

# Optics Letters

## Simultaneous all-optical phase noise mitigation and automatically locked homodyne reception of an incoming QPSK data signal

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**Simultaneous phase noise mitigation and automatic phase/frequency-locked homodyne reception is demonstrated for a 20–32 Gbaud QPSK signal. A phase quantization function is realized to squeeze the phase noise of the signal by optical wave mixing of the signal, its third-order harmonic, and their corresponding delayed variant conjugates, converting the noisy input into a noise-mitigated signal. In a simultaneous nonlinear process, the noise-mitigated signal is automatically phase- and frequency-locked with a “local” pump laser, avoiding the need for feedback or phase/frequency tracking for homodyne detection. Open eye-diagrams are obtained for in-phase and quadrature-phase components of the signal and  $\sim 2$  dB OSNR gain is achieved at BER  $10^{-3}$ .** © 2016 Optical Society of America

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Optical homodyne systems are known to provide superior sensitivity and performance as compared to heterodyne systems, and to enable detection of both amplitude and phase information of an incoming data signal [1]. For homodyne reception, the local oscillator **LO** should have the same frequency and phase as the incoming data signal. In other words, the data signal and the **LO** must be both phase- and frequency-“locked” to each other [2–6].

Several approaches have been developed for phase and frequency locking for homodyne reception. In one approach, the carrier is transmitted along with the data signal. This consumes some of the spectrum or polarization state which can be otherwise allocated to data [2]. To overcome this cost, a laser **LO** can

be used in the receiver side and coupled to a phase-locked loop (PLL) and/or signal processing algorithm to support locking [3,4]. However, feedback loops require a short loop delay in general and need time to achieve a stable “lock” [5].

Phase noise is another limiting factor of coherent communication systems, and thus phase noise mitigation is of great concern for efficient homodyne detection of phase-encoded signals, such as phase-shift-keying (PSK) [7–14]. Phase noise originates from different sources, including the linewidth-based phase noise of the transmitter laser and the **LO** of the receiver [13,14], as well as nonlinear phase noise [7–12]. Nonlinear phase noise originates from the interaction of amplified spontaneous emission (ASE) noise and Kerr nonlinearities, and its bandwidth can be as broad as the data signal (in contrast to the phase noise of commercial lasers, which is as small as a few kilohertz to megahertz) [7–12].

It is useful to simultaneously satisfy the two challenges of phase and frequency locking and phase noise mitigation in an optical homodyne system. Recently, a technique was reported that used two fixed pump lasers and nonlinear wave mixing to generate an **LO** that is automatically “locked” to the data signal to achieve homodyne detection without the need for feedback or phase and frequency tracking [6]. Although the homodyne reception scheme in [6] can mitigate phase noise with low bandwidth compared to the data signal, it falls short of mitigating higher bandwidth phase noise as broad as the data signal. In this Letter, we extend the idea of [6] and demonstrate a homodyne receiver with high-bandwidth phase noise mitigation. The high-bandwidth phase noise of a QPSK signal is squeezed by realization of a “phase quantization” function based on the coherent summation of higher-order signal harmonics [9].

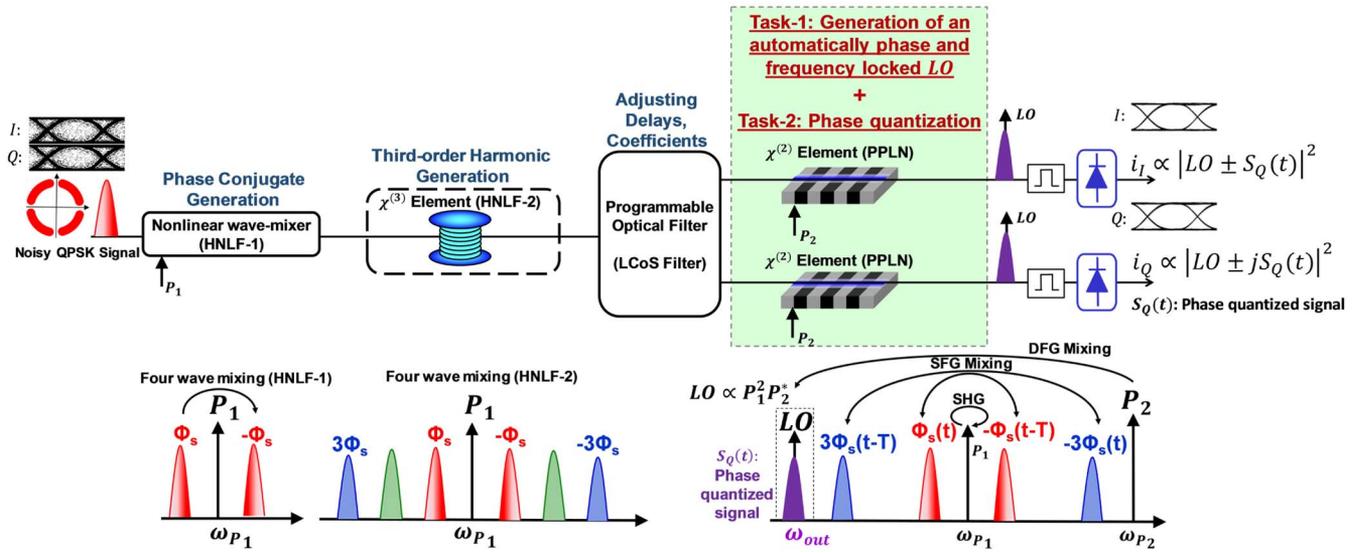


Fig. 1. Conceptual block diagram of the simultaneous phase noise mitigation and automatically locked homodyne reception.

In our proposed method, the phase quantization and the automatic locking of LO to the signal are realized simultaneously by concurrent nonlinear processes in a nonlinear element.

The conceptual block diagram of the simultaneous phase noise mitigation and automatically locked homodyne reception scheme is shown in Fig. 1. In the following, each nonlinear stage of the scheme will be explained in detail. An incoming QPSK signal contaminated with phase noise is coupled with a CW pump laser  $P_1$  and sent into a nonlinear wave mixer—a highly nonlinear fiber (HNLf)—to generate a conjugate copy of the signal. In the HNLf, the signal  $S(t)$  and the pump  $P_1$  interact through the four-wave mixing (FWM) nonlinear process and generate a conjugate copy of the signal with an electric field proportional to  $P_1^2 S^*(t)$ .

The signal, the pump  $P_1$ , and the conjugate copy are sent into a second nonlinear medium with the third-order nonlinear susceptibility  $\chi^{(3)}$  to generate the third-order harmonics of the signal. In this stage, the signal and its conjugate are mixed through a nonlinear FWM process in a second HNLf and generate the third-order signal harmonics with electric fields proportional to  $P_1^{*2} S^3(t)$  and  $P_1^4 S^{*3}(t)$ . In an optical programmable filter based on liquid crystal on silicon (LCoS) technology, one symbol delay ( $T$ ) is applied between: (i) the signal and its conjugate copy, and (ii) the third-order harmonic signals generated in the second HNLf. The adjusted signals, along with a new CW pump  $P_2$ , are injected into a final nonlinear stage with the second-order nonlinear susceptibility  $\chi^{(2)}$  in which two tasks will be done simultaneously. **Task-1**, phase quantization: a staircase phase transfer function is realized based on the signal, its conjugate, and the generated third-order harmonics to quantize the phase of the input signal [8,9]. In detail, the signal and its one-symbol-delayed conjugate copy are mixed through a cascaded process of sum-frequency-generation (SFG) and difference-frequency-generation (DFG) nonlinear processes and generate a new signal  $E_1(t)$ . Similarly, in a concurrent nonlinear processes, the conjugate third-order signal harmonic and one-symbol-delayed third-order signal harmonic are mixed through a cascaded SFG-DFG process and generate a signal  $E_2(t)$ . The coherent summation of the two fields  $E_1(t)$  and

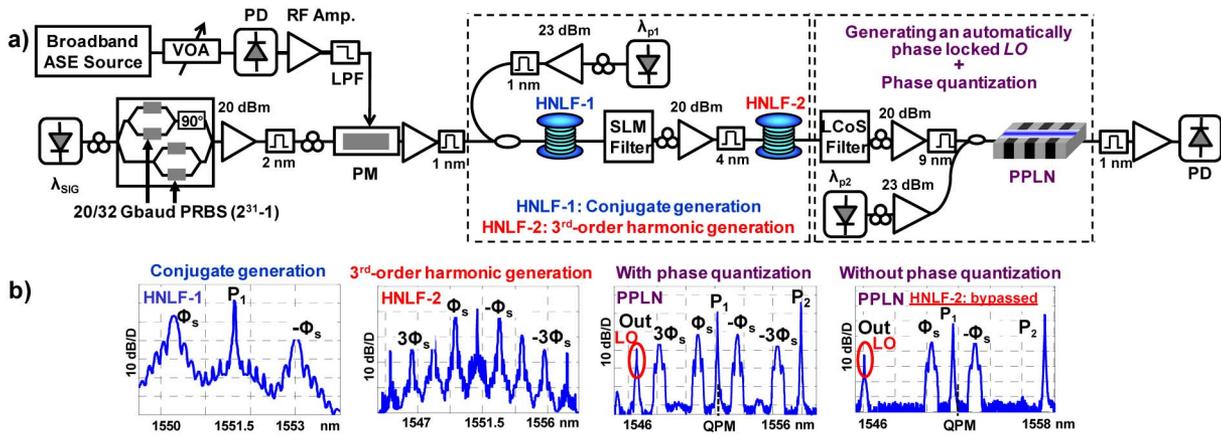
$E_2(t)$  results in phase quantization of the input signal. The phase quantized signal  $S_Q(t)$  can be written as

$$\begin{aligned} S_Q(t) &\propto P_2^* S(t) P_1^2 S^*(t-T) + \alpha P_2^* P_1^2 S^3(t-T) P_1^4 S^{*3}(t) \\ &= P_2^* P_1^2 [S(t) S^*(t-T) + \alpha [S(t) S^*(t-T)]^3] \\ &\propto e^{j(\Phi_s(t) - \Phi_s(t-T))} + \alpha e^{-j3(\Phi_s(t) - \Phi_s(t-T))} \\ &= e^{j\Delta\Phi_s(t)} + \alpha e^{-j3\Delta\Phi_s(t)}, \end{aligned} \quad (1)$$

where the appropriate value of  $\alpha$  can be adjusted in the LCoS filter by changing the relative phase and amplitude values of the signal and the harmonics [8]. In Eq. (1),  $\Delta$  is defined as a difference operator over one symbol interval  $T$ , i.e.,  $\Delta\Phi_s(t) = \Phi_s(t) - \Phi_s(t-T)$ . Equation (1) represents the phase quantization function which enables squeezing the phase noise of the input signal.

The second task, **Task-2**, is to generate a local oscillator, LO, which is automatically phase- and frequency-locked with the phase-noise-mitigated signal  $S_Q(t)$ . In detail, the pumps  $P_1$  and  $P_2$  generate a new field  $P_2^* P_1^2$  through the cascaded SFG-DFG processes which is used as an LO in the homodyne system. Although the input signal  $S(t)$  is from a laser which is not phase-locked to the pump lasers  $P_1$  and  $P_2$ , the noise-mitigated signal  $S_Q(t) \propto P_2^* P_1^2 [S(t) S^*(t-T) + \alpha [S(t) S^*(t-T)]^3]$  and the generated LO  $\propto P_2^* P_1^2$  have the same phase reference of  $2\Phi_{P_1} - \Phi_{P_2}$  due to the common term  $P_2^* P_1^2$  in the electric fields of LO and  $S_Q(t)$ . The noise-mitigated signal  $S_Q(t)$  and the LO are coherently mixed with an appropriate relative complex coefficient adjusted in the optical programmable LCoS filter. The final optical output can be written as  $S_{\text{out}}(t) \propto \text{LO} + w S_Q(t)$ , where  $w$  denotes a complex coefficient. By sending the output to a photodetector and setting  $w$  to  $\pm 1$  or  $\pm j$ , similar to a  $90^\circ$  optical hybrid, the in-phase and quadrature components of the noise-mitigated signal can be obtained.

If the value of  $\alpha$  in Eq. (1) is set to zero, the phase quantization will be removed and Eq. (1) simplifies to  $S_{\text{diff}}(t) = \exp(j\Delta\Phi_s(t))$ . This can be realized by bypassing the second HNLf for third-order harmonic generation in Fig. 1. In this



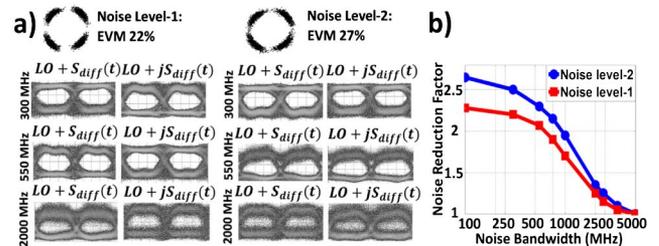
**Fig. 2.** Experimental setup. PD, photo detector; VOA, variable optical attenuator; LPF, low pass filter; PM, phase modulator; HNLFF, highly nonlinear fiber; PPLN, periodically poled lithium niobate; SLM, spatial light modulator. (b) 20-Gbaud optical spectra after HNLFF-1 (conjugate generation), HNLFF-2 (third-order harmonic generation), and PPLN (with and without phase quantization).

case, the scheme is reduced to the automatically locked homodyne detection method proposed in [6]. In  $S_{diff}(t)$ ,  $\Delta$  is a difference operator on the phase  $\Delta\Phi_s(t) = \Phi_s(t) - \Phi_s(t - T)$ , and is able to mitigate phase noise with low-bandwidth power spectral density (PSD) as follows: the phase of the signal consists of both phase noise and data. Hence, the phase of  $S_{diff}(t)$  can be written as  $\Phi_{diff}(t) = [\Phi_D(t) - \Phi_D(t - T)] + [\Phi_N(t) - \Phi_N(t - T)] = \Delta\Phi_D(t) + \Delta\Phi_N(t)$ . The term  $\Delta\Phi_D(t)$  represents just the encoded version of the original data, and the term  $\Delta\Phi_N(t)$  can be viewed as a differentiator on the phase noise that filters out the low-frequency phase noise components. Performing the Fourier transform of  $\Delta\Phi_N(t)$  results in  $|\Delta\Phi_N(\omega)| = |\sin(\omega T/2)| |\Phi_N(\omega)|$  in which the lower-frequency components of the phase noise are filtered out by the PSD of the differentiator, i.e.,  $|\sin(\omega T/2)|^2$ .

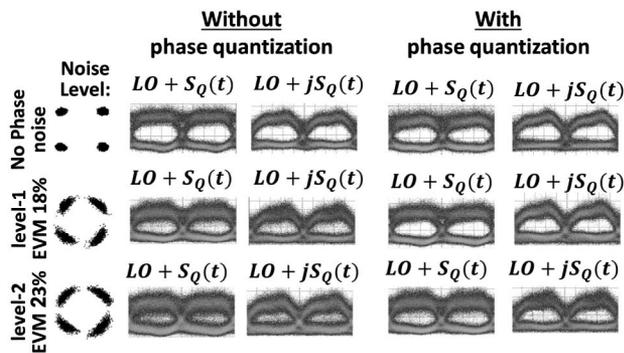
In the following, the experimental details of the simultaneous phase noise mitigation and homodyne reception system are presented. Figure 2 shows the experimental setup of the system. A 20- or 32-Gbaud QPSK data (PRBS 2<sup>31</sup> - 1) is modulated on a CW laser at 1550 nm by using a nested Mach-Zehnder modulator (MZM). The signal is phase-modulated with an ASE source followed by a variable optical attenuator (VOA) and an electrical low-pass filter (LPF) to induce phase noise with different power levels and bandwidths. The signal and a CW pump laser at 1551.5 nm are sent to a ~500 m HNLFF-1 with zero dispersion wavelength (ZDW) of ~1551 nm to generate the conjugate copy. The signals are sent to the spatial light modulator (SLM) filter to adjust amplitudes. They are then sent into a ~300 m HNLFF-2 with a ZDW of ~1551 nm to generate the third-order harmonic signals. The signals are sent into an optical programmable filter based on LCoS technology to adjust the delays and complex weights. The adjusted signals are amplified and coupled with a ~1558-nm CW pump and sent into a PPLN waveguide in which an LO is generated and coherently mixed with the signal, the conjugate copy, and the third-order harmonics to achieve simultaneous phase noise mitigation and automatically phase- and frequency-locked homodyne reception. The noise-mitigated signal and the locked LO are filtered, and sent to a photodiode to capture the eye diagrams and perform the BER measurements. The spectra of each nonlinear stage are

shown for 20-Gbaud QPSK data in Fig. 2(b). In particular, the spectrum of the PPLN output is shown for homodyne reception with phase quantization and homodyne reception without phase quantization when the third-order harmonic generation stage is bypassed by removing HNLFF-2.

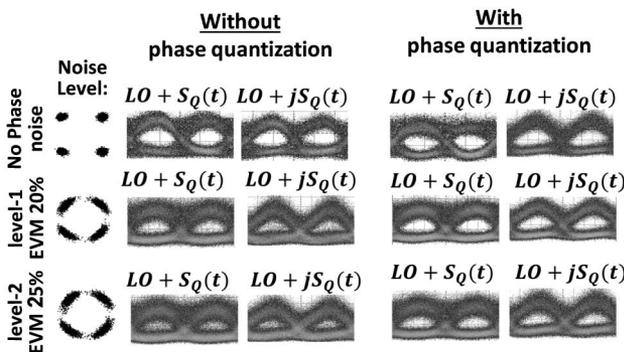
The system performance is assessed using 20- and 32-Gbaud QPSK signals. Figure 3 shows the results of the captured in-phase (I) and quadrature-phase (Q) eye diagrams by the homodyne reception scheme without phase quantization. In this case, a phase differentiator filters out the low-frequency components of the phase noise. Results are obtained for 20-Gbaud QPSK signals with phase noise at three different bandwidths of 300 MHz, 550 MHz, and 2000 MHz and two different noise levels. The eye diagrams indicate that phase noise reduction is significant for phase noise with lower bandwidths, e.g., 300 MHz. However, phase noise mitigation degrades for higher bandwidths such as 2000 MHz. The noise reduction factor is defined as the ratio of the standard deviation of the input phase noise over the standard deviation of the output phase noise [6]. The phase noise can be reduced by a noise reduction factor of more than 2.5 for the high phase noise with a 100-MHz bandwidth [Fig. 3(b)]. The noise reduction factor is reduced and approaches 1 for phase noise with high bandwidth, e.g., 5 GHz.



**Fig. 3.** (a) I/Q eye diagrams of 20-Gbaud QPSK signals contaminated with phase noise at three different bandwidths and two different noise levels obtained by the homodyne reception technique without phase quantization. (b) Phase noise reduction factor of the system for induced phase noise at the two different noise levels and different bandwidths.

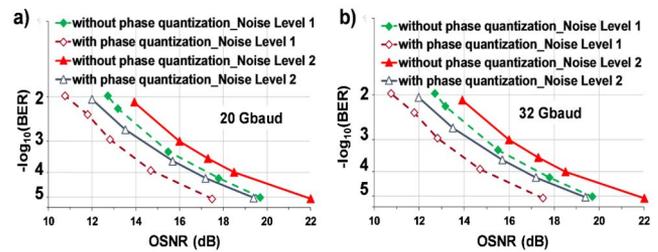


**Fig. 4.** Captured I and Q eye diagrams for 20-Gbaud QPSK signals with phase noise at two different power levels and a bandwidth of  $\sim 40$  GHz obtained by homodyne detection with and without phase quantization.



**Fig. 5.** Captured I and Q eye diagrams for 32-Gbaud QPSK signals with high-bandwidth phase noise at two different power levels using homodyne detection with and without phase quantization.

To mitigate phase noise with higher bandwidth, homodyne reception with simultaneous phase quantization is used. Results were obtained for QPSK signals contaminated with high-bandwidth phase noise at two different power levels. To emulate high-bandwidth phase noise, the electrical low-pass filter (LPF) after the RF amplifier and before the PM in Fig. 2 is removed. As a consequence, the phase noise bandwidth is limited by the 40-GHz PD and 40-GHz RF amplifier in Fig. 2 before the PM. I and Q eye diagrams are detected with and without the phase quantization approach for 20-Gbaud QPSK signals, as shown in Fig. 4. The corresponding estimated EVM for detected signals using homodyne reception without and with phase quantization are near (18.2%, 15%) for noise level-1 and (23%, 17.7%) for noise level-2. Homodyne reception with simultaneous phase quantization mitigates high-bandwidth ( $\sim 40$  GHz) phase noise compared to homodyne detection without phase quantization. Because the generated local oscillator is automatically “locked” in phase and frequency to the noise-mitigated signal in this method, there is no need for phase and frequency recovery for detection. This approach to homodyne reception is baud-rate tunable and the amount of the appropriate delay can be adjusted in the LCoS filter. The captured eye diagrams for 32-Gbaud QPSK signals at two different levels of phase noise are shown



**Fig. 6.** BER measurements for homodyne reception with and without all-optical phase quantization for QPSK signals contaminated with high-bandwidth phase noise at two different noise levels. (a) BER measurements for 20-Gbaud QPSK signals; (b) BER measurements for 32-Gbaud QPSK signals.

in Fig. 5. The corresponding estimated EVM for detected signals using homodyne reception without and with phase quantization are near (20.3%, 15%) for noise level-1 and (26%, 17.7%) for noise level-2.

Figure 6 shows the BER measurements for homodyne reception with and without all-optical phase quantization for 20- and 32-Gbaud QPSK signals contaminated with  $\sim 40$ -GHz phase noise at two different noise levels. All measurements are captured without any phase or frequency tracking, in contrast to conventional coherent detection schemes. This simultaneous phase quantization and homodyne detection system results in nearly a 2-dB OSNR gain at BER  $10^{-3}$ .

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