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Quadrature Decomposition of a 20 Gbaud 16-QAM Signal into 2×4-PAM Signals

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Abstract *We propose a novel phase-sensitive processor capable of operating at low nonlinear phase shifts. With a nonlinear phase shift of 2×0.15 rad, quadrature decomposition is demonstrated with penalty of 0.5 dB at BER=10^{-3}.*

Introduction
Triggered by the use of coherent optical receivers in conjunction with digital signal processing (DSP), transmission of spectrally-efficient M-ary quadrature-amplitude modulation (M-QAM) signals is becoming a common solution in optical communications. Therefore, demonstrations of all optical signal processing including wavelength conversion, regeneration, nonlinear mitigation and quadrature decomposition of M-QAM signals are of great interest. However, experimental all-optical signal processing of higher-order QAM (M>4) signals is very challenging because these signals impose large constraints on the optical signal-to-noise ratio (OSNR) degradation, phase noise or any other impairment caused by the processor. Due to these large constraints, experimental demonstration have been limited mainly to wavelength conversion[1]. Other demonstrations include low-noise amplification and mitigation of nonlinearities when transmitting conjugated pair of 16-QAM signals by using a phase-sensitive amplifier (PSA)[2]. This scheme however implies a 50% reduction of spectral efficiency which contrasts with the use of a spectrally-efficient modulation format. Regeneration of 8-QAM data has also been demonstrated but limited to the star 8-QAM format[3]. Therefore, there is lack of demonstrations concerning advanced functionalities of all-optical signal processing for higher-order QAM signals.

Another functionality provided by all-optical signal processing is quadrature decomposition, which could be of great interest in flexible networks for data deaggregation or as the first stage for regeneration of 16-QAM signals when followed by a two-level amplitude regenerator[4]. Such functionality has recently attracted much attention with proposals of different schemes where the demultiplexed signals are at different wavelength locations[5] or at the same wavelength as the input signal[6–8]. However, experimental demonstrations have been limited to quadrature demultiplexing of quadrature phase-shift keying (QPSK) signals. Differential quadrature decomposition, quadrature decomposition of the differential signal between two consecutive symbols, of a 8 phase-shift keying (PSK) signal has also been demonstrated[9] but this scheme is not suitable for multilevel amplitude signals such as 16-QAM. In this paper, we perform the first experimental demonstration of quadrature demultiplexing of a 16-QAM signal into two 4-PAM signals. We propose and demonstrate the use of a novel phase-sensitive processor scheme based on a polarization-diverse PSA. Similar to the polarization-assisted PSA[8], the scheme used in this paper can operate at low nonlinear phase shifts. In addition, the proposed scheme is not susceptible to the birefringence of the nonlinear medium which could be beneficial for integration. Our bit-error rate (BER) measurements shows that both quadratures can be obtained simultaneously with a low penalty of about 0.5 dB at BER=10^{-3}.

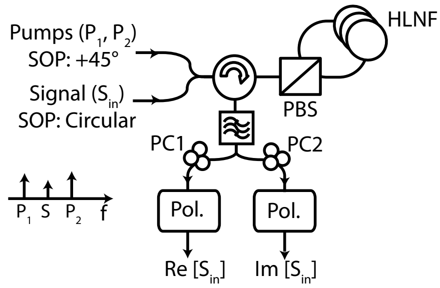

Fig. 1: Schematic for quadrature decomposition based on a polarization-assisted phase-sensitive processor with a polarization-diverse implementation.

Polarization-assisted phase-sensitive processor using polarization-diverse implementation
In order to perform quadrature demultiplexing we propose the scheme shown in Fig. 1. Two co-polarized pumps are combined with the signal, which is located at the middle frequency of the pumps, before a polarization-beam splitter (PBS). The state of polarization (SOP) of the pumps is adjusted to be linear +45° and the signal SOP to be right-hand (or left-hand) circular polarization. After the PBS, both the signal and pump waves

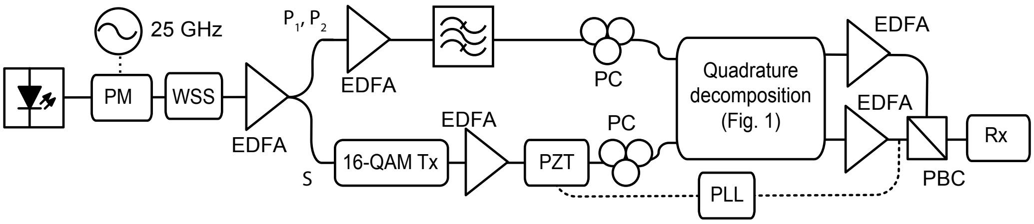

Fig. 2: Experimental setup.

are split in a 50% ratio in each direction. The waves are combined by the PBS and a circulator separates the output from the input. The signal after the circulator can be expressed as[10]

$$S_{\text{out}} = \frac{(\mu S_{\text{in}} + \nu S_{\text{in}}^{*})\hat{x} + j(\mu S_{\text{in}} - \nu S_{\text{in}}^{*})\hat{y}}{\sqrt{2}} \quad (1)$$

where μ and ν are complex coefficients which depend on the pump waves, fiber parameters and wavelength allocation. We can rewrite Eq. (1) as

$$\begin{aligned} S_{\text{out}} &= \text{Re}[S_{\text{in}}](\hat{x}(\mu+\nu) + j\hat{y}(\mu-\nu))/\sqrt{2} \\ &+ \text{Im}[S_{\text{in}}](j\hat{x}(\mu-\nu) - \hat{y}(\mu+\nu))/\sqrt{2}, \end{aligned} \quad (2)$$

where Re and Im represents the real and imaginary part. According to Eq. (2), the output signal can be expressed as the combination of two signals proportional to the real and imaginary part of the input signal. We can notice that quadrature decomposition can be performed by splitting the output signal with a 3 dB coupler and one polarizer at each output of the 3 dB coupler. To obtain the real part, the polarizer should be aligned to cancel out the component proportional to the imaginary part and viceversa to obtain the imaginary component. It is important to emphasize that quadrature decomposition can be ideally obtained regardless the gain/conversion efficiency in the amplification process, which would not be the case when using two independent PSAs. However, the power of the demultiplexed signals does depend on the gain/conversion efficiency.

The scheme proposed in this paper is similar to the recently proposed polarization-assisted phase-sensitive processor (PSP) based on vector parametric amplifiers[8]. The main difference is that the scheme proposed here utilizes the fiber in both directions. However, the integration of the scheme we proposed would be simpler since it does not require the design of a optical waveguide capable of propagating two polarization modes with similar loss and dispersion properties[11]. When integrating the proposed scheme, instead of the loop configuration, the polarization diversity could be implemented using two different nonlinear devices to avoid any penalty caused by reflections.

Experimental setup

The experimental setup is shown in Fig. 2. A 25 GHz phase modulator was overdriven to generate multiple tones, from which we filtered three waves, both pumps (λ=1552.9 and 1555.3 nm) and the signal (λ=1554.1 nm), with a wavelength-selective switch (WSS). An erbium-doped fiber amplifier (EDFA) compensated for the loss of the modulator and WSS. With a wavelength-division multiplexing (WDM) coupler, the signal was directed to the lower path whereas the pumps were directed to the upper path. The signal was modulated as a non-return-to-zero (NRZ) 20 GBaud 16-QAM signal with different patterns for the in-phase and the quadrature components. The pumps were amplified and filtered with an 3 nm filter before being combined with the signal with a WDM coupler which corresponds to the input of the demultiplexer shown in Fig. 1. A 150 m long highly-nonlinear fiber (HNLF) with nonlinear coefficient γ=10 (W·km)$^{-1}$ was used as nonlinear medium. The combined power at the input of the HNLF in each direction was about 100 mW which corresponds to a nonlinear phase shift of γPL =0.15 rad in each direction of the fiber.

A correct behaviour of the demultiplexer was assured by proceeding as follows. First, the pump input SOP was aligned to divide equally its power in both directions after the PBS. Then, the signal input SOP was aligned such that at the output of the circulator there were no power variations when the input signal was a continuous wave (CW). We aligned one of the polarization controllers (PC1 in Fig. 1) before the polarizer to achieve maximum phase-sensitive extinction ratio (PSER) when the signal was still a CW. The measured PSER was larger than 22 dB which highlights the capability of the proposed PSP without requiring large nonlinear phase shifts. Lastly, we assured that when maximum signal power was directed to one output of the demultiplexer, the signal power at the output of the other demultiplexer was minimized when operating in CW. The demultiplexed signals were amplified and combined with a polarization-beam combiner (PBC) before the receiver which consisted of a noise-loading stage and a intradyne coherent receiver. The combi-

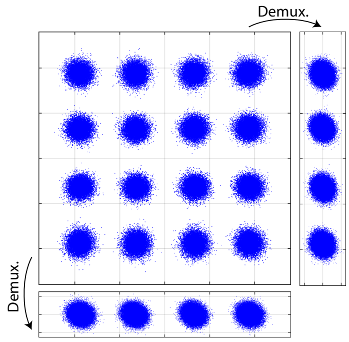

Fig. 3: Constellation diagrams of the incoming 16-QAM signal and the two quadrature demultiplexed 4-PAM signals.

nation of both 4-PAM signals with a PBC allowed us to measure both signals simultaneously by using a polarization-diverse coherent receiver. We however aligned the signal SOP to avoid polarization demultiplexing in the DSP. Moreover, one of the demultiplexed signals was used as feedback for the phase-locked loop (PLL), which stabilized the demultiplexer using the envelope detection scheme presented in[7].

Experimental results and discussion

The constellation diagrams of the input 16-QAM signal and both demultiplexed 4-PAM signals are shown in Fig. 3. Note that we verified that both 4-PAM signals corresponded to the different quadratures since the inphase and quadrature component of the 16-QAM signal had different bit patterns. We analyzed the penalty caused by the demultiplexer by evaluating the BER curves for each 4-PAM signal and compared to the 16-QAM signals. Figure 4 shows the BER of the generated 16-QAM signals and both demultiplexed 4-PAM signals as a function of the received OSNR. It should be emphasized that in the case of the 4-PAM signals, the OSNR was measured when we detected both signals simultaneously by polarization multiplexing. Therefore, in an ideal demultiplexer, the curves for 4-PAM signals and the 16-QAM signal should be identical. In our case, no major difference can be observed for BER above 10^{-4}. The required OSNR for BER=10^{-3} of the demultiplexed 4-PAM signals was about 17.8 dB and for input 16-QAM signal was 17.3 dB (about 1.7 dB implementation penalty at BER=10^{-3}). Therefore, the PSP introduced a penalty of about 0.5 dB which demonstrates the capability of the scheme to perform quadrature decomposition even though we were using a nonlinear phase shift of about 0.15 rad in each direction. At low BER, we can however observe that the penalty for the demultiplexed signals increases, which was mainly caused by a non-optimal performance of the PLL system. Since the gain/conversion efficiency of the system was very low, a thorough optimization of the PLL system would have improved the performance at

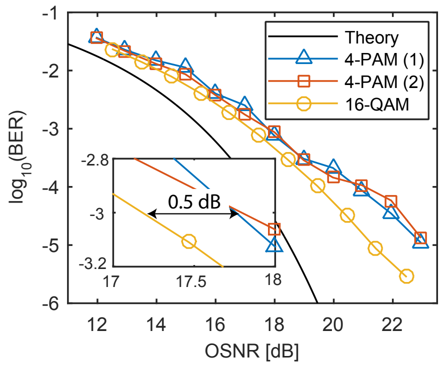

Fig. 4: BER vs. OSNR for the 16-QAM signal and both quadrature demultiplexed 4-PAM signals.

such low BERs. Another important parameter which could be further optimized is the alignment of the polarizers, which was critical due to the low nonlinear phase shift at which we operated.

Conclusions

We have proposed a novel scheme for performing quadrature demultiplexing at low nonlinear phase shifts and demonstrated quadrature decomposition of a 20 GBaud 16-QAM signal into two 4-PAM signals with low penalty. The nonlinear phase shift in each direction was about 0.15 rad, which highlights the potential for integration of the proposed scheme.

Acknowledgments

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