Sub-Poissonian-light generation by postselection from twin beams

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Abstract: States with sub-Poissonian photon-number statistics obtained by post-selection from twin beams are experimentally generated. States with Fano factors down to 0.62 and mean photon numbers around 12 are reached. Their quasi-distributions of integrated intensities attaining negative values are reconstructed. An intensified CCD camera with a quantum detection efficiency exceeding 20% is utilized both for post-selection and beam characterization. Experimental results are compared with theory that provides the optimum experimental conditions.

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OCIS codes: (030.5290) Photon statistics; (190.4975) Quantum detectors; (040.5570) Parametric processes.

References and links

1. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge Univ. Press, Cambridge, 1995).
2. J. Peřina, Z. Hradil, and B. Jurčo, *Quantum Optics and Fundamentals of Physics* (Kluwer, Dordrecht, 1994).
3. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 1991).
4. A. I. Lvovsky and M. G. Raymer, "Continuous-variable optical quantum state tomography," Rev. Mod. Phys. **81**, 299–332 (2009).
5. P. Grangier, G. Roger, and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: A new light on single-photon interferences," Europhys. Lett. **1**, 173—179 (1986).
6. C. Brunel, B. Lounis, P. Tamarat, and M. Orrit, "Triggered source of single photons based on controlled single molecule fluorescence," Phys. Rev. Lett. **83**, 2722—2725 (1999).
7. B. T. H. Varcoe, S. Brattke, and H. Walther, "The creation and detection of arbitrary photon number states using cavity QED," New J. Phys. **6**, 97 (2004).
8. C. Kurtsiefer, S. Mayer, P. Zarda, and H. Weinfurter, "Stable solid-state source of single photons," Phys. Rev. Lett. **85**, 290–293 (2000).
9. A. Faraon, P. E. Barclay, C. Santori, K.-M. C. Fu, and R. G. Beausoleil, "Resonant enhancement of the zero-phonon emission from a colour centre in a diamond cavity," Nat. Phot. **5**, 301–305 (2011).
10. C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon, and Y. Yamamoto, "Single-photon generation with InAs quantum dots," New. J. Phys. **6**, 89 (2004).
11. O. Alibart, D. B. Ostrowsky, P. Baldi, and S. Tanzilli, "High-performance guided-wave asynchronous heralded single-photon source," Opt. Lett. **30**, 1539—1541 (2008).
12. G. Brida, I. P. Degiovanni, M. Genovese, F. Piacentini, P. Traina, A. Della Frera, A. Tosi, A. Bahgat Shehata, C. Scarcella, A. Gulinatti, M. Ghioni, S. V. Polyakov, A. Migdall, and A. Giudice, "An extremely low-noise heralded single-photon source: A breakthrough for quantum technologies," Appl. Phys. Lett. **101**, 221112 (2012).
13. M. Förtsch, J. U. Fürst, C. Wittmann, D. Strekalov, M. V. Chekhova, A. Aiello, C. Silberhorn, G. Leuchs, and C. Marquardt, "A versatile source of single photons for quantum information processing," Nat. Comm. **4**, 1818 (2013).
14. G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, and A. Zeilinger, "Violation of Bell's inequality under strict Einstein locality conditions," Phys. Rev. Lett. **81**, 5039—5043 (1998).

#190675 - $15.00 USD Received 16 May 2013; revised 11 Jul 2013; accepted 12 Jul 2013; published 8 Aug 2013

15. M. Genovese, “Research on hidden variable theories: A review of recent progresses,” Phys. Rep. **413**, 319—396 (2005).
16. D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, “Experimental quantum teleportation,” Nature **390**, 575–579 (1997).
17. A. Migdall, “Correlated-photon metrology without absolute standards,” Physics Today **52**, 41—46 (1999).
18. A. F. Abouraddy, K. C. Toussaint Jr., A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, “Entangled-photon ellipsometry,” J. Opt. Soc. Am. B **19**, 656—662 (2002).
19. G. Brida, M. Genovese, and M. Gramegna, “Twin-photon techniques for photo-detector calibration,” Laser Phys. Lett. **3**, 115—123 (2006).
20. M. Lindenthal and J. Kofler, “Measuring the absolute photodetection efficiency using photon number correlations,” Appl. Opt. **45**, 6059—6063 (2006).
21. J. Peřina Jr., O. Haderka, M. Hamar, and V. Michálek, “Absolute detector calibration using twin beams,” Opt. Lett. **37**, 2475—2477 (2012).
22. T. Jennewein, C. Simon, G. Weihs, H. Weinfurter, and A. Zeilinger, “Quantum cryptography with entangled photons,” Phys. Rev. Lett. **84**, 4729–4732 (2000).
23. N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, “Quantum cryptography,” Rev. Mod. Phys. **74**, 145—195 (2011).
24. M. A. Nielsen and I. L. Juang, *Quantum Computation and Quantum Information* (Cambridge Univ. Press, Cambridge, 2000).
25. R. Short and L. Mandel, “Observation of sub-Poissonian photon statistics,” Phys. Rev. Lett. **51**, 384—387 (1983).
26. M. C. Teich and B. E. A. Saleh, “Observation of sub-Poisson Franck-Hertz light at 253.7 nm,” J. Opt. Soc. Am. B **2**, 275—282 (1985).
27. P. R. Tapster, J. G. Rarity, and J. S. Satchell, “Generation of sub-Poissonian light by high-efficiency light-emitting diodes,” Europhys. Lett. **4**, 293—299 (1987).
28. M. Koashi, K. Kono, T. Hirano, and M. Matsuoka, “Photon antibunching in pulsed squeezed light generated via parametric amplification,” Phys. Rev. Lett. **71**, 1164—1167 (1993).
29. J. M. Raimond, M. Brune, and S. Haroche, “Manipulating quantum entanglement with atoms and photons in a cavity,” Rev. Mod. Phys. **73**, 565—583 (2001).
30. J. Laurat, T. Coudreau, N. Treps, A. Maitre, and C. Fabre, “Conditional preparation of a quantum state in the continuous variable regime: Generation of a sub-Poissonian state from twin beams,” Phys. Rev. Lett. **91**, 213601 (2003).
31. J. Mertz, A. Heidmann, C. Fabre, E. Giacobino, and S. Reynaud, “Observation of high-intensity sub-Poissonian light using an optical parametric oscillator,” Phys. Rev. Lett. **64**, 2897—2900 (1990).
32. J. Peřina Jr., O. Haderka, and J. Soubusta, “Quantum cryptography using a photon source based on postselection from entangled two-photon states,” Phys. Rev. A **64**, 052305 (2001).
33. J. Peřina, J. Křepelka, J. Peřina Jr., M. Bondani, A. Allevi, and A. Andreoni, “Experimental joint signal-idler quasidistributions and photon-number statistics for mesoscopic twin beams,” Phys. Rev. A **76**, 043806 (2007).
34. J. Peřina, J. Křepelka, J. Peřina Jr., M. Bondani, A. Allevi, and A. Andreoni, “Correlations in photon-numbers and integrated intensities in parametric processes involving three optical fields,” Eur. Phys. J. D **53**, 373—382 (2009).
35. O. Haderka, M. Hamar, and J. Peřina Jr., “Experimental multi-photon-resolving detector using a single avalanche photodiode,” Eur. Phys. J. D **28**, 149—154 (2004).
36. J. Řeháček, Z. Hradil, O. Haderka, J. Peřina Jr., and M. Hamar, “Multiple-photon resolving fiber-loop detector,” Phys. Rev. A **67**, 061801(R) (2003).
37. D. Achilles, C. Silberhorn, C. Sliwa, K. Banaszek, and I. A. Walmsley, “Fiber-assisted detection with photon number resolution,” Opt. Lett. **28**, 2387 (2003).
38. M. J. Fitch, B. C. Jacobs, T. B. Pittman, and J. D. Franson, “Photon-number resolution using time-multiplexed single-photon detectors,” Phys. Rev. A **68**, 043814 (2003).
39. A. Allevi, M. Bondani, and A. Andreoni, “Photon-number correlations by photon-number resolving detectors,” Opt. Lett. **35**, 1707–1709 (2010).
40. M. Ramilli, A. Allevi, V. Chmill, M. Bondani, M. Caccia, and A. Andreoni, “Photon-number statistics with silicon photomultipliers,” J. Opt. Soc. Am. B **27**, 852—862 (2010).
41. L. A. Jiang, E. A. Dauler, and J. T. Chang, “Photon-number-resolving detector with 10 bits of resolution,” Phys. Rev. A **75**, 062325 (2007).
42. A. J. Miller, S. W. Nam, J. M. Martinis, and A. V. Sergienko, “Demonstration of a low-noise near-infrared photon counter with multiphoton discrimination,” Appl. Phys. Lett. **83**, 791—793 (2003).
43. A. Divochiy, F. Marsili, D. Bitauld, A. Gaggero, R. Leoni, F. Mattioli, A. Korneev, V. Seleznev, N. Kaurova, O. Minaeva, G. Goltsman, K. G. Lagoudakis, M. Benkahoul, F. Levy, and A. Fiore, “Superconducting nanowire photonnumber-resolving detector at telecommunication wavelengths,” Nat. Phot. **2**, 302—306 (2008).
44. D. Fukuda, G. Fujii, T. Numata, K. Amemiya, A. Yoshizawa, H. Tsuchida, H. Fujino, H. Ishii, T. Itatani, S. Inoue, and T. Zama, “Titanium-based transition-edge photon number resolving detector with 98% detection efficiency with index-matched small-gap fiber coupling,” Opt. Express **19**, 870—875 (2011).
45. L. Lolli, G. Brida, I. P. Degiovanni, M. Gramegna, E. Monticone, F. Piacentini, C. Portesi, M. Rajteri, I. Ruo-

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Berchera, E. Taralli, and P. Traina, “Ti/Au TES as superconducting detector for quantum technologies,” Int. J. Quant. Inf. **9**, 405—413 (2011).
46. O. Haderka, J. Peřina Jr., M. Hamar, and J. Peřina, “Direct measurement and reconstruction of nonclassical features of twin beams generated in spontaneous parametric down-conversion,” Phys. Rev. A **71**, 033815 (2005).
47. M. Hamar, J. Peřina Jr., O. Haderka, and V. Michálek, “Transverse coherence of photon pairs generated in spontaneous parametric downconversion,” Phys. Rev. A **81**, 043827 (2010).
48. J. Peřina Jr., M. Hamar, V. Michálek, and O. Haderka, “Photon-number distributions of twin beams generated in spontaneous parametric down-conversion and measured by an intensified CCD camera,” Phys. Rev. A **85**, 023816 (2012).
49. J. Peřina, *Quantum Statistics of Linear and Nonlinear Optical Phenomena* (Kluwer, Dordrecht, 1991).
50. J. Peřina and J. Křepelka, “Multimode description of spontaneous parametric down-conversion,” J. Opt. B: Quant. Semiclass. Opt. **7**, 246—252 (2005).
51. J. Peřina Jr., O. Haderka, V. Michálek, and M. Hamar, “State reconstruction of a multimode twin beam using photodetection,” Phys. Rev. A **87**, 022108 (2013).
52. J. Peřina and J. Křepelka, “Joint probability distributions of stimulated parametric down-conversion for controllable nonclassical fluctuations,” Eur. Phys. J. D **281**, 4705–4711 (2008).
53. B. E. A. Saleh and M. C. Teich, “Can the channel capacity of a light-wave communication system be increased by the use of photon-number-squeezed light?” Phys. Rev. Lett. **58**, 2656–2659 (1987).
54. V. Giovannetti, S. Lloyd, and L. Maccone, “Quantum metrology,” Phys. Rev. Lett. **96**, 010401 (2006).

1. Introduction

Nonclassical states of light have attracted a great deal of attention as soon as an experimental evidence of their existence has been given [1—3]. Their systematic study has resulted in an establishment of a new branch of optics called quantum optics. Sub-Poissonian photon-number distribution (PND) and anti-bunching of photons observed in fluorescence of single molecules [1] belong together with phase squeezing [4] to the most important manifestations of nonclassical light. Detailed theoretical studies of such fields have revealed that the crucial role in forming their non-classicality is played by states with well defined photon numbers but completely unknown phases. These Fock states represent a counterpart to ’classical’ or coherent states that allow interference due to their well defined phases.

For this reason the generation of the simplest Fock state with just one photon has become a challenge for the whole generation of experimental quantum opticians started by the experiments with photon pairs emitted from atomic cascades [5]. Due to a large progress in the field, one-photon Fock states can be obtained from several kinds of sources including molecules [6], super-conducting micro-cavities [7], NV centers [8, 9], and semiconductor hetero-structures [10] at present. One-photon Fock states of the highest quality are generated from the so-called heralded single-photon sources [11—13] that rely on post-selection from a photon pair arising in spontaneous parametric down-conversion (SPDC). These states of photon pairs have been found useful in showing many unexpected features of quantum physics (violation of Bell’s inequalities [14, 15], teleportation [16], dense coding, etc.). They have also been successfully exploited in precise metrology [17, 18] including absolute detector calibration [19—21] and quantum cryptography [22, 23] where they help to assure unconditional security. Also quantum computation [24] can be based upon the use of Fock states.

Properties of Fock states with larger numbers of photons are even more challenging [7]. However, their generation is even more difficult compared to the generation of one-photon Fock states which, despite a long effort devoted, is still not easy. States with sub-Poissonian PND have already been generated in resonance fluorescence [25] (Fano factor $F \approx 0.998$), Franck–Hertz experiment [26] ($F \approx 0.99$), high-efficiency light-emitting diodes [27] ($F \approx 0.96$), in the process of second-subharmonic generation [28] as well as in experiments with atoms passing micro-cavities [7, 29]. Stronger sub-Poissonian fields containing many photons have been successfully generated by continuous intensity post-selection from the beams coming from optical parametric oscillators [30]. Also an alternative method based on a feed-forward action on the

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beam has been verified [31].

Post-selection by a photon-number resolving detector from a twin beam generated in SPDC and containing many photon pairs [32] represents one of the most prospective ways for sub-Poissoian-light generation at present [33, 34]. A photon-number resolving detector with a sufficiently high quantum detection efficiency (QDE) plays the crucial role in this scheme. Time-multiplexed systems with avalanche photodiodes [35—38], hybrid photomultipliers [39, 40], semiconductor detector arrays and matrices [41], super-conducting bolometers [42—45] and intensified CCD cameras [21, 46] seem to have sufficiently high QDEs and low noise for this task.

2. Conditional states generated from twin beams by post-selection

Here, we demonstrate the generation of sub-Poissonian light using twin beams and an iCCD camera that serves both as detector post-selecting the sub-Poissonian light and monitoring the photocount statistics of this light. In more detail, both the signal and idler fields comprising a twin beam are monitored using a photocathode of the iCCD camera. Registration of a given number of, e.g., signal photocounts (detected photons) in certain area of the photocathode post-selects the idler field that attains the sub-Poissonian PND under suitable conditions. PND in this field is measured again using a different area of the photocathode [47]. Photocount distribution obtained in this area then allows to recover the PND of the post-selected idler field using, e.g., the expectation-maximization reconstruction method.

A histogram $f(c_s,c_i)$ giving the number of experimental realizations with c_s signal and c_i idler photocounts is available after a sufficiently high number of measurement repetitions. The normalized histogram $f_i(c_i;c_s) \equiv f(c_s,c_i)/\sum_{c_i} f(c_s,c_i)$ then describes the measurement on the idler field conditioned by the detection of c_s signal photocounts. The idler-field conditional photon-number distribution (CPND) $p_{c,i}(n_i;c_s)$ arising after detecting c_s signal photocounts can easily be reconstructed. The method of expectation maximization allows to find this distribution as a steady state available by the following iteration procedure [48]:

$$p_{c,i}^{(n+1)}(n_i;c_s) = p_{c,i}^{(n)}(n_i;c_s) \sum_{c_i} \frac{f_i(c_i;c_s) T_i(c_i,n_i)}{\sum_{n_i'} T_i(c_i,n_i') p_{c,i}^{(n)}(n_i';c_s)}. \quad (1)$$

In Eq. (1), the matrix elements $T(c_i,n_i)$ give probabilities of having c_i photocounts when detecting a field with n_i photons. These probabilities valid for an iCCD camera with N_i active pixels, QDE η_i and dark-count rate per pixel D_i have been derived in [48]:

$$T_i(c_i,n_i) = \begin{pmatrix} N_i \\ c_i \end{pmatrix} (1-D_i)^{N_i} (1-\eta_i)^{n_i} (-1)^{c_i} \sum_{l=0}^{c_i} \begin{pmatrix} c_i \\ l \end{pmatrix} \frac{(-1)^l}{(1-D_i)^l} \left(1 + \frac{l}{N_i} \frac{\eta_i}{1-\eta_i}\right)^{n_i}. \quad (2)$$

The reconstructed CPNDs $p_{c,i}(n_i;c_s)$ can be compared with the 'theoretical' ones $p_{c,i}^t(n_i;c_s)$ obtained from the reconstructed joint signal-idler PND $p_{si}(n_s,n_i)$ along the formula:

$$p_{c,i}^t(n_i;c_s) = \sum_{n_s} T_s(c_s,n_s) p_{si}(n_s,n_i). \quad (3)$$

The matrix elements $T_s(c_s,n_s)$ characterize detection in the signal field and are given by the formula analogous to that in Eq. (2). The joint PND $p_{si}(n_s,n_i)$ of a twin beam can be expressed as a two-fold convolution of three Mandel-Rice PNDs [49] characterizing paired, signal noise and idler noise parts of the field [21, 50]:

$$p_{si}(n_s,n_i) = \sum_{n=0}^{\min[n_s,n_i]} p(n_s-n;M_s,b_s) p(n_i-n;M_i,b_i) p(n;M_p,b_p); \quad (4)$$

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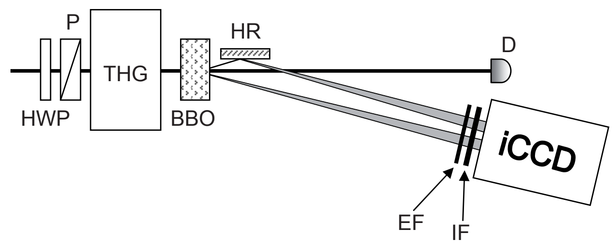

Fig. 1. Scheme of the experiment. An output of a femtosecond cavity dumped Ti:sapphire laser is converted to its third harmonics (THG, 280 nm) and used to pump a BaB_2O_4 nonlinear crystal. Nearly degenerate signal and idler (steered by high-reflectivity mirror HR) beams are selected using 14 nm wide bandpass filter IF and detected using an iCCD. Long-pass (above 490 nm) filter diminishes the noise. The intensity of the pumping beam is actively stabilized (rms below 0.3%) using motorized half-wave plate HWP and polarizer P based on the remnant UV intensity read by detector D.

$p(n;M,b) = \Gamma(n+M)/[n!\,\Gamma(M)]b^n/(1+b)^{n+M}$. Symbol Γ stands for the Γ-function. Each part a has its own number M_a of independent modes and mean number of photons (or photon pairs) b_a per mode, $a = p,s,i$. Appropriate values of these quantities as well as QDEs η_s and η_i can be derived from the histogram $f(c_s,c_i)$ using a fitting procedure (for details, see [21, 51]).

3. Sub-Poissonian-light generation

Sub-Poissonian PNDs have been experimentally detected using an iCCD camera and twin beams (see Fig. 1) centered at the wavelength 560 nm. Twin beams originated in a non-collinear type-I interaction in a 5-mm long BaB_2O_4 crystal pumped by the third harmonics of a femtosecond cavity dumped Ti:sapphire laser with pulse duration 150 fs at 840 nm (for details, see [47]). $N_s = N_i = 6272$ pixels of the photocathode with mean dark-count rates $D_s = D_i = 0.04/N_s$ have been used in detecting each field. The histogram $f(c_s,c_i)$ has been built after 2×10^5 measurement repetitions. Its analysis has revealed the following values of parameters: $\eta_s = 0.235$, $\eta_i = 0.243$, $b_p = 0.056$, $M_p = 180$, $b_s = 9.8$, $M_s = 0.012$, $b_i = 29$, and $M_i = 0.0009$. Covariance between the signal and idler photon-numbers n_s and n_i was 91%. There were $\langle c_s\rangle = 2.39$ and $\langle c_i\rangle = 2.45$ photocounts on average in the signal and idler detection areas, respectively. The field in front of the camera was on average composed of $\langle n_p\rangle = 9.87$ photon pairs, $\langle n_s\rangle = 0.12$ noise signal photons and $\langle n_i\rangle = 0.03$ noise idler photons.

The analysis of experimental data has revealed that sub-Poissonian idler-field CPNDs $p_{c,i}$ can be obtained for signal-field photocount numbers c_s in the range from 2 to 7 [see Fig. 2(a)] [50]. We note that sub-Poissonian statistics is quantified by its Fano factor F [$F = \langle(\Delta n)^2\rangle/\langle n\rangle$] attaining values lower than one [52]. The graph in Fig. 2(a) shows that sub-Poissonian PND is qualitatively preserved during detection and so also sub-Poissonian photocount statistics is observed. This behavior occurs as the number of noisy photons is much lower than the number of photon pairs. As a consequence, an imperfect QDE η_i only causes an increase in the values of Fano factor F_i maintaining sub-Poissonian character of the distribution. Both theoretical and experimental results show that the lowest values of Fano factor F_i are reached after post-selecting by the detected photocount numbers c_s considerably greater than the mean value $\langle c_s\rangle$. Greater values of the used photocount numbers c_s lead to greater mean values of conditional idler photon numbers $\langle n_{c,i}\rangle$, as documented in Fig. 2(b). However, sub-Poissonian idler-field generation conditioned by great values of c_s is not practical as the probability of detecting such photocount numbers is low [see Fig. 2(c)]. According to Fig. 2(c) the photocount numbers c_s up to 6 are acceptable in this respect. Values of the Fano factor F_i around 0.8 have been

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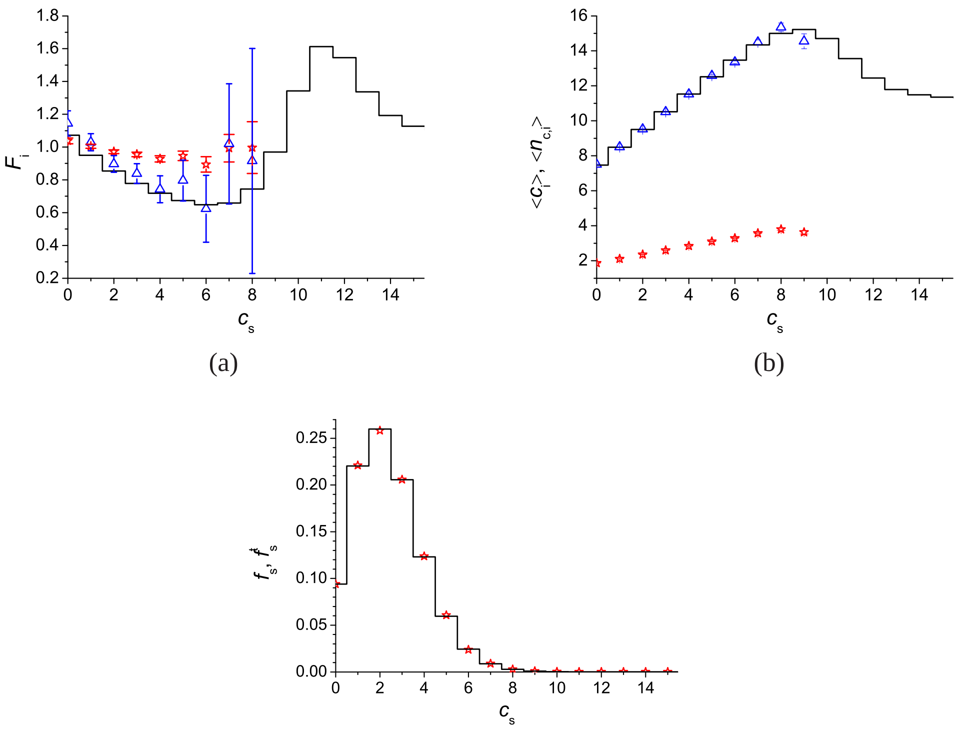

(a) (b) (c)

Fig. 2. (a) Fano factor F_i and (b) mean photon number $\langle n_{c,i}\rangle$ [photocount $\langle c_i\rangle$] of conditional idler photon-number [photocount] distribution as they depend on the number c_s of signal photocounts. (c) Marginal signal-field photocount distributions $f_s(c_s) = \sum_{c_i} f(c_s, c_i)$ and $f_s^t(c_s) = \sum_{n_s,n_i} T_s(c_s, n_s) p_{si}(n_s, n_i)$. Asterisks give experimental values, triangles mark values obtained in the maximum-likelihood reconstruction and solid curves arise from the theory. In plots (b) and (c) experimental errors are smaller than symbol sizes.

reached for $c_s \in (3,4,5,6)$ for fields containing around 12 photons on average. The lowest experimental value of F_i equals to 0.62 ± 0.18 and was observed for $c_s = 6$. We note that the experimental values of F_i were obtained with a relatively large uncertainty as the post-selection probability is low. However, the uncertainty can be substantially reduced just by increasing the number of measurement repetitions. The sub-Poissonian CPND $p_i(n_i; c_s = 4)$ with Fano factor $F_i = 0.74 \pm 0.08$ conditioned by the detection of $c_s = 4$ signal photocounts is shown in Fig. 3(a). This field is nonclassical by definition as its Glauber-Sudarshan quasi-distribution (QD) $P_{c,i}$ of integrated intensity W attains negative values. Even the QD related to the symmetric operator ordering keeps negative values [see Fig. 3(b)]. We note that QDs $W_{c,i}$ in Fig. 3(b) were obtained from the CPNDs $p_{c,i}$ using the decomposition into Laguerre polynomials [49].

There exist four important parameters that determine available values of Fano factor F_i: mean photon-pair number ($\langle n_p\rangle$), QDE of the camera η, mean number of noise signal photons ($\langle n_s\rangle$) used for post-selection, and mean number of noise idler photons in the post-selected field ($\langle n_i\rangle$). The dependence of Fano factor F_i on mean photon-pair number $\langle n_p\rangle$ is weak, as the curves in Fig. 4(a) showing the least available values F_i^l (optimized with respect to c_s) as well as the values F_i^m obtained with the maximum post-selection probability document. They indicate that moderate values of $\langle n_p\rangle$ are optimum, which is the case of the performed experiment. Whereas

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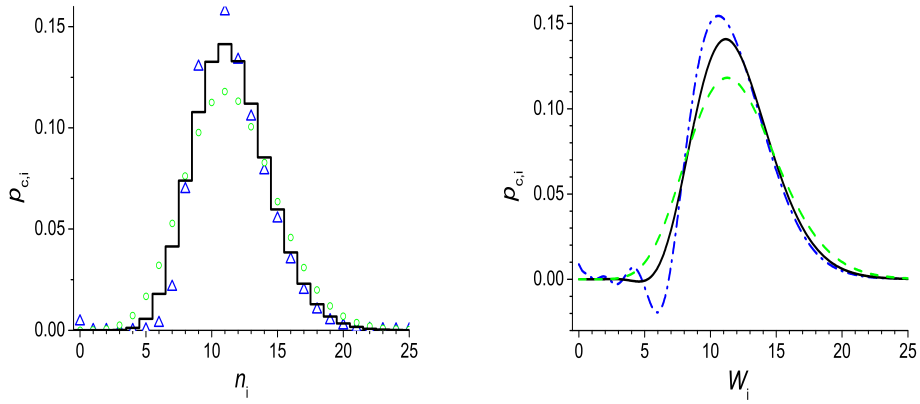
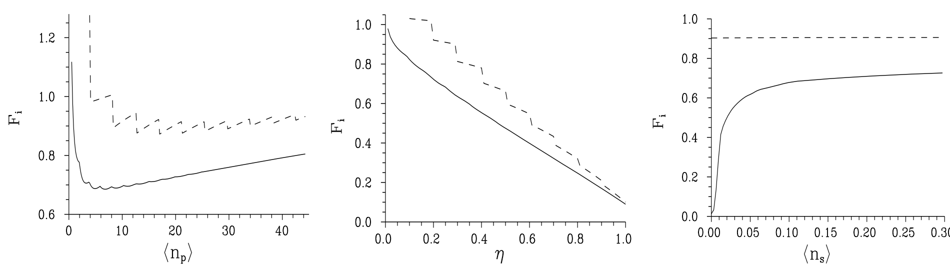


(a) (b)

Fig. 3. (a) Sub-Poissonian idler-field CPNDs $p_{c,i}(n_i)$ revealed by the maximum-likelihood reconstruction ($\triangle$) and the theoretical CPND (plain curve) for $c_s = 4$. (b) Corresponding QDs $P_{c,i}$ of integrated intensity W_i for the symmetric operator ordering ($\triangle \to$ dash-dot curve). Poissonian PND ($\circ$) and its distribution of integrated intensity (dashed curve) are shown for comparison.



(a) (b) (c)

Fig. 4. The least available value F_i^l of idler-field Fano factor (plain curve) and the most probable value F_i^m of Fano factor (dashed curve) for the conditional idler field $p_s(c_s)$ as they depend on (a) mean photon-pair number $\langle n_p \rangle$ [$M_p = 180$], (b) QDE $\eta \equiv \eta_s = \eta_i$, and (c) mean number of noise signal photons $\langle n_s \rangle$ [$M_s = 0.012$]; values of parameters are taken from the experiment.

fields with low values of $\langle n_p \rangle$ suffer from the noise ($\langle n_s \rangle$) when detecting the signal photons, greater values of $\langle n_p \rangle$ are handicapped by a lower signal QDE η_s. The QDE η_s crucially limits the available values of Fano factor F_i. The greater the values of η_s the smaller the values of F_i, as shown in Fig. 4(b). We note that the greater the values of η_s the smaller the post-selection probabilities $p_s(c_s)$. Nonzero noise in the post-selecting signal field ($\langle n_s \rangle$) degrades the post-selection process and, naturally, greater values of Fano factor F_i occur [Fig. 4(c)]. If this noise is negligible the values of F_i close to zero can be reached even for non-unit values of QDE η_s. However, this occurs when post-selecting by a greater number c_s of signal photocount. As such events are rarely observed this regime is practically not useful. Finally, the noise in idler field ($\langle n_i \rangle$) only conceals the sub-Poissonian character of the conditional idler field. The greater the values of $\langle n_i \rangle$ the greater the values of Fano factor F_i. This analysis shows that the used experimental conditions, namely the chosen parameters of the twin beam, have allowed to reach the nearly optimum values of Fano factor F_i allowed by the used iCCD camera. The improvement of camera's QDE opens the door for reaching lower values of Fano factor F_i.

A lower post-selection probability can be increased by considering the generation of several conditional idler fields differing in c_s simultaneously. Also post-selection does not necessarily have to be based upon the measurement of a fixed number c_s of signal photocounts – more sophisticated post-selection patterns are possible. This allows, for example, the generation of highly nonclassical CPNDs composed of several peaks provided that sufficiently low values of Fano factors are experimentally reached.

The confinement of the obtained sub-Poissonian pulsed field into a temporal window typically several tens or hundreds fs long represents a great advantage over other approaches. Among others it allows precise synchronization with other pulses or processes in quantum systems. Suppression of intensity fluctuations in sub-Poissonian fields has been found useful in optical communications where it enhances channel capacities [53]. The reduced intensity fluctuations are important in general in precise metrology where they allow to overcome classical limits in precision [54].

4. Conclusions

Sub-Poissonian light with Fano factors down to 0.62 containing on average around 12 photons has been generated using post-selection from a twin beam. Suitable experimental conditions for this method relying on photon-number-resolved detection of an iCCD camera have been theoretically found. Perspectives of this method have been experimentally confirmed.

Acknowledgments

Support by projects P205/12/0382 of GA ČR and CZ.1.05/2.1.00/03.0058 of the Czech Ministry of Education is acknowledged. The authors thank M. Hamar for his help with the experiment. J.P.Jr. thanks J. Peřina for discussions.

#190675 - $15.00 USD Received 16 May 2013; revised 11 Jul 2013; accepted 12 Jul 2013; published 8 Aug 2013
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