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Article

Polarization-Independent All-Optical Regenerator for DPSK Data

Valeria Vercesi [1],*, Claudio Porzi [2], Giampiero Contestabile [1] and Antonella Bogoni [2]

[1] Institute of Communication, Information and Perception Technologies, Scuola Superiore Sant'Anna, via Moruzzi 1, Pisa 56124, Italy; E-Mail: giampiero.contestabile@sssup.it

[2] National Laboratory of Photonic Networks, Consorzio Nazionale Interuniversitario per le Telecomunicazioni, via Moruzzi 1, Pisa 56124, Italy; E-Mails: claudio.porzi@cnit.it (C.P.); antonella.bogoni@cnit.it (A.B.)

* Author to whom correspondence should be addressed; E-Mail: valeria.vercesi@sssup.it; Tel.: +39-050-549-2174.

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Abstract: We demonstrate polarization-independent simultaneous all-optical phase-preserving amplitude regeneration and wavelength conversion of NRZ differential phase shift keying (DPSK) data by four-wave mixing (FWM) in a semiconductor optical amplifier (SOA). The dependence upon polarization state of the signals is eliminated by using a co-polarized dual-pump architecture. Investigation on the regenerative capability *vs.* pumps detuning shows significant BER threshold margin improvement over 6 nm conversion range.

Keywords: semiconductor optical amplifiers; signal regeneration; DPSK modulation format; four-wave mixing

1. Introduction

Optical networks continue to evolve in response to ever-increasing levels of traffic, with a growing emphasis on network flexibility. Nowadays, wide and metro optical networks needs subsystems with fast re-configurability, high capacity, and the ability to handle different modulation formats. All-optical gates enabling simultaneous signal regeneration and wavelength conversion, for instance, would enhance robustness and flexibility in light-wave path assignment operation for next generation wavelength-routed optical networks [1,2].

All-optical processing of phase-modulated data is thus of great importance in this scenario and, in this sense, several works investigated simultaneous regeneration and wavelength conversion for differential phase shift keying (DPSK) modulation format [3–8]. For instance, phase-sensitive amplification in nonlinear fiber has been proposed for realizing regenerative wavelength conversion of binary phase-modulated data [3]. Other approaches exploited DPSK-to-OOK conversion followed by a reshaping nonlinear interferometer stage where signal regeneration and back-encoding to DPSK format at a new wavelength takes place [4,5]. Four-wave mixing (FWM) effect in both fibers [6] and semiconductor optical amplifiers (SOAs) [7,8] has been also proposed to perform phase-modulated signals amplitude regeneration without altering their phase information by introducing excess phase noise. The advantage of this phase-preserving amplitude regeneration approach for phase-modulated data relies in a simpler implementation in respect to coherent architectures and in interferometer-based schemes. Among phase-preserving schemes, those based on SOAs offer the additional benefits of compactness, low-operating power levels and wide operating bandwidth, and we recently demonstrated strong regeneration of NRZ-DPSK signals over a broad conversion range of about 50 nm [9]. However, the technique suffers from the FWM dependence upon signals polarization state, thus practically limiting its exploitation in optical networks systems. To overcome the strong polarization dependency of the proposed FWM-based regeneration scheme in an SOA, a co-polarized pumps [10,11] architecture can be conveniently implemented.

Here, for the first time to our knowledge, the regenerative capability of the dual-pump FWM scheme is investigated. The efficient amplitude regenerative characteristic of FWM-based wavelength conversion with limited excess phase noise in SOAs, indeed, is preserved in presence of the two co-polarized pumps scheme, thus enabling polarization-independent regenerative wavelength conversion. The regenerative capability and the robustness of the system against conversion range are investigated, demonstrating Q-factor enhancement and corresponding BER threshold margin improvement with fair values of optical signal-to-noise ratio (OSNR) and FWM conversion efficiency within a range of 6 nm for an NRZ-DPSK 10 Gb/s data signal.

2. Set-Up and Principle

The experimental set-up we adopted to demonstrate polarization-insensitive phase-preserving all-optical regeneration of NRZ-DPSK data is illustrated in Figure 1; the inset within dashed lines in the figure schematically summarize the operating principle. Here, the pump signals *P1* and *P2* are two linearly co-polarized continuous waves (CWs) with wavelength λ_{P1} and λ_{P2}, respectively, whose polarization is aligned along one of the two principal axes of the SOA's waveguide by means of polarization controllers (PCs). On the other hand, the DPSK data input signal with wavelength λ_{DATA} has a generic state of polarization that, for the sake of simplicity, is represented to be linear with an angle θ with respect to the pumps within the figure. The beating between the two co-polarized pumps that propagates through the SOA creates a gain and index modulation along the amplifying medium, which affect with the same strength both TE and TM components of a probe signal traveling in the amplifier (if the polarization dependent gain, PDG, of the SOA can be neglected) [12]. The resulting FWM nonlinear interaction between the pumps and the data signal creates two sidebands placed at the pumps beating frequency away from the DPSK data carrier, whose intensities are insensitive to input signal polarization. The wavelength of the sidebands, representing replicas of the DPSK input data, is related to the pumps wavelength by:

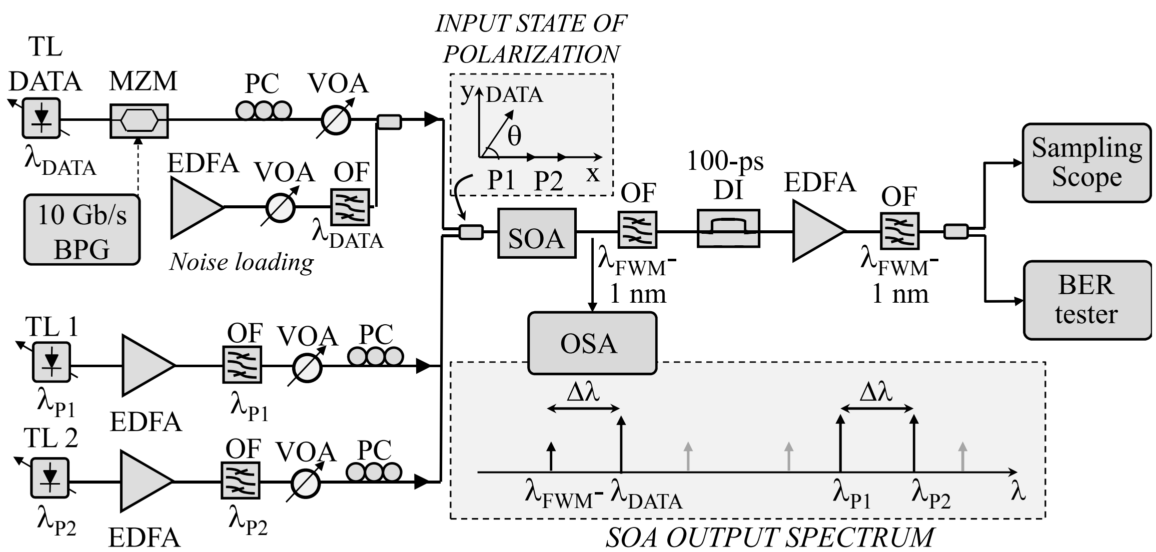
$$\lambda_{FWM}\pm = [1/\lambda_{DATA} \pm (1/\lambda_{P2} - 1/\lambda_{P1})]^{-1} \quad (1)$$

where $\lambda_{FWM}+$ and $\lambda_{FWM}-$ correspond to the longer and shorter-wavelength sideband, respectively. The power level of the output FWM terms depends on the pumps detuning $\Delta\lambda_P = |\lambda_{P1} - \lambda_{P2}|$, and it is insensitive to input signal polarization and wavelength, as long as the SOA PDG is negligible and the beating due to the two pumps is stronger than the beatings due to signal and pumps (preventing undesired cross-talk between the involved signals). This last condition can be practically implemented by placing the pump wavelengths close and far enough from the signal wavelength. A simplified lumped model developed for non-birefringent materials [12], provides an approximate expression for the SOA output power at FWM optical frequencies, $P_{FWM}\pm$:

$$P_{FWM}\pm = P_{DATA}\, P_{P1}\, P_{P2}\, G^3\, R \pm (\Delta\lambda_P), \quad (2)$$

where P_{DATA} is the input signal power, P_{P1} and P_{P2} are the pumps power levels, G is the saturated SOA gain, and the term $R\pm$, the relative conversion efficiency, takes into account the contribution to conversion efficiency of the different effects responsible for FWM in the SOA as a function of the conversion range [13]. Since the shorter-wavelength FWM term exhibits the highest conversion efficiency [14], it will be considered in the following. In presence of degraded DPSK input data, with a proper choice of input power levels, FWM signal at SOA output features a higher quality with respect to input signal [8]. The optical regeneration of the DPSK signal is originated by the strong amplitude-limiting capability of the saturated SOA, in conjunction with very small amplitude-to-phase noise transfer occurring in the amplifier [15].

Figure 1. Experimental setup for polarization independent differential phase shift keying (DPSK) regenerative wavelength converter characterization. TL: tunable lasers. MZM: Mach–Zehnder modulator. PC: polarization controllers. VOA: variable optical attenuator. OF: optical filter. DI: delay line. The operating principle is schematized within the dashed boxes.



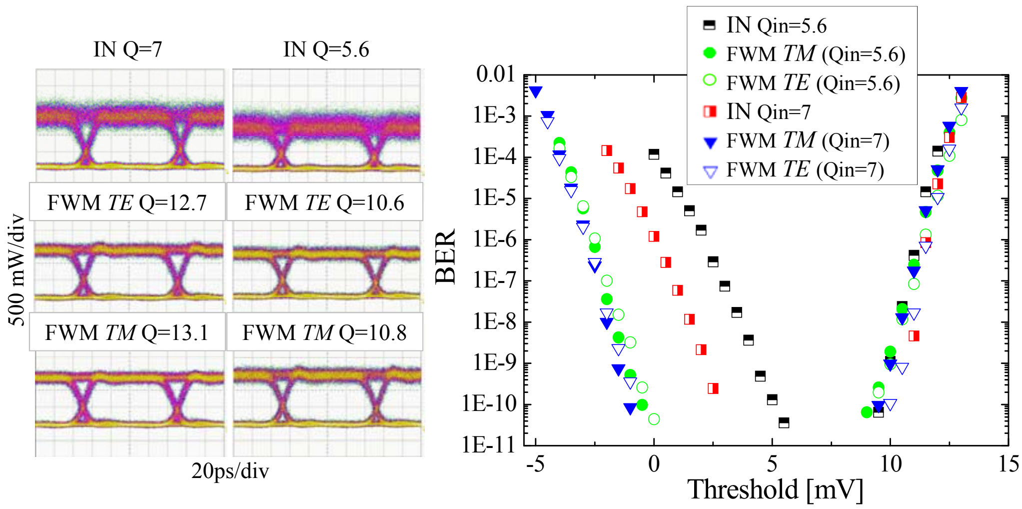
As shown, in the experimental setup of Figure 1, a 10 Gb/s DPSK data stream at λ_{DATA}, is generated by modulating the output of a tunable laser (TL) with a Mach–Zehnder modulator (MZM) biased at a null point and driven by a bit pattern generator (BPG) producing a $2^{31}-1$ pseudo-random bit sequence (PRBS). The modulator output is then coupled with an amplified spontaneous emission (ASE) noise loading stage, provided by an erbium-doped fiber amplifier (EDFA), followed by an optical filter (OF) with 1 nm bandwidth. Two TLs deliver the CW pump signals whose wavelengths λ_{P1} and λ_{P2}, lying in proximity of the SOA gain peak (~1560 nm), have been tuned in different experiments in order to investigate the regenerative operation as a function of conversion range. The pump signals are then coupled with the noisy data and injected into the SOA (CIP Technologies SOA-NL-OEC-1550), that is a multi-quantum-well device with ~27 dB small-signal gain, 13 dBm output saturation power, and ~1 dB polarization dependent gain. At its output, the converted data at λ_{FWM^-} are selected, and a standard delay-interferometer (DI) with a FSR of 10 GHz is used for DPSK demodulation. Input/output Q-factors are monitored by sending the signals to the 30 GHz optical head of a sampling oscilloscope and BER measurements are performed using a linear photo-receiver with 10 GHz bandwidth.

By means of PCs, the relative state of polarization of the input signals could be adjusted. By maximizing the FWM interaction between pump signals in absence of input data, the polarization state of both pumps waves has been aligned along the TE axis of the SOA. On the other hand, the polarization state of the input data has been varied in order to observe the residual polarization dependence of the regenerated FWM output signal. When the input signal is co-polarized to the pumps (TE polarization), the output power at λ_{FWM^-} is minimized due to the polarization-dependent pumps-signal FWM nonlinear interaction, which depletes the signal at λ_{DATA} to generate different FWM components symmetrically located around the data and pumps frequency at the pumps-data beating frequencies; on the other hand, when the input signal polarization is orthogonal to the pumps (TM polarization), the output power at λ_{FWM^-} is maximized. Variable attenuators, are also used for independently adjusting the power levels at SOA input. In the following experiments, the input signal power coupled into the SOA is about 10 dBm and the total power of the two pumps is about 7 dBm, for a total power at the SOA input which is typically around 12 dBm.

3. Experimental Results

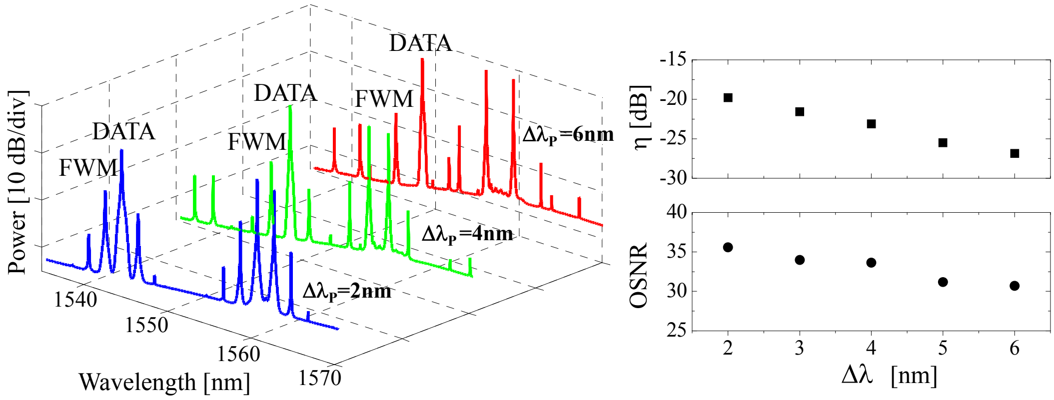
The regenerative capability of the DPSK wavelength converter under different conditions of input signal polarization states has been first evaluated for a fixed detuning $\Delta\lambda_P = 2$ nm between the pump signals, and for two different values of input Q-factor of $Q_{IN} = 7$ and $Q_{IN} = 5.6$, respectively. In Figure 2, the demodulated input and output eye diagrams for the two boundary conditions of TE ad TM input data polarization state are illustrated. As shown, the output Q-factor for both TE and TM input polarizations is clearly improved with respect to input Q-factor, with a nearly doubled value of the regenerated DPSK signal Q-factor with respect to the input data ($Q_{FWM}/Q_{IN} > 1.8$). By acting on the PC on the data path so that the input signal is no more linearly polarized along one of the two SOA orthogonal modes, we have observed values for the output Q-factors corresponding to any arbitrary state of input polarization which are comprised within the boundary values obtained with the TE and TM input states reported in Figure 2. Then, BER *vs.* voltage threshold at the receiver is measured for both input and output signals, in order to evaluate the performance of the system in terms of noise compression. The corresponding results are shown in Figure 2 (right): the improvement in terms of noise compression at the receiver is noticeable for both TE- and TM-polarized input signals with a Q-factor of 5 and 7. All the FWM output signals BER curves show the regenerative capabilities of the scheme, presenting a threshold margin improvement with respect the inputs curves; furthermore, their overlapping confirms the independency of the results from the input polarization state.

Figure 2. (**left**) Eye diagrams and measured Q-factors of the input (IN), four-wave mixing (FWM) when input is polarized TE (FWM *TE*), and FWM when input is polarized TM (FWM *TM*) signals; (**right**) BER *vs.* voltage threshold measurements for the input (IN), FWM when input is polarized TE (FWM *TE*), and FWM when input is polarized TM (FWM *TM*) signals. Pumps detuning is fixed at 2 nm; λ_{DATA} = 1540 nm, λ_{P1} = 1556 nm and λ_{P2} = 1558 nm.



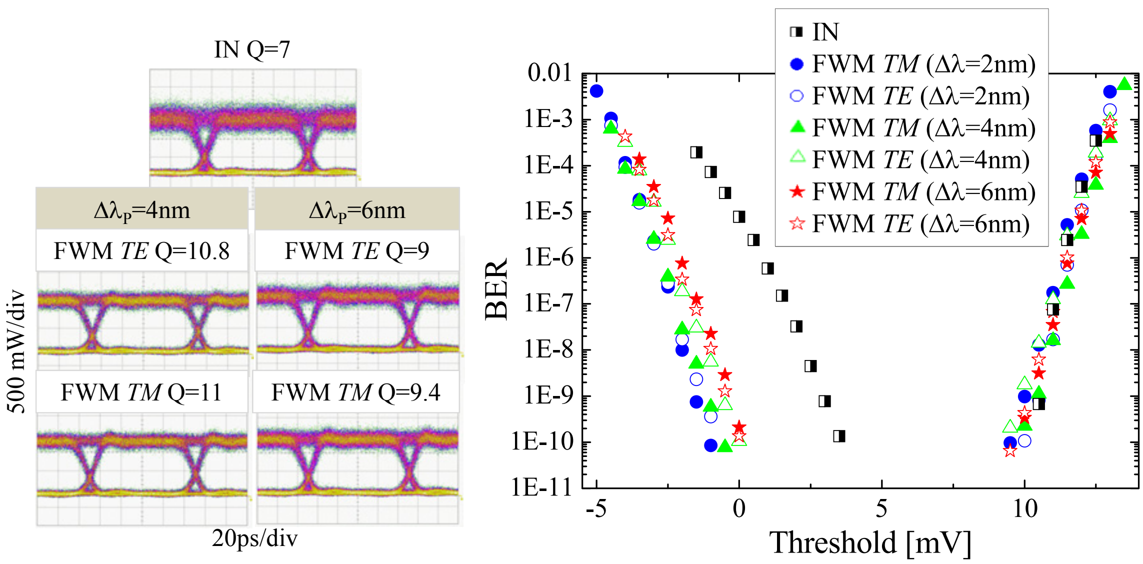
In a subsequent set of measurements, we performed a characterization of the DPSK polarization-independent regenerator by varying the pumps detuning and keeping the input Q-factor fixed at Q_{IN} = 7. Typical sample spectra at SOA output for different values of $\Delta\lambda_P$ and λ_{DATA} are shown in Figure 3 (left). By tuning the data wavelength, a constant conversion efficiency was obtained as long as data-pumps detuning is higher than pumps detuning. Here we show optical spectra when, λ_{DATA} is 1540, 1545 and 1550 nm for $\Delta\lambda_P$ equals to 2, 4 and 6 nm, respectively, pointing out the robustness of operation against variations in the input signal wavelength. In Figure 3 (right), the measured conversion FWM efficiency, η_{FWM}, and OSNR for different values of the conversion span, defined as $\Delta\lambda = \lambda_{DATA} - \lambda_{FWM}$, are shown. In the OSNR and η_{FWM} evaluation, the worst case for the polarization state of the input signal (which is TE case, as discussed before) has been considered. From the reported data, it can be observed that the output signal maintains an OSNR higher than 30 dB up to a conversion range of 6 nm. On the other hand, the FWM conversion efficiency is about −20 dB at small values of $\Delta\lambda$, whereas it exhibits degradation starting from a pump detuning larger than 3 nm, where the corresponding beating frequency approaches the cut-off frequency of carrier-density modulation mechanism, which is responsible for the strongest FWM response in the amplifier. Nevertheless, the value of η_{FWM} is well above −30 dB up to $\Delta\lambda$ = 6 nm. The FWM conversion efficiency variation between input TE and TM cases has also been measured to be around 1 dB.

Figure 3. (**left**) Optical spectra at semiconductor optical amplifier (SOA) output for different pumps detuning; (**right**) FWM conversion efficiency (ŋ) and optical signal-to-noise ratio (OSNR), *vs.* the conversion span when input is polarized TE.



The FWM demodulated output eye diagrams corresponding to pumps detuning of 4 and 6 nm for both TE and TM input polarizations are shown in Figure 4 (left). Also in these cases, strong Q-factor improvement is observed for both the orthogonal TE and TM input polarizations, and by acting on the PCs we observed values of Q_{FWM} comprised between these two boundary conditions. For all the considered cases, BER *vs.* voltage threshold at the receiver is measured for both input and output signals, and the results are shown in Figure 4 (right). From the curves in the plot, it is evident the independence of the regenerative operation from input polarization and the robustness against conversion span for all the considered values of pumps detuning.

Figure 4. (**left**) Eye diagrams and measured Q-factors of the input (IN), FWM when input is polarized TE (FWM *TE*), and FWM when input is polarized TM (FWM *TM*) signals for $\Delta\lambda_P$ = 4 and 6 nm; (**right**) BER *vs.* voltage threshold measurements for the input (IN), FWM when input is polarized TE (FWM *TE*), and FWM when input is polarized TM (FWM *TM*) signals for different values of the conversion span Δλ.



4. Conclusions

We have proposed and experimentally characterized polarization independent all-optical phase-preserving amplitude regeneration of DPSK signals exploiting FWM effect in a single SOA. A dual co-polarized pump architecture allows FWM independence from input signal polarization and wavelength. In addition, the system operates at moderate input powers levels and it is suitable for photonic integration. Investigation of the system regeneration capability upon wavelength conversion span is performed. Remarkable Q-factor and threshold margin improvement regardless of input signal polarization state over a conversion range up to 6 nm have been measured. The technique also has potential in DQPSK signal regeneration, according to the recent results obtained in [16].

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Author Contributions

Valeria Vercesi and Claudio Porzi implemented the polarization-independent all-optical regenerator for DPSK data and measured its performance. Valeria Vercesi, Claudio Porzi, Giampiero Contestabile and Antonella Bogoni discussed the experiments to perform and the results obtained.

Conflicts of Interest

The authors declare no conflict of interest.

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