Quadrature demultiplexing using a degenerate vector parametric amplifier

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Abstract: We report on quadrature demultiplexing of a quadrature phase-shift keying (QPSK) signal into two cross-polarized binary phase-shift keying (BPSK) signals with negligible penalty at bit-error rate (BER) equal to 10^{-9}. The all-optical quadrature demultiplexing is achieved using a degenerate vector parametric amplifier operating in phase-insensitive mode. We also propose and demonstrate the use of a novel and simple phase-locked loop (PLL) scheme based on detecting the envelope of one of the signals after demultiplexing in order to achieve stable quadrature decomposition.

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1. Introduction

In long-haul transmission systems, the use of multilevel modulation formats such as m-level phase-shift keying (PSK) or quadrature-amplitude modulation (QAM) in conjunction with coherent detection has increased steadily in recent years. Due to this, research on schemes which perform all-optical signal processing of advanced modulation formats has also attracted much attention. There have been different demonstrations which covered different applications and modulation formats such as phase and amplitude regeneration of quadrature-phase-shift keying (QPSK) [1] and 8-QAM [2] signals and compensation of non-linear-transmission distortions of QPSK [3] and 16-QAM [4] signals.

An important functionality attractive for future network applications is all-optical quadrature decomposition where the in-phase (I) and quadrature (Q) components of a signal are separated. Decomposition of quadratures would enable many modulation format conversions such as obtaining two binary-phase-shift keying (BPSK) signals from a QPSK signal or two 4-level amplitude-shift keying (ASK) signals from a 16-QAM signal. Quadrature demultiplexing can be utilized to achieve regeneration of QPSK signals by performing quadrature demultiplexing, subsequent regeneration of both BPSK signals and lastly combining both regenerated signals into a QPSK signal [5]. A scheme to demultiplex a QPSK signal into two BPSK signals at two different wavelengths has already been demonstrated numerically [6], and experimentally [7, 8] using phase-sensitive four-wave mixing (FWM). This scheme is challenging due to the need to control and lock the phases of four pump waves such that the QPSK signal is correctly decomposed. Another limitation of this scheme is that the output signals are located at two different wavelengths from the input signal. Using a conventional two-pump degenerate scalar phase-sensitive amplifier (PSA) to obtain one of the signal quadratures has also been demonstrated experimentally [9]. A QPSK signal can be converted into a BPSK signal corresponding to either the I or the Q quadrature with a correct phase relation between the signal carrier and the pumps. However, this scheme outputs only one quadrature and the other quadrature could only be obtained by parallelization which increases the complexity.

Decomposition of both quadratures on two signals at the same wavelength but with orthogonal polarizations has also been proposed and demonstrated numerically [10]. This scheme requires the use of four phase-locked waves and the output wavelength is different from the input wavelength which makes this scheme less attractive. Recently, we proposed the use of a dual-pump driven degenerate vector fiber-optic parametric amplifier (FOPA) in order to convert a QPSK signal into a dual-polarization (DP)-BPSK signal [11]. To achieve quadrature demultiplexing, the input signal needs to be co-polarized with one of the pumps and cross-polarized with the other pump. The output idler is a conjugated copy of the input signal at the same wavelength but with orthogonal polarization. The combination of the signal and idler correspond to the decomposition of the signal quadratures on two cross-polarized waves when they are equalized in power. Therefore, this scheme does not have such strong requirements regarding the number of locked waves. Moreover, the output is at the same wavelength as the input.

Experimentally, demultiplexing one quadrature using a low-gain degenerate vector FOPA and a polarizer has recently been demonstrated [12]. The second quadrature could be simultaneously demultiplexed with another polarizer. In that work, bit-error rate (BER) measurements were reported but with noticeable error-floor. Both quadratures were obtained at different times by aligning a PC before the polarizer. As the quadratures were driven by inverse sequences and differentially detected, it is not clear how the quadratures were distinguished. Similarly, in [13], a high-gain FOPA followed by a polarization-beam splitter (PBS) were used to demonstrate quadrature demultiplexing. While constellation diagrams show that the scheme demultiplexes both quadratures, full BER measurements are necessary in order to fully understand the limitations and penalties of the scheme. Therefore, there is need for an experimental demonstration of decomposition of both quadratures without major penalty using the degenerate vector FOPA. Furthermore, a complete theoretical description of this scheme still needs to be reported in order to better understand its limitations

In this paper, we analyze the use of the vector FOPA in order to perform quadrature decomposition. We comprehensively analyze the proposed scheme theoretically and derive the dependence of the output wave on the input wave and fiber parameters. The theoretical description shows that the polarizations of the waves into which the signal is decomposed are only stable when the relative phase between the signal and the pumps is kept constant. We experimentally demonstrate QPSK to DP-BPSK conversion with very low penalty at a BER of 10^{-9}. To overcome the phase fluctuations induced by ambient perturbations (e.g. temperature drifts and mechanical vibrations), we describe and implement a novel phase-locked loop (PLL) scheme.

2. Principle of operation

The scheme of a degenerate vector FOPA operating in phase-insensitive (PI) mode (no input idler, Id) is shown in Fig. 1. The input consists of three waves, two cross-polarized pumps, P_1 and P_2, and the signal, S, which is co-polarized with one of the pumps. Besides amplifying the signal, the vector amplifier creates a fourth wave, the idler, which is a conjugated copy

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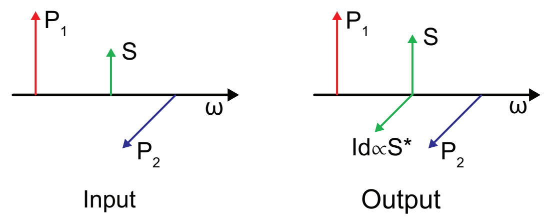

Fig. 1. Polarization diagram of a degenerate vector amplifier operating without input idler

of the signal at the same frequency but with orthogonal polarization. The output degenerate wave defined as the combination of the signal and the idler, $\vec{D_{\text{out}}} = S_{\text{out}}\vec{x} + Id_{\text{out}}\vec{y}$, is determined by [14]

$$\vec{D_{\text{out}}} = \mu S_{\text{in}}\vec{x} + \nu S_{\text{in}}^{*}\vec{y} = |S_{\text{in}}|\left[(\mu\vec{x} + \nu\vec{y})\cos(\phi_{\text{S}}) + j\,(\mu\vec{x} - \nu\vec{y})\sin(\phi_{\text{S}})\right], \tag{1}$$

where μ and ν are the transfer coefficients (related by $|\mu|^2 - |\nu|^2 = 1$) and the input signal is defined as $S_{\text{in}} = |S_{\text{in}}|e^{j\phi_{\text{s}}}$. The orthogonal vectors, $\vec{x}$ and $\vec{y}$, express the pump polarizations which do not need to be linearly polarized. Equation (1) indicates that the output degenerate wave can be expressed as the sum of two waves with two different polarizations which carry the I/Q information of the input signal. Therefore, we can obtain the I and the Q components of the input signal with a polarizer aligned to the polarizations defined by

$$\vec{P_{\text{I}}} = (\nu\vec{x} + \mu\vec{y})/\sqrt{|\mu|^2 + |\nu|^2}, \tag{2}$$

$$\vec{P_{\text{Q}}} = (\nu\vec{x} - \mu\vec{y})/\sqrt{|\mu|^2 + |\nu|^2}. \tag{3}$$

The output of this polarizer, S_{pol}, can be expressed as

$$S_{\text{pol,I}} = 2\mu\nu|S_{\text{in}}|\cos(\phi_{\text{S}})/\sqrt{|\mu|^2 + |\nu|^2} \tag{4}$$

$$S_{\text{pol,Q}} = 2\mu\nu|S_{\text{in}}|\sin(\phi_{\text{S}})/\sqrt{|\mu|^2 + |\nu|^2} \tag{5}$$

when selecting the I, Eq. (4), and the Q, Eq. (5) components. Thus, in order to demultiplex only one quadrature by the means of a vector FOPA and a polarizer, the gain required for the parametric amplifier can be relatively low which translate in low requirements in pump powers. However, the loss of the total scheme (degenerate vector FOPA and polarizer) would be in the order of $|\nu|$ in this case. A similar concept, using a vector FOPA followed by a polarizer, was also investigated in order to achieve phase squeezing with low pump powers [15].

The polarization axes with I and Q information are orthogonal in the limit $|\mu|, |\nu| >> 1$ since $\vec{P_I} \cdot \vec{P_Q} = \frac{|\nu|^2 - |\mu|^2}{|\mu|^2 + |\nu|^2} = \frac{-1}{|\mu|^2 + |\nu|^2}$ approaches zero with high parametric gain. This means that with high gain, the signal quadratures are decomposed into two orthogonal waves at the same wavelength as the incoming signal and therefore, we can split the two independent signals by the means of a PBS. The same decomposition can be obtained if signal and idler are equalized after the amplifier, although equalization would reduce the gain of the overall system.

Creating a wave and its orthogonally polarized conjugated copy was experimentally achieved for the purpose of cancelling impairments due to the nonlinearities in the fiber transmission [16]. In contrast to the scheme presented here based on a degenerate vector FOPA, Liu et al. [16] created both conjugated waves by electro-optic modulation within the transmitter. Thus, the scheme proposed in this paper has the capability to create such pair of conjugated waves all optically.

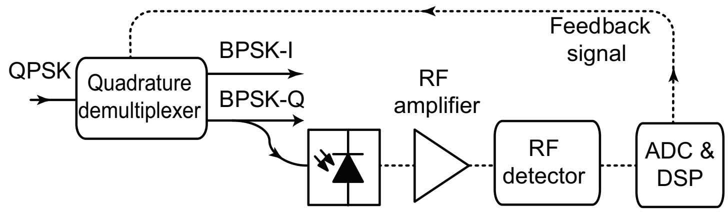

Fig. 2. Schematic of the proposed PLL. RF, radio frequency; ADC, analog-to-digital converter; DSP, digital signal processing.

3. Phase-locked loop for quadrature decomposition

In the previous section, we have explained that the degenerate vector FOPA with high gain can demultiplex the signal quadratures into two orthogonal polarizations. Thus, a QPSK signal can be split into two BPSK signals or a 16-QAM in two 4-ASK signals by a PBS after the degenerate vector PI amplifier. However, splitting the output signal by means of a PBS is not trivial since the orientation of the polarization axes depends on the phase of the coefficients μ and ν as seen in Eqs. (2) and (3); i.e., the polarization orientation depends on the pump phases relative to the signal carrier phase. Therefore, a drifting phase relation between the pump phases and the signal carrier phase means that the signal quadratures are decomposed into drifting polarizations axes. These polarization variations can be compensated for in digital signal processing (DSP) in a coherent receiver but both BPSK signals cannot be split into two different paths unless their polarization is orthogonal and stable. Thus, a PLL is required in order to overcome the polarization instability and achieve quadrature demultiplexing.

The design of a PLL scheme for quadrature decomposition is not trivial and different PLL solutions have been implemented in previous experimental demonstrations of quadrature decomposition [7–9,12,13]. A PLL scheme based on a complex and hardware-demanding scheme which involved the use of an additional parametric amplifier, the so-called phase-comparator [17]), was demonstrated to perform well at a BER as low as 10^{-7} [9]. A PLL scheme based on detecting the mean power of one of the BPSK signals was also implemented [7,8,12]. It is not clear how this PLL scheme worked since the mean power of a quadrature does not depend on the constellation rotation for the QPSK decomposition. Furthermore, the penalty in the measured BER curves due to the PLL was not negligible, implying that it is essential to design a simple and efficient PLL scheme to perform quadrature decompositions.

In order to further understand the importance of the PLL, we assume that the input signal is a QPSK signal defined with constant amplitude and $\phi_s = \phi_{\text{Drift}} + \phi_{\text{Data}}$, with $\phi_{\text{Data}} \in \{\pm\pi/4, \pm 3\pi/4\}$ defining the constellation symbol and ϕ_{Drift} being the rotation of the signal constellation with respect to the pumps which is usually caused by thermal and mechanical effects (for simplicity we assume that the pump phases are stable and the signal constellation is rotating with regard to them). Then, the wave after a polarizer aligned to obtain the I component is

$$S_{\text{pol,I}} = 2\mu\nu|S_{\text{in}}|\cos(\phi_{\text{Data}} + \phi_{\text{Drift}})/\sqrt{|\mu|^2 + |\nu|^2}. \quad (6)$$

Equation (6) implies that maintaining $\phi_{\text{Drift}} = 0$ rad is required to obtain a BPSK signal corresponding to the I component of the input QPSK signal. We also observe that the mean power of the optical signal after the polarizer does not depend on the constellation rotation, ϕ_{Drift}, because the data information is still present. However, the optical power of the signal after the polarizer is constant in the ideal case, $\phi_{\text{Drift}} = 0$ rad. Due to symmetry, the optical power is also constant when $\phi_{\text{Drift}} = \{\pm\pi/2, \pi\}$ rad. Otherwise, the optical power of the signal after the polarizer has variations determined by the data. Maximum power variation correspond to

$\phi_{\mathrm{Drift}} = \{\pm\pi/4, \pm 3\pi/4\}$ rad. The fact that the instantaneous optical power depends on the constallation rotation, ϕ_{Drift} is used for the feedback to the proposed PLL whose block diagram is shown in Fig. 2. As depicted, one of the signals in which the input signal is decomposed is detected by a fast photodetector (as fast as the data modulation) whose electrical output current is $I_{\mathrm{PLL}} \propto \cos(2\phi_{\mathrm{Data}} + 2\phi_{\mathrm{Drift}})$, where we neglect the direct current (DC) component. Under ideal conditions, without having ambient perturbations, the electrical signal is constant. In practice, instead of constant amplitude, the electrical signal has fast transitions on the order of the symbol rate determined by the phase drift, ϕ_{Drift}. We can use an envelope detector (square law) in order to extract the phase fluctuations due to environmental drifts. The envelope detection outputs $I^2_{\mathrm{PLL}} \propto \cos(4\phi_{\mathrm{Data}} + 4\phi_{\mathrm{Drift}})$ and therefore the fast transitions due to the data modulation have been removed. This signal is digitized by an analog-to-digital converter (ADC) in order to be processed such that a feedback signal minimizing I^2_{PLL} is created. The ideal BPSK signal is then obtained from the demultiplexing. The ADC bandwidth is determined by the speed of the drift which are induced by the kHz-speed ambient perturbations (e.g. temperature and vibrations).

The proposed PLL circuit is valid to any quadrature QPSK demultiplexer regardless of the demultiplexing scheme. This concept can also be applied when decomposing a 16-QAM signal despite the different power levels of the signals. Note that in the proposed scheme for quadrature decomposition based on a degenerate vector FOPA, the PBS is not required for the PLL implementation. The output degenerate wave could be tapped after the vector amplifier. Then, we can obtain one of the quadratures by placing a polarization controller (PC) followed by a polarizer. The signal after the polarizer can be used as the feedback signal such that the DP-BPSK signal would have stable polarization on both waves carrying the BPSK data.

4. Quadrature demultiplexing of a QPSK signal into two cross-polarized BPSK signals

4.1. Experimental setup

The experimental setup is shown in Fig. 3. An electro-optic comb driven by a tunable laser was created with about 40 lines and 25 GHz frequency separation. From this comb, a wavelength-selective switch (WSS) selected three lines at wavelengths of 1554.0 nm (P_1), 1556.2 nm (S) and 1558.4 nm (P_2). These three waves were divided in three different paths by a wavelenght-division multiplexing (WDM) coupler. The path for the two pumps, waves at 1554 nm and 1558.4 nm, corresponded to the upper and lower branch in Fig. 3. They were amplified by two high power EDFAs after injection locking (EM4 distributed feedback lasers, injected power of about -5 dBm) which assured a good optical signal-to-noise ratio (OSNR). Note that a high pump OSNR was required due to the low signal power launched into the FOPA, about -23 dBm, and the low pump power after the comb. A comb with lower insertion loss and smaller number of lines would have avoided the use of injection locking. After the EDFAs, both pumps were filtered with 1 nm bandwidth optical band-pass filters (OBPFs) and their state of polarizations (SOPs) were controlled using PCs. The signal propagated through the middle branch and was modulated in the transmitter consisting of an IQ-modulator driven at 10 Gbaud. The I quadrature was modulated with a non-return to zero (NRZ) pseudo-random binary sequence (PRBS) of length equal to $2^{15} - 1$ and the Q quadrature with the inverse signal delayed by 23 ns. After the modulator, we included a PC in order to tune the signal polarization at the input of the vector amplifier. The three waves were combined before the PSA which consisted of a cascaded four stages of strained higly-nonlinear fiber (HNLF) separated by isolators similar to the one previously reported [18]. The pump powers were 29 dBm each and the signal power was -23 dBm. Through monitor ports placed at both the HNLF input and the HNLF output, we tracked the input spectrum, the constellation diagram with a coherent receiver and the orthogonality between the pumps with a polarimeter. After the HNLF, the combined signal/idler wave was filtered out and split in two paths by a 3 dB coupler. In the upper path, the degenerate wave was split by a

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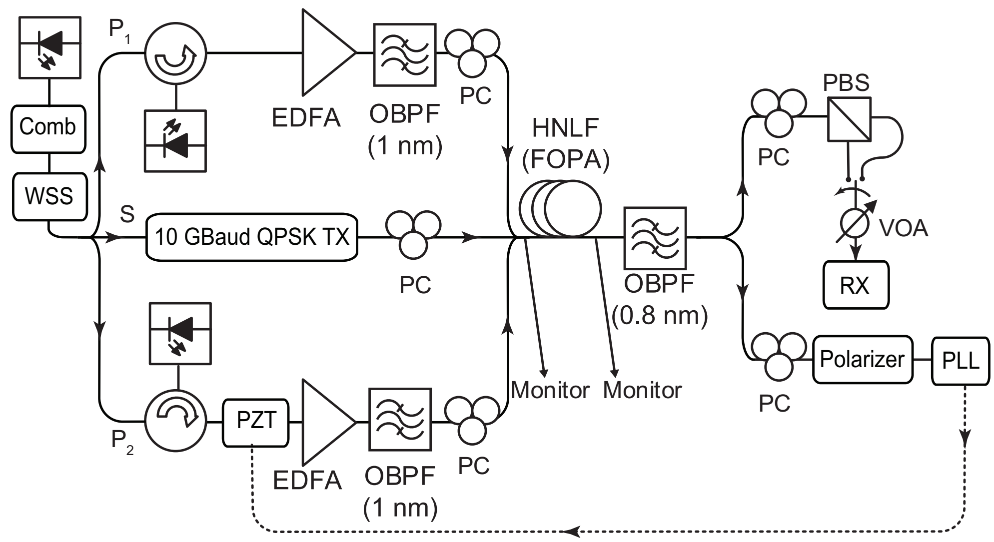

Fig. 3. Block diagram of the experimental setup used for quadrature demultiplexing. The monitor port included optical spectrum analyzers (OSA), polarimeter and digital coherent receiver. WSS, wavelength-selective switch; PC. polarization controller, EDFA, erbium-doped fiber amplifier; OBPF, optical band-pass filter; TX: transmitter; PZT, piezo-elecro transducer; PBS, polarization beam splitter; VOA, variable optical attenuator, RX: preamplified differential receiver; PLL, phase-locked loop.

PBS into either the signal and the idler or the waves corresponding to quadrature demultiplexing by controlling a PC before the PBS. One of the PBS output was connected to a preamplified balanced receiver and therefore we could either evaluate the performance of the QPSK signal and conjugated QPSK idler, or the performance of the BPSK signals by aligning the polarization of the degenerate wave into the PBS. In the lower path, the combined signal/idler wave was first amplified and then passed through a polarizer to obtain the feedback signal for the PLL scheme which was based on the proposed PLL in Section 3. In our experiments, we use a photodiode of 40 GHz bandwidth, RF amplifier of 14 GHz bandwidth and RF dectector of 50 GHz bandwidth. After the RF detector, the ADC sampled the electrical at a speed of 320 kSamples/s (8 times the frequency of the dithering tone).

4.2. Experimental results

We first aligned the polarizations such that the pumps were cross-polarized at the input of the HNLF as well as the output. Due to the fiber polarization-mode dispersion (PMD), the pumps could get partially co-polarized along the fiber if they were not launched with specific states of polarizations. To make sure that the pumps were orthogonal, we monitored the pump degree of polarization (DOP) at the input and the ouput of the HNLF using a polarimeter. During the measurements, we kept the pump DOP minimal at both input and ouput of the HNLF. Note that in an ideal case the P_1-P_2 DOP is 0 only when the pump have equal powers and are cross-polarized. Then, the input signal polarization was aligned such that we minimized the output signal/idler power variations when the input signal was not modulated and the relative phase between the pumps and signal was not stabilized by the PLL. An ideal PI behavior would correspond to 0 dB swing and PS operation, input signal not being co-polarized with one of the pumps, translates into signal/output power variations if the input signal is not modulated. Note that power variations in PS mode would also vanish if the input signal is modulated as

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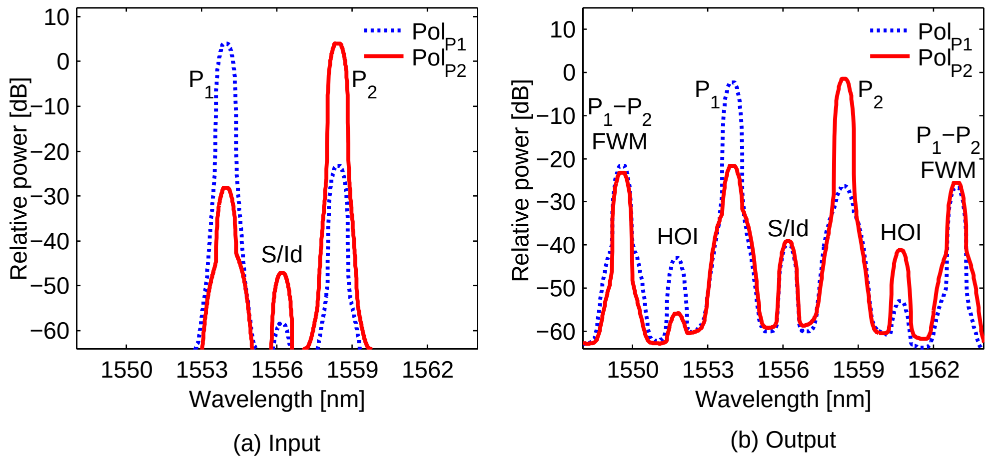

Fig. 4. Spectra of the vector FOPA input and output decomposed on the polarizations given by the P_2 and the P_1 polarizations . FWM, four-wave mixing; HOI, higher-order idler.

a QPSK signal. The power variations of the combined signal/idler wave at the HNLF output (no modulation on the input signal) were measured to be in a 0.7 dB range which confirmed we were operating close to PI mode as desired. The spectra after a PBS when the input polarization was aligned to obtain P_2 at the output in one output port are shown in Fig. 4(a). The pumps had a extinction ratio of about 30 dB (limited by the extinction ratio of the PBS). The signal polarization was almost parallel to the P_2 polarization with an extinction larger than 11 dB. One could expect larger power extinction, however previous studies show that degenerate vector FOPAs are very affected by the PMD in the HNLF [11].

Once we made sure we were operating in PI mode, we evaluated the output of the amplifier. The spectra of the signal and idler at vector FOPA output are shown in Fig. 4(b). As can be seen, the signal and the idler are quite equal in power with a power imbalance of 0.8 dB. The net gain (defined as combined output idler-signal power with respect of the input signal power) of the vector amplifier was about 12.9 dB (16.5 dB on-off gain). At the FOPA output, higher-order idlers (HOIs) were also present. These HOIs do not affect the FOPA performance in order to achieve quadrature demultiplexing. Furthermore, additional waves were also created in the FOPA due to weak FWM between the pumps caused by PMD. We show the signal constellation at the input and output of the vector FOPA in Fig. 5. The constellations were measured using an intradyne coherent receiver. For the input constellation, we used the standard constant-modulus algorithm (CMA), frequency estimation based on the Fourier transform and Viterbi-Viterbi phase estimation. For the output constellation, we adapted the CMA algorithm used for polarization-switched-QPSK signals [19] in order to obtain the DP-BPSK signal. This CMA algorithm works for any polarization-switched-m-level-PSK and the DP-BPSK format is equivalent to polarization-switched-BPSK given a certain polarization rotation. We represent the output as a DP-BPSK signal, but it could be also represented as a DP-QPSK signal where one QPSK signal is conjugated with regard to the other one.

Once known that the QPSK signal was converted to a DP-BPSK signal, we investigated the performance of the proposed scheme by measuring BER curves, shown in Fig. 6, after the PBS which output either the signal and idler or both BPSK signals by controlling the PC before the PBS. As reference, we also measured the BER curves of the back-to-back (without degenerate vector FOPA) BPSK and QPSK signals using the same receiver. When measuring the signal and the idler, the QPSK signal and the conjugated copy, we first connected one output of the PBS to

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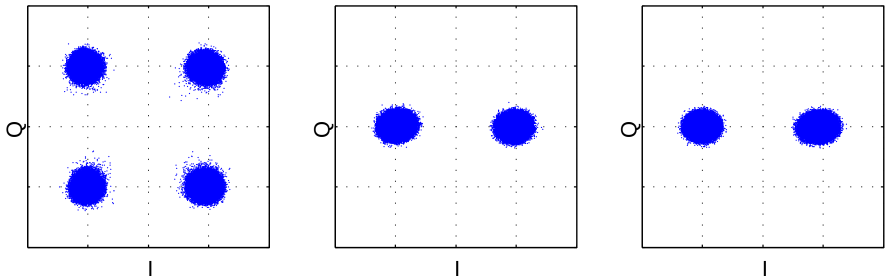

(a) Input, 'Y polarization' (b) Output, 'X+Y polarization' (c) Output, 'X−Y polarization'

Fig. 5. Constellation diagrams of the degenerate wave at the vector FOPA input (QPSK signal) and output (DP-BPSK signal). The input signal is a single-polarized QPSK signal co-polarized with P_2 and cross-polarized with P_1. The polarization for each output BPSK signal forms at 45° (Jones space) angle with each pump polarization. Note that pump polarizations are chosen to be 'X' and 'Y' in order to maintain the definitions used in Section 2.

the receiver and then we connected the other output without modifying the PC before the PBS. This ensures that both signals are orthogonally polarized. The same procedure was carried out when measuring the BPSK signals in which the I and Q components were demultiplexed. We aligned the PC before the PBS such that we obtained the I component at one PBS output and the Q component at the other output. Since the proposed PLL does not distinguish whether we are decomposing the I or Q component, we additionally delayed one of the components by about 10 ps. Then, when measuring the BER of one of the PBS outputs, we were sure that it always corresponded to the same quadrature and when changing to the other output it also corresponded to the other quadrature since due to the symmetry between quadratures we could not otherwise distinguish between them. This small delay between the quadratures did not bring any improvement in the BER curves or PLL performance, and the only function was to distinguish between the quadratures of the QPSK signal.

Regarding the QPSK signals, the sensitivity of the QPSK signal without being amplified by the vector FOPA is -35.5 dBm at BER $= 10^{-9}$. The penalty introduced by the vector FOPA is about 1.1 dB in both the signal and the idler (QPSK signal and conjugated copy) at BER $= 10^{-9}$ and negligible penalty at BER $= 10^{-3}$. We believe that the main penalty source is the weak PS behavior of the vector FOPA since with a continuous wave (CW) signal, the output power of the degenerate wave varied about 0.7 dB. The performance of the signal and the idler are comparable. We also aligned the PC before the PBS to demultiplex the QPSK into its I and Q components. Both BPSK signals had also similar with sensitivity at BER $= 10^{-9}$ of -38.2 dBm which corresponds to a penalty of 1.9 dB with respect to a BPSK signal detected with the same receiver. Comparing the sensitivity penalties when measuring the signal and the idler sensitivities to the DP-BPSK, we observe a 0.8 dB extra penalty in the BPSK signals. The main reason for this extra penalty is due to the imbalance between the signal and the idler powers and thus, the penalty due to the PLL is low.

4.3. Discussion on quadrature decomposition

The experimental results demonstrate that a QPSK signal can be converted into a DP-BPSK signal using a degenerate FOPA operating in PI mode and thus its quadratures can be demultiplexed by means of a PBS. Converting a QPSK into a DP-BPSK signal mitigates the penalty seen using coherent receivers with large local-oscillator phase-noise [20]. In differential direct-detection, such conversion can also improve the receiver sensitivity since the penalty of differ-

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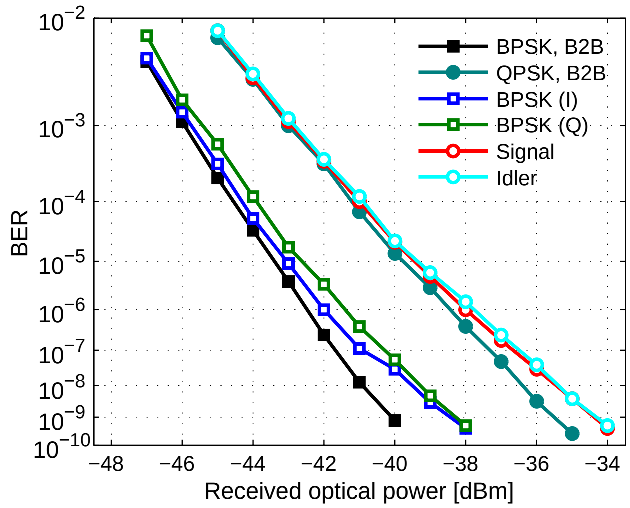

Fig. 6. BER vs. received optical power for a BPSK signal, QPSK signal, signal (QPSK) after the vector FOPA, idler (conjugated QPSK) after FOPA, and BPSK signals in which the I and Q components are demultiplexed.

entially detecting a QPSK signal at BER=10^{-9} is about 2.3 dB larger than when differentially detecting a BPSK signal [21]. Using the degenerate vector FOPA, obtaining a DP-BPSK from a QPSK signal can be achieved with high gain in the parametric amplifier. Achieving high gain without the use of phase-modulated pumps in a FOPA is possible using strained HNLFs [18] although straining the fibers increases the PMD [22, 23]. For example, in this case the fiber differential-group delay (DGD) was about 0.4 ps which is at least one order of magnitude higher than the DGD of a conventional HNLF with the same length (600 m). Correct aligning of the pump and signal polarizations in presence of high PMD is essential in order to achieve the expected behaviour of the FOPA [11]. Indeed, our results show that the penalty for the QPSK signals after the vector FOPA is 1.1 dB and the main reason for this penalty is expected to be not exclusive PI behaviour of the degenerate vector FOPA. Counter-phase-modulated pumps could be used in order to use standard HNLFs which are not strained [24]. Apart from increasing the complexity, counter-phase-modulated pumps still causes a certain penalty in practice.

When using a low-gain FOPA, quadrature demultiplexing can also be performed by splitting the FOPA output degenerate wave into two paths with one polarizer in each path. Each polarizer is aligned such that we obtaining each quadrature in one of the branches. If the purpose is QPSK-to-DP-BPSK format conversion, the DP-BPSK can be obtained by combining both BPSK signals with a PBC. However, using a low-gain FOPA and a polarizer introduces loss over the output BPSK signals which should be compensated with an additional amplifier.

4.4. Discussion on PLL

Regarding the PLL performance, we believe that no major penalty is caused by the PLL. Usually PLL-caused penalty manifest as an error floor at low BERs (e.g. BER equal to 10^{-9}). We did have an additional penalty of 0.8 dB in the sensitivity of the BPSK signals compared to the penalty of the QPSK signal after the vector FOPA. However, as mentioned, the main reason for this penalty is the 1 dB power imbalance of the signal and idler. The proposed PLL can work in any quadrature demultiplexing scheme which requires stabilization. The DSP code in the PLL minimized the electrical input signal to the ADC which means that we were obtaining a

BPSK signal at the input of the photodetector used in the PLL circuit. Maximizing the electrical signal, $\phi_{Drift} = \pm\pi/4$ to the DSP would translate into an three-level signal at the input of the photodetector for the PLL according to Eq. (6). The amplitude of this signal would carry the information of the bits given by XOR operation between the quadrature and inphase bits used to generate the QPSK signal. The FOPA output degenerate wave would still be a DP-BPSK signal, with stable polarization but with a 90° rotation in the Poincaré sphere of the polarization axes for each BPSK signal. However, if the polarization of the degenerate wave into the PBS after the vector FOPA is not realigned, the PBS outputs will not correspond to the BPSK signal but to the three-level signal; which in turn means that modulation switching can be performed by only controlling the DSP implementation.

5. Conclusion

We have demonstrated quadrature demultiplexing of a QPSK signal into two BPSK signals using a degenerate vector parametric amplifier operating on phase-insensitive mode. The vector amplifier created an idler (conjugated copy of the signal) at the same frequency of the signal but with orthogonal polarization. The combination of the output signal and idler enables quadrature demultiplexing when the signal and the idler are equalized in power. The signal constellations at the input and the output of the amplifier verified the quadrature decomposition. A novel phase-locked loop circuit proposed here based on a envelope detector allowed us to split both BPSK signals in two different path by the means of a PBS and detect both of them with low penalty (1.9 dB with respect a back-to-back BPSK signal). The performance was mainly limited by the PMD in the HNLF. Overcoming this limitation while maintaining the parametric gain would enable quadrature decomposition with even lower sensitivity penalty.

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