different monitor modules after a 10-Gb/s NRZ ($2^{31} - 1$ PRBS) transmission link, as shown in Fig. 2. A piece of polarization-maintaining fiber (PMF) is placed along the link with a polarization controller before it to align the input polarization states with 45° to each of the two principal states of the PMF. The OSNR of the link is varied by changing the input power into the erbium-doped fiber amplifier (EDFA). Monitored OSNR values are compared with the measurement results using an optical spectrum analyzer (OSA) with a 0.1-nm resolution.

First, we use the equivalent DOP method in Fig. 1(a) to monitor OSNR only (without PMD). Two optical filters with different bandwidths (3-dB bandwidth of 1.0 and 0.5 nm, respectively) are used, and the monitored OSNR values are compared with the ones measured using OSA. Fig. 3(a) and (b) shows the linear relationship between the DOP method and OSA measured results. We can see that, without PMD involved, the monitored OSNR can be accurate after initial linear calibration according to the bandwidth of the optical filter or demultiplexer.

However, in the case that PMD gets involved, we compare the difference using the proposed module. As shown in Fig. 4(a), if only one arm is used (a polarizer followed by a photodetector), we can get the OSNR information from $(V_{1\max} - V_{1\min})/V_{1\min}$. Similarly, and as expected, without PMD, the monitored OSNR is correlated with OSNR very well (linear relationship), but when PMD (here DGD $\sim$ 70 ps) is introduced, the monitored results will change dramatically. On



(a) (b)

Fig. 5. PMD monitoring results. (a) Depolarization factor (δ) in (13) and (15) as DGD $\sim$ 70 and 44 ps under different OSNR values. (b) Depolarization factor as a function of link DGD.

the contrary, using the proposed approach [Fig. 4(b)], even when large DGD is involved, we still can get the monitored OSNR results to be close to the one without PMD. Since the 1.0-nm filter bandwidth cannot accommodate WDM systems with less than 100-GHz channel spacing, in the comparison, we use the 0.5-nm filter as the DWDM demultiplexer, and another filter with $\sim$ 0.3-nm bandwidth for the narrow-band filtering [before PD2 in Fig. 1(b)]. Different narrow-band filters can be used according to various requirements; however, the factor α should be calibrated before real measurements.

As mentioned in the previous section, we can also monitor PMD using (6). Fig. 5(a) and (b) shows the PMD monitoring results. The depolarization here is mainly due to the DGD of the PMF. In Fig. 5(a), we show that as the OSNR changes, the monitored depolarization factor remains constant ($< 5\%$), and the relationship between the depolarization factor and the DGD in Fig. 5(b) provides an effective method to gather the PMD information of the link. For an NRZ signal, the depolarization factor can vary from 0 to 0.2 as DGD changes from 0 to $\sim$ 70 ps. The depolarization can be considered as the reduction of the signal's DOP, which is format dependent [for example, the return-to-zero (RZ) data format normally has higher DOP sensitivity than the NRZ signal]. The results measured here for NRZ data are consistent with previous reported results where polarization scrambling is applied [4]. Note that, as we get the OSNR and PMD simultaneously, we can separate the degrading effects due to optical noise or depolarization, which is highly desirable for network designers and operators. In addition, when the link has nonnegligible PDL, the monitored results will be affected due to the measurement fluctuations of the signal power. This problem may be partially solved by applying polarization scrambling at the input of the link.

IV. CONCLUSION

This paper proposed and demonstrated a novel and simple approach that can monitor two important parameters, optical-signal-to-noise ratio (OSNR) and polarization-mode dispersion (PMD), simultaneously using polarization scrambling and polarization beam splitting. The monitored OSNR is not sensitive to the link PMD, while the monitored PMD is also independent of OSNR. Isolation of these two parameters will enable network operators to determine separately the contribution of optical noise and depolarization (or PMD) along the link.

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