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Novel coherent self-heterodyne receiver based on phase modulation detection

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Abstract: We propose a novel coherent self-heterodyne receiver structure based on phase modulation detection that potentially simplifies the front-end of a coherent optical receiver. The scheme has been demonstrated via simulations and experimentally for a 10 Gb/s DQPSK transmission system.

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1. Introduction

In recent years the exponential growth of Internet data traffics has resulted in a steady increase of the transmission capacity of Dense Wavelength Division Multiplexed (DWDM) optical networks. Advanced optical modulation formats that offer high spectral efficiency are being increasingly deployed to cope with this trend [1–3]. The state-of-the-art optical coherent receiver employs a 90° hybrid front end and a local oscillator (LO) laser for homodyne demodulation [1, 4]. The integration of the hybrid remains a technical challenge and the laser phase noise requirements on the LO can be difficult to achieve, especially with higher order modulation formats. Differential modulation techniques, such as DQPSK, that employ self-homodyne direct detection using delay line interferometers (DLIs) [3, 5] could potentially reduce the requirements on the laser linewidth. However, the DLI approach would require significantly more complex hardware implementation to migrate to higher order modulation formats such as differential m-PSK and differential m-QAM. The authors in [2] have reported the realization of a direct-detection multilevel transmission for 16-QAM incorporating phase pre-integration and advanced digital signal processing (DSP).

In this paper, we propose a novel coherent receiver scheme based on the phase modulation (PM) detection method [6] that can recover the differential E-field from the harmonics of the

modulating carrier without an LO laser. In previous work, we employed PM detection method for characterizing the laser phase noise [7]. Similar approaches to harmonic demodulations have been employed in near-field scanning optical microscopy [8] and Fourier-domain optical coherence tomography [9], but to our knowledge this is the first demonstration in coherent optical communications. In this work we demonstrate a self-coherent DQPSK system operating at 10 Gb/s by implementing our PM detection method at the receiver. The performance of the proposed technique is compared with other widely employed DQPSK receiver structures through simulations and experimental results. The proposed receiver configuration provides a cost effective solution for the front-end of optical coherent receivers, and has the potential of migrating to higher order modulation formats without a significant increase in complexity.

2. Analytical model

In the following, we develop the analytical model for the proposed receiver scheme in Fig. 1(a). The E-field of the modulated optical output from an IQ modulator can be expressed in complex notation (for brevity we have omitted the laser phase and intensity noises) as

$$E(t) = \sqrt{P}a(t)e^{j\varphi(t)}e^{j\omega_o t}, \tag{1}$$

where ω_o is the angular optical frequency, P is the optical output power of the laser, and $\phi(t)$ and $a(t)$ respectively are the symbol phase modulation and the normalized symbol amplitude modulation such that $a(t) = 1$ for PSK modulation format. The upper arm of the interferometer in Fig. 1(a) has a one-symbol delay and the lower arm is phase modulated by a sinusoidal waveform. The incident E-field falling on the photo-detector can be written as

$$E_i(t) = \frac{1}{2} \times \left[E(t-T_s) - E(t) \times e^{j[b\sin(\omega_c t + \varphi_c)]} \right], \tag{2}$$

where T_s is the symbol duration. The input signal to the phase modulator is $b\sin(\omega_c t + \phi_c)$, where b is the PM index, ω_c and ϕ_c are the angular frequency and phase of the modulating carrier, respectively. The output current of the photo-detector with responsivity $\Re$ is proportional to the intensity of the incident field:

$$i(t) = \Re \times E_i(t)E_i^*(t)$$
$$= \frac{1}{4} \times \Re P \left\{ a^2(t) + a^2(t-T_s) - 2a(t)a(t-T_s)\cos\left[\omega_o T_s + \phi(t) - \phi(t-T_s) + b\sin(\omega_c t + \phi_c)\right] \right\} \tag{3}$$

Ignoring the first two terms in Eq. (3) (which are constant for PSK and can be cancelled using balanced photo-detectors, or a single photo-detector with a DC-block) and expanding the third term:

$$i(t) = -\frac{1}{2} \times \Re Pa(t)a(t-T_s)\cos\left[\omega_o T_s + \phi(t) - \phi(t-T_s) + b\sin(\omega_c t + \phi_c)\right] \tag{4}$$

$$i(t) = -\frac{1}{2}\Re Pa(t)a(t-T_s) \times$$
$$\left\{ \cos\left[\omega_o T_s + \phi(t) - \phi(t-T_s)\right]\cos\left[b\sin(\omega_c t + \phi_c)\right] - \sin\left[\omega_o T_s + \phi(t) - \phi(t-T_s)\right]\sin\left[b\sin(\omega_c t + \phi_c)\right] \right\} \tag{5}$$

Using the Bessel coefficient expansions:

$$\cos\left[b\sin(\omega_c t + \phi_c)\right] = J_o(b) + 2\sum_{k-even} J_k(b)\cos\left[k(\omega_c t + \phi_c)\right], \tag{6}$$

$$\sin\left[b\sin(\omega_c t + \phi_c)\right] = 2\sum_{k-odd} J_k(b)\sin\left[k\left(\omega_c t + \phi_c\right)\right], \quad (7)$$

here $J_k(b)$ is the Bessel function of the first kind with order k. It is clear from Eqs. (5), (6) and (7) that the I and Q components of the complex differential optical modulation envelope, $a(t)a(t-T_s)e^{j[\varphi(t)-\varphi(t-T_s)]}$, can be found at the even and odd harmonics of $i(t)$. For bandwidth efficient demodulation, we can also obtain the I and Q components from the baseband and the first harmonic, respectively. The output current of the photo-detector in terms of baseband and first harmonic could be expressed as:

$$i(t) = \frac{1}{2}\Re P\left[-J_0(b)I(t) + 2J_1(b)Q(t)\sin(\omega_c t + \phi_c)\right], \quad (8)$$

where

$I(t) = a(t)a(t-T_s)\cos\left[\phi(t) - \phi(t-T_s) + \omega_o T_s\right]$ and

$Q(t) = a(t)a(t-T_s)\sin\left[\phi(t) - \phi(t-T_s) + \omega_o T_s\right]$. Figure 2(a) shows the block diagram of the off-line DSP for the captured photo-detector current. A simple carrier phase recovery algorithm for ϕ_c was applied prior to demodulation. The least mean-square (LMS) algorithm compensates for the differential drift in the interferometer arms due to the random fluctuation, for example, in temperature. For balanced I/Q outputs the PM index b is adjusted so that $J_o(b) = 2J_1(b) \sim 0.81$, or $b \sim 0.90$, as verified on the electrical spectrum analyzer.

3. Experiment setup

Figure 1(a) shows the experimental setup for a back-to-back 5 Gbaud/s DQPSK link using the coherent PM detection method. The transmitter employed a sample grating distributed Bragg reflector (SGDBR) laser [10] that has a linewidth of 5 MHz at 1547.6 nm when biasing only the gain section at 100 mA. The I and Q arms of a dual parallel Mach-Zehnder modulator (biased close to the null points) was driven at 5 Gb/s by the complementary PRBS outputs of an Anritsu pulsed pattern generator (PPG), which were decorrelated by 59 bits using an electrical delay. The received power of the DQPSK signal was monitored after the first variable optical attenuator (VOA). The first low noise EDFA served as the pre-amplifier for the receiver front-end. The output signal was further amplified by a second EDFA. Each EDFA was followed by 2 nm optical filters to reduce the ASE noise, and the second VOA maintained the optical power falling on the photo-detector.

The one-symbol delay in one arm of the interferometer was set to T_s = 200 ps at 5 Gbaud/s. An EOspace Z-cut lithium niobate phase modulator in the other arm was driven by a 5 GHz signal generator. The signal generator output was amplified to provide sufficient drive (modulation index b) to the phase modulator in order to achieve balanced power at baseband and the first harmonic as observed on an RF spectrum analyzer. The light from the delayed and phase modulated arms were recombined via a coupler whose output was detected by an 11 GHz photo-detector with an integrated transimpedance amplifier (TIA). Two polarization controllers (one on each arm of the interferometer) were employed to manually optimize the beat signal at the TIA output and minimize the polarization mode dispersion effect of the modulator. An Agilent real-time scope captured the output signal at 40 GSamples/s that was then fed into a computer for off-line DSP processing as illustrated in Fig. 2(a). Matched filtering [4] was applied to the baseband I-component and the demodulated Q-component.

In order to evaluate the PM detection technique, we also implemented a self-homodyne, optical coherent receiver [4] as shown in Fig. 1(b). The two arms of the delay interferometer were now fed into an optical 90° hybrid with the output signals detected by a pair of 43 Gb/s photo-detectors with integrated TIAs. The I and Q output signals from the photo-detectors were also captured by the Agilent real-time scope at 40 GSamples/s for post-processing as shown in Fig. 2(b).
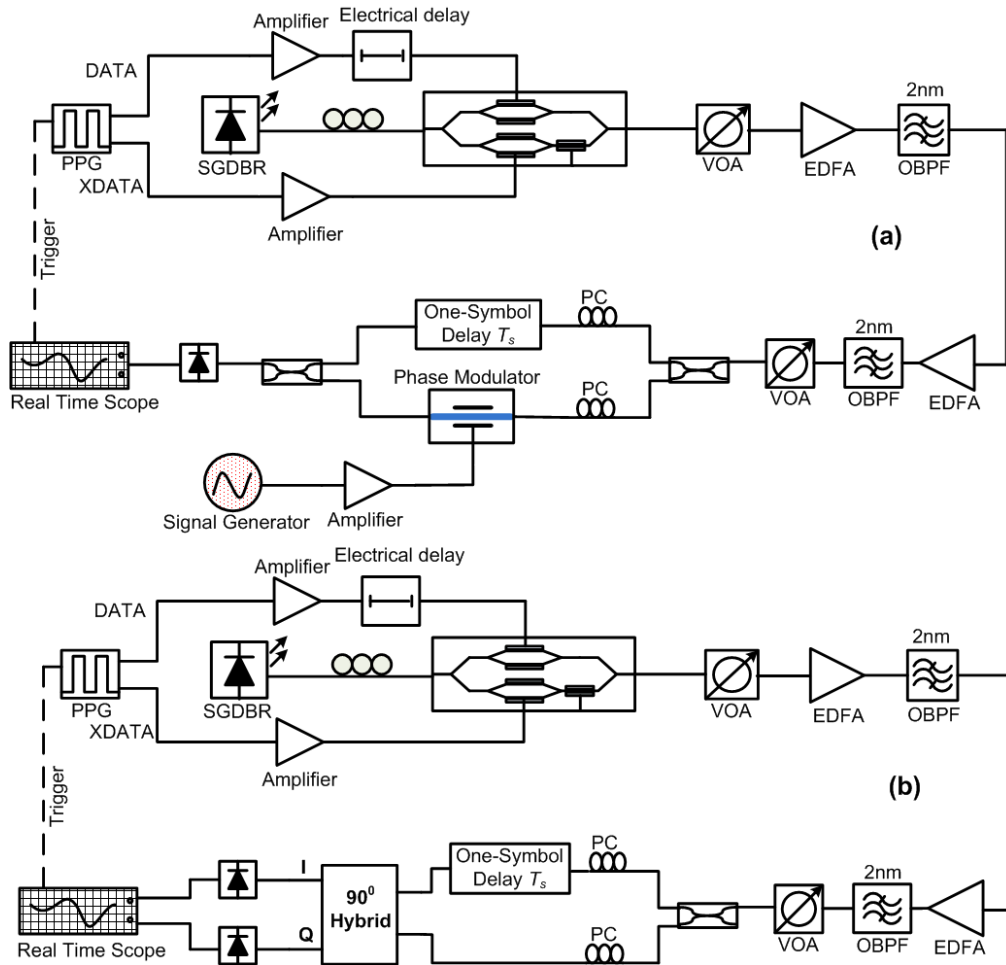
Fig. 1. Experiment setup for self-heterodyne receiver with PM detection (a) and self-homodyne receiver with 90° hybrid (b).

4. Simulation and experimental results

The first VOA in the experimental setup adjusted the back-to-back optical power in order to compare the receiver sensitivity of the PM detection method with the self-homodyne optical receiver. We also performed simulations of both experimental systems in Fig. 1, and of a direct detection DQPSK receiver with two DLIs [3, 5], using VPIphotonics software. The results were compared in terms of the error vector magnitudes (EVM).

Figures 2(c) and 2(d) show the example experimental symbol constellations at −30 dBm received power for the self-heterodyne receiver with PM detection and the self-homodyne receiver with 90° hybrid, respectively. The experimental results show that the recovered DQPSK symbols have an EVM of 18% with PM detection and 14.7% with the 90° hybrid. Figure 3(a) compares the receiver sensitivity of the two methods. The plots show that PM detection has a power penalty that is about 3 dB (at 21% EVM) relative to the self-homodyne receiver with 90° hybrid. The simulation results in Fig. 3(b) are in general agreement with the experimental results and confirmed the sensitivity reduction between PM detection method and self-homodyne receivers.
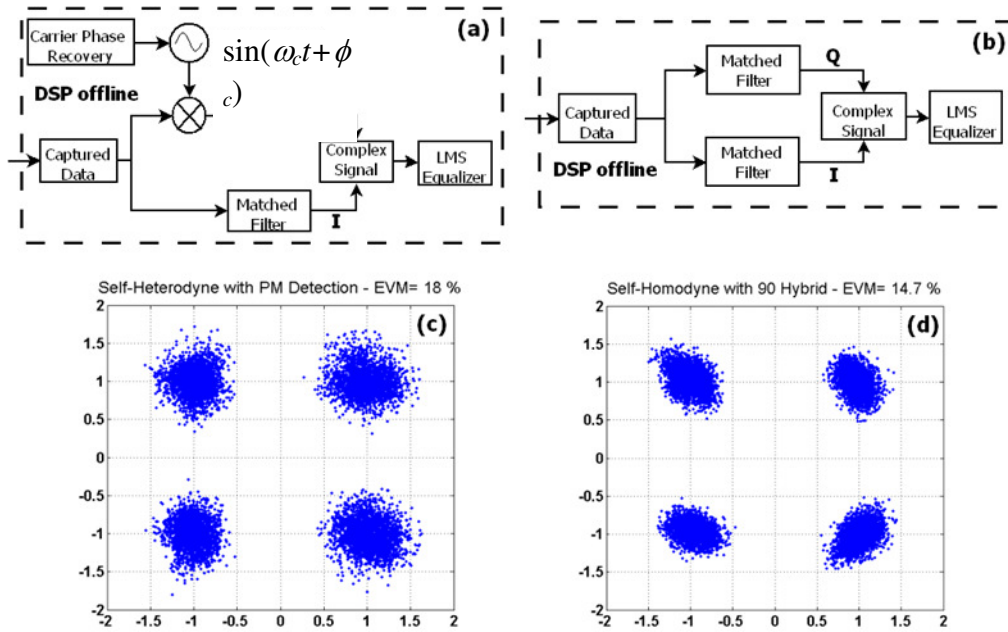
Fig. 2. Off-line DSP and DQPSK constellation of self-heterodyne receiver with PM detection method (a), (c), and self-homodyne receiver with 90° hybrid method (b), (d).

The 3dB penalty of PM detection method was primarily caused by the additional ASE beat noise from the EDFAs due to heterodyne demodulation. The accumulated number of noise photons after the EDFAs chain was $m(G-1)n_{sp}$ (where n_{sp} is the spontaneous emission factor, m is the number of EDFAs, and G is the amplifier gain), which is much greater than the number of photons from shot-noise (1 photon) [1].

The carrier-to-noise ratio after the EDFAs chain was largely determined by ASE noise, as the shot-noise-limit is negligible in such a system [1]:

$$\gamma_s = \frac{GN_s}{m(G-1)n_{sp}} \approx \frac{N_s}{mn_{sp}}, \tag{9}$$

where N_s is the number of photons per symbol. For the self-homodyne receiver, the signal bandwidth was equal to the baud rate at 5 GHz, while the bandwidth for the self-heterodyne receiver with PM detection was twice at 10 GHz (if we used the baseband and first harmonic for I and Q). This can be seen by comparing the example power spectral densities of the photo-detector outputs for the two receiver methods in Fig. (4). Consequently, the in-band ASE noise of the self-heterodyne receiver was two times that of the self-homodyne receiver. This leads to a 3 dB penalty in the receiver sensitivity for PM detection.
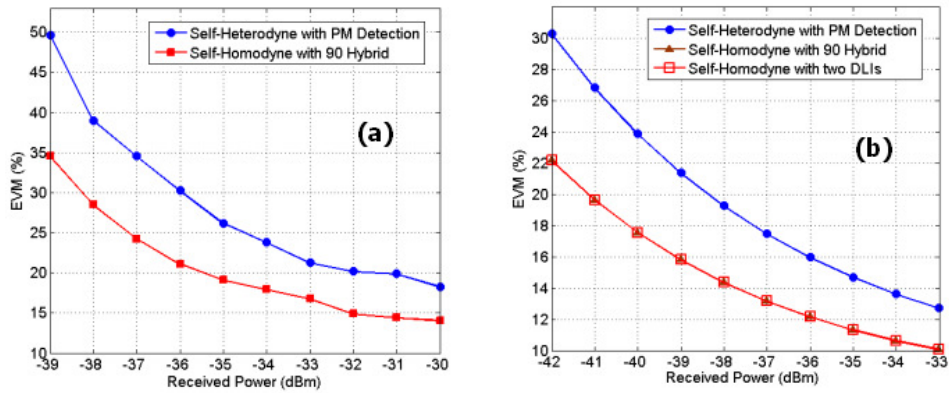
Fig. 3. EVM versus received power from experimental results (a) and simulation results (b).
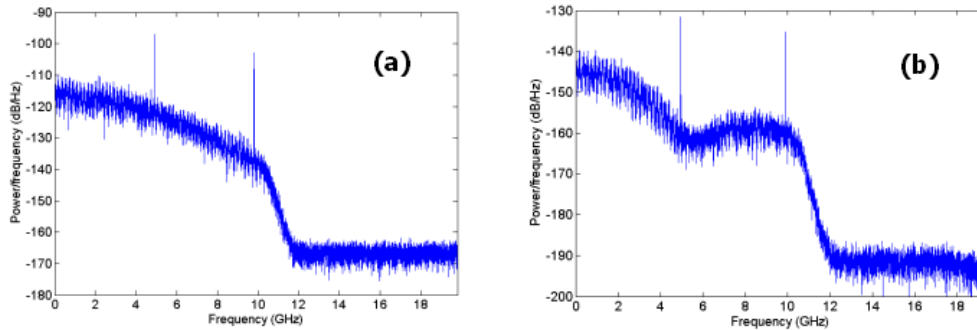

Fig. 4. Example power spectral densities of the photo-detector outputs with PM detection (a) and self-homodyne methods (b).

5. Conclusion

We have proposed and demonstrated for the first time a coherent self-heterodyne receiver based on PM detection for DQPSK modulation through analytical model, simulations and experiments. The DQPSK signal from a back-to-back 10 Gb/s link was successfully demodulated using the proposed method. Although there is a 3dB penalty associated with heterodyne demodulation under ASE-limited condition, the coherent PM detection receiver not only offers the potential for a low-cost integrated solution but can also significantly simplify the front end of optical coherent receivers. Moreover, this receiver configuration could be feasibly migrated toward higher order modulation formats such as differential m-PSK and differential m-QAM without a significant increase in hardware requirements.

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