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Conditional preparation of a quantum state in the continuous variable regime : generation of a sub-Poissonian state from twin beams

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We report the first experimental demonstration of conditional preparation of a non-classical state of light in the continuous variable regime. Starting from a non-degenerate OPO which generates above threshold quantum intensity correlated signal and idler "twin beams", we keep the recorded values of the signal intensity only when the idler intensity falls inside a band of values narrower than its standard deviation. By this very simple technique, we generate a sub-Poissonian state 4.4 dB (64%) below shot noise from twin beams exhibiting 7.5 dB (82%) of noise reduction in the intensity difference.

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A well-known technique to generate a single photon state from quantum correlated photons ("twin photons") is to use the method of conditional measurement: if one labels (1) and (2) the two modes in which the twin photons are emitted, it consists in retaining in the information collected on mode (1) only the counts occurring when a photon is detected in mode (2) (within a given time window ΔT). This method has been widely and very successfully used over the past decades, firstly with twin photons generated by an atomic cascade [1], then by using the more efficient technique of parametric down conversion [2]. Various protocols have been proposed to use conditional preparation in order to generate other kinds of non-classical states, for example Schrödinger cat states using a squeezed vacuum state transmitted through a beamsplitter and a measurement conditioned by the counts detected on the reflected port [3]. In a similar way, teleportation of a quantum state of light can be achieved by using conditional measurements [4] and the degree of entanglement can be improved by photon subtractions [5]. In cavity QED, conditional measurements on the atomic state have also led to the experimental generation of non-classical photon states [6].

State reduction is obviously not restricted to the case of photon counting, so that it may be interesting to extend this technique to the continuous variable regime, where a continuously varying photocurrent is measured instead of a series of photocounts. Continuous detection conditioned by a photon counting event has been implemented in various schemes [7]. Closer to our proposal where continuous measurements are used both for triggering and characterizing the generated state, many theoretical protocols have been suggested relying on two-mode squeezed vacuum produced by a non-degenerate optical parametric amplifier [8, 9]. For instance, homodyne measurements on the idler can be used to condition the detection of the signal and would reduce it to a squeezed state [8].

In a conditional state preparation, the generation of the non-classical state can be seen as the collapse of the entangled wave-function induced by the measurement on one of its components. However, very frequently, the measurement is made by post-selection of the relevant events in the record of all the values measured on the two channels, which can be made after the end of the physical measurement, so that no wave-function collapse actually occurs during the experiment. Note that, in contrast to the methods of direct generation of a non-classical state, the exact time window when the state is produced is not controlled in a conditional measurement, and what we will call the "success rate", i.e. the probability of generating the non-classical state in a given time interval, is an important parameter to characterize its efficiency.

To the best of our knowledge, no scheme has been suggested so far to generate non-classical intense beams by the technique of conditional measurement performed on continuous variables. This is the purpose of the present letter, which proposes a very simple way of conditionally preparing a bright sub-Poissonian beam from twin beams, and reports on its experimental implementation. The theory of the presented technique will be detailed in a forthcoming publication [10].

It is well known that a non-degenerate optical parametric oscillator (ND-OPO) produces above threshold intense signal and idler "twin beams" [11] : in the ideal case of a system without losses, the Fourier components of the signal and idler intensity quantum fluctuations which lie inside the cavity bandwidth are perfectly correlated. The correlations are characterized by the "gemellity", which is the remaining noise on the intensity difference between the signal and idler intensities normalized to the corresponding quantum noise level [12]. The instantaneous values of the signal and idler photocurrents play therefore the role of the occurrence of counts in the photon counting regime. The conditional measurement technique that we propose consists in selecting the signal photocurrent I_s only during the time intervals when the idler intensity I_i has a given value I_0 (within a band ΔI smaller than the photocurrent standard deviation). The measurements outside these time intervals are discarded. If the correlation is perfect and the interval ΔI close to

zero, the recorded signal intensity is perfectly constant, and an intense number state is generated by this conditional measurement.

In a real experiment, the correlation between the signal and idler photocurrents is not perfect, and the selection band ΔI is finite, so that the method will not prepare a perfect number state, but a sub-Poissonian state instead. The density matrix describing the state of light which is produced by such a state reduction technique can be determined within the approximation that the signal and idler photon distributions are Gaussian [10]. In the limit where ΔI is very small, one finds that, whatever the initial intensity noise of the beams are, the conditional measurement produces a sub-Poissonian signal beam, characterized by a Fano factor equal to the conditional variance of the intensity fluctuations of the signal beam knowing the intensity fluctuations of the idler beam, which plays an important role in the characterization of Quantum Non Demolition measurements [13]. In other words, in the limit of large correlations, the intensity noise reduction on the conditionally prepared state is equal to the twin beam noise reduction minus 3dB.

Obviously, if ΔI is very small, the probability that the idler intensity lies within the chosen band is also very small, and the success rate of the non-classical state production by such a conditional measurement is also very low. Computer simulations, as well as analytical calculations [10], show that the Fano factor of the generated state remains almost constant in a wide range of ΔI values, whereas the success rate of the method increases quickly. It is only when ΔI reaches values comparable to the shot noise standard deviation that the post-selection process becomes less efficient, and the Fano factor tends to its uncorrected value.

The present conditional measurement technique has strong analogies with the method of active feed-forward correction of the signal beam intensity, by opto-electronics techniques, using the information obtained from the measurement of the idler intensity [14, 15], which produces a sub-Poissonian state with a Fano factor also equal to the conditional variance. The present technique is much simpler to implement, whereas the active correction technique is non-conditional, and has the advantage of producing the non-classical state at all times.

The experimental setup is shown in Figure 1. A continuous frequency-doubled Nd:YAG laser pumps a triply resonant ND-OPO above threshold, made of a semi-monolithic linear cavity : in order to increase the mechanical stability and reduce the reflection losses, the input flat mirror is directly coated on one face of the 10mm-long KTP crystal. The reflectivities for the input coupler are 95.5% for the pump (532nm) and almost 100% for the signal and idler beams (1064nm). The output coupler (R=38mm) is highly reflecting for the pump and its transmission is 5% for the infrared. At exact triple resonance, the oscillation threshold is less than 15mW.

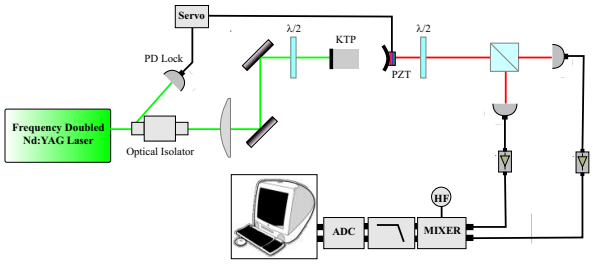

FIG. 1: Experimental layout. The 1064nm orthogonally polarized bright twin beams generated by the ND-OPO are separated by a polarizing beam splitter (PBS) and detected. The high frequency components of the photocurrents are amplified and demodulated at a given Fourier frequency. The two channels are digitized and simultaneously recorded on a computer.

The OPO is actively locked on the pump resonance by the Pound-Drever-Hall technique: we detect by reflection the remaining 12MHz modulation used in the laser to lock the external doubling cavity. In order to stabilize the OPO infrared output intensity, the crystal temperature has to be drastically controlled (within a mK). The OPO can operate stably during more than one hour without mode-hopping. The signal and idler orthogonally polarized beams (in the 1-5mW range) generated by the OPO are then separated by a polarizing beam-splitter and detected on a pair of balanced high quantum efficiency InGaAs photodiodes (Epitaxx ETX300, quantum efficiency: 95%). An half-wave plate is inserted before the polarizing beam-splitter. When the polarization of the twin beams is turned by 45° with respect to its axes, it behaves as a 50% usual beam-splitter, which allows us to measure the shot noise level[11].

In almost all the bright twin beams experiments to date [11], the photocurrents are subtracted and the difference is sent onto a spectrum analyzer which gives the variance of the photocurrent distribution. We have implemented a different protocol to have access to the full photon-number quantum statistics of the signal and idler beams at a given Fourier frequency Ω (see also [16]): each photocurrent is amplified and multiplied by a sinusoidal current at frequency Ω produced by a signal generator, and filtered by a 22kHz low-pass filter in order to obtain the instantaneous value of the photocurrent Fourier component at frequency Ω, which is then digitized at a sampling rate of 200 kHz by a 12-bit, 4-channel acquisition card (National Instruments PCI-6110E), which also simultaneously records the instantaneous values of the DC photocurrents. Two successive acquisitions (200 000 points for each channel) are required, one for calibrating the shot noise by rotating the half-wave plate and the other to record the quantum correlated signals.

Figure 2 sums up the measurements obtained with a demodulation frequency $\Omega/2\pi = 3.5MHz$. Figure 2a shows the actual recording of the fluctuations of the idler

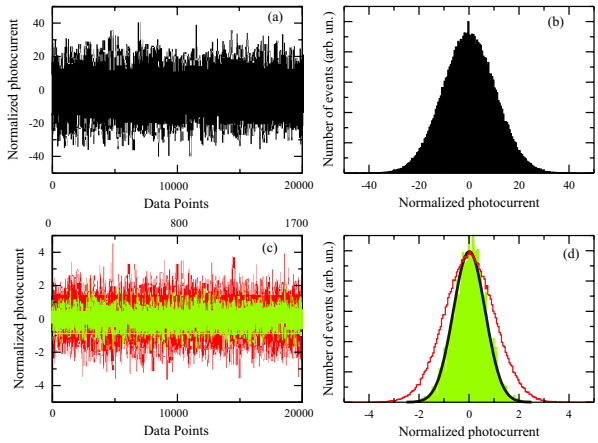

FIG. 2: Experimental results: (a) Idler intensity fluctuations: 200 000 acquired points at 3.5 MHz demodulation frequency (only 20 000 shown). (b) Corresponding probability distribution. The unit is the width σ_0 of the Poisson distribution of same mean intensity (shot noise). (c) Values of the signal intensity conditionally selected by the value of the idler intensity recorded at the same time (the selection bandwidth ΔI equal to 0.1 σ_0 around the mean), superimposed to the corresponding experimentally measured shot noise. (d) Corresponding probability distribution, compared to the Poisson distribution (grey line), displaying the sub-Poissonian character of the conditionally generated state. The black line is a gaussian fit of the intensity distribution

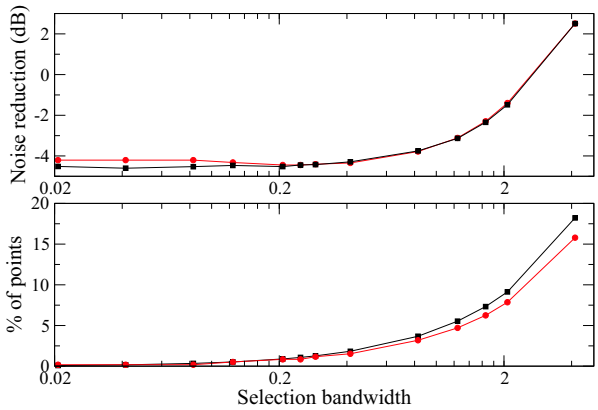

FIG. 3: Measured intensity noise on the post-selected signal (a) and success rate (proportion of selected points)(b) as a function of the selection bandwidth on the idler normalized to σ_0. Circles: experimental data. Squares: theoretical predictions.

beam during a time interval of 100ms. As the OPO is pumped close to threshold, the signal and idler beams have intensity fluctuations which are much larger than the standard quantum limit, as can be seen on curve 2b, giving the probability distribution of the intensity fluctuations normalized to the shot noise. The corresponding Fano factor exceeds 100 (20 dB above the shot noise level). From the recorded data, one can calculate the noise variance on the difference between the signal and idler intensities. It reaches a value of 7.5 dB below the standard quantum limit (8.5 dB after correction of dark noise), in good agreement with the value of the noise variance measured on the spectrum analyzer. The dark noise, which is more than 6 dB below all measurements, is not subtracted in the following experimental results.

The conditional measurement is performed in the following way : the signal intensity values are kept only if the idler intensity values recorded at the same time fall inside a narrow band around its mean value. The remaining ensemble of values of the signal intensity is given in figure 2c, in which the shot noise is given at the same time : one indeed observes a significant narrowing of the probability distribution below the shot noise level. Let us stress that the shot noise is unchanged by this selection process: the beam exists only in the selection intervals so that the unselected intervals do not contribute to the average value. Figure 2d gives the probability distribution of the intensity fluctuations of the conditionally prepared state normalized to the shot noise, together with the Poissonian distribution of photons for the same mean intensity. With a selection bandwidth ΔI equal to 0.1 times the standard deviation σ_0 of a coherent state having the same power (shot noise level), the conditionally prepared light state exhibits 4.4 dB of noise reduction below the Poisson distribution. This value is very close from the theoretical expectation in the case of vanishingly narrow intensity band. The success rate of the conditional preparation is around 0.85% (1700 points out of 200 000 are accepted). This value would be higher for an initial state with less excess noise above shot noise.

The success rate can be improved by increasing the selection bandwidth, at the expense of a decreased non-classical character of the selected state. Figure 3 shows the measured residual noise in the conditionally produced state, and the success rate of the state generation, as a function of the selection bandwidth normalized to the σ_0. The noise reduction turns out to be almost constant until the normalized selection bandwidth becomes of the order of 0.1, whereas the success rate steadily increases, in very good agreement with numerical simulations. However, one can see a slight increase in the noise when the selection bandwidth becomes very narrow. This artefact is due to the sampling process on a finite range of bits (12), which restricts the resolution of the acquisition.

In figure 4, we give the measured residual noise for different amounts of intensity correlations between the beams, which can be varied by inserting losses on the OPO beams. One checks on the figure the validity of the prediction that the noise reduction is equal to the gemellity minus 3dB. One also observes than, when the intensity difference noise is reduced by less than 3dB below the standard quantum level, the conditional state has reduced intensity noise fluctuations in comparison with the very noisy initial beam, but that it is not a non-classical

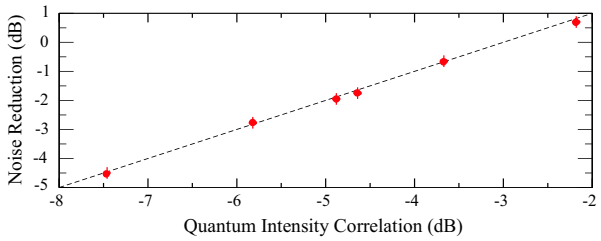

FIG. 4: Measured intensity noise reduction for different values of the signal-idler correlation. The selection bandwidth is taken equal to 0.1 times the shot noise. Circles: experimental data. Dotted line: theoretical prediction at the limit of a very small selection bandwidth (gemellity minus 3 dB).

sub-Poissonian state.

The continuous variable regime offers a unique possibility to improve dramatically the efficiency of conditional strategy, by choosing multiple selection bands with different mean values on the idler intensity. Independent selection bands will correspond to independent sets of time windows. By using hundreds of independent intervals, one keeps most of the values of the signal, each of these intervals reducing the signal to a given sub-Poissonian state. Figure 5 shows that the noise reduction does not depend of the band center and that the success rate follows the initial gaussian noise distribution.

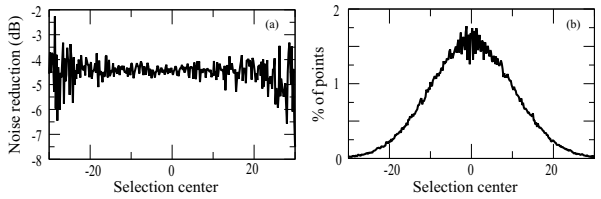

FIG. 5: Measured intensity noise on the reduced state (a) and success rate (b) as a function of the band center normalized to σ_0. The selection bandwidth is taken equal to 0.1 times the shot noise.

To conclude, we have shown the first experimental demonstration of conditional preparation of a quantum state in the continuous variable regime. We have studied the influence of the selection bandwidth of the conditioning measurement on the obtained non-classical state and on the success rate of its preparation and shown that many sub-Poissonian states can be produced in parallel. This method to generate non-classical states of light in the continuous variable regime is equivalent to sending the signal beam through an intensity modulator which either totally transmits the beam when the idler beam has the right value, or blocks it when it is not the case. It therefore drastically changes the light state, and seems to be very different from the usual technique which consists of correcting the beam fluctuations by a feed-forward or feed-back opto-electronic loop which only slightly modifies the quantum fluctuations. This strongly non-linear character of the action on the light may lead to the generation of non-Gaussian states. One could also envision other criteria of conditioning the quantum state than simply imposing to the idler beam intensity to lie within a given band. This could also lead to the generation of new families of non-classical bright states of light.

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