All-optical Signal Processing in PDM Systems

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ABSTRACT

Driven by the need for high-capacity data traffic, various approaches have been deployed to enable the network spectral efficiency and overall capacity. Among them, polarization-division-multiplexing (PDM) has been extensively investigated during last few years due to the fact that it can double the spectral efficiency and system capacity directly. Since two data channels carry the same wavelength while with orthogonal polarization states, most all-optical signal processing schemes that are used for single-polarization channels, we need find cost-effective approaches for PDM systems. We review different schemes for signal processing in PDM systems using different nonlinear elements. Recent experimental demonstration results at 10-Gb/s are discussed with various functionalities such as all-optical signal regeneration, wavelength conversion, mitigating channel degrading effects and so on.

Keywords: All-optical signal processing, polarization division multiplexing, highly nonlinear fiber

INTRODUCTION

All-optical processing of signals, enabled by nonlinear-optical elements, represents critical technology for future optical communication systems. Over the past few years, extensive research has carried out to realize numerous network functionalities, such as format conversion, wavelength conversion, regeneration, and so on. Most of these functionalities are achieved by utilizing nonlinear effects, including self-phase modulation (SPM), cross-gain modulation (XGM), four-wave mixing (FWM), cross-phase modulation (XPM) and so on, in different nonlinear elements [1-14].

Hitherto, most all-optical signal processing research focused on single-polarization channel, single or several wavelength channels [11-14]. However, PDM technique has been deployed to enable the network spectral efficiency and overall capacity due to the fact that it can double the spectral efficiency and capacity directly by carrying two independent data traffics in orthogonal polarization states [15, 16]. Therefore, signal processing for such systems may be desired in future optical communication systems.

Recently, PDM signals wavelength conversion based on FWM in different nonlinear medium have been demonstrated, such as wavelength conversion based on orthogonal or parallel pumps FWM in highly nonlinear fiber [17-19] and semiconductor optical amplifier (SOA) [20]. To overcome the performance degradations in PDM systems induced by chromatic dispersion, polarization mode dispersion (PMD), nonlinearity and so on, various schemes or approaches have been demonstrated, including: (i) electronic signal processing [21]; (ii) DSP-assisted coherent detection [22, 23]; (iii) polarization tracking followed by optical PMD compensators [24-26]; and (iv) novel data formats, e.g. optical orthogonal frequency division multiplexing (OFDM), etc. [27]. However, most of these schemes are carried out in electronic domain.

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In this paper, we focus on two examples of all-optical SPM-based PDM signals regeneration and a scheme of XPM-based wavelength conversion that we have recently demonstrated. One schemes of PDM signals regeneration is based on counter-propagation configuration, and the other is based on polarization nonlinear loop mirror. Both schemes realize the regeneration of two polarization tributaries of a PDM signals simultaneously. Mitigation of polarization mode dispersion (PMD) in PDM system is demonstrated by utilizing the polarization nonlinear loop mirror as well. The wavelength conversion of PDM signals is achieved by spectral filtering from XPM induced spectral broadening in the polarization nonlinear loop mirror. The conversion wavelength range is covered the whole C-band.

PDM SIGNALS REGENERATION

2.1 Counter-propagation scheme

Fig.1 show the schematic of the counter-propagating all-optical regenerator for PDM signals [28]. The degraded PDM pulse streams first transmit through a high power optical amplifier. Then the PDM signals are demultiplexed by a polarization beam splitter (PBS) and propagate bidirectionally in a single section of highly nonlinear fiber (HNLF: the length, zero dispersion wavelength, dispersion slope, and nonlinear coefficient of the highly nonlinear fiber are 1-km, 1556 nm, 0.02 ps/nm^2/km, and 30 (W·km)$^{-1}$, respectively) for SPM-based spectrum broadening. The optical circulators can guide two PDM signals out and two signals recombine through a polarization beam combiner (PBC). One polarization controller (PC2 or PC3) has to be used for each channel to align with the PBC port. The second OBPF2 is used to filter the broadened spectrum and reshape signals for both polarization states.

By using the counter-propagation configuration, impairments due to inter-channel nonlinearities between two channels, such as XPM, FWM and stimulated Brillouin scattering (SBS) can be mitigated, as the tow signals propagate bidirectional in the HNLF with orthogonal states of polarization [12]. A polarizer (i.e. one port of the PBC in the setup) inserted before the offset filter (i.e. the OBPF2 after the PBC) is used to reject inter-channel backward SBS noise, for the states of polarization of most SBS spontaneous photons are identical to the pump, especially when the pump power is high enough [29]. Furthermore, the SBS effect on the regenerated signal can be further mitigated by slicing the broadening spectrum at the short wavelength region, for the wavelength of spontaneous photons is larger than the pump's.

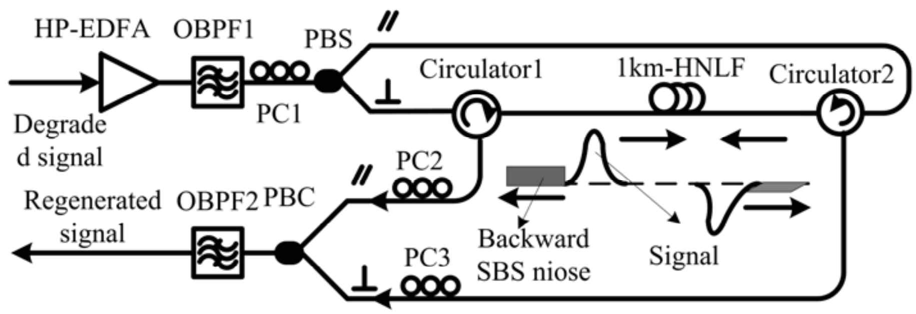


Fig. 1 Schematic of the counter-propagating all-optical regenerator for PDM signals. HP-EDFA: high-power EDFA; OBPF: optical bandpass filter; PC: polarization controller; HNLF: highly nonlinear fiber; PBS: polarization beam splitter; PBC: polarization beam combiner

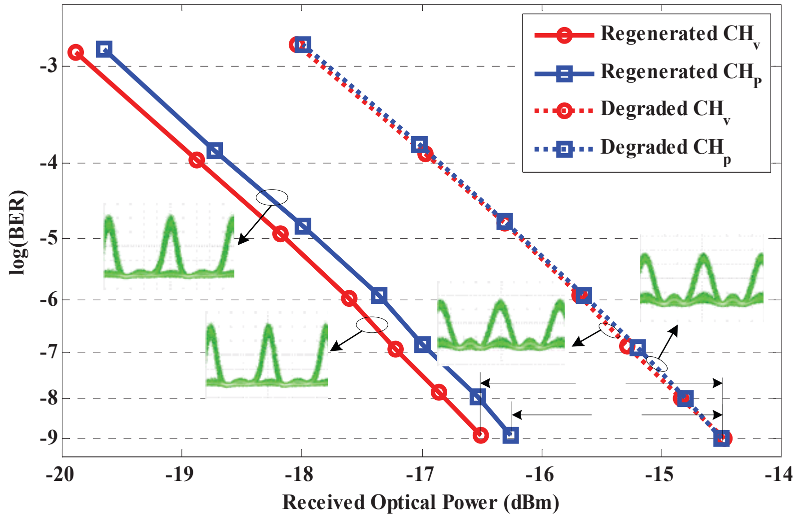


Fig. 2 Measured BER results and corresponding eye diagrams of degraded and regenerated signals for the two PDM channels

The efficiency of this scheme is confirmed in the 2×10.65-Gb/s RZ-OOK PDM system with pulse width of ~ 33 ps. Fig. 2 shows the bit-error-rate (BER) and corresponding eye diagrams results of the degraded and regenerated signals for the two PDM channels. In the measurement, the degraded PDM signals are boosted to an optimized power level of ~27.5dBm (~24.5dBm for each channel) before polarization demultiplexing. At the spectral slicing port, the bandwidth and detuned wavelength of the OBPF (i.e. OBPF2 or OBPF3) are ~ 0.6 nm and ~ -0.3 nm, respectively. As shown in Fig.2, the power penalty improvement compared to the degraded input signals at the reference BER of 10^{-9} is 2.0 and 1.8 dB for channel CHv and CHp (the channel with 1-km decorrelating SMF reference as CHp and the other channel referenced as CHv), respectively.

2.2 Polarization nonlinear loop mirror

The conceptual diagram of the proposed all-optical PDM regenerator using the polarization nonlinear loop mirror is shown in Fig.3 (a) [30, 31]. Amplified and degraded PDM signals at the wavelength of λ_0 are demultiplexed by the polarization controller (PC) and the polarization beam splitter (PBS) and then counter-propagate through the polarization nonlinear loop mirror. Based on the loop configuration, two orthogonal polarization components of PDM signals exhibit the same spectral broadening due to the SPM effect in the nonlinear medium under the pump of high-power EDFA. Inside the loop, an in-line Faraday rotator (IFR) with a round-trip polarization rotation of 90° is used to automatically change the state of polarization (SOP) of the signals in both directions. Therefore two counter-propagating orthogonal polarization components are recombined at the input port of the PBS after traveling through the loop, and then guided out of the loop by the circulator (Port 3). Finally, a single tunable optical band-pass filter (OBPF) is used to slice the broadened spectra of PDM signals at the wavelength of $\lambda_0 \pm \Delta\lambda$ to obtain the regenerated signals (The spectra of input (degraded), broadened and output (regenerated) are shown in Fig.3 (b)). Note that there are only one high power EDFA, one section of nonlinear medium and one OBPF for both orthogonal polarization components (i.e. a single regeneration module). The nonlinear medium is composed of two sections of HNLF and one piece of dispersion-compensating fiber (DFC) (as shown in Fig.3 (b)). The lengths of HNLF1, DCF and HNLF2 are 1 km, 200 meters and 1 km, respectively. The dispersion of the 200-m DCF is ~ 27-ps/nm. The zero dispersion wavelength, dispersion slope, and nonlinear coefficient of the HNLF are 1-km, 1556 nm, 0.02 ps/nm^2/km, 30 (W·km)$^{-1}$, respectively.

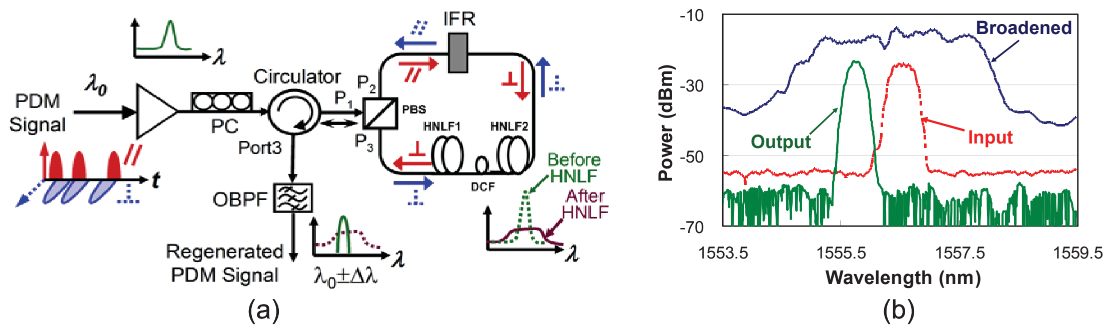


Fig.3 (a) Configuration of PDM signals regeneration by the nonlinear polarization-diversified loop. ILF: in-line Faraday rotator. (b) Spectra of input (degraded), broadened and output (regenerated)

Fig.4 shows the regeneration performance, i.e. power transfer functions of the PDM regenerator (input pulse peak power vs. normalized output power) and typical eye-diagram and BER results, in the 2×10-Gb/s RZ-OOK PDM system with pulse width of ~ 18 ps. The average power is boosted to ~ 16.6 dBm for each polarization channel before entering the loop. The bandwith and detuned wavelength of the OBPF at port3 of the circulator are ~ -1.1 nm. There is about 1.8 dB power penalty improvement is achieved for each polarization tributary of the PDM signals at the value of BER=10^{-3}.

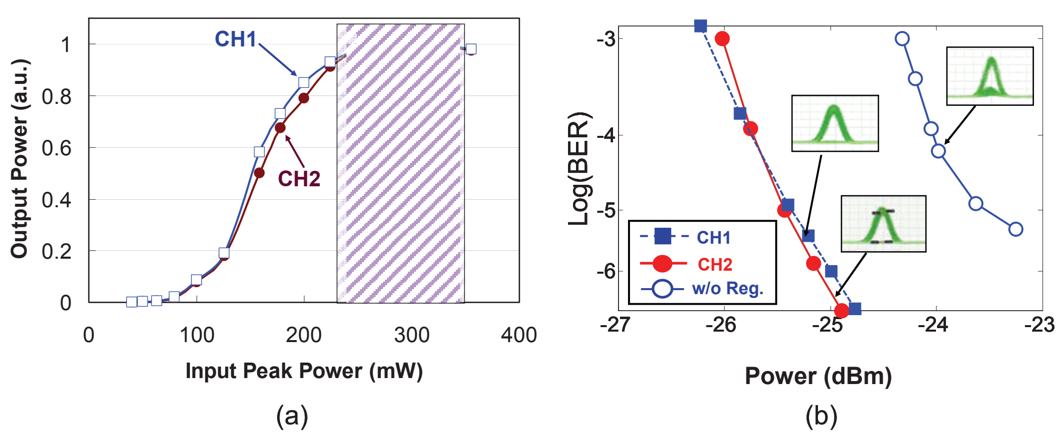
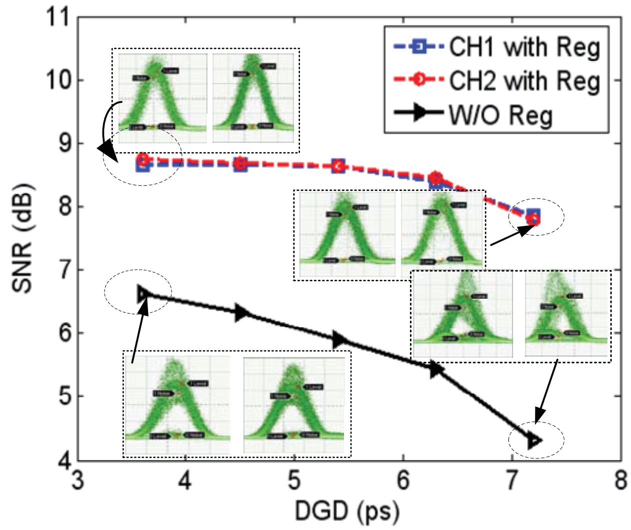


Fig.4 (a) Power transfer functions of the PDM regenerator (input pulse peak power vs. normalized output power), (b) BER results and some typical eye-diagram

We further evaluate the proposed PDM regenerator to mitigate PMD effects in PDM systems. Fig. 5 shows the SNR values with and without all-optical regeneration in the presence of different DGD values. The maximum improvement is ~ 3.5-dB at the present of 7.2-ps DGD. Several points should be noted: (i) The pulsewidth of RZ-OOK PDM signals is ~18 ps for our experiments, indicating higher data rate regeneration (e.g. >40-Gb/s) is feasible (generally the PMD tolerance exhibits a linear relationship with the pulsewidth of RZ signal). Alternatively, for 10-Gb/s RZ-OOK signals with 50% duty cycle (50-ps pulsewidth), ~17-ps PMD mitigation is achievable for PDM signals. (ii) There is an upper limit of PMD mitigation (e.g. ~ 8-ps) using all-optical regeneration in our experiment.



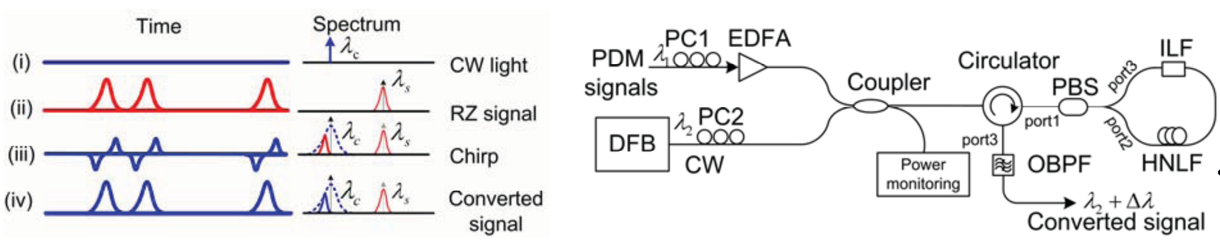
SNR=8.75 dB

Fig. 5 SNR values without and with all-optical regeneration in the presence of different DGD values (eye diagrams inserted)

PDM SIGNALS WAVELENGTH CONVERSION

3.1 Principle and experiment

The principle of the wavelength conversion using XPM in a HNLF with subsequent filtering is as follows (Fig. 5) [32]: continuous-wave (CW) pump is launched into the fiber along with the data pulse. The data pulse will impose a phase modulation that generates sidebands on the CW pump. By extracting the red-chirped components at longer wavelength side or blue chirped components at the shorter wavelength side, the wavelength converted signal can be obtained.



.63 dB

(a) (b)

Fig.6 (a) Schematic illustration of wavelength conversion by spectral slicing of XPM broadened signal spectrum (time and spectrum domain). (i) CW pump to be converted; (ii) incoming RZ signal to be converted; (iii) XPM induced frequency chirp; (iv) output of the wavelength converted signal. (b) Experimental setup of all-optical wavelength conversion for PDM signals based on XPM; DFB: distributed feedback laser.

Fig.6 (b) shows the experiment setup. In our experiment, continuous-wave (CW) pump emitted by the DFB laser is combined with the amplified RZ-OOK PDM signals by coupler and then injected to the nonlinear polarization-diversified loop through the circulator and PBS. Signals power is monitored at the other port of coupler. The SOP of the CW pump is aligned to be 45° with respect to the principle of the PBS (by adjust PC2) to equally divide the pump power into two orthogonal components, while the amplified RZ-OOK PDM signals are demultiplexed by the PC and PBS and counter-propagate through the loop. After propagating through the loop, the spectrally broadened two orthogonal components are recombined at port1 of PBS and guided out of the loop by the circulator. The OBPF at port3 of the circulator is used to filter out the original signals and slice the broadened CW pump spectrum to obtain the wavelength converted signals.

3.2 Results and discussion

Fig. 7 shows the eye-diagram-based SNR penalties and some typical eye-diagram results in the wavelength conversion when the to-be-converted wavelengths range from 1535 nm to 1565 nm. The measurement condition for the oscilloscope is the same as mentioned before. As it is shown in Fig.7, different converted performances are obtained at different wavelengths. This may be able to explain as follows: when the separation between two wavelengths gets smaller, the spectrally broadened input signals will interfere with the CW pump, which generates interferometric noise in the converted signals. In addition, as the HNLF used in our experiment has a large nonlinear coefficient (30 $(W\cdot km)^{-1}$), strong backscattering noise and FWM signals may also interfere with converted signals as two wavelengths close to each other. Furthermore, similar to XPM-based optical regenerators [3], it might also somewhat come from the interaction between the nonlinearity and dispersion.

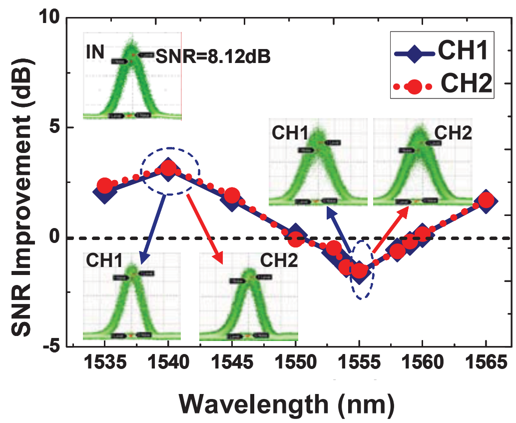


Fig. 7 Eye-diagram-based SNR improvement vs. pump wavelength, and corresponding eye-diagrams

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