# Tunable Homodyne Detection of an Incoming QPSK Data Signal Using Two Fixed Pump Lasers

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*(Invited Paper)*

***Abstract*—Homodyne detection is of significant interest in optical communications because it detects both the amplitude and phase information of the incoming data channel. One of the challenges in implementing a homodyne receiver is to recover the phase and frequency of the incoming data and to lock these to the local oscillator. We proposed and demonstrated a tunable homodyne detection scheme using two continuous wave pumps to automatically lock a “local” pump laser to an incoming 20-to-40-Gbaud QPSK data signal. Open eyes are obtained for both in-phase and quadrature components of the signal after ∼200-km transmission over single mode fiber (SMF-28) and dispersion compensation fiber without any carrier recovery. The BER performance of the proposed homodyne detection scheme is also performed with and without transmission.**

***Index Terms*—Homodyne detection, nonlinear wave mixing, optical coherent communication, phase noise, quadrature phase shift keying (QPSK).**

## I. Introduction

THERE has been significant interest in coherent optical communication [1]–[4] because digital coherent communication enables spectrally efficient higher-order modulation formats, such as phase-shift keying (PSK) and quadrature-amplitude modulation formats [5]–[9]. It can also support a variety of post-processing functions, such as dispersion compensation, in the digital domain [4].

It has been known for decades that optical homodyne detection provides better performance and is inherently 3-dB more sensitive than optical heterodyne detection [1], [2]. However, homodyne-systems require the local oscillator to have the same frequency and phase as the incoming data signal, i.e., the data signal and local oscillator must be equal and “locked” to each other [10]–[17].

Conventional intradyne detection utilizes digital signal processing to recover the carrier and track the phase and frequency of the incoming data signal. It is flexible and can support different modulation formats at the cost of higher signal processing load at the receiver [4], [13].

One previous approach for homodyne detection has been to transmit the carrier along with the data signal [18]–[20]. With this approach, the carrier: (a) occupies some part of the spectrum and polarization state, and (b) suffers from fiber loss and can accumulate phase noise. Another approach employs a local laser oscillator in the receiver, for which a phase locked loop [21]–[23] ensure the locking of the local laser to the same frequency and phase. However, this approach tends to be fairly complex and requires time to achieve a stable “lock”.

Additionally, there have been optical methods to recover the carrier of an incoming data signal using nonlinear processing, but these techniques typically require an optical feedback loop for stabilization [24]. We considered a different approach that enables optical homodyne detection in which the local laser oscillator is automatically “locked” in frequency and phase to the incoming data signal without the need for feedback or phase/frequency tracking [25].

In this paper, we propose and demonstrate this tunable homodyne detection using two fixed lasers to automatically lock a “local” pump laser to an incoming 20-to-40-Gbaud QPSK data signal [25]. Our proposed scheme uses the signal conjugate to coherently add the signal and the local oscillator with an appropriate complex weight [26]–[28]. Open eyes are obtained for both in-phase and quadrature components of the signal after transmission over ∼160-km single mode fiber (SMF-28) and ∼40-km dispersion compensated fiber (DCF). The BER performance of the proposed homodyne detection scheme is also performed for back-to-back and after transmission.

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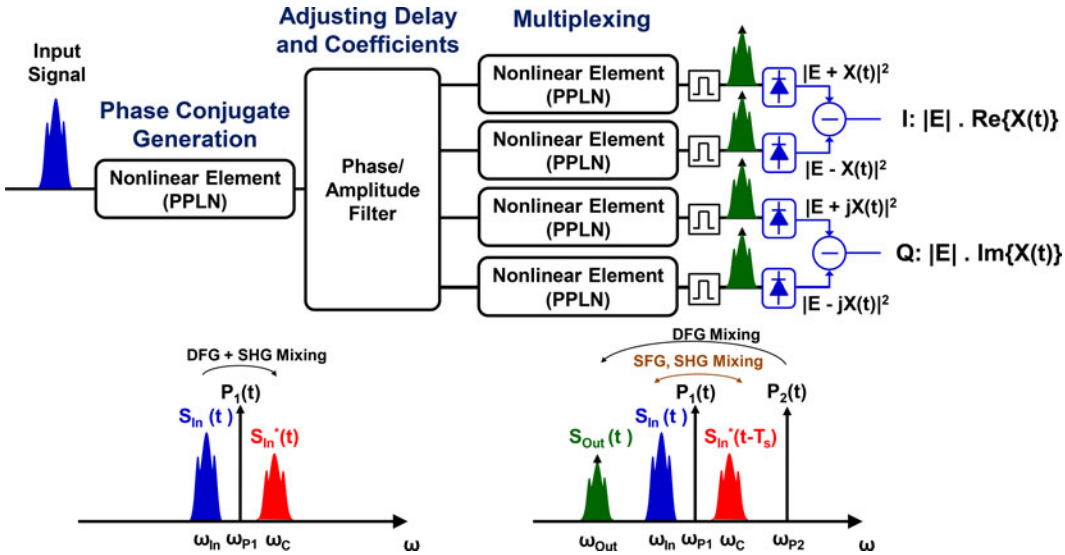


Fig. 1. Conceptual block diagram of the proposed homodyne detection scheme. First, a PPLN waveguide as a nonlinear element generates a phase conjugate copy of the input signal by using an injected CW laser pump. Next, a phase/amplitude filter induces a relative delay between the signal and its conjugate copy and adjusts the phase and amplitude of the signals. Then a set of nonlinear elements are utilized to mix the signal and its phase conjugate copy and combine it with a SHG term with four possible weights. Finally, the outputs of the multiplexing stage are sent to a photodiode to capture in-phase (I) and quadrature (Q) components of the signal.

## II. Concept

The principle operation of our proposed homodyne detection scheme is shown in Fig. 1. First, the input signal and a continuous wave (CW) pump laser are coupled and injected into a wave mixer element to generate a phase conjugate copy of the input. A programmable filter then induces one symbol period of delay between signal and its conjugate copy, compensates for the relative phase between the pump and the signal, and adjusts the required amplitude levels of the signal. The output of the filter is then sent to nonlinear elements to mix the signal, its phase conjugate copy, and another injected CW pump and coherently combine them with the first pump to extract the in-phase (I) and quadrature (Q) components of the input signal. In our proposed scheme, periodically-poled-lithium-niobate (PPLN) waveguides are used as these nonlinear elements. Each data stream in the demonstrated scheme travels through two wavelength-converting PPLN waveguides, a programmable filter, and a tunable bandpass filter. It is understood that this additional optical complexity might result in some signal degradation due to the second order nonlinear processes in PPLN waveguides, linear distortion in filtering stages, or optical losses because of the components insertion losses. In our measurements of Fig. 6 the penalty due to added complexity does not appear to be significant for our case. Third-order nonlinear materials (e.g., highly nonlinear fibers) can also be used to potentially enhance the conversion efficiency of our approach [29].

The wavelength of the first CW pump laser $\omega_{\mathrm{P1}}$ with electric field $\mathrm{P}_1\,(t)$ is set to the PPLN quasi-phase matching (QPM) wavelength. This signal interacts with itself through second-harmonic-generation (SHG), and creates the mixing term ${\mathrm{P}_1}^2(t)$ at $2\omega_{\mathrm{P1}}$. The SHG product then mixes with the input signals with electric field $\mathrm{S}_{\mathrm{In}}(t)$ at frequencies $\omega_{\mathrm{In}}$ through the difference-frequency-generation (DFG) nonlinear processes to create a

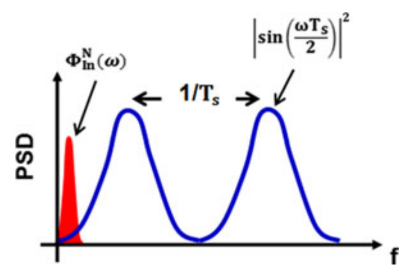


Fig. 2. A linear differentiator in the phase domain: the laser linewidth-induced phase noise (the red signal) which is low-speed and low bandwidth in nature, can be significantly reduced by implementing a linear differentiator (the blue curve) with power spectral density (PSD) $\left|\sin\left(\frac{\omega T_s}{2}\right)\right|$.

phase conjugate copy at $\omega_{\mathrm{C}} = 2\omega_{\mathrm{P1}} - \omega_{\mathrm{In}}$ with the electric field proportional to ${\mathrm{P}_1}^2(t) \times {\mathrm{S}_{\mathrm{In}}}^*(t)$.

The output of the first PPLN waveguide is sent into a liquid crystal on silicon (LCoS) programmable filter to i) reduce the out of band amplified spontaneous emission (ASE) noise, ii) select the signal, the phase conjugate copy, and the CW pump laser, iii) apply a relative complex coefficient weight $w$ between the signal and CW pump, and iv) induce a relative delay of one symbol period $(T_s)$ between the signal and its conjugate copy. Consequently, the signal, the copy and the CW pump electric fields are $\mathrm{w} \times \mathrm{S}_{\mathrm{In}}(t)$, ${\mathrm{P}_1}^2(t - T_s) \times {\mathrm{S}_{\mathrm{In}}}^*(t - T_s)$, and $\mathrm{P}_1(t)$ at the LCoS filter, respectively.

The input signal, the conjugate copy, and the CW pump are then sent to the second nonlinear stage to create the mixing product with appropriate weights. In this stage, the QPM wavelength of the PPLN waveguide is set to the QPM wavelength of the first PPLN. Therefore, the signal $\mathrm{S}_{\mathrm{In}}(t)$ at $\omega_{\mathrm{In}}$ and the delayed copy ${\mathrm{P}_1}^2(t - T_s) \times {\mathrm{S}_{\mathrm{In}}}^*(t - T_s)$ at $2\omega_{\mathrm{P1}} - \omega_{\mathrm{In}}$ are located symmetrically around $\omega_{\mathrm{P1}}$, interact through a sum-frequency-generation (SFG) nonlinear process and mixed, and generate a new signal

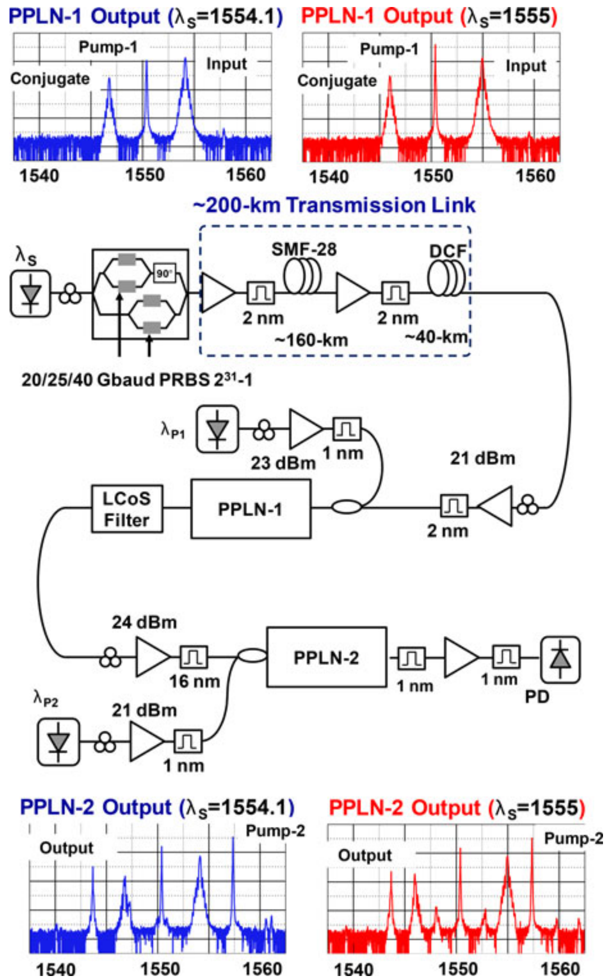


Fig. 3. Experimental setup for the proposed homodyne detection scheme. Two PPLN waveguides are used for detection of all possible combinations of the CW pump (E($t$)) and the data signals (x($t$)).

at $2\omega_{\mathrm{P1}}$ with electric field of

$$\mathrm{X}(t) \triangleq \mathrm{P}_1 \mathrm{P}_1^2(t - T_s) \times \mathrm{S_{In}}^*(t - T_s) \times \mathrm{S_{In}}(t). \tag{1}$$

Similarly, the CW pump $\mathrm{P}_1\,(t)$ at $\omega_{\mathrm{P1}}$ (the QPM frequency of the second nonlinear stage) mixes with itself through SHG process and generate a new pump at $2\omega_{\mathrm{P1}}$ with electric field of

$$\mathrm{E}(t) \triangleq \mathrm{P}_1^2(t). \tag{2}$$

The challenge in combining the new generated pump and signal is that they need to be phase and frequency locked to each other [8]. According to Equations (1) and (2) the phases of $\mathrm{X}(t)$ and $\mathrm{E}(t)$ can be expressed as:

$$\phi_{\mathrm{X}}(t) \triangleq\ 2\phi_{P1}(t - T_S) + \phi_{\mathrm{In}}(t) - \phi_{\mathrm{In}}(t - T_S) \tag{3}$$

$$\phi_E(t) \triangleq\ 2\phi_{P1}(t) \tag{4}$$

in which $\phi_E$, $\phi_X$, $\phi_{P1}$ and $\phi_{\mathrm{In}}$ are the phases of E, X, $P_1$, and $S_{\mathrm{In}}$, respectively.

In order to ensure the coherence between E $(t)$ and X $(t)$, the phase noise of the two signals needs to be identical. The phase of the input signal consists of data $\Phi_{\mathrm{In}}^{\mathrm{D}}(t)$ and the phase noise $\phi_{\mathrm{In}}^{\mathrm{N}}\,(t)$ (i.e., $\phi_{\mathrm{In}} = \phi_{\mathrm{In}}^{\mathrm{D}}\,(t) + \phi_{\mathrm{In}}^{\mathrm{N}}(t)$). Thus,

$$\phi_{\mathrm{X}}^{\mathrm{N}}(t) \triangleq 2\phi_{P1}(t - T_S) + \phi_{\mathrm{In}}^{\mathrm{N}}(t) - \phi_{\mathrm{In}}^{\mathrm{N}}(t - T_S) \tag{5}$$

and

$$\phi_{\mathrm{E}}^{\mathrm{N}}(t) \triangleq \phi_E(t) = 2\phi_{P1}(t) \tag{6}$$

where $\phi_{\mathrm{X}}^{\mathrm{N}}(t)$ and $\phi_{\mathrm{E}}^{\mathrm{N}}(t)$ are the phase noises of X and E, respectively [16]. Assuming the source of phase noises for both $P_1\,(t)$ and $S_{\mathrm{In}}\,(t)$ are from laser linewidth, the fluctuation of $\phi_{\mathrm{In}}^{\mathrm{N}}\,(t)$ and $\phi_{P1}\,(t)$ are significantly slower than the symbol rate and we can assume

$$\phi_{Diff}(t) \triangleq \phi_{\mathrm{In}}^{\mathrm{N}}(t) - \phi_{\mathrm{In}}^{\mathrm{N}}(t - T_S) \approx 0 \tag{7}$$

and

$$\phi_{P1}(t) \approx \phi_{P1}(t - T_S). \tag{8}$$

Thus,

$$\phi_{\mathrm{X}}^{\mathrm{N}}(t) \approx \phi_{\mathrm{E}}^{\mathrm{N}}(t) = 2\phi_{P1}(t). \tag{9}$$

Fig. 2 shows how a differentiator on the phase domain with a small delay $(T_S)$ can significantly reduce the phase noise generated from the laser linewidth $(\Delta\upsilon)$ and validate (7). By performing a Fourier transform of (7), one can obtain:

$$\Phi_{Diff}(\omega) = 2\mathrm{j}\mathrm{e}^{-\mathrm{j}\omega \mathrm{T}/2} \sin(\omega \mathrm{T_S}/2) \times \Phi_{\mathrm{In}}^{\mathrm{N}}(\omega). \tag{10}$$

Because $\left|\sin\left(\frac{\omega \mathrm{T_S}}{2}\right)\right|^2$ rejects the lower frequency components of $\Phi_{\mathrm{In}}^{\mathrm{N}}\,(\omega)$, the power spectral density (PSD) of the $\phi_{Diff}\,(t)$ contains almost no power assuming $\Delta\upsilon \ll 1/T_S$.

Therefore, although the input signal $\mathrm{S_{In}}$ is generated from a laser different from $\mathrm{P}_1$ with independent phase noise (i.e., non-phase-locked), the signal is locked to the generated pump E after mixing with its delayed conjugate copy.

In this stage, another CW pump at $\omega_{\mathrm{P2}}$ with electric field $\mathrm{P}_2\,(t)$ is injected to the PPLN waveguide to perform DFG process; it will convert the multiplexed signal back to $\omega_{\mathrm{Out}} = 2\omega_{\mathrm{P1}} - \omega_{\mathrm{P2}}$; and generate the output signal:

$$S_{\mathrm{Out}}(t) = P_2^*(t).(E(t) + w.X(t)). \tag{11}$$

By sending the output to the photodetectors and setting $w$ to $\pm 1$ or $\pm$j, similar to a 90° optical hybrid, both in-phase and quadrature components of the X($t$) can be obtained, due to the

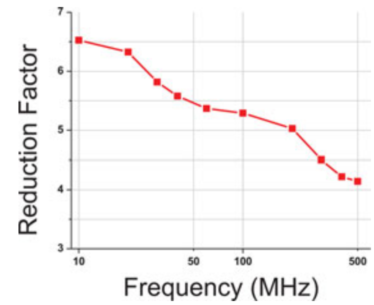


Fig. 4. Phase noise power reduction factor versus frequency of a phase differentiator. The signal is modulated with sinusoidal waveform with variable frequencies and the output phase noise reduction factor is measured [16].

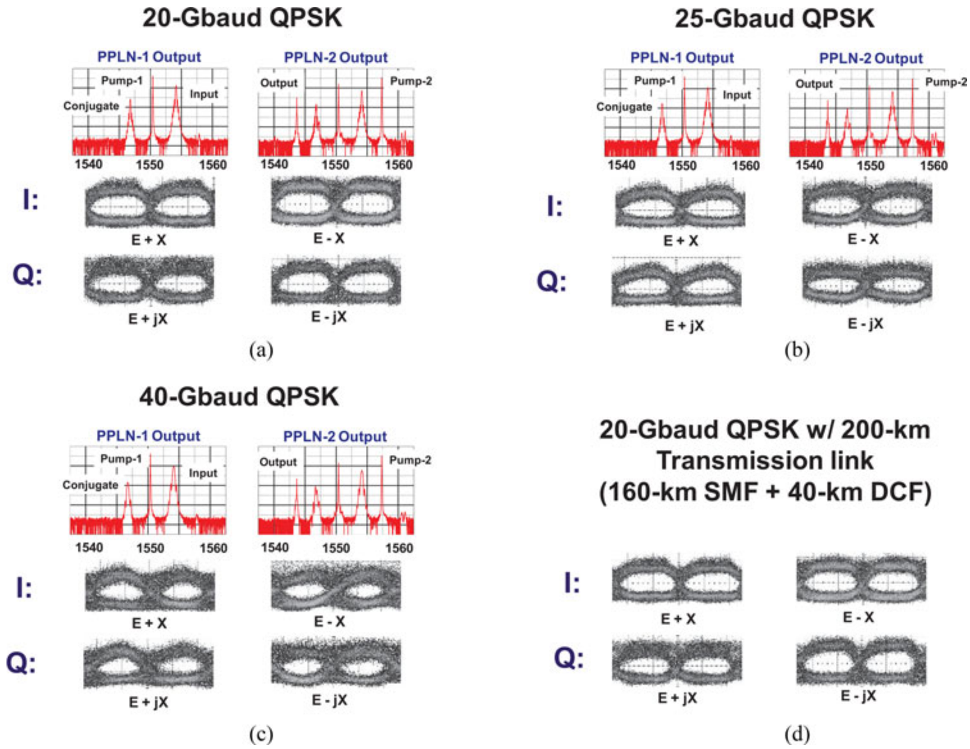


Fig. 5. Homodyne detection results for incoming QPSK data for variable baud rate with and without transmission. 3(a), (b),(c) optical spectra of the first and second PPLN waveguides output for homodyne detection of 20- 25- and 40-Gbaud QPSK signals and the eyes correspond to all possible combination of the CW pump and the incoming data signals. 3(d) Eye diagrams for 20-Gbaud QPSK detection after 200-km (160-km SMF and 40-km DCF) transmission.

phase and frequency locking between $E\left(t\right)$ and $X\left(t\right)$. Further, if both constructive and destructive multiplexing of the signal and the CW pump are simultaneously generated, a balanced photodiode can cancel the common intensity noise.

## III. Experimental Setup

The experimental setup for the homodyne detection scheme is depicted in Fig. 3. A nested Mach–Zehnder modulator is used to generate the 20/25/40-Gbaud QPSK data (PRBS $2^{31}-1$) at either 1555 nm or 1554.1 nm. The signal is sent to a 200-km optical fiber link ($\sim$160-km SMF-28 and $\sim$40-km DCF) to emulate transmission before homodyne detection. The signal is then amplified and coupled with an amplified $\sim$1550.6 nm CW pump and sent to a PPLN waveguide to produce the phase conjugate of the signal. The QPM of the first PPLN is set to the wavelength of CW pump. The CW pump interacts with the injected modulated signal through SHG + DFG nonlinear processes and generate a copy of the signal at 1546.2 nm (1547.1 nm). The output of the first PPLN including the signal, the CW pump and the conjugate copy is sent to a programmable filter based on LCoS technology for adjusting the delay, phase and the complex weights. The signal, the conjugate copy, and the first CW pump are amplified and coupled with another amplified 1560 nm CW laser and sent to the second PPLN to mix the signal and the conjugate copy and multiplex them with the first pump. The QPM wavelength of the second PPLN waveguide is temperature tuned to QPM of the first PPLN. In the second PPLN waveguide, the signal mixes with the conjugate copy through a SFG nonlinear process, the first CW pump interacts with itself and generates a SHG term, and the combination of these two mixing products interacts with the second CW pump through the DFG nonlinear process to generate the output signal. The multiplexed signal is then filtered, amplified and sent to a photodetector to capture the eye diagram and perform the bit-error measurement. In this figure the spectra of the first and second PPLN waveguides are also depicted for two different input signals at different wavelengths. The multiplexed signal is always frequency and phase locked to the generated carrier. In this demonstration only a single PPLN waveguide is used and tuned to generate all possible coherent combinations of the signal and the pump in the multiplexing stage.

## IV. Results and Discussion

The performance of the linear phase differentiator in reducing laser phase noise is depicted in Fig. 4. First, a phase modulator is used to apply phase noise with different bandwidths on the input signal. The signal containing phase noise is passed through the proposed scheme to suppress its phase noise. The transfer function of the phase noise suppression can be obtained by calculating the ratio of the input signal phase noise to the phase noise of the output signal [16]. Here, the reduction factor is defined as the ratio of the input phase noise standard deviation to the output phase noise standard deviation in a linear phase differentiator when the original signal is 20-Gbaud QPSK signal. Fig. 4 shows the reduction factor for frequency $\sim$10-MHz (significantly higher than the commercial laser linewidth range)

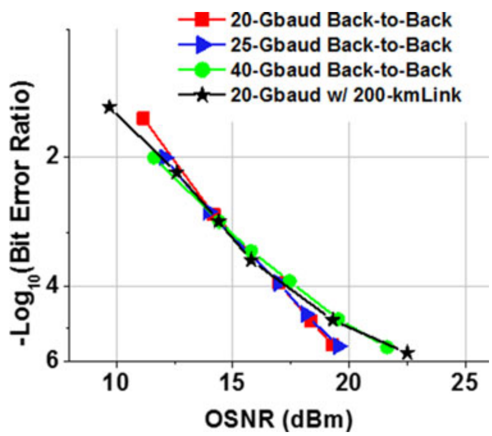


Fig. 6. The BER performance of the proposed homodyne receiver for 20-, 25-, and 40-Gbaud QPSK incoming data with and without transmission.

can be as high as ∼6.5 and it increases when the frequency decreases. This measurement is performed for the bandwidth of <600-MHz because the phase noise induced by the communication laser linewidth tends to be narrowband in nature (<1-GHz).

The performance of the system is assessed by implementing the proposed homodyne detection scheme on 20/25/40 Gbaud QPSK signals. The proposed homodyne receiver does not require phase and frequency recovery because the local oscillator is automatically "locked" in frequency and phase to the incoming data signal.

In Fig. 5(a) the spectra of the first and second PPLN waveguides are shown for 20-Gbaud QPSK data. In the first PPLN waveguide, a conjugate copy of the original input signal is generated using the fist CW pump located at QPM wavelength. In the second PPLN waveguide, first the signal mixes with the delayed conjugate copy. The first CW pump is then combined with them coherently. Finally, the second CW pump converts the multiplexed signal to the output wavelength.

In order to show the performance of the system in creating all four possible combinations of the local oscillator $E\,(t)$ with the signal $X\,(t)$, the $E\,(t) + X\,(t)$, $E\,(t) - X\,(t)$, $E\,(t) + jX\,(t)$, and $E\,(t) - jX\,(t)$ are generated and sent to a photodiode in the proposed homodyne receiver. The resulting open eye diagrams for all of these combinations are shown. In order to generate I and Q with lower level of intensity noise, a balanced photodiode can be utilized to combined the constructive and destructive terms.

In Fig. 5(b) and (c), the same results are shown for 25 and 40-Gbaud QPSK signals, respectively. Similarly, constructive and destructive combination of the local oscillator and the signal is shown for both I and Q components of the signal. In order to reconfigure the system to a new baud rate, the induced delay between the signal and its conjugate copy needs to change in the programmable filter. The 40-Gbaud eye diagrams shows lower level of signal-to-noise ratio, which we believe was a result of lower efficiency of the PPLN waveguide in nonlinear wave mixing at higher bandwidth.

Fig. 5(d) shows the four eye diagrams for 20-Gbaud QPSK detection using the proposed homodyne scheme after 200-km transmission. As can be seen, the degradation of the signal after transmission is low and error free eye diagram is captured.

Fig. 6 shows the BER performance of the proposed homodyne detection scheme for 20- 25- and 40-Gbaud QPSK. The BER curve for 20-Gbaud QPSK is also obtained and shown after 200-km with 160-km SMF and 40-km DCF fiber spool. We did not use the balanced detection method which can improve the performance of the results.

All results are captured without phase and frequency tracking as opposed to conventional intradyne detection. Moreover, in the proposed homodyne scheme the BER measurement can be performed in real-time. Our coherent receiver uses post processing for performing the BER measurements. Due to the limited sample size of our recorded data, our results are only shown down to $\sim 10^{-6}$ BER level.

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