Phase-Sensitive Amplification of 28 GBaud DP-QPSK Signal

A. Lorences-Riesgo, T. A. Eriksson, C. Lundström, M. Karlsson, and P. A. Andrekson

Dept. of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden

lorences@chalmers.se

Abstract: We demonstrate, for the first time, amplification of a DP-QPSK signal using a vector phase-sensitive amplifier (PSA). The PSA-based receiver shows an about 0.7 dB sensitivity improvement compared to an EDFA-based receiver.

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1. Introduction

Phase-sensitive amplifiers (PSAs) ideally provide noiseless amplification with a 0 dB quantum-limited noise figure (NF) [1]. In contrast with PSAs, phase-insensitive amplifiers (PIAs) such as erbium-doped fiber amplifiers (EDFAs) or Raman amplifiers have a 3 dB quantum-limited NF. Using the copier-PSA configuration [2], low-noise PSAs have been demonstrated experimentally in order to achieve high-sensitivity receivers [1] and increase transmission distance [3]. However, these demonstrations have been performed with scalar PSAs where all-waves are co-polarized and thus polarization-diversity would be required in order to amplify dual-polarization (DP)-modulated signals. Polarization diversity can be implemented within a loop configuration. However, degradation of the performance of phase-insensitive fiber-optic parametric amplifier (PI-FOPA) operating in biderectional mode has already been reported [4]. This degradation is expected to affect PSAs more severely. A PPLN-based PSA was already demonstrated with limited gain in order to amplify DP-modulated signals [5]. In order to further enhance the performance of the polarization-diverse PSA and avoid penalties due to reflections but still with limited net gain, a scheme with two cascaded PSAs was reported [6]. However, polarization diversity increases the complexity of the scheme and even more so when two isolated mediums are used. Without the need of extra complexity of polarization-diversity schemes, amplification of a DP-binary phase-shift keying (DP-BPSK) signal with a degenerate vector PSA was recently demonstrated [7]. Although, the degenerate vector PSA is neither modulation-format independent nor wavelength-division multiplexing (WDM) compatible.

In this work, we propose and implement a copier-PSA configuration with a non-degenerate vector parametric amplifier for the first time. This configuration is WDM compatible and can theoretically amplify any DP-modulation format without the need of polarization-diversity. In our experiments, we demonstrate PS amplification of a 28 Gbaud DP-quadrature phase-shift keying (QPSK) signal with the proposed configuration achieving about 0.7 dB sensitivity improvement with regard an EDFA-based receiver. To the best of our knowledge, this is the first demonstration of phase-sensitive (PS) amplification of any DP multilevel-modulated signal with large net gain.

2. Experimental setup and results

The experimental setup is shown in Fig. 1. The signal, S, at 1554.2 nm was divided into two different paths with an I/Q modulator in each one. Each I/Q component of the I/Q-modulators were driven with decorrelated PRBS at 28 Gbaud, and the DP-QPSK was created by combining these two paths with a polarization-beam combiner (PBC). The signal after the transmitter was combined with both pumps before being launched into the copier with a power of about -3 dBm. The two pumps, P_1 and P_2, with wavelengths of 1541.4 nm and 1563.0 nm were phase dithered by driven a phase modulator (PM) with three tones (100, 300 and 900 MHz) in order to avoid stimulated Brillouin scattering (SBS) in both parametric amplifiers. Then, they were amplified by high-power EDFAs before being combined with the signal. The cross-polarized pumps were launched into the copier with a power of about 31 dBm each. The copier

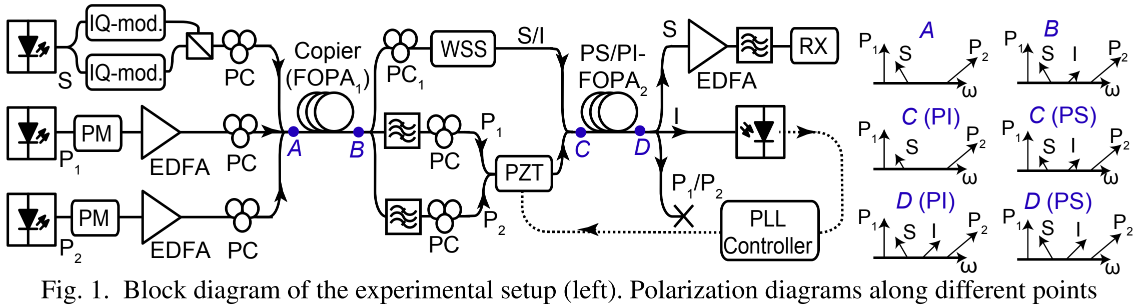

Fig. 1. Block diagram of the experimental setup (left). Polarization diagrams along different points marked in the setup (right) for one of the polarization channels. Acronyms are explained in the text.

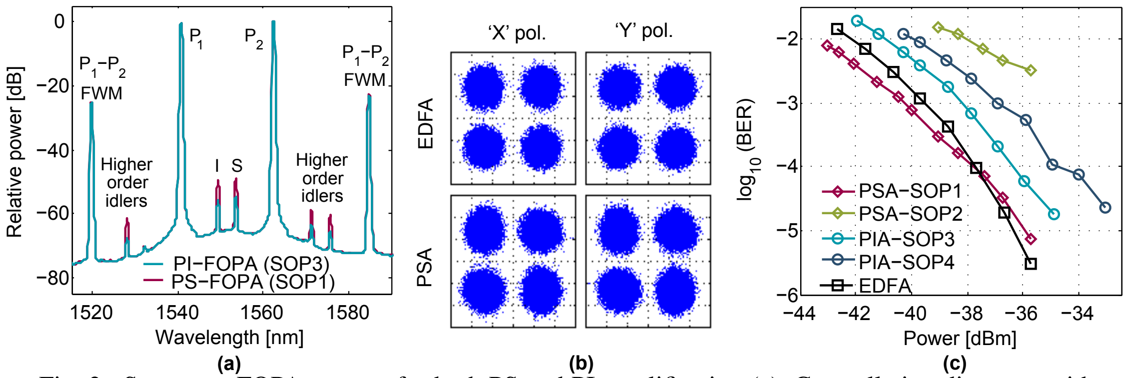

Fig. 2. Spectra at $FOPA_2$ output for both PS and PI amplification (a). Constellation diagrams with EDFA-based and PSA-based receivers (b). BER curves (average BER of both polarization channels) as a function of the signal (combined signal and idler power in PS mode) power for the EDFA-based and PS(PI)-FOPA-based receivers (c).

consisted of a highly-nonlinear fiber (HLNF) of 35 m length, zero dispersion wavelength (ZDW) of 1550 nm, 1 dB loss, nonlinear coeffecient of 11.8 $(W{\cdot}km)^{-1}$ and polarization-mode dispersion (PMD) of 0.01 ps. Monitor ports at the input and output of the copier enabled us to track that the pumps were cross-polarized. In the copier, the idler, I, at a wavelength of 1550.0 nm was created with a conversion efficiency of about -9 dBm. As shown in the polarization diagrams, Fig. 1, represented for only one polarization channel of the DP-QPSK signal, the created idler is always orthogonally polarized with the signal, even if the signal state of polarization (SOP) changes from symbol to symbol.

After the copier, the pumps were filtered out to remove additional waves created in the copier before being launched into $FOPA_2$ with orthogonal polarization. In this path, we also included a piezoelectro transducer (PZT) to control the relative phase between the pumps, the signal and the idler. The signal and the idler were directed to a wavelength-selective switch (WSS) which allowed us to operate $FOPA_2$ in either a PI or PS mode by selecting only the signal or the signal and the idler. The WSS also acted as a variable attenuator in order to control the signal launch power into $FOPA_2$. The signal or signal/idler were then combined with the pumps before being launched into the PI/PS-FOPA, $FOPA_2$. Note that when operating in PS mode, the signal and the idler must be orthogonally polarized when launched into $FOPA_2$ as shown in Fig. 1. The pumps powers were about 26 dBm each. $FOPA_2$ consisted of a 500 m long HNLF with 1.1 dB loss, ZDW of 1552 nm, nonlinear coefficient of 11.8 $(W{\cdot}km)^{-1}$ and PMD of 0.04 ps. We monitored that the pump were cross-polarized before and after $FOPA_2$. After $FOPA_2$, the signal and idler were split into two different paths and the pumps were entirely attenuated. The signal was further amplified by an EDFA before being detected by an intradyne coherent receiver. The signals were processed offline using a typical DP-QPSK receiver based on the constant modulus algorithm and Viterbi-Viterbi-based phase estimation. The idler was detected by a low-speed photodectetor to feedback the phase-locked loop (PLL) controller.

We characterized the gain of $FOPA_2$ as a function of the signal/idler SOP by tuning the polarization controller (PC) in the signal/idler branch, PC_1. In PI mode, the vector PIA is theoretically polarization-insensitive but polarization-dependent gain is induced by the PMD in the HNLF. In our case, the maximum $PI - \mathrm{FOPA}_2$ net gain was about 6.3 dB. The spectrum at the output of the PI-FOPA when achieving maximum gain is shown in Fig. 2 (a). As can be seen, apart from amplifying the signal, the idler was created in the FOPA. Higher-order idlers were also created in the fiber with relative low power. Weak four-wave mixing (FWM) between the pumps due to PMD in the HNLF can also be observed. The minimum $PI - \mathrm{FOPA}_2$ gain with regard to the signal SOP was about 6 dB. Therefore, this PIA showed a polarization dependent gain of about 0.3 dB. When operating in PS mode (equal signal and idler input power), the gain also varied as a function of the signal/idler SOP although in a ideal fiber, the gain does not depend on the signal/idler SOP when rotating both signal and idler simultaneously. The spectrum at the $PS - \mathrm{FOPA}_2$ when achieving the maximum gain is shown in Fig. 2 (a). This spectrum resembles the spectrum when operating in PI mode and same signal input power but for the larger gain. The maximum PS gain was about 11.7 dB. This mean that the PSA gain is about 5.4 dB higher than the PIA gain which agrees well with the 6 dB larger gain theoretically predicted for a high-gain FOPA. The constellation diagrams when the input signal and idler powers were about -33 dBm each are shown in Fig. 2 (b) and compared to the case of an EDFA-amplified signal (input power of -36 dBm). The constellation diagrams demonstrates that the DP-QPSK signal can be amplified by the vector PSA. The PS gain was about 8.9 dB with the worse conditions in the signal/idler SOP. This is only 2.6 dB higher gain than the lowest PIA gain showing that vector amplification is more affected by the PMD when operating in PS mode.

We also evaluated the performance of the PS/PI-FOPA as preamplifier and measured bit-error rate (BER) curves, Fig. 2 (c), with regards to the input power. As a benchmark, we measured the BER curve of the DP-BPSK signal when the preamplifier was based on an EDFA with NF of about 4.2 dB. In the EDFA case, the sensitivity at BER=10^{-3}

was about -39.6 dBm, which given the EDFA NF means that our implementation penalty was about 0.9 dB. When measuring the performance of the PI-FOPA we evaluated the cases for maximum (PIA-SOP3) and minimum (PIA-SOP4) signal amplification with regard to the SOP. Sensitivities were different for these cases, when we achieved maximum gain at the PIA, the sensitivity was about -38.3 dBm. On the other hand, when the PIA gain was minimized with regard to the signal SOP, the sensitivity power was about -36.9 dB. This different behaviour in a vector PI-FOPA with regard to the signal SOP has also been noticed when measuring the NF of a vector PIA [8]. When evaluating the PSA performance, we accounted for the combined power of the signal and idler. When the signal/idler SOP was aligned to achieve maximum amplification in the PSA (PSA-SOP1), the sensitivity was about -40.3 dBm. When signal/idler SOP was aligned such the PSA gain was the lowest (PSA-SOP2), we were not able to measure error-free performance.

3. Discussion

We have compared the performance of vector PS and PI amplifiers and EDFA. The EDFA-based receiver had 1.3 dB better sensitivity than the PI-FOPA-based receiver although both amplifiers have the same quantum limited NF, 3 dB. The reason is that the PI-FOPA was limited by the PMD in the HNLF and the pump phase dithering. Furthermore, the low gain of the PI-FOPA also degraded the performance relative to the ideal theory. The theoretical improvement of the FOPA when operating in PS mode relative to PI mode operation is 3 dB for a high-gain FOPA. In our measurements, the sensitivity improves about 2 dB in the PS-FOPA-based receiver relative to the PI-FOPA-based receiver. Characterization of the idler after the copier is necessary to further understand what limits the performance of the PS-FOPA. However, the pump phase modulation prohibits this since the phase modulation is transferred to the idler. Any degradation on the idler generated at the copier reduces the performance of the PS-FOPA. Modulating the pump phases with opposite would enable the characterization of the idler after the copier and after $FOPA_2$. The PMD in the HNLF also manifested as gain dependence on the signal (signal/idler) SOP of the vector FOPA in both PS and PI modes in contrast to what it is predicted theoretically. The effects of the PMD can be decreased using a shorter HNLF and larger pump power. Lower pump wavelength separation will also decrease the PMD-induced deviation from theoretical predictions. However, higher-order idlers are enhanced when the pump separation is small, and this deteriorates the performance of the FOPA. An HLNF in which the dispersion is designed such that the pump spacing can be small with negligible presence of high-order idlers, would reduce the limiting PMD effects. Not only PMD in the fiber, but also PMD in the components between the copier and the PS-FOPA limited the PSA performance.

Compared to previous experiments where PSAs were implemented in a polarization-diverse configuration using two different mediums [6], the vector PSA shows larger dependance on the signal/idler SOP. However, analysis of such PSA as preamplifier and comparison with EDFA-based receiver were not done since that PSA was limited by the input coupling loss and low net gain. Further research should be carried out in order to compare vector PSAs with scalar PSAs in polarization-diverse configurations with large gain in both cases.

4. Conclusion

We have experimentally assessed the performance of a non-degenerate vector PSA to amplify a 28 Gbaud DP-QPSK signal. To the best of our knowledge, this is the first demonstration of PS amplification of a single-channel signal with bit rates over 100 Gbit/s with large net gain due to the fact that the proposed PSA can work with DP modulation formats. This proof-of-principle demonstration shows that the vector PSA can amplify DP-modulated signal without requiring additional complexity of polarization-diverse schemes. Compared to an EDFA-based receiver, an about 0.7 dB sensitivity improvement was achieved when operating the PSA with optimum signal/idler SOP. However, the PSA performance was degraded by the PMD in the HNLF. Overcoming this limitation would enable an amplifier capable of low-noise amplification of DP-modulated signals as well as WDM compatible.

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References

1. Z. Tong et al., “Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers,” Nat. Photonics, **5**, 430-436 (2011).
2. R. Tang et al., “Gain characteristics of a frequency nondegenerate phase-sensitive fiber-optic parametric amplifier with phase self-stabilized input,” Opt. Express, **13**, 10483-10493 (2005).
3. S. L. I. Olsson et al., “Long-Haul (3465 km) transmission of a 10 GBd QPSK signal with low noise phase-sensitive in-line amplification,” ECOC’14, paper PD.2.2.
4. G. K. P. Lei and M. E. Marhic, “Amplification of DWDM channels at 1.28 Tb/s in a bidirectional fiber optical parametric amplifier,” Opt. Express, **22**, 8726-8733 (2014).
5. T. Umeki et al., “First demonstration of high-order QAM signal amplification in PPLN-based phase sensitive amplifier,” Opt. Express, **22**, 2473-2483 (2014).
6. T. Umeki et al., “First demonstration of PDM signal amplification using PPLN-based polarization-independent phase sensitive amplifier,” ECOC’14, paper We.2.5.3.
7. A. Lorences-Riesgo et al., “Phase-sensitive amplification and regeneration of dual-polarization BPSK without polarization diversity,” ECOC’14, paper Tu.1.4.3.
8. P. Kylemark et al., “Noise in orthogonally pumped fiber-optical parametric amplifiers,” IEEE Photon. Tech. Letters, **19**, 88-90 (2007).