OSNR monitoring technique based on cascaded long-period fiber grating with optically tunable phase shifter

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Abstract: An optical signal-to-noise ratio (OSNR) monitoring technique using a cascaded long-period fiber grating with a tunable phase shifter is proposed for non return-to-zero on-off-keying (NRZ-OOK) and differential phase shift keying (DPSK) signals. This method is based on two key points: first, the cascaded long period fiber grating (CLPG) acts as an optical delay interferometer (ODI) by Mach-Zehnder configuration consisting of the core and cladding modes inside the CLPG. Secondly, an optically tunable phase shifter using an Yb³⁺ doped optical fiber (YDF) is inserted between the CLPG. The phase of the modulated signal propagating along the core mode of YDF is controlled by adjusting pumping power of 976-nm laser diode (LD). By combining the CLPG with the optically tunable phase shifter, the OSNR monitoring could be successfully executed.

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References and links

1. Introduction

In fiber optic system, performance monitoring such as channel power, chromatic dispersion and signal-to-noise ratio (SNR) are important to assess system performance. Performance monitoring has been done in the electrical domain. However, in optical networks, optical performance monitoring is crucial because it guarantees optical transparency to bit rates and data formats of the incoming signal. Furthermore, optical signal-to-noise ratio (OSNR) monitoring provides a vital means to directly measure the quality of the optical signal on the wavelength propagating through the amplified WDM networks. Recently, several OSNR monitoring methods have been proposed for in-band OSNR because out-of-band OSNR can be varied due to the channel crosstalk and the erbium doped fiber amplifier (EDFA) gain profile. The polarization-nulling method [1] and degree-of-polarization (DOP) [2] were introduced to distinguish in-band signal and noise power. The amplified spontaneous emission (ASE) was selected by removing the polarized laser signal using a linear polarizer and a quarter-wave plate under the assumption that the signal is fully polarized, and the ASE noise is completely unpolarized. When the ASE noise has nonzero DOP or the signal is depolarized by polarization-mode dispersion (PMD), errors occur in the measured OSNR [3]. To increase immunity to PMD, another method based on orthogonal-polarization heterodyne mixing of two spectral components of signals orthogonally polarized to each other has been proposed [4]. This method also assumed that the ASE noise is completely depolarized. Other approaches used the interference pattern formed by adopting Mach-Zehnder interferometer (MZI) [5], a 1-bit optical delay interferometer (ODI) [6], and a phase modulator embedded fiber loop mirror [7]. These monitoring techniques are insensitive to PMD and chromatic dispersion (CD). They also monitor the OSNR by measuring maximum and minimum power at the constructive and destructive interference, respectively.

In this paper, a novel OSNR monitoring technique based on the cascaded long period fiber grating (CLPG) with an optically tunable phase shifter using an Yb\(^3+\) doped optical fiber (YDF) is proposed. Differentially from the conventional waveguide-type MZI; it uses two light paths along the core and cladding modes inside the CLPG as two different arms. By using the phase shifter inserted in the CLPG, the phase difference of the lights in the core and cladding regions can be exactly controlled, thereby, the OSNR measurement is possible by changing the phase difference more than \(\pi\). This proposed method is independent of PMD, CD, and bit rate. Moreover, it is insensitive to environmental fluctuations compared to any other optical delay interferometers because the two modes undergo almost same perturbation along the fiber. In the following section, we show the feasibility through OSNR experimental measurement from NRZ-OOK and DPSK signals at 1, 2.5, and 10-Gb/s bit rate.

2. Operating principle

The basic concept of the OSNR monitor is depicted in Fig. 1. It consists of two serialized LPGs separated by fiber length of \(L_1\) (the distance between mid-points of each LPG). Between the two LPGs, the YDF of length \(L_2\) is inserted. When the input light propagating in the fiber core meets the first LPG (LPG1), the signal splits into two propagation modes: the core and cladding modes. At the second LPG (LPG2), these two modes combine and again split into another core and cladding modes. Although the traveling distances for the two modes are equal, the propagating times are different due to the differential effective group indices (DEGI). The time difference is given by [8]
\[ \Delta t = \frac{(L_1 - L_2) \Delta n_{\text{eff (SMF)}} + L_2 \Delta n_{\text{eff (YDF)}}}{c}, \]  

where \( \Delta n_{\text{eff (SMF)}} \) and \( \Delta n_{\text{eff (YDF)}} \) are the DEGI between the two modes in the SMF and YDF respectively. The definition of the DEGI is \( \Delta n_{\text{eff}} = n_{\text{eff}}^{\text{core}} - n_{\text{eff}}^{\text{clad}} \), where \( n_{\text{eff}}^{\text{core}} \) and \( n_{\text{eff}}^{\text{clad}} \) are the effective index of fiber core and cladding respectively. \( c \) is the speed of light in the vacuum, \( L_1 \) is the distance between the LPGs and \( L_2 \) is the length of the YDF. Also, the FSR can be calculated by taking the inverse form of the time difference. When a pumping light of 976-nm LD is launched into the YDF through the WDM coupler, the refractive index of the core of the YDF is changed, thus, the relative phase between core and cladding mode is changed. The relative phase by an LPG pair is well known as the following equation [9]

\[ \Phi \approx -(\beta_{co} - \beta_{cl})L_1, \]  

in which \( \beta_{co} \) and \( \beta_{cl} \) are propagation constants of core and cladding modes. The definition of the propagation constants are \( \beta_{co} = 2\pi n_{\text{eff}}^{\text{core}} / \lambda \) and \( \beta_{cl} = 2\pi n_{\text{eff}}^{\text{clad}} / \lambda \) respectively. By using the Eq. (2), the relative phase (\( \Phi \)) of the two modes can be optically controlled by the pump power of 976-nm LD. If the relative phase (\( \Phi \)) is set to \( \pi \), the minimum power including only incoherent ASE noise is extracted in the destructive interference. On the other hand, the maximum power (the coherent optical signal and the ASE noise) is extracted in the constructive interference when the phase difference is 0. By applying the low-frequency sinusoidal signal to the pump LD, the maximum and minimum powers can be periodically measured. The detected powers can be used to calculate the OSNR, and the equation is given by [7]

\[ \text{OSNR} = \frac{1 - a}{a(1 - \gamma_{\text{sig}}) - (1 + \gamma_{\text{sig}})}, \]  

where \( a = P_{\text{max}} / P_{\text{min}} \) and \( \gamma_{\text{sig}} \) is the distinctness of the signal interference.

3. Experimental setup

The experimental setup for the proposed OSNR monitoring method is shown in Fig. 2. The output signal of the tunable laser source was externally modulated using an intensity modulator for the NRZ-OOK signal and a phase modulator for the NRZ-DPSK signal. For each signal, we adjusted the transmission rate as 1, 2.5 and 10-Gb/s pseudo random binary sequence of length of \( 2^{31} - 1 \). We used the variable optical attenuator (VOA) to make the OSNR change by controlling levels of signal and ASE noise respectively. The modulated signals were combined with ASE noise and amplified by an erbium-doped fiber amplifier (EDFA). After passing through the PMD emulator to investigate the effect of differential group delay and the optical BPF with 3-dB bandwidth of 1.2 nm, the noise added signal was split by a 1x2 coupler to compare the measured OSNR by the optical spectrum analyzer (OSA) with the OSNR calculated using the proposed scheme. The CLPG was composed of two same LPGs.
and an YDF. The length, $L_1$, of the fabricated CLPG was about 16 cm consisting of conventional SMF with 6 cm length and YDF with 10 cm length, i.e., $L_1 = 10$ cm and $L_2 = 6$ cm. The DEGIs of the used SMF and YDF are $7.5 \times 10^{-3}$ and $1.38 \times 10^{-2}$ at 1550 nm respectively. Thus, the calculated time difference is 6.1 ps from Eq. (1) and the corresponding FSR is 163.9 GHz, 1.31 nm in wavelength at 1550 nm. Grating was written on a conventional single mode fiber (SMF) by irradiation of a KrF excimer laser beam through a uniform phase mask of 550 μm period. Before writing the LPG, the SMF was hydrogen loaded at 100°C under a pressure of 10 MPa for a week. After writing the LPG on the bare fiber, fibers were annealed at 100°C for 24 h. The 976-nm pumping light driven by the sinusoidal signal of 500 mHz was launched into the YDF through a 980/1550-nm WDM coupler. At high pumping power, the residual pump power influenced the measurement accuracy. For this reason, we used two WDM couplers after the CLPG in a cascaded form to get narrower pass band. The sweeping speed was limited below 500 mHz for the reproducibility of the measured value. It samples the output power from the CLPG every 10 ms and gives the maximum and the minimum values for the calculation of OSNR.

4. Results and discussion

Figure 3 shows the amount of the wavelength shift and phase change according to pumping power. In Fig. 3(a), the optical spectra of the fabricated CLPG were measured at pumping power of 0, 44.62, and 87.04 mW. This fringe pattern was generated by the interference between the core and cladding modes. Thereby, the peak and dip values around the operating wavelength of our interest can be obtained by changing the pumping power. The wavelength dependence of the CLPG was determined by the envelope of the fringe pattern and the output power of the CLPG for the operating wavelength apart from the center wavelength of the envelope will be lower. Thus, the device is adequate to the small wavelength range WDM system. To obtain π phase shift, pumping power of about 87 mW is required. It means that the measurement of maximum and minimum powers is possible by generating pump power, varying from 0 mW to 87 mW. The interference fringe pattern was observed with the FSR of about 1.3 nm close to the 3-dB optical band pass filter of 1.2 nm necessary for measuring in-band OSNR. Figure 3(b) shows that the phase shift increases linearly according to the amount of pumping power.

The measured OSNR and monitoring error of NRZ-OOK and NRZ-DPSK signals compared to the OSNR obtained by using the OSA are shown in Fig. 4, respectively. In Fig. 4(a), the measured OSNR of an NRZ-OOK signal, having different bit rates, increases linearly
with the OSNR of the OSA. The dynamic range of the OSNR was about 30 dB without reference to bit rates. In Fig. 4(b), the monitoring error measured with the proposed technique is < 0.2 dB in the OSNR range of 0 to 30 dB when the modulation format is an NRZ- OOK. 4 (c) and (d) show that the OSNR and errors of an NRZ-DPSK signal have similar characteristics with an NRZ- OOK. The results in Fig. 4 show that the proposed technique can precisely achieve the OSNR monitoring of the OOK and DPSK signals regardless of bit rates with an accuracy of ±0.2 dB, respectively.

![Figure 3](image1)

**Fig. 3.** (a) Spectra for pumping power of 0, 44.62 and 87.04 mW, (b) phase change by pumping power calculated from the wavelength shift.

![Figure 4](image2)

**Fig. 4.** Measured OSNR and monitoring errors at 1, 2.5, and 10 Gbit/s: (a) OSNR and (b) monitoring error for NRZ-OOK signal, (c) OSNR and (d) monitoring errors for NRZ-DPSK signal.

The effects of the PMD on the OSNR monitoring performance of 10-Gbit/s NRZ-OOK signal are investigated by using the PMD emulator. Fig. 5 shows the OSNR monitoring errors when the PMD is induced. When the OSNR of the 10-Gbit/s NRZ-OOK signal was set to be
10 and 20 dB, the monitoring error was below 0.2 dB for all PMD values with the range from 0 ps to 50 ps. This result reveals that the proposed method is insensitive to the PMD.

To estimate the variation of the OSNR by the CD, the CD was accumulated up to about 600 ps/nm by increasing fiber length and plotted in Fig. 6. When the influence of the CD was measured, the PMD is not externally induced. Because the monitoring error was less than 0.2 dB for the 10 and 20-dB OSNR of the 10-Gbit/s NRZ-OOK signal, the proposed technique was also insensitive to the CD. On the other hand, this device has the temperature dependence of about 0.04 nm/°C due to the CLPG.

![Fig. 5. Measured OSNR monitoring error induced by PMD for 10 and 20-dB OSNR.](image)

![Fig. 6. Measured OSNR monitoring error induced by CD for 10 and 20-dB OSNR.](image)

5. Conclusion

A novel OSNR monitoring technique based on the CLPG with an optically tunable phase shifter using an YDF has been proposed. The CLPG has Mach-Zehnder configuration consisting of the core and cladding modes and YDF can optically control the phase difference between two modes. The proposed technique, having two functions, precisely measures the OSNR regardless of transmission rates and is insensitive to PMD and CD. Hence, the novel scheme can be used to monitor optical performance in future high-speed transparent networks. As a result, the monitoring errors were less than 0.2 dB in 1, 2.5, and 10-Gbit/s NRZ-OOK and NRZ-DPSK signals, respectively. And, the dynamic range was 30 dB. The errors on the effect of induced PMD and CD were smaller than 0.2 dB, respectively.
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