Optimal sub-Poissonian light generation from twin beams by photon-number resolving detectors

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We generate nonclassical conditional states by exploiting the quantum correlations of multimode twin-beam states endowed with a sizeable number of photons. A strong relation between the sub-shot-noise correlations exhibited by twin beams and the sub-Poissonian character of the conditional states is experimentally revealed, determining the optimal conditions for sub-Poissonian light generation.   © 2013 Optical Society of America

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1. INTRODUCTION

During the last decade, the generation of nonclassical states in the continuous variable domain by means of conditional measurements has been extensively investigated for many quantum optical applications, including quantum information processing, quantum computing, and quantum cryptography [1–3]. In general, conditional quantum-state preparation schemes benefit from the existence of correlations between a signal mode and an ancilla system, such as two output ports of a beam splitter [4], signal and idler modes in spontaneous parametric down-conversion (SPDC) [5], cavity mode and atomic levels in cavity QED [6]. The schemes are based on the fact that, when some observable is measured on the ancilla, the state of the signal mode is irreversibly modified.

In principle, conditional measurements are not directly related to nonclassicality, since classical conditional states can also be prepared (e.g., by photon subtraction on thermal states or phase-averaged coherent states [7,8]). From the experimental point of view, the production of nonclassical states by means of conditional measurements has been achieved in the macroscopic regime, starting from a nondegenerate optical parametric oscillator operated above threshold [9,10], in the mesoscopic domain, by selecting a small specific interval in a very noisy condition [11], and at a very low level, by a number of photon-counting detectors, mostly operated in a single-photon regime [12–17].

It is worth noting that the use of photon-counting detectors, instead of single-photon detectors, offers the possibility not only to enhance the heralding of single-photon states by suppressing higher-photon-number components [18–20], but also to perform multiple photon-counting operations to produce

quasi-Fock states endowed with a number of photons larger than 1 [17].

The possibility to extend the experimental results presented so far to a more mesoscopic photon-number domain, where the states are more robust with respect to losses is, thus, desirable and still subject to active research. Indeed, the main limitation to achieve this goal is related to the performances of the available detectors. For instance, the fiber-loop detectors can work only at very low light levels due to the number of single-photon detectors that constitute their structures [19,21,22]. Silicon photomultipliers are characterized by dark counts and cross-talk effect [23–26], electron-multiplying CCD (EMCCD) and intensified CCD (iCCD) cameras are rather noisy because of the gain spreading [5,27], and superconductors, such as the transition-edge sensor (TES) [28] and the superconducting nanowires [29], must operate at cryogenic temperatures and are, therefore, rather cumbersome.

The detectors we used to perform our experimental work are commercial photon-counting detectors, usually called hybrid photodetectors (HPD, mod. R10467U-40, Hamamatsu, Japan), whose main limitation is given by the actual detection efficiency, which is much lower than 50% due to the non perfect photon-number resolution. Nevertheless, in this work, we demonstrate that, thanks to the good linearity of such detectors, it is possible to generate nonclassical conditional states from a multimode twin-beam (TWB), with sizeable numbers of photons. A systematic study of the quantum properties of the TWB state, given in terms of the noise reduction factor [11], is performed to show that the optimal generation of sub-Poissonian conditional states strongly depends on the

existence of nonclassical correlations [17,30–32] and is also affected by several other experimental parameters.

2. MULTIMODE TWB IN THE MESOSCOPIC PHOTON-NUMBER REGIME

In general, TWB states are intrinsically spectrally multimode [33]. We have already demonstrated that a compact description of a multimode TWB is given by [34]

$$|\psi_\mu\rangle = \sum_{n=0}^{\infty} \sqrt{p_n^\mu} \, |n^\otimes\rangle_s \otimes |n^\otimes\rangle_i, \tag{1}$$

where $|n^\otimes\rangle = \delta(n - \sum_{h=1}^\mu n_h) \otimes_{k=1}^\mu |n_k\rangle$ represents the n-photon state coming from μ equally populated modes that impinge on the detector and:

$$p_n^\mu = \frac{(n + \mu - 1)!}{n!(\mu - 1)!(N/\mu + 1)^\mu(\mu/N + 1)^n}, \tag{2}$$

is the multimode thermal photon-number probability distribution for N mean photon numbers. The TWB state in Eq. (1) exhibits pairwise correlations, which are preserved even when the state is detected by nonideal detection efficiency ($\eta < 1$). The quantification of such correlations can be experimentally obtained by measuring the noise reduction factor:

$$R = \frac{\sigma^2(m_1 - m_2)}{\langle m_1 + m_2\rangle}, \tag{3}$$

where m_j is the number of detected photons in the j arm, $\langle m_1 + m_2\rangle$ represents the shot-noise level, symbol $\langle\rangle$ denotes the mean value of the distribution, and $\sigma^2()$ indicates the variance. R is a good nonclassicality criterion because it is possible to demonstrate that, for nonclassical states, $1 - \eta < R < 1$ [11]. When one of the two parties, say the idler beam, is detected, and m_2 photons are obtained in the measurement, it is possible to demonstrate that the conditional state in the signal arm is characterized by a Fano factor $F = \sigma^2(m)/\langle m\rangle$ that, in the case of a multimode TWB state [35], reads as follows:

$$F = (1 - \eta)\left[\frac{M(m_2 + \mu)(M + \eta\mu)}{(M + \mu)[(m_2 + \mu)(M + \eta\mu) - \eta\mu(M + \mu)]} + 1\right], \tag{4}$$

where η is the overall detection efficiency that is assumed equal in the two arms and for each of the μ modes, and M is the mean number of detected photons of the unconditioned state $M = \eta N$.

As shown in Fig. 1, the SPDC process was obtained by sending the third-harmonics (at 266 nm) of a cavity-dumped Kerr lens mode-locked Ti:Sapphire laser (Mira 900, Coherent Inc. and PulseSwitch, A.P.E.) to a type I BBO crystal
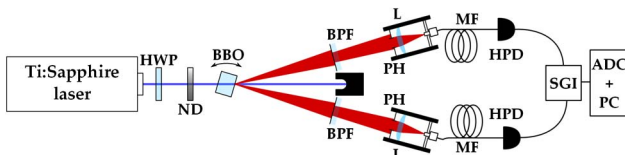
(8 mm × 8 mm × 5 mm, cut angle $\vartheta_c = 48$ deg). The pulses, with a duration of 144 fs, were delivered at 11 kHz, to match the maximum repetition rate of the detection apparatus. The pump-beam profile was well approximated by a plane-wave, with its polarization adjusted by means of a half-wave plate (HWP) and its power changed by a variable neutral density (ND) filter. We collected two noncollinear frequency-degenerate (at 532 nm) parties of the TWB state, at a distance of 200 mm from the BBO crystal. In each arm, the light, spectrally filtered by a bandpass filter (BPF), was selected by an iris with variable aperture (PH), focused into a multimode fiber (MF, 600-μm-core diameter) and delivered to a photon-counting detector. In particular, we used two HPD, whose photocathodes are characterized by 50% quantum efficiency in the spectral region we investigated [36,37]. However, we want to notice that the actual value of the detection efficiency, which is estimated by the experimental data presented in the next Sections, is definitely lower because of different sources of loss, such as reflection and absorption of the optical elements, imperfect coupling of light into fibers, and the asymmetric geometrical filtering caused by the collection of light. The TWB was generated in the linear gain regime, as testified by Fig. 2(a), in which we show the mean number of photons measured in the idler arm as a function of the
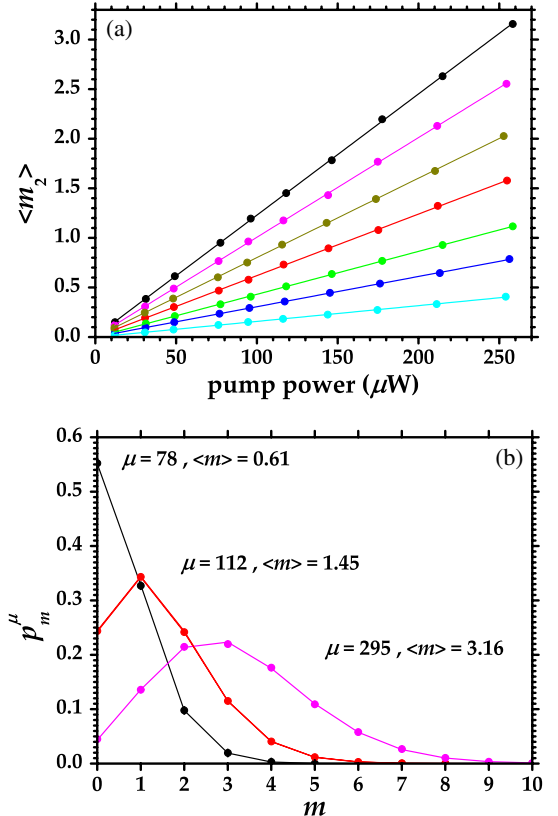

Fig. 2.   Panel (a) Mean number of detected photons in the idler arm as a function of the pump mean powers for different iris sizes. Dots: experimental data, lines: linear fits. Panel (b) Detected photon-number distributions of some realizations of TWB (black color: number of modes $\mu = 78$ and mean number of detected photons $\langle m\rangle = 0.61$; red color: number of modes $\mu = 112$ and mean number of detected photons $\langle m\rangle = 1.45$; magenta color: number of modes $\mu = 295$ and mean number of detected photons $\langle m\rangle = 3.16$). Dots: experimental data, lines: theoretical expectations according to Eq. (2).

Fig. 1.   Sketch of the experimental setup. See the text for details.

pump mean power for different choices of the iris size (200,000 subsequent laser shots). The fitting curves are, indeed, straight lines, as it is expected in the case where the gain of the SPDC process is linear. The same figure also shows that our study was performed on states containing sizeable numbers of photons (up to 3.2 mean detected photons), as also proved by the detected-photon distributions presented in Fig. 2(b).

3. EXPERIMENTAL CHARACTERIZATION OF QUANTUM PROPERTIES OF TWB

Quantum properties of the TWB state were investigated by measuring the pulse-by-pulse sub-shot-noise correlations at different pump mean powers and for different choices of the collection iris size. It is important to remark that our results have been obtained in terms of detected photons by processing the experimental data in a self-consistent way [36,37], without any *a priori* calibration of the detection chain and background subtraction. In Fig. 3(a), we plot R as a function of the pump mean power for different choices of the iris size. It is rather evident that the noise reduction is independent of the pump power, which was changed by means of a variable ND filter to keep the beam profile constant. In fact, we have already demonstrated that changing the pump beam intensity by also varying the beam size determines a strong variation of R [11]. Moreover, it is important to notice that this behavior is more evident in the macroscopic regime, in which
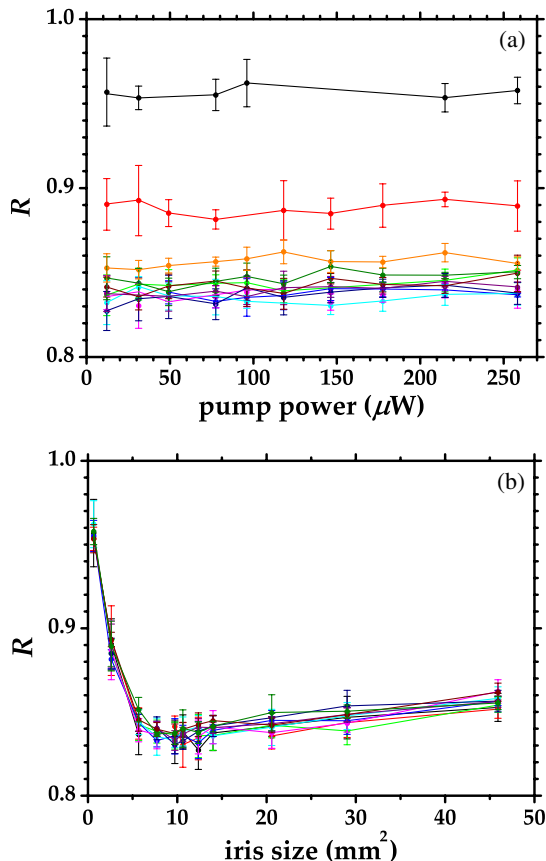
the effects of the electronic noise, on the one side, and of the laser fluctuations, on the other side make the investigation of quantum properties more challenging. The dependence of the noise reduction factor on the iris size, for fixed choices of the pump mean power, is shown in Fig. 3(b), in which R exhibits a minimum as a function of the iris size. The minimum occurs when the irises are $\sim$3 mm wide and coincides with the selection of the largest possible correlated portions of the twin cones [38]. When the irises are smaller, the number of collected photon pairs decreases and the noise reduction factor R increases, due to geometrical filtering inside the correlated areas of the twin beams [39]. On the other hand, larger values of iris sizes, exceeding the width of the cone, do not substantially increase the collection of twin components; however, they collect contributions from the unpaired areas. In both panels of Fig. 3, the theoretical expectations, shown as lines for guiding the eye, are obtained by using the experimental parameters, determined in a self-consistent way, as described in [8], in the definition of R given in [40], for the case of a single-mode state and, here, extended to the multimode case. In particular, the multimode expression of R reads as:

$$R = 1 - 2\eta \frac{\sqrt{\langle m_1 \rangle \langle m_2 \rangle}}{\langle m_1 \rangle + \langle m_2 \rangle} + \frac{(\langle m_1 \rangle \langle m_2 \rangle)^2}{\mu(\langle m_1 \rangle + \langle m_2 \rangle)}, \qquad (5)$$

where $\langle m_1 \rangle$ and $\langle m_2 \rangle$ are the experimental mean values of detected photons, η was calculated by imposing $R = \sigma^2(m_1 - m_2)/(\langle m_1 \rangle + \langle m_2 \rangle) = 1 - \eta$; that is, by assuming that the measured state is actually a twin beam and μ is the average of the values of the modes in signal and idler that have been determined using the first two moments of the detected-photon distribution, namely, $\mu_i = \langle m_i \rangle^2 / (\sigma^2(m_i) - \langle m_i \rangle)$, $i = 1, 2$.

4. SUB-POISSONIAN LIGHT GENERATION

By exploiting the TWB states characterized above, we performed conditional measurements by selecting one or two photons in the idler beam and obtaining the conditional states $\varrho_{m_2=1}$ and $\varrho_{m_2=2}$ on the signal beam, respectively [17]. This choice gives us the possibility to show that our detection apparatus can be used to perform conclusive photon subtractions by exploiting the photon-counting capability of our detectors. In particular, we remark that the results obtained in the case $\varrho_{m_2=1}$ are definitely different from those that can be achieved by employing single-photon detectors operated in Geiger ON–OFF mode, because we do not need to assume that the output states contain 1 photon at most. The two conditioning operations presented in this work are useful to investigate the dependence of the nonclassical nature of the conditional states on the different experimental parameters involved in their production. The nonclassicality of the conditional states can be quantified by measuring the Fano factor of detected photons. In general, for any state detected with Bernoullian probability, the mean value and the variance of the detected-photon distribution read as $\langle m \rangle = \eta \langle n \rangle$ and $\sigma^2(m) = \eta^2 \sigma^2(n) + \eta(1 - \eta)\langle n \rangle$, respectively, where η is the overall detection efficiency. The Fano factor for detected photons is, therefore, given by $F_m = \eta F_n + (1 - \eta)$, where F_n is the Fano factor for photons. If $F_n < 1$, the light is nonclassical and is called sub-Poissonian. Note that the value 1 for the boundary between classical and nonclassical behavior still

Fig. 3. Panel (a) Noise reduction factor R as a function of the pump mean power for fixed choices (different colors) of the iris size. Panel (b) R as a function of the iris size for fixed choices (different colors) of the pump power. Color dots: experimental data; colored lines: theoretical expectations.

holds for detected photons. It is interesting to notice that the minimum value of this expression coincides with the minimum value of the noise reduction factor $R = 1 - \eta$ in the noiseless limit. In Fig. 4, we plot F_m for $\varrho_{m_2=1}$ [panel (a)] and $\varrho_{m_2=2}$ [panel (b)] as a function of the iris size for four choices of the pump power. We ascribe the discrepancy between experimental data (colored dots) and theoretical expectations (colored open symbols + lines, which are a guide for the eye) to possible fluctuations caused by the limited number of experimental data giving the conditional states. For the same reason, the data corresponding to the same low pump mean power (i.e., 31.2 μW) are characterized by bigger error bars in the case $\varrho_{m_2=2}$. Despite this, the minima of F_m, as functions of the iris size, coincide with the minimum value of R for the TWB states. We notice that the irregularities in the theoretical curves are due to the fact that, as in the case of Fig. 3, the theoretical expectations were evaluated at each data point in the very values of the experimental parameters (the mean number of photons is in the range 0–3.2, the number of modes varies from 2 to 200, whereas the overall detection efficiency changes from 0.06 to 0.17), as calculated from the data. The experimental results confirm that the amount of nonclassicality in a TWB state represents the critical parameter for sub-Poissonian-light generation. Moreover, the largest sub-Poissonianity, that is the lowest value of Fano factor F_m, is obtained for low pump powers, i.e., when the TWB is weak. This experimental conclusion is predicted by theory, considering F_m as a function of M for $\eta = 0.15$, and

Fig. 5. Panel (a) Simulations of F_m as a function of M for different choices of μ (black color: $\mu = 1$; red color: $\mu = 5$; green color: $\mu = 10$; blue color: $\mu = 20$; magenta color: $\mu = 100$). Panel (b) Simulations of F_m as a function of μ for different choices of M (black color: $M = 0.1$; red color: $M = 0.2$; green color: $M = 0.5$; blue color: $M = 1$; magenta color: $M = 3$). In both panels, the quantum efficiency is $\eta = 0.15$ and the conditioning values are $m_2 = 1$ (solid lines) and $m_2 = 2$ (dots).

different choices of μ in the case $m_2 = 1$ [solid line in Fig. 5(a)] and $m_2 = 2$ (dots). It is evident that the lower the mean value of the unconditioned state, the more sub-Poissonian the conditional state. However, we note that the weaker the TWB, the smaller the postselection probability in this regime, which imposes restrictions from the practical point of view.

It is worth noting also that the number of modes μ influences the achievable values of Fano factor F_m. The larger the number of modes, the smaller the values of Fano factor [see Fig. 5(b)]. In fact, larger values of μ lead to narrower photon-pair statistics (transition from thermal to Poissonian distributions), which improves the postselection capability of the applied scheme for nonideal detection efficiency η.

5. CONCLUSION

In conclusion, we have experimentally generated sub-Poissonian conditional states in the low gain regime, starting from a multimode TWB state. By exploiting the linearity of our HPD, we have confirmed the correspondence of optimal generation conditions of sub-Poissonian conditional states with those needed for nonclassical pairwise correlations, even in the case of limited quantum efficiency. In principle, similar results can be obtained by choosing larger conditioning values. Of course, to achieve this goal, larger samples of data are required to accumulate enough statistics. Moreover, the experimental scheme presented in this paper could be exploited for the production of conditional states optimized to have selected properties, such as a given mean value or
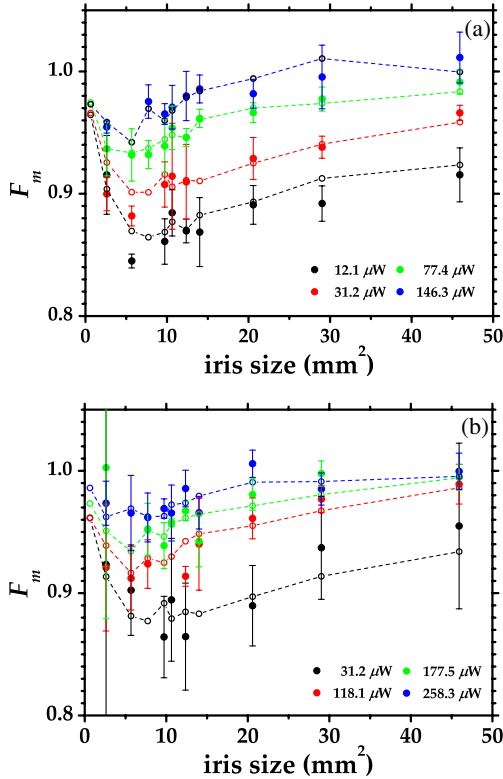

Fig. 4. Fano factor F_m of the conditional states obtained on the signal by detecting $m_2 = 1$ [Panel (a)] and $m_2 = 2$ [Panel (b)] photons on the idler. The different colors correspond to different pump mean values [black color: 12.1 μW (a) and 31.2 μW (b); red color: 31.2 μW (a) and 118.1 μW (b); green color: 77.4 μW (a) and 177.5 μW (b); blue color: 146.3 μW (a) and 258.3 μW (b)]. Dots: experimental data. Open symbols + dashed lines: theoretical expectations.
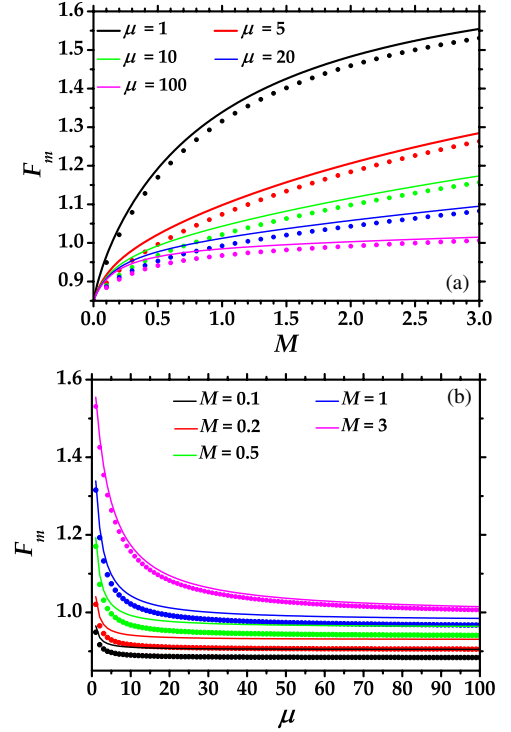
a given amount of sub-Poissonianity. Finally, in a previous paper [34] we have already demonstrated that conditioning operations generate conditional states that are also non-Gaussian. This property, together with nonclassicality, is crucial for the realization of some quantum information protocols, such as entanglement distillation. To quantify the amount of non-Gaussianity, different proposals have been recently introduced [41–43]. Among them, we want to mention the relative entropy of non-Gaussianity, which is defined as the difference between the von Neumann entropy of a reference state, namely, a state with the same mean value and the same covariance matrix of the state under investigation, and the von Neumann entropy of the state itself [44]. However, according to the simulations presented in Ref. [34], the behavior of this non-Gaussianity measure as a function of the different experimental parameters is not the same as that exhibited by the Fano factor. Work is in progress to find the best compromise between sub-Poissonianity and non-Gaussianity for the exploitation of the states in real protocols.

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