MUTUAL INFORMATION IN WEAK - COHERENT – STATE DETECTION USING A HOMODYNE OPTICAL COSTAS LOOP WITH DIFFERENT PHASE ERRORS.

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ABSTRACT

A free-space experimental set-up for measuring the quadrature components of weak-coherent-state laser signals, based on a homodyne Costas loop configuration is presented. Loop parameters are optimized as a trade-off between quantum and phase noises. Using BPSK modulation, measurements on the mutual information are presented for different photon numbers and phase errors.

KEY WORD: mutual information, optical Costas loop, weak coherent state, homodyne detection.

1. INTRODUCTION

In communication systems, the main goal is the maximization of the mutual information between the transmitter and the receiver, i.e. Alice and Bob in cryptography systems. In optical communications, both with fiber and free space, and particularly those employing low optical power levels (i.e. quantum level signals), several practical structures for the mutual information maximization have been proposed, in order to approach the information theoretical limits [1]. Theoretical analysis and experimentation with coherent states are widely reported since they are easily produced with standard stabilized semiconductor laser sources, and the generation of faint signals for quantum levels is easily obtained by strong attenuation of the laser light, leading to weak coherent states [2, 3].

For the optimum detection of weak coherent states, several configurations have been proposed and experimentally demonstrated, such as the Kennedy and Dolinar receivers, operating in open and closed loops, respectively, approaching the fundamental detection limit; however, these are based on single photon counting [4], which performs poorly at the telecommunications waveband of 1550 nm, in terms of efficiency and speed.

2. HOMODYNE AND COSTAS LOOP RECEIVERS

On the other hand, homodyne detection with standard p.i.n. photodetectors has been extensively used in the optical telecommunications waveband, providing the required speed and, for very low photon numbers, performing better than the Kennedy receiver [4].

Furthermore, the adaptive homodyne detection is linear in the optical-electric field, therefore, many of the results from the communications theory in the radio electric domain could be incorporated, such as error correction and advanced post-processing signal. For example adaptive homodyne detection has been proposed and experimentally demonstrated for quantum optical states (coherent, squeezed and number states); in this kind of detection, the phase of the local oscillator is changes within a specific time interval, according to a feedback signal resulting from the processing of the phase error [5, 6].

Homodyne reception can be relatively easy implemented with balanced detectors, using beam splitters or fiber optic couplers, in order to collect all the available light, and approach the so-called standard quantum limit [2, 7]. Homodyne receivers allow the detection of only one of the quadratures of the optical field, that defined by the local oscillator phase, and are useful for binary phase-shift-keying modulations (BPSK). However, for higher order modulations usually needed in optical communications such as QPSK, the simultaneous measurement of the two quadratures is required. For this task, the optical Costas loop is proposed as a structure for the simultaneous detection of the in-phase and quadrature components, and is based on the use of two balanced homodyne receivers, with a 90-degree local oscillator phase difference between them. The Costas loop receiver structure possesses many interesting features, such as the detection of suppressed carrier signals, conserving the possibility of post-processing [8], thus constituting an interesting alternative in a variety of applications in power efficient optical communications systems, for example optical satellite communications and quantum cryptography [3, 9].

In this letter we present the design and experimental realization of a self-homodyne optical Costas loop working at the standard quantum limit (SQL) for the detection of weak-coherent-states (WCS) and the measurement of the mutual information. Our experimental set-up is in free space and is based on the manipulation of the state of polarization (SOP) of the weak-coherent-state signal and of the local oscillator. Finally, we obtain the mutual information for different cases of phase noise introduced externally.

3. EXPERIMENT.

The experimental set-up for the optical Costas loop is shown in figure 1; it comprises of a narrow linewidth external cavity laser operating at 1550.1 nm; in this self-homodyne configuration, the local oscillator signal E_{LOT} is obtained using a fiber beam splitter and fiber polarization controller (PC); both the local oscillator and the data signal E_{ST} are transmitted in free space using a grin lens (GL).

BPSK is produced with a phase modulator (PM) driven by an electrical pseudorandom binary sequence from a digital data generator of a digital transmission analyzer, to produce the suppressed carrier with -90^o to +90^o excursion at a symbol transmission rate of 350 kHz. In order to minimize the residual amplitude modulation in the PMs, the SOPs were fixed as linear at 90^o with an extinction ratio better than 60 dB. In order to produce the WCS, a set of neutral density filters (ND) was used to achieve several attenuation levels, up to 120 dB.

A half wave plate (HWP) sets a SOP linear at 45^o for E_{ST}, and a quarter wave plate (QWP) sets a circular SOP for E_{LOT}. The optical power (or photon number) is continuously monitored with a sensitive optical power meter with a 10×10^{-15} W in a straight way, as well as with a single photon detector (SPD).

The balanced mixing of the optical beams is made in free space after being separated based in the SOP of the mixed signals (E_1 and E_2) using two polarized beam splitter (PBS): each polarization component (horizontal and vertical) is detected in the corresponding balanced homodyne detector (BHD), with a 5 MHz bandwidth and a 3×10^4 V/V maximum gain, for the detection of low photon numbers. Our experiment operates in the self homodyne mode, i.e. a single laser provides the signal and the local oscillator, thus relaxing the need of an automatic frequency control (AFC), however, in order to operate under more realistic conditions of phase noise, we introduce a controlled amount of noise in the WCS by superimposing electrical noise on the binary signal prior to the phase modulation at the PM: deep modulation of 15^o and 28^o that correspond to 1.4 Vpp and 2.4 Vpp of additional voltage respectively. In order to generate the phase error signal, the Costas loop suppresses the modulation with a non-linear operation on the post-detection (electrical) signals corresponding to the in-phase and quadrature components; in our experiment we use an analog multiplier in an electronic circuit to obtain the phase error signal that will be processed in order to perform the phase lock, using inverter, amplifiers, voltage followers and integrator. A set of optimum electronic active first order filters was implemented for WCS signals with 0.25, 0.5, 1, 2, 3, 4 and 5 photons per bit.

4. RESULTS

The equivalent voltage controlled oscillator (VCO) in our experiment has a gain of 20.65×10^3 rad / (volt.sec) determined mainly by the bandwidth of the integrator circuit, 113 kHz. With the set of electronic filters used, we obtain a loop bandwidth from 168 Hz to 1.21 kHz for different photon numbers and specific gains of the BHDs. The overall efficiency of the experimental set-up is $\eta = 0.7$, which includes the efficiency of the photodetectors, the mixing efficiency due to the spatial-temporal mode matching of the WCS signal and the local oscillator, and power losses. We perform a post-processing of the quadrature components with a sampling rate of 4×10^9 samples per second and using 50,000 samples for the analysis to obtain the mutual information (I_{AB}) between the transmitter and the receiver based on Shannon's theorem (1) [10, 11].

$$I_{AB} = 1 + P_e \log_2 P_e + (1 - P_e) \log_2 (1 - P_e) \tag{1}$$

Where, P_e is the error probability given by:

$$P_e = \frac{1}{2} erfc\left(\sqrt{\eta N_S} \cos \theta_e\right) \tag{2}$$

Where N_S is the photon number and θ_e is the error phase signal. The error probability or experimental bit error rate (BER) for different errors phase is presented in the figure 2 according to equation (2).

Figure 3 shows the theoretical performance in terms of the mutual information as a function of the photon number for different phase errors, in an optimized design of the Costas loop considering the phase and quantum noises. While for low photon numbers there exists a departure between the theoretical and experimental performances, for higher photon numbers the measurements are closer to the predicted performance [12].

Also, we may describe the mutual information between Alice and Bob as in reference [2], using the equations (1) and (2) to relate the optical losses (detector efficiencies, i.e. $\eta<1$), with the BER performance for different values of the phase errors. Then, using the equation (3) it is possible to determine the secure key rate ($\Delta I \geq I_{AB} - I_{AE}$), required for a secure link.

$$\Delta I = \frac{1}{2}\log_2[(V+\chi)/(1+\chi)] - \frac{1}{2}\log_2[(\eta G)^2(V+\chi)(V^{-1}+\chi)] \qquad (3)$$

Where V is the variance of Alice modulation, χ is the equivalent noise taking into account the quantum noise and the noise in Bob as well. In our case G has a unit value because of the no existence of Eve on the quantum channel. All of the parameters are normalized to the shot noise value.

5. CONCLUSIONS

In this paper we report experimental results of the maximization of the mutual information between Alice and Bob in an opto-electronic Costas loop receiver with different values of phase errors. We present, as well, the simultaneous measurement of the quadrature components of an optical field with weak coherent states based on its state of polarization and phase noise insertion. Additionally, the bit error rate measured is compared against the theoretical value. Our experimental results have a good performance for a given range of photon numbers and different values of the phase errors.

As it is well known, with small improvements on the quantum efficiency of the receiver systems (specially the single photon detectors) we do not get a significant improvement on the mutual information [5]. In a similar way, small phase noise variations do not significantly decrease the mutual information mainly because of the use of a phase lock system. The measured values of I_{AB} and $I\Delta$ give information regarding the effect on the receiver performance and the secrecy value on the message sent. For the case of $I\Delta$, we observe that for the values of the phase errors used, the security in the communication it is assured. If we reduce the parameter χ, it is possible to increase the mutual information and the security level of the system. So, we demonstrate that using the optimum feedback loop in the quantum communications systems, it is possible to increase the mutual information.

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FIGURES.

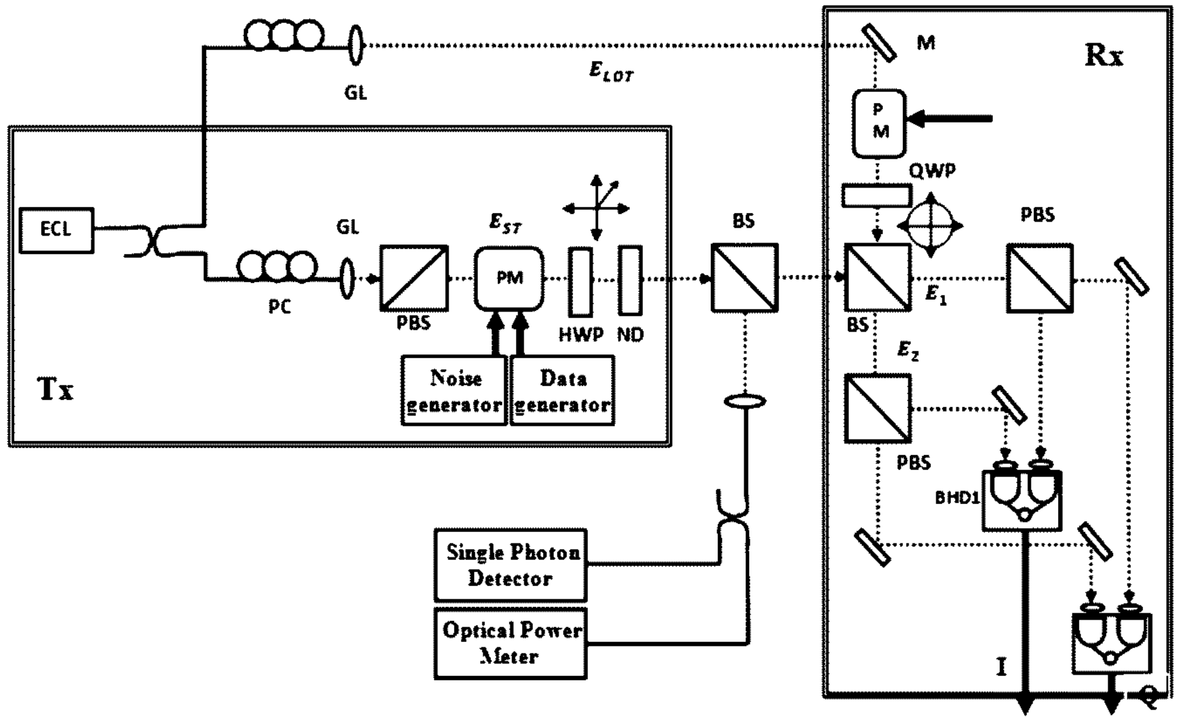

Figure 1: Experimental set-up show the transmitter and receiver systems. ECL: External Cavity Laser, PC: Polarization Controller, PBS: Polarized Beam Splitter, GL: Green lens, HWP: Half Wave Plate, QWP: Quarter Wave Plate, BS: Beam Splitter, BHD: Balanced Homodyne Detector, PM: Phase Modulator, ND: Neutral Density Filter, M: Mirror

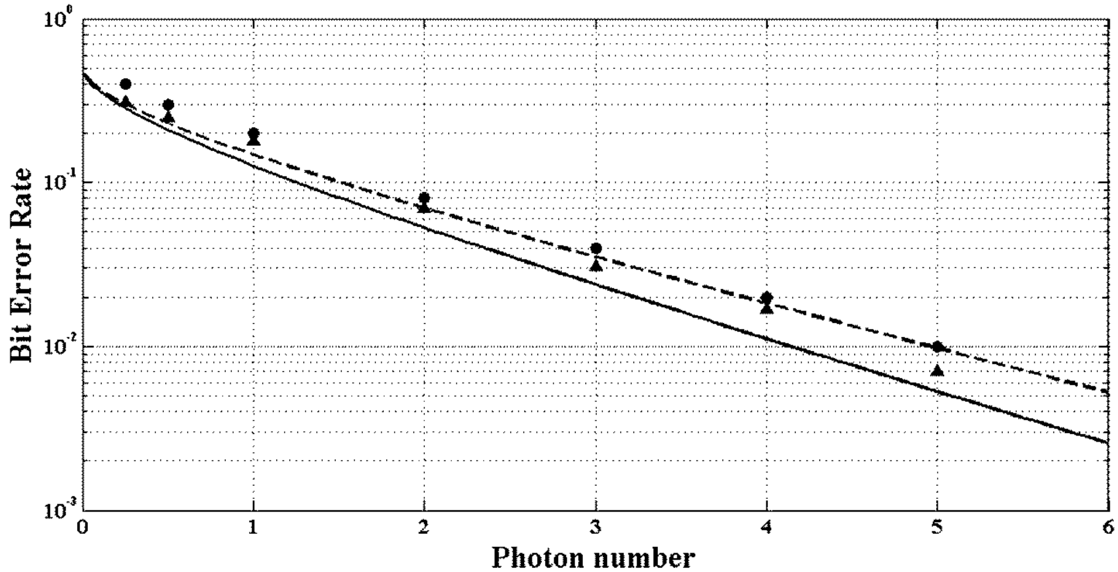

Figure 2: Measurement of the bit error rate (BER) for different photon numbers and phase errors. Solid line: theoretical performance of error signal of 15^{o}, dashed line: theoretical performance of error signal of 28^{o}, triangle symbol: practical results of error signal of 15^{o}, circular symbol: practical results of 28^{o}

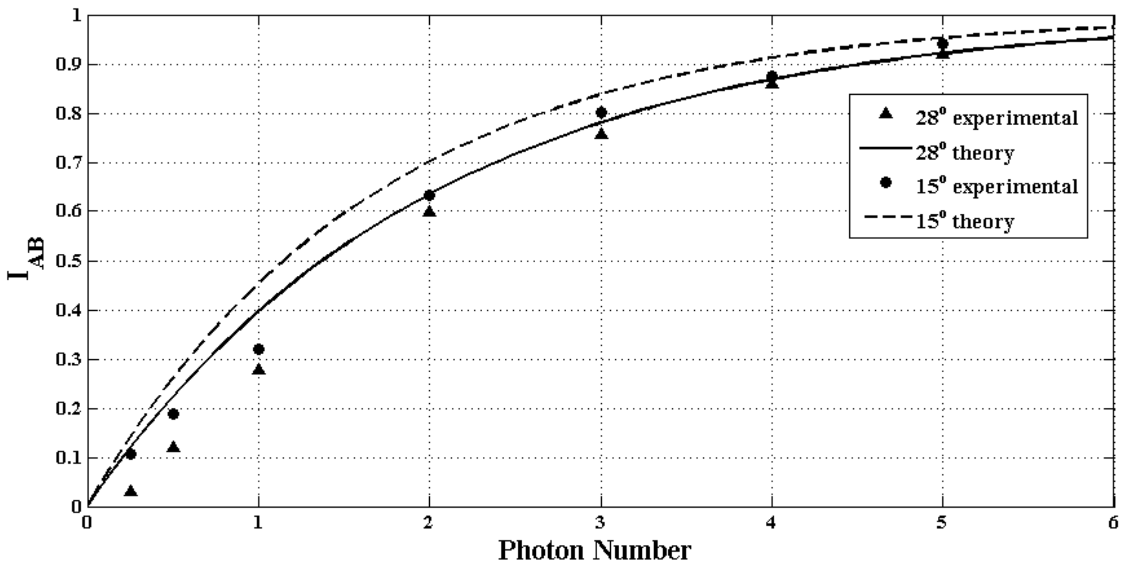

Figure 3: Theoretical and practical mutual information between the transmitter and receptor systems for different photon numbers and errors phase.

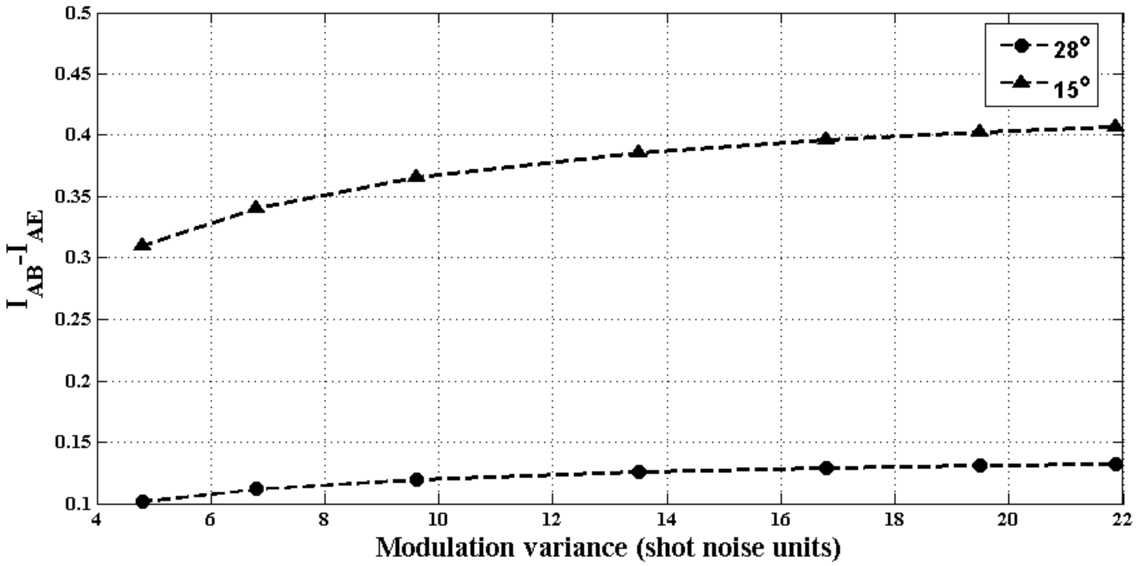

Figure 4: Practical results of the differential argument of the mutual information ($\Delta I = I_{AB} - I_{AE}$) between Alice-Bon and Alice-Eva for different errors phase.