Enhancing the monitoring sensitivity of DOPbased OSNR monitors in high OSNR region using off-center narrow-band optical filtering

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Abstract: Recently, OSNR monitoring based on the measurement of degree of polarization (DOP) has attracted much attention, thanks to its simplicity and high efficiency. However, the OSNR monitoring sensitivity is quite poor in the high OSNR region, resulting in high estimation error and narrow dynamic range. In this paper, we propose and experimentally demonstrate a narrow-band off-center optical filtering technique for DOP-based OSNR monitors. In 40-Gb/s RZ-OOK systems, OSNR monitoring sensitivity and DOP dynamic range are successfully enhanced to 3.14%/dB and 31.4%, respectively, in the high OSNR region (25~35dB/0.1nm).

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1. Introduction

Optical signal-to-noise ratio (OSNR) is an important performance parameter to be monitored in future high-speed reconfigurable optical networks. Recently, several in-band OSNR monitoring schemes have been proposed [1], such as the degree of polarization (DOP)-based scheme, the polarization nulling scheme, the fiber-loop-based scheme [2], the orthogonal polarization heterodyne scheme [3], and the scheme based on beating noise measurement [4]. Based on the correlation between DOP and OSNR, the DOP-based scheme is a promising alloptical monitoring approach thanks to its simplicity, on-the-fly processing, scalability to highspeed systems, and insensitivity to chromatic dispersion. However, as reported in Ref. [5], the OSNR monitoring sensitivity is severely degraded in the high OSNR region (\geq 25 dB/0.1nm), resulting in increased estimation errors. Therefore, it is desirable to explore a DOP-based

#76963 - \$15.00 USD (C) 2007 OSA Received 10 November 2006; revised 22 January 2007; accepted 22 January 2007 5 February 2007 / Vol. 15, No. 3 / OPTICS EXPRESS 823 OSNR monitoring scheme with high monitoring sensitivity, especially for high-speed (\geq 40 Gb/s) optical systems.

In this paper, we show, via numerical simulation and experiment, that the DOP's behavior against OSNR of the system is highly dependent of the bandwidth and the offset position of the filter, which is placed prior to the DOP analyzer. The OSNR monitoring performance for 10-Gb/s and 40-Gb/s return-to-zero on-off keying (RZ-OOK) systems using different optical filtering techniques is experimentally investigated. The results show that, using off-center narrow-band optical filtering, the OSNR monitoring sensitivity can be significantly improved.

2. Operation principles



Fig. 1. Illustration of optical filtering scheme for DOP-based OSNR monitoring, (i) symmetric optical filtering with bandwidth of (a) 2, (b) 1 and (c) 0.22 nm; (ii) 0.22-nm-wide off-center optical filtering with offset of (d) 0.2 and (e) 1 nm from the center frequency.

In a typical DOP-based OSNR monitoring scheme, OSNR is derived from the measured DOP values by Eq. (1) [5].

$$OSNR(dB/0.1nm) = 10 \log[(\frac{DOP}{1 - DOP})(\frac{NEB_{f}}{0.1})]$$
(1)

where NEB_f is the noise equivalent bandwidth (in nm) of the tunable filter prior to the DOP analyzer. However, when DOP is approaching 100%, i.e., OSNR is above 25 dB for 10-Gb/s systems, a small change in DOP value results in a large variation of OSNR, and leads to a poor monitoring sensitivity and large estimation error in OSNR monitoring. It is mainly due to the flat slope of the DOP versus OSNR curve in the high OSNR region.

From Eq. (1), it is obvious that the DOP behavior against OSNR depends on the profile of the tunable filter [6]. Using symmetric or off-center optical filtering with different filtering bandwidth before the DOP measurement, it is possible to enhance the DOP sensitivity to input OSNRs. As shown in Fig. 1, the broad-band symmetric filtering will involve more ASE noise for DOP measurement, while the off-center narrow-band filtering will extract a smaller part of the signal's power. Both of these approaches result in the de-polarization effect for the filtered signal, which will reduce the measured DOP value, intentionally. In the OSNR monitoring, with the measured DOP, OSNR value is estimated based on the pre-calibrated relation between the measured DOP after the filtering, it operates in a high-sensitivity region of the DOP response curve for OSNR monitoring. With this filtering effect, the monitoring sensitivity can be effectively improved in the high OSNR region. For these two approaches, higher improvement could be achieved using off-center narrow-band filtering, especially in a system with a broad spectrum. This is because the signal can be severely depolarized with the off-center filter placed in the edge of the signal's spectrum.

If applying this scheme to dense wavelength division multiplexing (DWDM) systems, when deciding a suitable offset for the filter, we should take into consideration the channel spacing of the DWDM systems to reduce the effect from adjacent channels. Also in

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reconfigurable optical networks, the cascaded OADM filters may result in an aggregated filter response with time-variant profile and destroy the deterministic relation between the measured DOP and the OSNR. This will limit the application of the proposed scheme for reconfigurable optical networks.

In the next section, the OSNR monitoring performance is experimentally investigated using different optical filtering techniques in a 10-Gb/s RZ-OOK system with 28-ps pulsewidth and a 40-Gb/s RZ-OOK system with 2.5-ps pulse-width, respectively. Note that, as a measured DOP after narrow-band filtering is used to estimate OSNR, Eq. (1) is invalid for accurately modeling the relation between the measured DOP with narrow-band filtering and the OSNR. Therefore, a numerical simulation is performed to verify the experimental result using a commercial simulator, *OptSim*, with a setup similar to that of the experiment.

3. Experiment and results



Fig. 2. Experimental setup, FMLL: fiber mode-locked laser, OBPF: optical band-pass filter, OSA: optical spectrum analyzer, EAM: electroabsorption modulator.

3.1 10-Gb/s RZ system

To investigate the monitoring performance using different optical filtering techniques, the experiment for a 10-Gb/s RZ-OOK system with full-width at half-maximum (FWHM) pulse-width of 28 ps was conducted first. As shown in Fig. 2, CW light from a DFB laser was first carved into a pulse train with pulse-width of 28 ps by a clock-driven electroabsorption modulator (EAM). Then, it was data-modulated into a 10-Gb/s RZ-OOK signal by the following LiNbO₃ intensity modulator with 2³¹-1 pseudorandom binary sequence (PRBS). An amplified spontaneous emission (ASE) noise source was generated by cascading two erbium-doped fiber amplifiers. Two attenuators were inserted in both signal and noise branches. Thus, the OSNR can be adjusted from 13 to 43 dB/0.1nm by combining the signal with the ASE noise source at different power levels to emulate different OSNR scenarios. At the receiver side, a small portion (10%) of the signal power was sent to the monitoring module, which involved an optical tunable filter followed by a DOP analyzer. To investigate the optical filtering effect on the OSNR monitoring sensitivity, different optical filtering schemes were employed to measure the DOP response curves when OSNR varied from 13 to 35 dB/0.1nm.

Figure 3 shows the measured curves of DOP versus OSNR values using different optical filtering techniques, where each of the DOP values is the average of 100 measured samples. The numerical simulation curves agree well with the experimental results, as depicted in Fig. 3. The OSNR monitoring sensitivity is defined as the DOP variation within 1-dB OSNR change, $\Delta DOP/\Delta OSNR$ (unit: %/dB). It is clear that the symmetric broad-band (1nm) filtering and 0.2-nm-off-center narrow-band (0.22nm) filtering approaches ($\Delta DOP/\Delta OSNR$ =0.63 %/dB) offer significant improvement compared with the approach using symmetric narrow-band

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(0.22nm) filtering ($\Delta DOP/\Delta OSNR$ =0.13 %/dB). In the high input OSNR region (25~35 dB/0.1nm), only ~1.3% DOP variation is obtained for the symmetric narrow-band filtering, whereas ~6.3% DOP change is achieved for the symmetric broad-band and 0.2-nm-off-center narrow-band filtering.

Similar improvements of the monitoring sensitivities have been observed for the off-center narrow-band and broad-band symmetric filtering approaches. Higher improvement can be expected with the approach using off-center narrow-band filtering in a high-speed system or a system with broader spectrum. Next, the monitoring performance will be investigated in a 40-Gb/s RZ-OOK system.



Fig. 3. Measured DOP response curves against OSNR in a 10-Gb/s RZ-OOK system using different optical filtering schemes by simulation (line) and experiment (symbol), BW=bandwidth, OS=offset.

3.2 40-Gb/s RZ system

To further compare the OSNR monitoring performance using different filtering techniques, the experiment was also performed in a 40-Gb/s RZ-OOK optical time-division-multiplexing (OTDM) system with 2.5-ps (FWHM) pulse-width, which provides broader spectrum. As shown in Fig.2, the experimental setup was similar to that of 10-Gb/s RZ system except that a 40-Gb/s RZ-OOK transmitter, instead of a 10-Gb/s one, was employed. A pulse source, generated from a 10-Gb/s 1550.3-nm fiber mode-locked laser, was externally modulated by a LiNbO₃ intensity modulator with 2^{31} -1 PRBS, and the signal output was time-multiplexed to 40 Gb/s. In the monitoring module, different optical filtering schemes were employed to characterize the DOP response with respect to different input OSNR varying from 13 to 43 dB/0.1nm.

For the symmetric filtering, optical Gaussian filters with bandwidth of 2 nm, 1 nm and 0.2 nm were used to filter out the signal symmetrically, whereas for the off-center optical filtering, a 0.22-nm narrow-optical filter was offset at 0.2 or 1 nm from the center frequency. The DOP responses against different OSNR values using different optical filtering were experimentally evaluated. The results are shown in Fig. 4. It clearly shows that, for the symmetric filtering, the broad-band filtering offers higher monitoring sensitivity over the narrow-band symmetric

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filtering, especially in the high OSNR region, whereas for the off-center filtering, the narrowband optical filtering with 1-nm offset from center frequency shows the highest sensitivity over all other schemes. This is mainly attributed to the aforementioned effect induced by broad-band symmetric filtering or off-center narrow-band filtering. As the filtered signal is much de-polarized using 1-nm off-center narrow-band filtering, the slope of the DOP response curve is significantly steeper, thus resulting in the highest monitoring sensitivity among these filtering approaches. Table 1 summarizes and compares the monitoring sensitivities ($\Delta DOP/\Delta OSNR$) for these optical filtering schemes in the high OSNR region of 25~35 dB/0.1nm in the 40-Gb/s RZ-OOK system. The narrow-band 1-nm off-center filtering technique offers the largest DOP variation of 31.4 %, corresponding to the highest monitoring sensitivity of 3.14 %/dB. This represents an improvement of 3.7 to 16.5 times compared with other filtering approaches. To verify the experimental results, a numerical simulation for symmetric optical filtering was also carried out. An excellent agreement between simulation and experimental results are achieved, as shown in Fig. 4.



Fig. 4. Measured DOP response curves against OSNR in a 40-Gb/s RZ system using different optical filtering schemes by simulation (line) and experiment (symbol), BW=bandwidth, OS=offset.

Table 1. OSNR monitoring sensitivities in the high OSNR region (25~35 dB/0.1nm) using different optical filtering approaches.

	Symmetric Filtering			Off-center Filtering	
	(a) BW= 2nm	(b)BW= 1nm	(c)BW= 0.22nm	(d)OS= 0.2nm	(e)OS= 1nm
Monitoring Sensitivity (%/dB)	0.86	0.58	0.19	0.29	3.14

BW: bandwidth, OS: offset

4. Conclusions

In this paper, we experimentally investigated the DOP-based OSNR monitoring sensitivities using different optical filtering schemes. The results show that off-center narrow-band optical filtering dramatically enhances the OSNR monitoring sensitivity. In a 10-Gb/s RZ-OOK system with a 28-ps pulse-width, the symmetric broad-band and off-center narrow-band filtering techniques show a similar improved monitoring sensitivity, 0.63 %/dB in the high OSNR region. In a 40-Gb/s RZ-OOK system with a 2.5-ps FWHM pulse-width, a high monitoring sensitivity of 3.14 %/dB was successfully achieved in the high OSNR region by using 1-nm off-center narrow-band filtering with bandwidth of 0.22 nm. The proposed scheme is simple and easily upgradeable.