Optical Engineering

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SPIE

Optical Engineering 51(10), 105002 (October 2012)

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Abstract. We describe a homodyne optical Costas loop receiver intended to detect weak coherent states with diffused phase and suppressed carrier phase modulation. In order to get the information contained in the quadrature components of the optical field, we implement an 8-port receiver operating at 1550 nm, based on the manipulation of the state of polarization of both the local oscillator and the data signal. Employing binary phase-shift keying, we make measurements in the time and frequency domain of the quantum noise and bit error rate using an optimum loop filter, and compare the performance of our receiver against the standard quantum limit for the simultaneous quadrature detection, considering both ideal conditions and the overall efficiency of our set up. [DOI: 10.1117/1.OE.51.10.105002]

Subject terms: optical Costas loop; weak coherent states; phase noise; homodyne detection; suppressed-carrier; state of polarization; quantum communication.

Paper 120782P received May 29, 2012; revised manuscript received Jul. 30, 2012; accepted for publication Aug. 31, 2012; published online Oct. 1, 2012.

1 Introduction

In modern optical communications systems working at low photon number levels, spectrally efficient optical modulations are necessary to obtain good bit error rate (BER) performances. Sensitive applications, either in quantum communication or in quantum cryptography, require the use of suppressed carrier modulation; however, at the receiver stage a phase/frequency synchronization subsystem[1–4] is usually required.

In order to implement synchronization structures in the optical domain, there exists an optical phase locked loop (OPLL) for residual carrier modulations or Costas-type loops for suppressed carrier. The Costas loop has the advantage of simultaneously getting the data and the carrier but with additional noise observable due to quantum effects,[2,5] arising from the simultaneous detection of the in-phase and quadrature components of the carrier field.

With the OPLL approach, in order to obtain the in-phase and quadrature components of the carrier signal, switched detection techniques have been proposed[6–8]; however, the transmitted bit rate must be twice that of the modulated signal. In this work, to avoid this problem, we use simultaneous quadrature detection techniques, at the cost of increasing the quantum noise, because we have to consider the effect of unused ports in the system.[2,9,10]

To obtain a simultaneous detection of the quadrature components of the optical field, we may use devices such as: 1. 90-deg optical hybrids with 2×4 ports (implemented either on free-space or optical fiber),[11] 2. schemes with $N \times N$ ports using multimodal interference devices and beam splitters,[12,13] and 3. schemes with 4×4 ports using polarizing and nonpolarizing beam splitters,[14] among others.[15–17]

Of course, all the above mentioned devices have practical trade-offs (with reference to the phase error) on their implementation, use, and performance because of delays and power imbalances; besides, they usually require several control points to reach their optimum performance.[18] It is possible to implement, with discrete optical components, a free-space experimental setup, to simultaneously detect the two quadrature components of an optical field using the state of polarization (SOP) of the impinging signals. The use of a free-space set up allows us to operate with high SOP stability without the requirement of an automatic SOP control or polarization preserving optical fiber.[19]

In this paper, we present an experimental optical Costas loop setup capable of simultaneously measuring the quadrature components of a low photon number optical field issued from a strongly attenuated, coherent-state laser at 1550 nm with a suppressed carrier binary phase shift keying (BPSK) modulated signal. As an alternative to the conventional photon counting receivers used in low photon number field detection, we use homodyne detection techniques with a coherent conversion gain (without trading-off the noise figure) capable of operating at higher bit rates, as well as being highly wavelength-selective. This last feature leads to very good rejection of out-of-band parasitic radiation (a very attractive feature for free-space optics applications). We make use of the SOP of both the optical data signal and the optical local oscillator, in an experimental 8-port scheme implemented with discrete optical devices in free space. In order to provide optical carrier synchronization from the suppressed carrier optical signal, we present the design and experimental realization of a Costas loop optimized to operate close to the simultaneous measurement quantum limit.

2 Theory

The optical sources more commonly used in telecommunications have optical coherent states with diffused phase (that may be described by a Wiener process),[9,20] having an important effect on the performance of the optical synchronizer structures.[21]

Using an optical Costas loop scheme as shown in Fig. 1, it is possible to simultaneously measure the quadrature components of the received optical field; it consists of a 90-deg optical hybrid (8-port), an electronic processing block to provide a phase error (feedback) signal, and a block to modify, in a controlled way, the phase of the reference signal (the local oscillator).

The operation of the above mentioned structure is based on the mixing of the data (E_{ST}) and local oscillator (E_{LOT}) signals:

$$E_{\mathrm{ST}} = [E_S + \delta I_S + \delta Q_S]e^{i\theta_S} \tag{1}$$

$$E_{\mathrm{LOT}} = [E_{\mathrm{LO}} + \delta I_{\mathrm{LO}} + \delta Q_{\mathrm{LO}}]e^{i\theta_{\mathrm{LO}}}, \tag{2}$$

where δI_S, δQ_S, δI_{LO}, and δQ_{LO} are the canonical uncertainties of the quadrature components defined by the Heisenberg principle for the coherent states E_{LOT} and E_{ST}. The phase components are $\theta_S = \omega_S + \varphi_S(t) + \varphi_d(t)$ and $\theta_{\mathrm{LO}} = \omega_{\mathrm{LO}} + \varphi_{\mathrm{LO}}(t)$, where $\varphi_{\mathrm{LO}}(t)$ and $\varphi_S(t)$ are the temporal phases (described by a Wiener process), ω is the optical angular frequency, $\varphi_d(t)$ is the modulated phase, and E_S, E_{LO} are the optical fields amplitudes.

In our scheme, the SOP of the signals E_{LOT}(circular) and E_{ST} (linear at 45 deg) are very important because they allow the simultaneous measurement of the quadrature components of the optical field. Because of a $\pi/2$-lag between the orthogonal polarization components of E_{LOT} and the linear 45 deg SOP of E_{ST}, we produce the necessary relationship between the horizontal and vertical components of both fields to get the simultaneity characteristic. A half wave plate (HWP) and a quarter wave plate (QWP) are used to get a linear 45 deg SOP for the data beam and a circular polarization state for the local oscillator, in order to maintain a balanced power distribution for the quadrature components.[22]

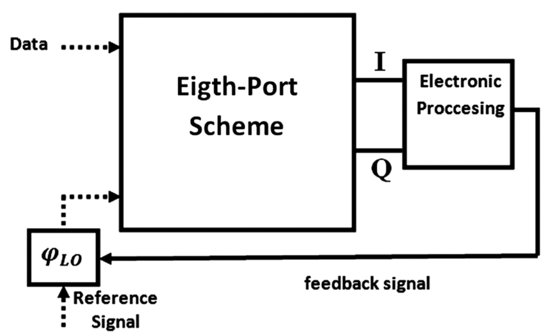

Fig. 1 Block diagram of an optical Costas loop as a simultaneous quadratures measurement system. *I*, *Q*: in-phase and quadrature components, φ_{LO}: local oscillator optical phase. Dashed line: optical signal, Solid line: electrical signal.

Using the transmission matrices of the above mentioned HWP and QWP devices [described by the Jones vectors $\binom{\cos\rho}{\sin\rho}$ and $\binom{\cos\varepsilon}{\sin\varepsilon e^{i\frac{\pi}{2}}}$, respectively], and the transmission matrix of the beam splitter at the input of the 8-port hybrid, we get E_1 and E_2 as:

$$E_1 = \frac{1}{\sqrt{2}}\left[\begin{pmatrix}\cos\varepsilon \\ \sin\varepsilon e^{i\frac{\pi}{2}}\end{pmatrix} E_{\mathrm{LO}} e^{i\theta_{\mathrm{LO}}} + \begin{pmatrix}\cos\rho \\ \sin\rho\end{pmatrix} E_S e^{i\theta_S}\right], \tag{3}$$

$$E_2 = \frac{1}{\sqrt{2}}\left[\begin{pmatrix}\cos\varepsilon \\ \sin\varepsilon e^{i\frac{\pi}{2}}\end{pmatrix} E_{\mathrm{LO}} e^{i\theta_{\mathrm{LO}}} - \begin{pmatrix}\cos\rho \\ \sin\rho\end{pmatrix} E_S e^{i\theta_S}\right], \tag{4}$$

where ε and ρ are the parameters required by the HWP and QWP to get the needed SOP in our system.

If we only take into account the canonical uncertainties of the optical fields, the proposed scheme (with a strong local oscillator) is able to measure the Wigner function of the quantum state of E_{ST} just before the polarized beam splitters (PBS) affect the observables.[23] When we take into account the separation of the polarization components of Eqs. (3) and (4) on the PBS, and also the respective horizontal and vertical states of polarization on each balanced homodyne detector (BHD) (see Fig. 2), the observed signals carrying the I and Q information of the optical field are represented as:

$$i_I \alpha \left|\frac{E_{\mathrm{LO}}}{2} e^{i\theta_{\mathrm{LO}}} + \frac{E_S}{2} e^{i\theta_S} + E_V e^{i\theta_V}\right|^2 - \left|\frac{E_{\mathrm{LO}}}{2} e^{i\theta_{\mathrm{LO}}} - \frac{E_S}{2} e^{i\theta_S} + E_V e^{i\theta_V}\right|^2 \tag{5}$$

$$i_Q \alpha \left|\frac{E_{\mathrm{LO}}}{2} e^{i\theta_{\mathrm{LO}}+\frac{\pi}{2}} + \frac{E_S}{2} e^{i\theta_S} + E_V e^{i\theta_V}\right|^2 - \left|\frac{E_{\mathrm{LO}}}{2} e^{i\theta_{\mathrm{LO}}+\frac{\pi}{2}} - \frac{E_S}{2} e^{i\theta_S} + E_V e^{i\theta_V}\right|^2. \tag{6}$$

As shown in Eqs. (5) and (6), there are three different signals on the observables (in the classical theory, it should be a quadratic binomial) for each field impinging on the respective photodetectors of the BHD. The variable E_V is added to represent the vacuum fluctuations that enter through the unused ports of the PBS with an orthogonal SOP with respect to that of the polarization components E_1 and E_2 (i.e., E_{1x} is mixed with E_{Vy} and E_{2y} is mixed with E_{Vx}).[24]

Manipulating Eqs. (5) and (6), and taking into account only the terms that have a conversion gain by the local oscillator, we get the current signals at the output of the BHDs as:

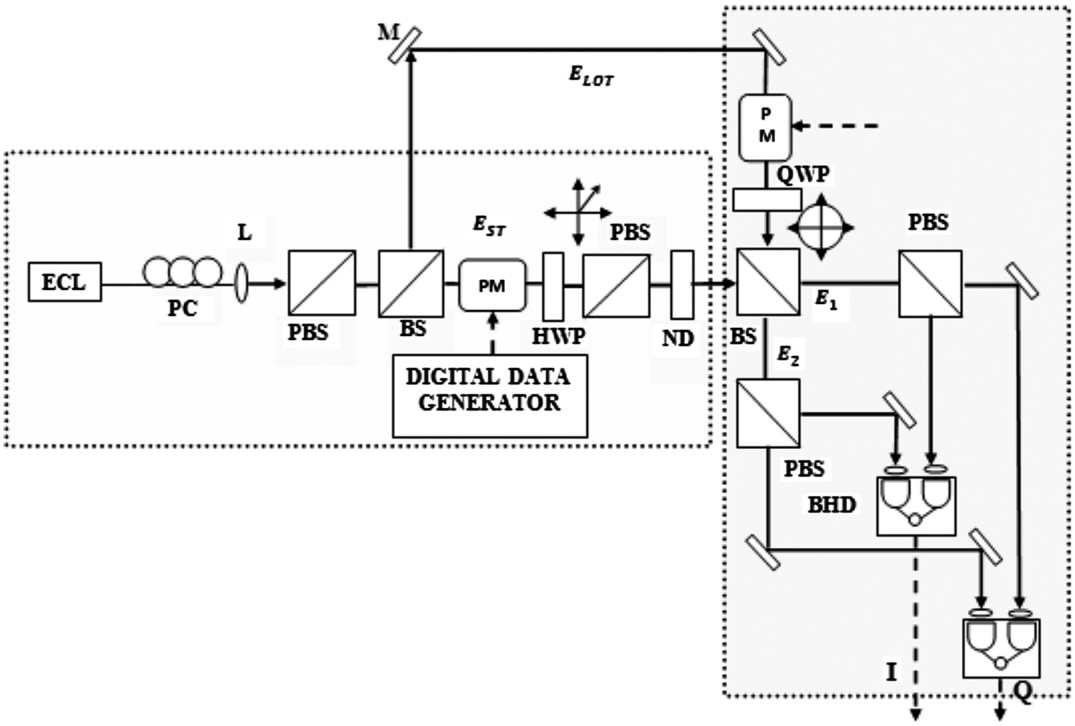

Fig. 2 Optical 8-port hybrid scheme. ECL: external cavity laser, PC: polarization controller, BS: beam splitter, ND: neutral density attenuators, PBS: polarized beam splitter, L: lens, M: mirror, PM: phase modulator, BHD: balanced homodyne detector. The thin line means optical paths and dashed line means electrical path.

$$i_I \alpha E_{\mathrm{LO}}(E_S + \delta I_S + \delta Q_S + \delta I_V + \delta Q_V)\cos[\varphi_{LO} - \varphi_S - \varphi_d] \tag{7}$$

$$i_Q \alpha E_{\mathrm{LO}}(E_S + \delta I_S + \delta Q_S + \delta I_V + \delta Q_V)\sin[\varphi_{\mathrm{LO}} - \varphi_S - \varphi_d]. \tag{8}$$

In order to get the signal-to-noise-ratio (SNR) of our scheme (when the receiver performance is shot-noise limited), we first obtain the expected values and variances of the observed signals using; $\langle(X - \langle X\rangle)^2\rangle = \langle X^2\rangle - \langle X\rangle^2$, with:

$$\langle X\rangle^2 = (E_{\mathrm{LO}}E_S)^2 \approx N_{\mathrm{LO}}N_S, \tag{9}$$

In Eq. (9) several products are negligible because they don·t have the conversion gain by the local oscillator signal. Using the relationship for the canonical uncertainty for the coherent states:[6] $\langle \Delta I^2\rangle\langle \Delta Q^2\rangle \geq 1/16$, we get:

$$\langle X^2\rangle = N_{LO}[\delta I_S^2 + \delta Q_S^2 + \delta I_V^2 + \delta Q_V^2] \tag{10}$$

$$\langle X^2\rangle = N_{\mathrm{LO}}\left[\frac{1}{4} + \frac{1}{4}\right] = \frac{N_{\mathrm{LO}}}{2}. \tag{11}$$

Finally, the SNR is:

$$\mathrm{SNR} = \frac{\langle X\rangle^2}{\langle X^2\rangle} = 2N_S, \tag{12}$$

As shown in the above equation, the SNR is related only to photon number (number of photons in the bit interval of the phase modulated data signal),[2,25] therefore, for Gaussian fluctuations are:

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\mathrm{SNR}}{2}}\right). \tag{13}$$

Equation (13) corresponds to an ideal 8-port receiver; however, for more realistic receivers:

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left[\sqrt{\eta N_S}\cos(\theta_e)\sin\frac{\pi}{M}\right], \tag{14}$$

where η is the general efficiency in an experimental implementation, N_S is the number of received photons in the data signal, M is the number of symbols, and θ_e is the residual phase error between the signal and the LO for an imperfect phase-locking.

The experimental efficiency is $\eta = \eta_{\mathrm{mm}}\eta_p\eta_{\mathrm{loss}}$, where η_{mm} is the efficiency of the mixing of the temporal and spatial modes of the beams, η_p is the photodetector's quantum efficiency and η_{loss} are the optical powers loss. The SNR of the homodyne scheme that simultaneously measures the quadrature components of a BPSK modulated signal, similarly to the detection scheme using heterodyne reception with switched quadratures (the noise contribution consists of the vacuum fluctuations and the image signal in the frequency domain, respectively).

The value of the parameter θ_e is highly dependent on the design of the Costas loop; the design must take into account the phase diffusion of the coherent states E_{LOT} and E_{ST} with probability function Q_{qs}:

$$Q_{qs}(I,Q) = \frac{1}{2\pi} e^{\left[-\frac{(r^2+r_n^2)}{2}\right]} I_0(rr_n), \tag{15}$$

When this equation is obtained, the asymptotic behavior of the Bessel's function for a large number of photons is not taken into account, and I_0 is the first type, order zero modified Bessel's function Bessel, r is the vector value that represents the instantaneous phase described by $r = \sqrt{I^2 + Q^2}$, and r_n is the Bohr-Somerfield's radius described by $r_n = \sqrt{2n+1}$ for a given photon number n.[9] It is important to note, that the Poissonian statistics in the detection process do not change, even when the laser has a phase diffusion behavior.

The feedback loop takes into account the phase noise θ_n and the amplitude noise $n(t)$ to get the phase error variance, $\sigma_e^2 = \theta_n(t) \otimes [1 - h(t)] + \frac{1}{A} n(t) \otimes h(t)$, where $\otimes$ is the convolution function, and $h(t)$ is the impulse response of the linearized Costas loop.[26,27]

An important issue for the Costas loop implementation that must be theoretically taken into account is the total delay of the feedback signal. According to Keang Po-Ho,[21] the delay affects $h(t)$ because of the e^{-sT} factor (where s represents the Laplace domain, and T is the delay time in seconds). Using the spectral density functions of the above-mentioned noises, as well as the transfer function of a first order active filter, and knowing that the delay time of the feedback signal is negligible, we have $\sigma_e^2 = \Delta v/\sqrt{2} f_n + 3\pi T_p f_n / 2\sqrt{2} N_S$. In this equation, there is a trade-off among the several noises and their contribution to the variance of the phase error. The natural frequency that optimizes the performance of the feedback loop may be expressed as:[8,21]

$$f_n = \sqrt{\frac{2\Delta v N_S}{3\pi T_p}}, \tag{16}$$

where T_p is the bit duration, N_S is the number of photons of the data signal for an observation time, and Δv is the linewidth of the lasers. The structure described in this paper is able to get a minimum value of the phase error variance (σ_e^2) between E_{LOT} and E_{ST}.

3 Experimental Setup

Figure 2 shows a block diagram of our experimental setup, consisting of a laser transmitter operating at 1550.1 nm (external cavity laser), a phase modulator, and pseudorandom bit sequence generator that provides the data signal at a rate of 350 Kbps. For convenience, we use an interferometric system to relax the automatic frequency control for large optical frequency departures, and a nonsymmetrical, nonpolarizing beam splitter produces the signal to be modulated, and the local oscillator with few mW of optical power. Obviously, in a practical system, the local oscillator must be an independent optical source with a linewidth small enough to assure a good performance at the receiver stage. This interferometric scheme allows us to work at a low bit rate for preliminary demonstration purposes; we need large gain amplifiers at the electrical post-detection stages since we are working with faint low photon number fields.

In our setup, the precise knowledge of the SOP of E_{LOT} and E_{ST} is very important, as a inadequate SOP in one optical signal may affect the development of the Eqs. (3)–(8), so we evaluate the performance of the HWP and QWP with the following results: a) the HWP has a standard deviation of 0.113 deg for the vertical linear SOP (required to minimize the residual amplitude modulation of the phase modulator) and a linear SOP at 45 deg, both SOPs with a 99.9% degree of polarization (DOP) and an extinction ratio of 60 dB, while b) the QWP has a standard deviation of 0.046 deg and a 91.9% DOP. For these measurements, we use a free-space SOP analyzer with 200 samples for each measurement. In agreement with the results obtained in the measurement of the quadrature components, the experimental setup exhibits a total efficiency of approximately 0.7. This is due to the losses of optical power in the implementation as well as the imperfect mixing between the temporal and spatial modes of E_{LOT} and E_{ST}.

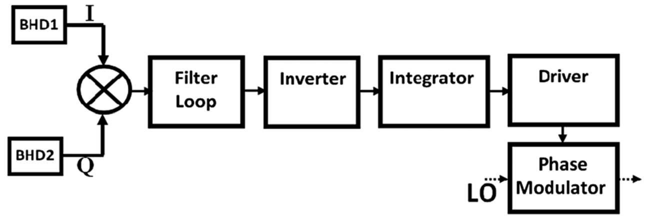

Fig. 3 Block diagram of the electronic control to generate the error and feedback signals for the phase lock, this is the electronic part of the Costas loop. LO: optical local oscillator signal. BHD: balanced homodyne detector.

The electronic diagram of our Costas loop is shown in Fig. 3. We used an analog multiplier to remove the modulation from the data signal and to obtain the phase error signal, φ_e; in addition, we used a filtering and integration stage to eliminate the higher order harmonics. An inverter circuit was implemented to match the feedback signal and filtering and integration stages with the additional advantage of a better performance in the feedback stage. The gains of the diverse devices within the loop are important in the design of an optimum loop filter; the value we used for the integrator gain was 0.3 V/V, the gain of the phase modulators was (operating at 1550.1 nm), and the gain of the equivalent oscillator was 20.655×10^{-3} rad/(V × sec). There is also a gain related with the driver of the phase modulator located in the path of the local oscillator and the total attenuation of the feedback electrical circuit. We designed the filter of our loop using the above-mentioned gains as well as the gains of the balanced homodyne detectors (BHD) (from 1 V/V until 30,000 V/V); the designed filter is a first order, low-pass active filter with a natural frequency of 360.97×10^3 Hz, and a phase detector gain of 5.8×10^{-6} V/rad, optimized for 5 photons per bit, according to Eq. (16).

4 Results

We measure the shot noise for different values of the local oscillator optical power and with different gains of the BHDs with a spectrum analyzer, with the purpose of assuring the standard quantum limit and the SNR obtained using Eqs. (9)–(12). In order to measure the shot noise, we block the data signal at the input of the 90-deg optical hybrid, so a vacuum noise signal is introduced by the unused port of the beam splitter (BS). Figure 4 shows the measured shot noise is well above the electronic noise in the frequency region of interest. The nonlinearity of the curves for high

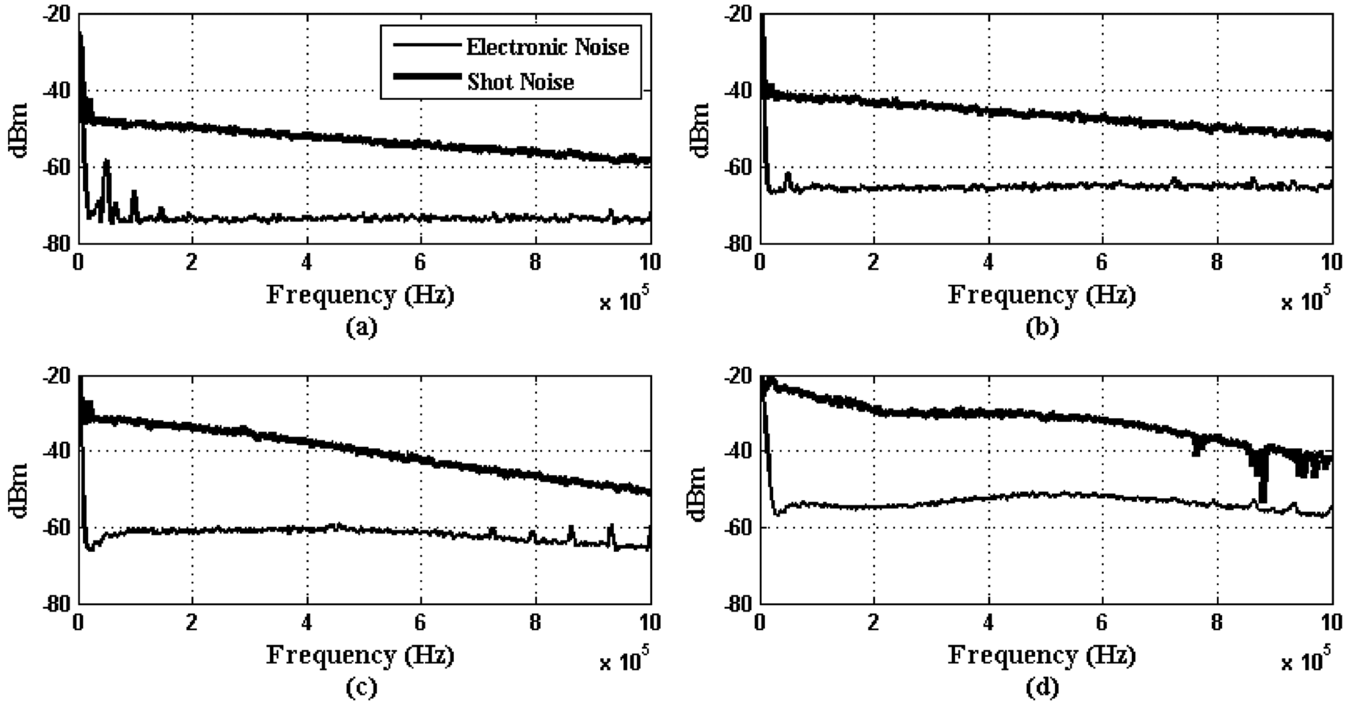

Fig. 4 Spectra of the shot-noise for different gains of the balanced homodyne detectors (BHDs) at 2 mW of local oscillator power, considering the maximum gain for loop filter design, where the gain (V/V) of the BHDs is (a) 1000, (b) 3,000, (c) 10,000, and (d) 30,000.

gains of the BHDs is to a large extent caused by the instability of the detector.

The linear behavior of the shot noise with reference to an increase in the local oscillator optical power is shown in Fig. 5 (results were reported with acquired data from an oscilloscope with 50,000 points at 4 G samples per second). The above-mentioned linear behavior may be modeled as $y = ax + b$, with y being the total noise (Volts), x is the local oscillator optical power (Watts), a is related with a conversion factor of the photodetectors (in our case $a = 0.66$ V/mW), and $b = 0.8$ mV is related with the electronic noise without data signal present (Volts). Therefore, for a local oscillator optical power of 2 mW, the root mean square (rms) voltage is 2.154 mV.

The measurement of the shot noise (shown in Figs. 4 and 5) is important to validate the performance of the experiment described by Eqs. (13) and (14). In the electronic stage implemented for the Costas loop, we have a total delay of approximately 700 ns in the feedback loop (negligible in comparison with the bit duration of 2.85 μs). For a higher

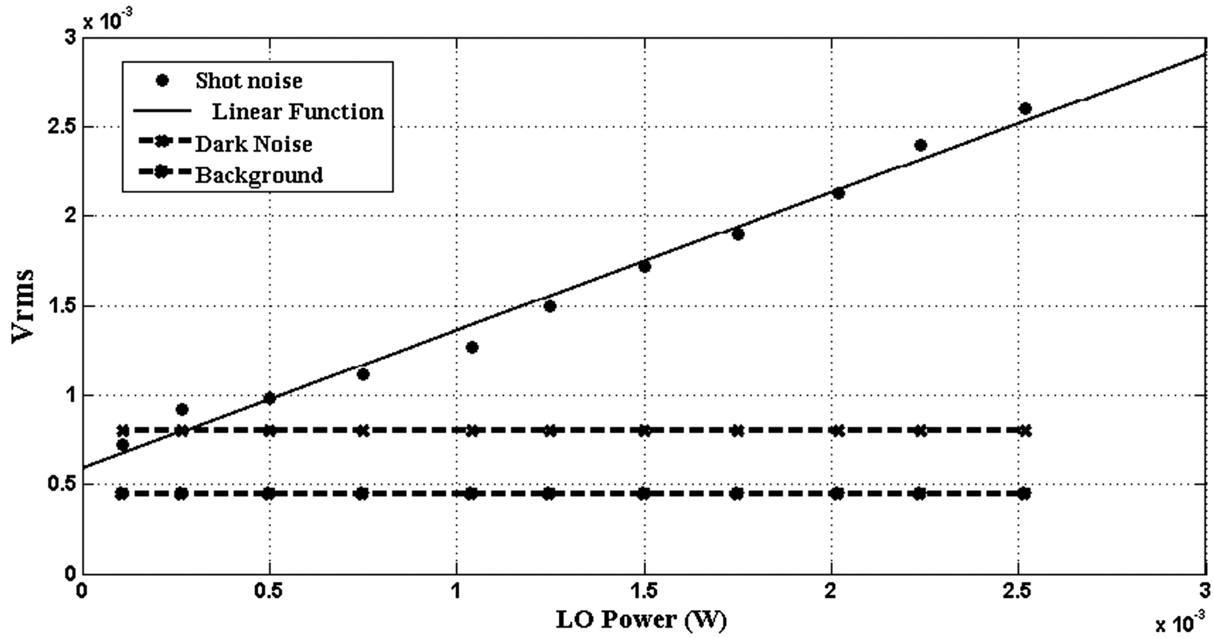

Fig. 5 Shot-noise variance for different optical powers of the LO in the temporal domain.

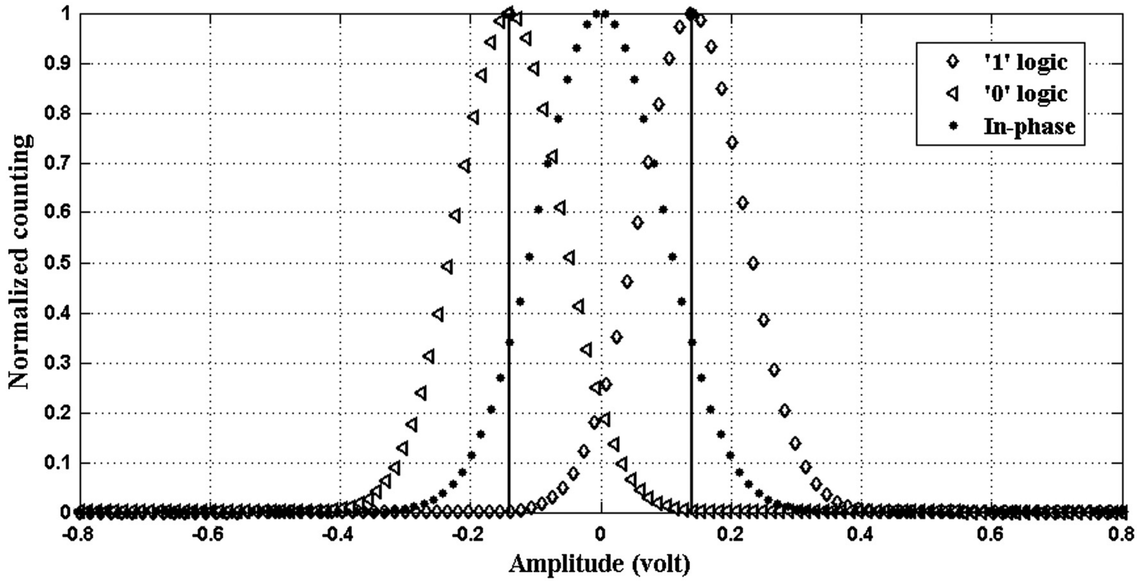

Fig. 6 Normalized histograms of the quadratures components for 5 photon per bit.

bit rate, however, the loop filter must be redesigned to account for the total delay time of the system and/or by using optical sources with smaller linewidths.[28,29]

We obtained (by means of post-processing) the measured statistics of the quadrature components for several optical powers (from 225×10^{-15} to 11.25×10^{-15} W, corresponding from 5 to 0.25 photon per pulse, respectively). Figures 6 and 7 show the normalized histograms for 5 and 0.25 photons, and the experimental mean value for each quadrature component. The histogram of the in-phase component shows a small increment of the variance due to the slightly nonsymmetrical experimental implementation. As related to Eq. (15), the phase diffusion effects are minimized when the optimum Costas loop is used, making it possible to obtain the histograms shown.

Finally, the theoretical performance at the quantum limit using coherent states is limited by the Helstrom's limit, which has been addressed using different techniques.[30–32] In our experiment, the coherent detection at the standard quantum limit using simultaneous measurements of the quadrature components (with homodyne detection) led us to a penalty on the BER in comparison with the Helstrom's limit (with photon counting detection).

Figure 8 shows the BER as a function of the photon number for our experimental setup (using weak coherent states). In a previous paper,[33] we reported the performance of both open and closed loop operating at 5 photon per pulse. In this case, all the BER measurements are made in a closed loop using the optimal feedback loop. From Fig. 8, it is possible to observe that the experimental performance is very close to

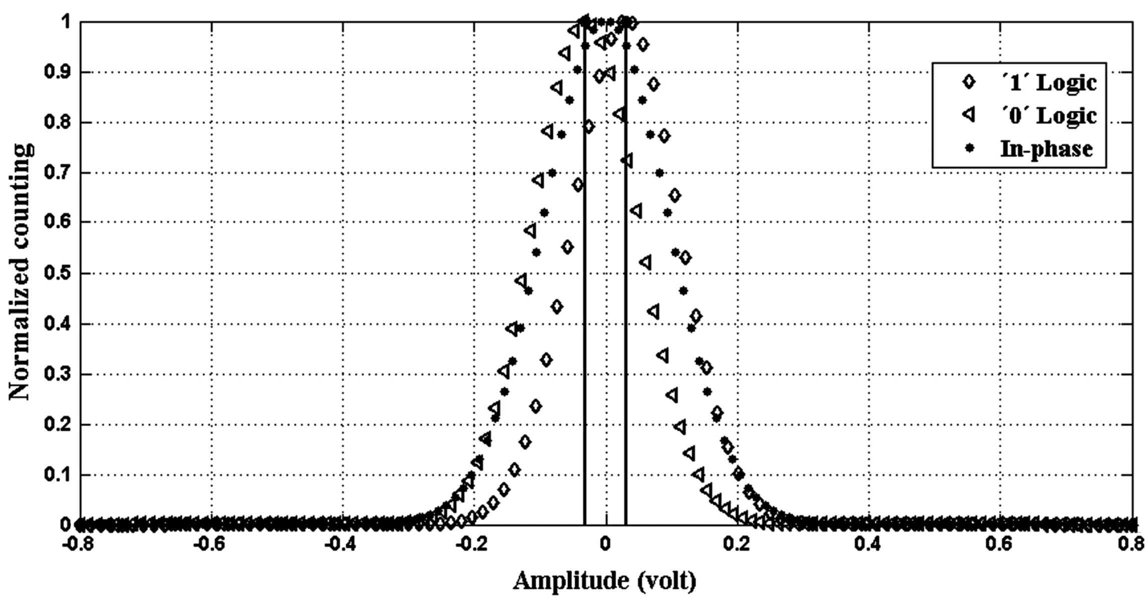

Fig. 7 Normalized histograms of the quadratures components for 0.25 photons per bit.

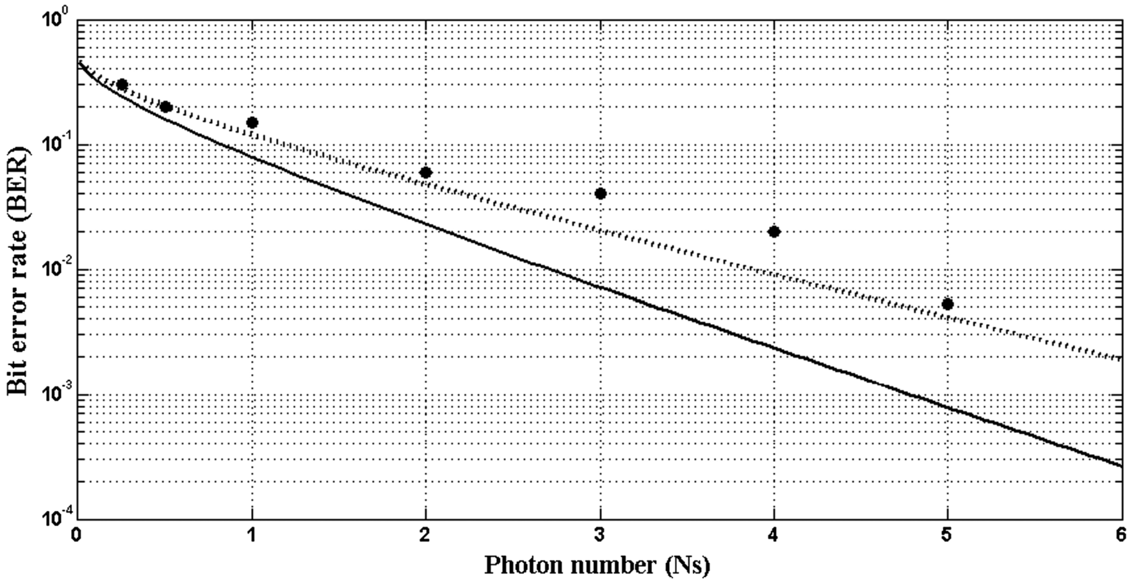

Fig. 8 Bit error rate (BER) penalties for different photon numbers.

the theoretical performance, while taking into account the non idealities and the experimental efficiency.

5 Conclusions

We reported the design, implementation, and performance evaluation of an optical Costas loop for a low photon number signal consisting of weak coherent states at 1550 nm using suppressed carrier modulation, which is required for power economy. We made an optimum design and implementation of the Costas loop to improve the performance of the experiment. The shot-noise measurements on the optical power of the local oscillator are 20 dB above the total electronic noise in the required frequency region. Using BPSK modulation, the measured BER from 0.25 to 5 photons per pulse has a good performance, with potential application in the distribution of cryptographic keys using continuous variables while accounting for the relationship between speed and transmission distance. The measured mean electrical delay (because of optical and electronic processing time in the diverse devices used) was 700 ns (negligible in comparison with the operating speeds); however, an increase in transmission speed will require an adjustment on the parameters of the experimental scheme to reduce the total delay. In order to deal with such a problem, as a future study, we are implementing a digital signal processing stage in combination with file-programmable gate arrays (FPGAs).

A distinctive feature of our work is that we use the SOP of the optical signals to get the simultaneity characteristic in the measurement of the in-phase and quadrature components of the optical field. In this way, we get very good stability in comparison with 8-port designs based on an electro-optic phase shift of the local optical oscillator, generally requiring several adjusting and control points. This system may be used in quantum communications systems such as quantum keys distribution using continuous variables (CV-QKD). Finally, our detector may be an interesting application as a generic scheme to measure the quasiprobability Q function in tomography applications for information-carrying optical states.

Acknowledgments

The authors would like to thank to Ricardo Nuñez for helpful discussions and assistance during preparation of this paper. This work has been performed with the support of the CONACYT, Mexico.

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