Robust optical signal-to-noise ratio monitoring scheme using a phase-modulator-embedded fiber loop mirror

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We propose and experimentally demonstrate a novel in-band optical signal-to-noise ratio (OSNR) monitoring technique using a phase-modulator-embedded fiber loop mirror. This technique measures the in-band OSNR accurately by observing the output power of a fiber loop mirror filter, where the transmittance is adjusted by an embedded phase modulator driven by a low-frequency periodic signal. The measurement errors are less than 0.5 dB for an OSNR between 0 and 40 dB in a 10 Gbit/s non-return-to-zero system. This technique was also shown experimentally to have high robustness against various system impairments and high feasibility to be deployed in practical implementation. © 2007 Optical Society of America

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To ensure the signal integrity and performance in wavelength division multiplexing networks, it is essential to monitor the in-band optical signal-to-noise ratio (OSNR) of each wavelength channel. Several polarization-assisted methods, such as the polarization-nulling method [1], have been recently proposed to monitor the in-band OSNR. However, these methods are susceptible to polarization-mode dispersion (PMD), as PMD can induce depolarization of the modulated signal and therefore violate the assumption of polarized data signal [2]. Another challenge to the polarization-nulling method is the partial polarization of the amplified spontaneous emission (ASE) noise. When the ASE has a nonzero degree of polarization (DOP), the OSNR measurement based on the assumption of unpolarized ASE becomes inaccurate [3].

In this Letter, we propose and experimentally demonstrate a robust in-band OSNR monitoring scheme using a phase-modulator-embedded fiber loop mirror (PM-FLM) [4]. By observation of the output power variation of a fiber loop mirror filter in which the transmittance is dithered by using an embedded phase modulator, the OSNR could be determined accurately.

The idea of our proposed scheme is to estimate the incoherent noise from the input signal by periodically shifting the transfer function of a fiber loop mirror filter by using an embedded phase modulator. Figure 1(a) shows the schematic diagram of our proposed OSNR monitoring module. Our proposed OSNR monitoring module consists of a fiber loop mirror with an embedded low-frequency sinusoidal-signal-driven optical phase modulator (i.e., a PM-FLM) and an optical powermeter at the output port. The optical phase modulator is pigtailed with polarization-maintaining fibers. The polarization controller inside the loop is set to produce a polarization rotation of $\pi/2$ for signals passing through in both directions. As there is intrinsic birefringence inside the loop induced by the embedded phase modulator and its pigtail, polarization-independent periodic transmission and reflection bands in the output spectrum can be realized [5]. Periodically altering the voltage applied to the embedded phase modulator changes the phase difference between the counterpropagating signals passing through different principal axes of the phase modulator and thus leads to a periodic shift in the transfer function, as illustrated in Fig. 1(b). Consequently, the input signal can be switched out or reflected back periodically. On the other hand, there are always noises leaking out as long as the noise equivalent bandwidth (NEB) is large enough. As a result, the signal power can be extracted in the case of constructive interference, while the noise level can be extracted in the case of destructive interference for the data signal. The choice of the free spectral range (FSR) of the fiber loop mirror is critical to ensure good measurement performance. If the FSR is too narrow compared with the signal bandwidth, the signal would not be effectively nulled. On the other hand, if the FSR is too wide compared with the bandpass filter (BPF) bandwidth, there would not be enough noise to leak out in the case of destructive interference.

A low-frequency sinusoidal signal is used to drive the optical phase modulator to scan through different amounts of phase differences between the counterpropagating signals, and an optical powermeter is used to track the maximum and the minimum output

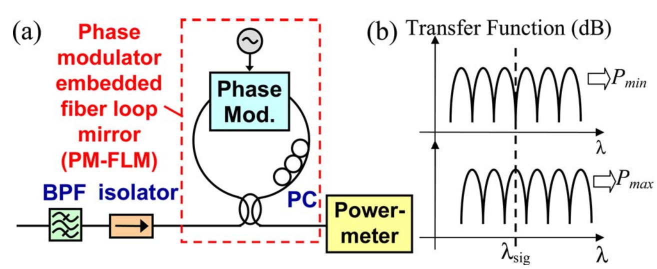

Fig. 1. (Color online) (a) Schematic diagram of a transmission link with the proposed OSNR monitoring module. PC, polarization controller; (b) Illustrated PM-FLM transfer function when destructive and constructive interference for the data signal occurs.

powers (P_{max} and P_{min}). The OSNR can be derived [6] as

$$\mathrm{OSNR(dB/0.1\ nm)} = \frac{P_{sig,in}\mathrm{NEB}_f}{P_{ASE,in} \times 0.1\ \mathrm{nm}} = \frac{(1-r)\mathrm{NEB}_f}{[r(1-D_{sig})-(1+D_{sig})] \times 0.1\ \mathrm{nm}}, \tag{1}$$

where $r = P_{max}/P_{min}$, NEB_f is the NEB of the BPF at the module's input, and $D_{sig} = (P_{max} - P_{min})/(P_{max} + P_{min})$ is the distinctness of the signal interference when noise is absent.

The proposed OSNR monitoring scheme was experimentally characterized in a 10 Gbit/s NRZ on–off keying system, as shown in Fig. 2. The signal source was a distributed-feedback laser at 1545.6 nm, externally modulated by a $LiNbO_3$ optical intensity modulator with 10 Gbit/s $2^{31}-1$ pseudorondom binary sequence (PRBS) NRZ data. An erbium-doped fiber amplifier (EDFA) was used to produce different levels of ASE noise, which was then combined with the modulated signal by a 3 dB fiber coupler. The OSNR level was controlled by the optical attenuators before the fiber coupler, and it was adjusted from 0 to 40 dB in our experiment. The noise-added signal was then amplified by another EDFA, and a PMD emulator was inserted to simulate the effects of different differential group delay (DGD) values varying from 0 to 50 ps. Finally, the composite signal was fed to an

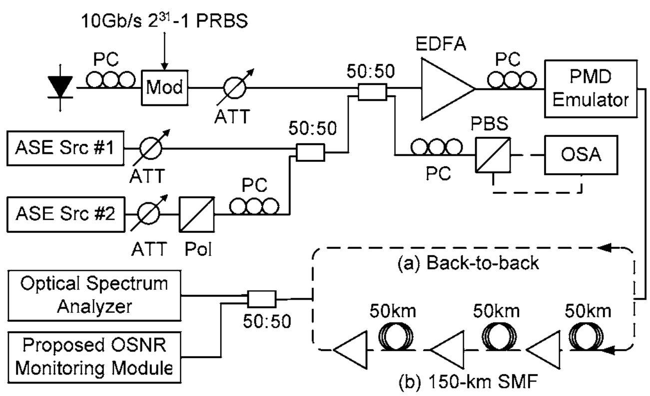

Fig. 2. Experimental setup. ATT; optical attenuator.

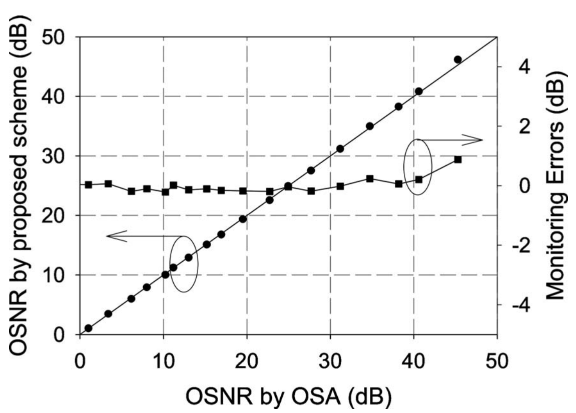

Fig. 3. Measured OSNR and monitoring errors.

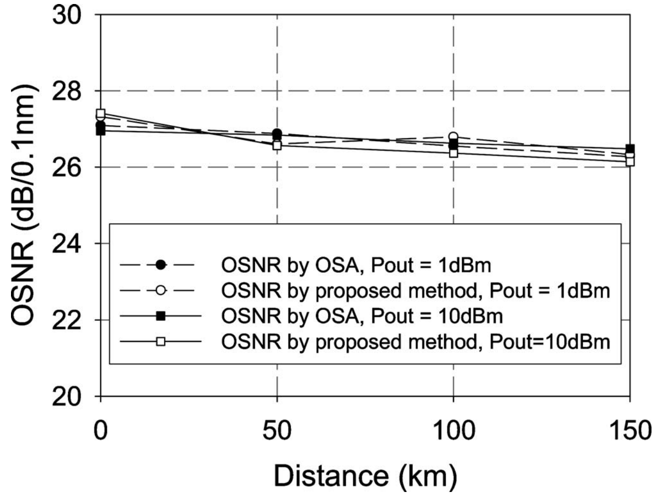

Fig. 4. OSNR monitoring results in a 150 km SMF link (PMD < 1.5 ps).

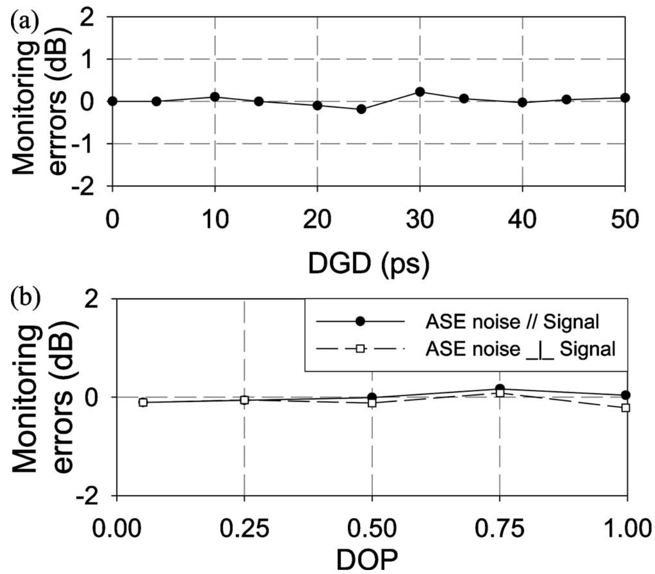

Fig. 5. Monitoring errors for (a) different DGDs and (b) partially polarized ASE with different DOPs and alignment to signal, for 25 dB OSNR.

optical spectrum analyzer (OSA) and also to our proposed OSNR monitoring module, for comparison. The BPF bandwidth was about 1 nm, which was wide enough to cover the whole signal spectrum. The length of the fiber loop is only around 2 m; therefore it is immune to environmental fluctuation. The polarization dependence of the periodic filtering characteristics was shown to be negligible by randomly changing the input signal polarization by using a polarization controller. The sampling time of the optical powermeter was set to be 20 ms. The driving frequency of the phase modulator was set to be 1 Hz, and the driving amplitude was set to be little bit larger than V_π of the phase modulator to ensure that the whole range of output power can be covered. The total measurement time for our scheme was within 30 s. The FSR of the PM-FLM transfer function was measured to be around 0.6 nm. D_{sig} and D_{ASE} were measured to be about 0.975 and 0.01, respectively, in our experiment.

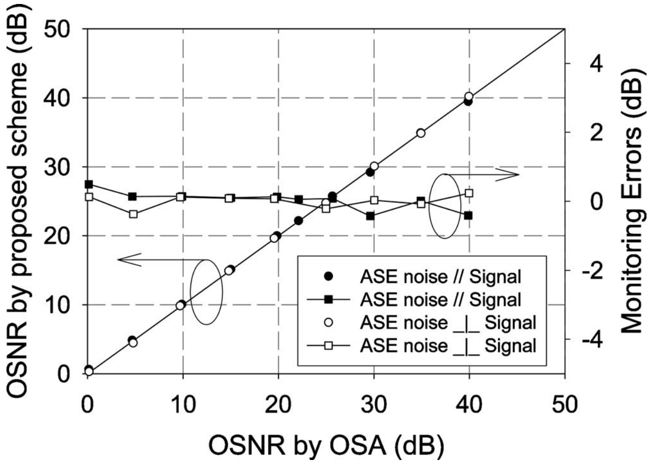

Fig. 6. Measured OSNR (circles) and monitoring errors (squares) for polarized ASE (DOP=99.69%) that is parallel (black) or orthogonal (white) to signal.

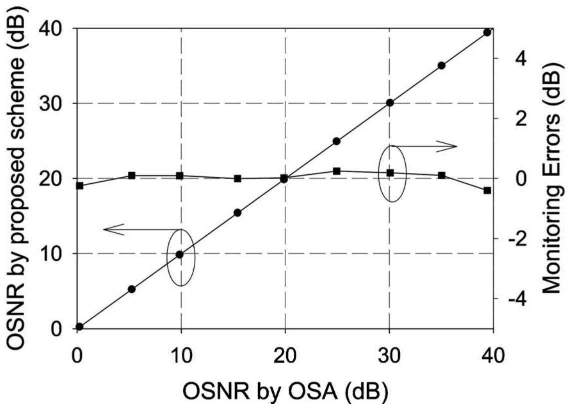

Fig. 7. Measured OSNR and monitoring errors for 2.5 Gbit/s data rate.

Figure 3 compares various levels of OSNRs monitored by our proposed scheme with the conventional OSNR measurements by linear interpolation. The OSNRs agreed very well with the reference OSNRs. The measured monitoring error was less than 0.5 dB for OSNRs varying from about 0 to 40 dB/0.1 nm. This shows the high sensitivity and large input dynamic range of the proposed scheme.

Next the performance of our scheme after 150 km single mode fiber (SMF) transmission was investigated. An EDFA was added after each 50 km SMF span and the output power from each EDFA was maintained at 1 and 10 dBm, respectively. Figure 4 shows that the monitoring errors were negligible, indicating that our scheme was rather insensitive to both the chromatic dispersion, a typical value of PMD (<1.5 ps in our case), and power in long-haul transmission.

Figure 5(a) shows the monitoring errors when DGD was introduced. For reference, the OSNR was set to be 25 dB/0.1 nm by the OSA. The monitoring error was smaller than 0.25 dB for DGD varying from 0 to 50 ps, which shows the high robustness to PMD of our proposed scheme.

The influence of partially polarized ASE in our scheme was also investigated. Partially polarized ASE was generated by combining the output of a polarized ASE source with the output of an unpolarized ASE source, using a 3 dB coupler. Two independent attenuators were used to control the DOP of the resulting ASE. The DOP of the unpolarized ASE source was measured to be 5.16%, while the polarized source had a DOP of 99.69%. Figure 5(b) shows that the monitoring errors were negligible for different values of noise DOP, showing that our proposed scheme is insensitive to partially polarized ASE noise. For instance, Fig. 6 shows the OSNR measurement performance under the worst case (polarized ASE). The monitoring errors were held to less than 0.5 dB over the whole 40 dB monitoring range. This further confirms the robustness of our proposed OSNR monitoring scheme against partially polarized ASE.

Finally, the data rate dependency of our proposed scheme was investigated. The OSNR monitoring errors (for 25 dB OSNR) for bit rates from 2.5 to 10 Gbits/s were measured to be less than 0.3 dB, and the OSNR monitoring performance for a 2.5 Gbit/s data rate in particular is shown in Fig. 7. This shows that our proposed scheme is bit-rate independent in the range from 2.5 to 10 Gbits/s, which is a desirable feature in OSNR monitoring.

To summarize, various characterization experiments have shown that the proposed technique has high accuracy, high sensitivity, and a large dynamic range in OSNR measurements. For instance, the monitoring errors were less than 0.5 dB for OSNRs between 0 and 40 dB in a 10 Gbit/s NRZ system. This technique has also been shown to be PMD insensitive, chromatic-dispersion insensitive, bit-rate independent, and robust to partially polarized ASE noise.

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