Experimental Demonstration of Tunable Phase-Noise Mitigation and Automatic Frequency/Phase Locking for a 20-32 Gbaud QPSK Homodyne Receiver using Optical Mixing of Nonlinearly Generated Higher Harmonics

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Abstract: We experimentally demonstrate tunable phase-noise mitigation and automatic frequency/phase locking to a "local" pump laser for a 20-32 Gbaud QPSK homodyne receiver using nonlinear optical signal processing. For the input noisy signal, open eye-diagrams are obtained for in-phase and quadrature components and ~2 dB OSNR gain is achieved at BER 10^{-3}.

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1. Introduction

Homodyne systems have a long history of achieving highly sensitive reception in optical communication systems [1-3]. Similar to coherent systems in general, homodyne systems also enable the recovery and digital signal processing of phase-encoded data signals (e.g., phase-shift-keying, PSK). Such phase-encoded systems can also achieve high spectral efficiency, such as in quadrature PSK (QPSK) and 16 quadrature-amplitude-modulation (QAM) [2-4].

However, efficient PSK homodyne systems present difficult challenges, including: (1) the need to phase and frequency lock the incoming signal to the local oscillator (LO). Typically, this can be accomplished using electronic circuitry, feedback loops, or transmitting pilot tones [2-6]. (2) the need for phase noise mitigation, which is a key limitation for phase-based communication systems [7-10].

There may be a desire to meet these two challenges using optical signal processing. For example, approaches for phase and frequency locking for homodyne reception include optical phase-locked loops that require some electronics and optical nonlinear mixing which may not need additional electronic circuitry [12].

In terms of phase-noise mitigation in coherent systems, methods have included different variations of a phase-sensitive-amplifier-based approach to achieve a level of "phase squeezing" [9-11]. However, these methods tend to require coherency between a data signal and a pump, thereby typically necessitating phase-based feedback loops and injection locking [9-11]. A laudable goal might be to attempt to meet simultaneously both these challenges of automatic frequency/phase locking and phase-noise mitigation in a homodyne system.

In this paper, we experimentally demonstrate tunable phase-noise mitigation and automatic frequency/phase locking for a 20-32 Gbaud QPSK homodyne receiver using optical mixing of nonlinearly generated higher harmonics.
In our scheme, a "local" pump laser is used to generate the signal conjugate and the 3rd-order signal harmonics. By utilizing a second pump laser, the signal and the generated harmonics are multiplexed and the signal phase noise is mitigated. Simultaneously, in another nonlinear process, in the same nonlinear element, the "local" first pump laser is automatically locked and multiplexed to the noise mitigated signal. Open eyes are obtained for the both in-phase and quadrature components of the signal after the noise mitigation and ~2 dB OSNR gain is achieved at BER 10^{-3}.

2. Concept

The conceptual block diagram of the homodyne phase noise mitigation scheme is shown in Fig. 1. A QPSK signal contaminated with phase noise along with a CW pump, P_1, are injected into a nonlinear wave mixer to generate the conjugate copy of the original signal. The signal, the pump, and the conjugate copy are then sent into another nonlinear medium with the third-order nonlinear susceptibility, $\chi^{(3)}$, to generate the third-order harmonics of the signal and the conjugate copy. These signals are sent into an optical programmable filter to apply appropriate delays, amplitudes, and relative phases. The amounts of the delays are adjusted based on the signal-baud rate. The adjusted signals with a second CW pump are injected into a last nonlinear stage with the second-order nonlinear susceptibility, $\chi^{(2)}$. In this stage two tasks will be done simultaneously: 1) phase noise mitigation by building a staircase phase transfer function based on the signal and the generated third-order harmonics [10,13]. This function is built by coherently mixing the

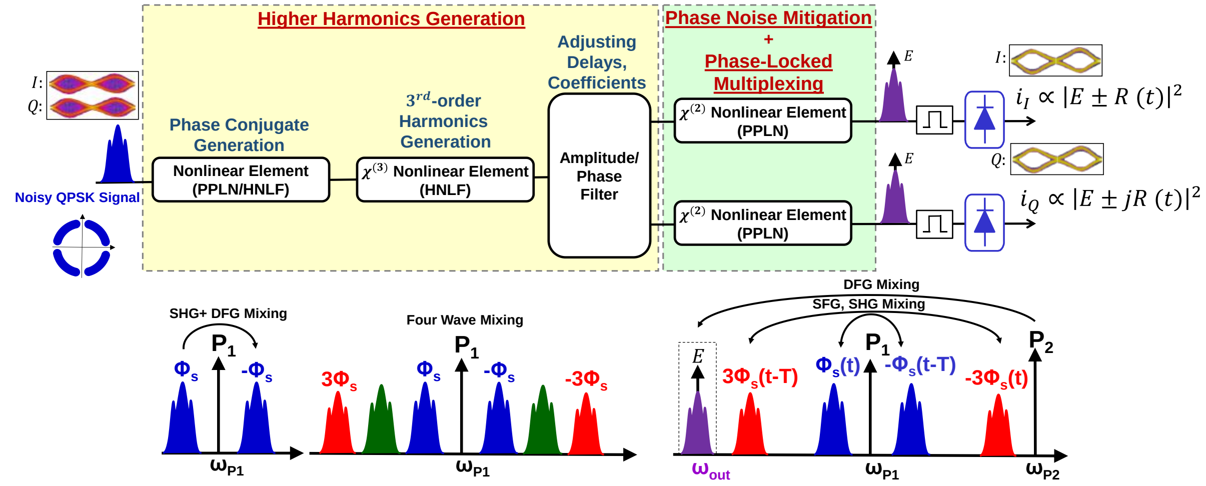

Fig. 1. The concept of the homodyne phase noise mitigation scheme. A "local" fixed laser,P_1, and $\chi^{(3)}$ nonlinear elements are used to generate higher-order signal harmonics. By utilizing another pump laser and a $\chi^{(2)}$ nonlinear element, the signal and the generated harmonics are multiplexed in order to mitigate the signal phase noise. Simultaneously, the "local" laser, P_1, is automatically locked and multiplexed to the noise mitigated signal with an appropriate complex coefficient adjusted in the programmable filter. Finally the output is sent to a photo-detector.

product of the signal and its delayed conjugate, and the product of the delayed third-order harmonic and the conjugate third-order harmonic. We denote the noise mitigated output signal by $R(t)$. 2) Phase-locked multiplexing by the "local" laser P_1: this can be done by multiplexing the phase noise mitigated signal $R(t)$ with the CW pump, P_1, with an appropriate relative complex coefficient adjusted in the programmable filter. The final optical output can be denoted as $S_{out}(t) = E + wR(t)$, where $E = P_1^2$. By sending the output to photo-detectors and setting w to ±1 or ±j, similar to a 90^0 optical hybrid, both in-phase and quadrature components of the noise mitigated input signal can be obtained.

3. Experimental Setup

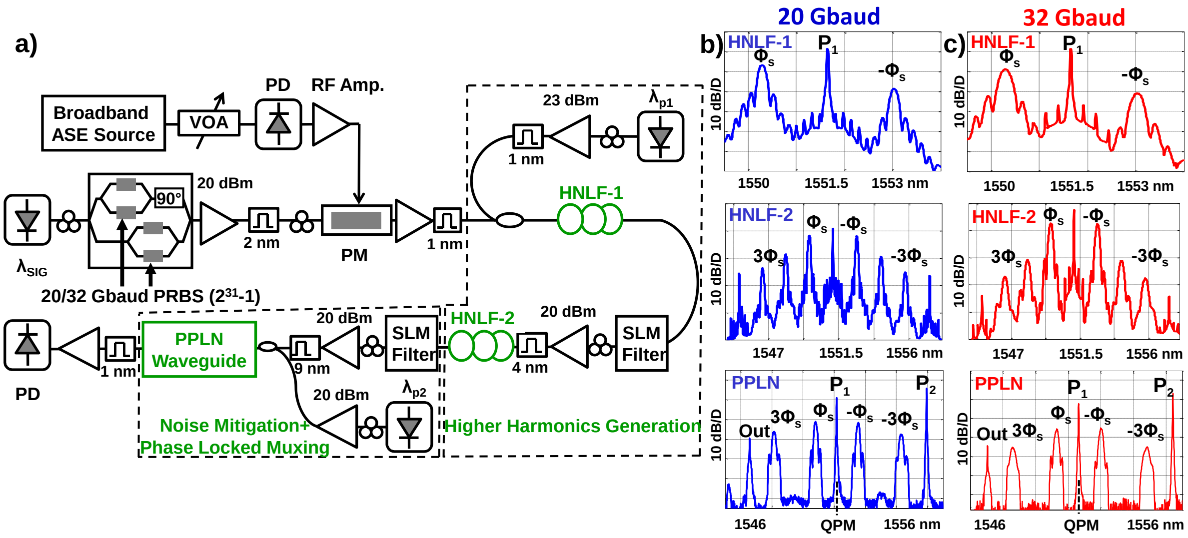

Fig. 2. Experimental setup. PM: Phase modulator, HNLF: Highly nonlinear fiber, PPLN: Periodically poled lithium niobate, SLM: Spatial light modulator, PD: Photo detector, VOA: Variable optical attenuator. (b) 20 Gbaud optical spectra (c) 32 Gbaud optical spectra.

The experimental setup for the homodyne phase noise mitigation scheme is depicted in Fig. 2 (a). A nested Mach–Zehnder modulator is used to generate 20/32-Gbaud QPSK data (PRBS 2^{31}-1) at ~1550nm. The signal is amplified and phase modulated with an ASE source to emulate phase noise. The noisy signal is amplified and coupled with an amplified CW pump around 1551.5 nm and sent to a ~500 m HNLF-1 with ~1551 nm zero dispersion wavelength (ZDW). The HNLF-1 output are sent to a SLM filter for adjusting the signals amplitudes. The output is sent to a ~300 m HNLF-2 with ZDW ~1551 nm to generate the third-order harmonics. The HNLF-2 output is sent to a SLM filter to apply appropriate delays, phases, and amplitudes on the signals. The resulting signals are amplified and coupled with another CW pump around 1558 nm and sent to the PPLN waveguide to 1) coherently mix the product of the signal and its conjugate copy and the product of the third harmonic and its conjugate through the cascaded processes of sum frequency generation (SFG) followed by difference frequency generation (DFG), and, 2) to multiplex the first pump in the output through the cascaded processes of second harmonic generation followed by DFG. The multiplexed signal is then filtered, amplified and sent to a photodiode to capture the eye diagrams and perform the BER measurement. In the Fig. 2 (b,c) the output spectra of the HNLFs, and the PPLN are shown for 20/32-Gbaud QPSK data. As can be seen, the multiplexed signal is always in frequency/phase locked with respect to the generated carrier.

4. Results and Discussion

The performance of the system is assessed by implementing the proposed homodyne phase noise mitigation scheme on 20-32 Gbaud QPSK signals. In order to show the performance of the system, the incoming data signal are contaminated with two different levels of phase noise. Both in-phase and quadrature-phase components of the data signal are detected. The eyes are detected based on 1) the homodyne detection scheme without phase noise mitigation [14] and 2) the proposed homodyne phase noise mitigation method. Figures 3 and 4 show the resultant eye-diagrams for 20, and 32 Gbaud signals, respectively. Open eyes can be achieved in both methods when the incoming data signal is not noisy. As can be seen in case of noisy input signal for the two different noise levels, the homodyne noise mitigation scheme reduces the amount of noise in detected in-phase (I) and quadrature (Q) eyes compared to the homodyne receiver without phase noise cancellation. Since the local oscillator is automatically "locked" in frequency and phase to the incoming data signal, the proposed homodyne receiver does not require phase and frequency recovery.

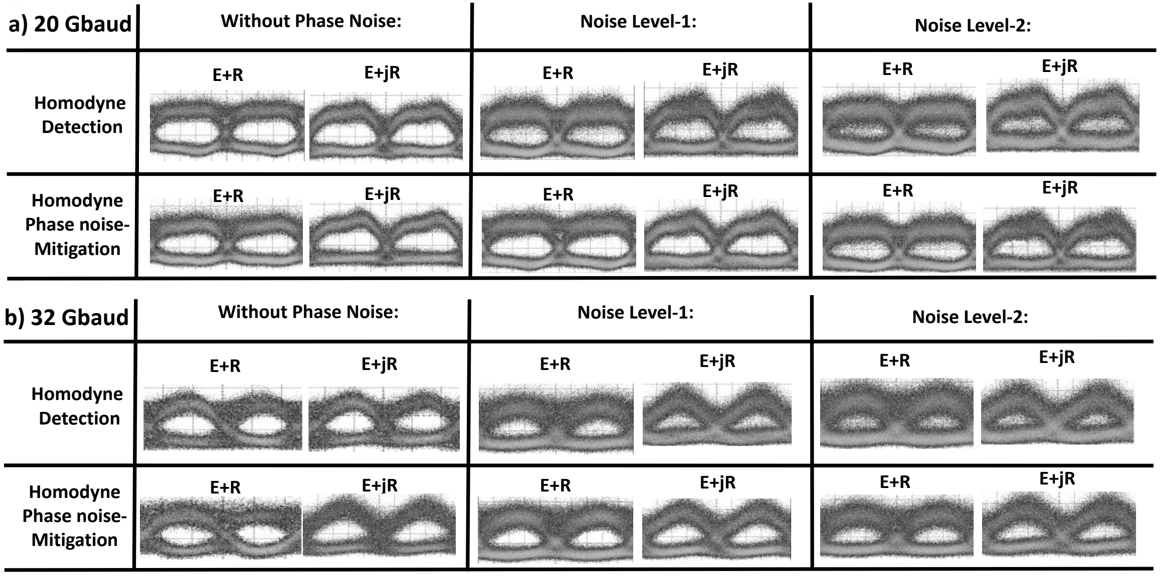

Fig. 3. The I and Q eye diagrams of 20/32 Gbaud QPSK signals without noise, with noise level-1, and with noise level-2. The results are shown for the homodyne detection scheme without phase noise mitigation, and, the proposed homodyne phase noise mitigation method.

Fig. 4 shows the BER performance of the homodyne phase noise mitigation for two different noise levels. This scheme results in ~2 dB OSNR gain at a BER of 10^{-3}. All results are captured without phase and frequency tracking as opposed to conventional intradyne detection.

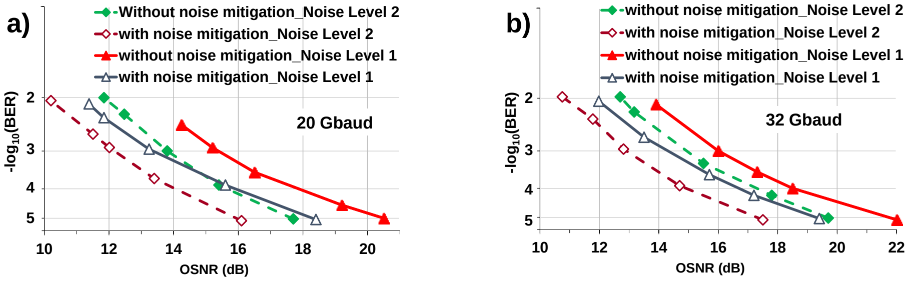

Fig. 4. BER versus for homodyne detection scheme with/without phase noise mitigation and for two different noise levels.(a) 20Gbaud (b) 32 Gbaud.

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