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Tunable cavity-enhanced photon pairs source in Hermite-Gaussian mode

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The spatial modes of light have grasped great research interests because of its great potentials in optical communications, optical manipulation and trapping, optical metrology and quantum information processing. Here we report on generating of photon pairs in Hermite-Gaussian (HG) mode in a type-I optical parametric oscillator operated far below threshold. The bandwidths of the photon pairs are 11.4 MHz and 20.8 MHz for two different HG modes respectively, therefore the photons can be stored in cold Rubidium atomic ensembles. The non-classical properties of HG modes are clearly verified by the violation of Cauchy-Schwarz inequality. Our study provides an effective way to generate photon pairs with narrow bandwidth in high order spatial modes for high dimensional quantum communication. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4942461]

In modern optical science, the spatial degree of freedom of photon has drawn great research interests for its wide applications in many fields including optical communications,1–3 optical manipulation and trapping,4 optical metrology5–7 and quantum information processing.8–12 Quantum information processing benefits greatly from improved manipulation of different photonics degrees of freedoms.13,14 Various studies of photon’s spatial degree of freedoms are motivated by the advantage that such modes can increase greatly the information carried by photons.15–18

In quantum communications, quantum memories for orbital angular momentum (OAM) qubit or qutrit states19–21 and entangled states22 have been realized. Recently, Laurat’s group has demonstrated quantum memory for vector polarized beams.23 In addition to OAM modes and vector polarized modes, Hermite-Gaussian (HG) mode is another very important spatial mode of the photon, which is also the eigenmode of an optical cavity. To build quantum memories for HG modes, one need to prepare photons states in this mode which has a matched bandwidth to couple with the memory. Usually, photon pairs or single photons are generated through spontaneously parametric down-conversion (SPDC) process in a nonlinear crystal, but the photon generated has so wide bandwidth (∼THz) that it can’t effectively couple with atoms (natural bandwidth: ∼MHz), which is a key for realizing quantum communication and linear quantum computation. So it is very important to generate non-classical correlated photons with narrow bandwidth. One of the common methods to reduce the bandwidth of photon pairs emitted from SPDC in a nonlinear crystal is to use an optical parametric oscillator (OPO) operated far below the cavity’s threshold.21–32 A type-II OPO to generate hyper-entanglement continuous-variable in HG mode was reported in Ref. 33 recently, where entanglements in polarization and orbital angular momentum is verified. So far there is no any report on generating photon pairs in the discrete-variable regime in HG modes using an OPO operated far below the cavity threshold.

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In this letter, we report on generating photon pairs in HG mode in a type-I OPO operating far below threshold. From correlation measurements, we show that the photon pairs have non-classical correlations and the bandwidth of the photon pairs generated is 11.4MHz and 20.8MHz for two different HG modes. We also show that the HG modes can be easily adjusted by tuning the cavity. Our work provides an effective way to generate photon pairs with narrow bandwidth in high order spatial modes for high dimensional quantum communication.

The Hamiltonian for a type-I OPO operated far below threshold is expressed by\(^{33,34}\):

\[
H_{\text{int}} = i\hbar \chi \hat{a}_p \hat{a}_s \hat{a}_l^\dagger + H.c
\]

Here \(\hat{a}_p(\hat{a}_s, \hat{a}_l)\) is (are) the annihilation (creation) operator for the pump field (signal, idler photon), respectively. \(l\) represents the OAM index of the emitted photons, we focus on \(l = 1\) in this work. For conservation of OAM in the SPDC process, the signal and idler photons have opposite OAM. Therefore, there are two possible ways by which the paired photons are created. The two possibilities are (i) a signal photon is emitted in \(LG_0^1\) and an idler photon is emitted in \(LG_{-1}^0\), and (ii) a signal photon is emitted in \(LG_{-1}^0\) and an idler photon is emitted in \(LG_0^1\). Because of the overlap of \(LG_0^1\) and \(LG_{-1}^0\) in space and time, the \(LG_0^1 + e^{i\theta}LG_{-1}^0\) mode is created in the output of the OPO, where \(\theta\) depends on the tilting of the cavity.

For SPDC process with a Gaussian pump beam in single pass configuration, the signal and idler state generated is an infinite superposition of LG modes. The cavity acts as a spatial and frequency filter for the generated superposition modes. When the cavity is locking to a specific LG mode, the generated photon pair mode is projected to the cavity mode.

The experimental setup is depicted in Fig. 1. In our experiment, the 795nm laser beam from Ti: sapphire laser is divided into two parts by using a polarized beam splitter (PBS). One part of the beam is used for second harmonic generation (SHG) to generate 397.5nm UV beam as the input for the OPO; the other part of the beam is modulated with an electrical optical modulator (EOM) with a frequency of 10.8 MHz, which generates side band for locking the cavity using Pound-Drever-Hall (PDH) method.\(^{35}\) The Gaussian locking beam is converted to \(LG_0^1\) mode using a vortex phase plate (VPP) before it couples to the OPO.

The OPO cavity consists of two mirrors with a radius of curvature of 80 mm, the input coupling mirror CM2 (high reflection coated at 795nm and high transmission coated at 397.5nm) is attached to a piezoactuator for scanning and locking the cavity, and mirror CM1 (4.5% transmission at 795nm and high transmission at 397.5nm) is used as output coupling mirror. A type-I periodically poled KTP crystal (PPKTP, from Raicol crystals, 1 mm × 10mm) is placed at the center of the cavity, whose temperature is controlled with a homemade temperature controller.

The OPO cavity and the UV pump beam are mode-matched using a single mode fiber (SMF). The locking beam and the pump beam are combined using a dichromatic mirror (DM). We use a chopper to time-divided between the locking beam and the created photon pairs for detection. The reflected beam from the cavity is rotated by a Faraday rotator (FR) and detected with a fast photodiode (PD) for locking the cavity. A pinhole is placed before the separation of generated photon pairs with a half wave plate (HWP) and a PBS. The separated photon pair from the two output ports of the PBS are collected using single mode fibers and detected using avalanche photon detector (APD) for coincidence measurement (Timeharp 260, from Pico quanta).

The non-classical correlation between the generated photons can be proved by checking whether the Cauchy-Schwarz inequality is violated.\(^{28,36}\) Usually classical lights satisfy the following equation:

\[
R = \frac{[g_{s1,s2}(\tau)]^2}{g_{s1,s1}(0)g_{s2,s2}(0)} \leq 1
\]

where \(g_{s1,s2}(\tau), g_{s1,s1}(0), \) and \(g_{s2,s2}(0)\) were the normalised second-order cross-correlation and auto-correlation of the photons respectively. The normalised \(g_{s1,s2}(\tau)\) can be obtained by normalizing the true two-photon coincidence counts to the accidental two-photon coincidence counts \(g_{s1,s2}(\infty)\). With \(\tau = t_{s1} - t_{s2}\) the relative time delay between paired photons.

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025114-2 Zhou et al. AIP Advances 6, 025114 (2016)
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025114-2 Zhou et al. AIP Advances 6, 025114 (2016)
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For measurements of cross-intensity correlation of signal and idler photon in HG mode, we use a pinhole to filter out one petal of the spatial mode and couple it to single mode fibers, a better detection method is to use spatial light modulator to transform the HG mode to TEM00 mode and coupling it to single mode fiber, which will be used in our future experiment. The cross correlation over the beam is measured from the same petal. The pump power of the 397.5 nm light is 60 $\mu$W. The experimental results for HG mode in different modes are showed in figure 2. Figure 2(a) is the results when the cavity mode is tuned to diagonal direction, the spatial shape leaked from the cavity is depicted in the inserted image, the image is measured using a CCD camera (BC106N-VIS, thorlabs) before filtering by pinhole when the cavity is on locking with a specific HG mode. The value of the normalized cross-intensity correlation is $g^{(2)}_{s,s}(0) = 7.2$ in a time bin of 0.8 ns, the time for the coincidence measurements is 600 s. Due to the fact that photons from signals 1 and 2 exhibited photon statistics typical of thermal light, the self-correlation function should be less than 2, we assume $g_{s1,s1}(0) = g_{s2,s2}(0) \approx 2$ to evaluate the lower bound of the Cauchy-Schwarz inequality, therefore the corresponding Cauchy-Schwarz inequality factor $R$ is much larger than 1. The Cauchy-Schwarz inequality is strongly violated, clearly demonstrating a non-classical correlation between photons. The full wave half maximum (FWHM) of the cross-correlation time is 19.4 ns, and the estimated bandwidth of the photon pairs is 11.4 MHz.

Fig. 2(b) is the result for HG mode in the horizontal directions. To rotate the beam position from diagonal to horizontal, we need to slightly tilt the directions of the cavity mirrors and the PPKTP crystal. The corresponding value of the normalized cross-intensity correlation is $g^{(2)}_{s,i}(0) = 5.7$, therefore the Cauchy-Schwarz inequality is also strongly violated. The FWHM of the cross-correlation time is 10.6 ns, and the bandwidth of the photon pair is 20.8 MHz.
diff. different FWHMs between these two situations are arising from the different mode losses inside the cavity. Curves of the cross-intensity correlation should have comb-like shapes, but because of limited response speed of the APDs and a relative small round trip time (0.94 ns) of the photon inside the cavity, the comb-like shape cannot be observed. The detailed reasons can be found in Ref. 32. The free spectral range of the cavity is 1.06 GHz, the number of the longitude modes which can simultaneously resonance with the cavity for the two cases are 1500 and 2100. The estimated spectral brightness of the photon pairs in account for the all losses is 16 (s.MHz.mW)$^{-1}$ and 4.4 (s.MHz.mW)$^{-1}$ respectively.

Because of the existence of astigmatic effect for different HG modes in the cavity, to generate orbital angular momentum qubits needs compensation by using another crystal with orthogonal axes. In the future research, we will design a type-II OPO as reported in Ref. 33 to generate hyper-entangled photon pair source, then a more rigorous method based on mode projection measurements by using spatial light modulator will be used. The present experiment is focus on the first order cavity mode, to access high order cavity modes is the target of future research with better cavity design.
Our experimental results clearly show that we could easily generate a photon pair non-classical correlated in different HG modes by locking the cavity in different HG modes. Besides, by using the type-I OPO operating far below threshold, we could also greatly reduce the bandwidth of the photon, which makes the effective coupling between the photon and atomic-based memory possible. The bandwidth of the photon pairs obtained experimentally are 11.4 MHz and 20.8 MHz for two different HG modes. In the present demonstration, the output spectral of the photon pair is in multi-longitude mode. Single longitude operation can be obtained by a filter. The filter methods introduced in Refs. 30 and 37 meet the requirements in our experiments. In the present experiments we aim to show the possibility to generate narrow bandwidth photon pairs in cavity’s high order modes. This primary study will provide an effective way to generate HG mode narrow bandwidth photon pairs, which can be coupled to high dimensional quantum communications.

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1 J. Wang, J.-Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, and A. E. Willner, Nat. Photon., 6, 488 (2012).
2 N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. E. Willner, and S. Ramachandran, Science 340, 1545 (2013).
3 G. Vallone, V. D’Ambrosio, A. Spasenelli, S. Slussarenko, L. Marrucci, F. Sciarrino, and P. Villoresi1, Phys. Rev. Lett. 113, 060503 (2014).
4 S. Franke-Arnold, L. Allen, and M. Padgett, Laser photon. Rev. 2, 299 (2008).
5 V. D’Ambrosio, N. Spagnolo, L. Del Re, S. Slussarenko, Y. Li, L. C. Kwek, L. Marrucci, S. P. Walborn, L. Aolita, and F. Sciarrino, Nat. Commun. 4, 2432 (2013).
6 Z.-Y. Zhou, Y. Li, D.-S. Ding, Y.-K. Jiang, W. Zhang, S. Shi, B.-S. Shi, and G.-C. Guo, Opt. Lett. 39, 5098 (2014).
7 M. P. J. Lavery, F. C. Speriti, S. M. Barnett, and M. J. Padgett, Science 341, 537 (2013).
8 J. T. Barreiro, T.-C. Wei, and P. G. Kwiat, Nat. Phys. 4, 282 (2008).
9 E. Nagali, L. Sansoni, F. Sciarrino, F. De Martini, L. Marrucci, B. Piccirillo, E. Karimi, and E. Santamato, Nat. Photon. 3, 720 (2009).
10 J. Leach, B. Jack, J. Romero, A. K. Jha, A. M. Yao, S. Franke-Arnold, D. G. Ireland, R. W. Boyd, S. M. Barnett, and M. J. Padgett, Science 329, 662 (2010).
11 R. Fickler, R. Lapkiewicz, W. N. pliek, M. Krenn, C. Schaeff, S. Ramelow, and A. Zeilinger, Science 338, 640 (2012).
12 A. C. Dada, J. Leach, G. S. Buller, M. J. Padgett, and E. Andersson, Nat. Phys. 7, 677 (2011).
13 P. Kok, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, Rev. Mod. Phys. 79, 135 (2007).
14 J.-W. Pan, Z.-B. Chen, C.-Y. Lu, H. Weinfurter, A. Zeilinger, and M. Zukowski, Rev. Mod. Phys. 84, 777 (2012).
15 J. Barreiro, N. Langford, N. Peters, and P. Kwiat, Phys. Rev. Lett. 95, 260501 (2005).
16 G. Vallone, R. Ceccarelli, F. De Martini, and P. Mataloni, Phys. Rev. A 79, 030301(R) (2009).
17 R. Ceccarelli, G. Vallone, F. De Martini, P. Mataloni, and A. Cabello, Phys. Rev. Lett. 103, 160401 (2009).
18 J. T. Barreiro, T.-C. Wei, and P. G. Kwiat, Nat. Phys. 4, 282–286 (2008).
19 D.-S. Ding, Z.-Y. Zhou, B.-S. Shi, and G.-C. Guo, Nat. Commun. 4, 2527 (2013).
20 D.-S. Ding, W. Zhang, Z.-Y. Zhou, S. Shi, J.-S. Pan, G.-Y. Xiang, X.-S. Wang, Y.-K. Jiang, B.-S. Shi, and G.-C. Guo, Phys. Rev. A 90, 042301 (2014).
21 A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein, and J. Laurat, Nat. Photon. 8, 234 (2014).
22 D.-S. Ding, W. Zhang, Z.-Y. Zhou, S. Shi, G.-Y. Xiang, X.-S. Wang, Y.-K. Jiang, B.-S. Shi, and G.-C. Guo, Phys. Rev. Lett. 114, 050502 (2015).
23 V. Parigi, V. D’Ambrosioy, C. Arnolds, L. Marrucci, F. Sciarrino, and J. Laurat, Nat. Commun. 6, 7706 (2015).
24 E. Y. Ou and Y. J. Lu, Phys. Rev. Lett. 83, 2556 (1999).
25 C. E. Kuklewicz, F. C. Wong, and J. H. Shapiro, Phys. Rev. Lett. 97, 223601 (2006).
26 E. Y. Wang, B. S. Shi, and G. C. Guo, Opt. Lett. 33, 2191 (2008).
27 X. H. Bao, Y. Qian, J. Yang, H. Zhang, Z. B. Chen, T. Yang, and J. W. Pan, Phys. Rev. Lett. 101, 190501 (2008).
28 M. Scholz, L. Koch, and O. Benson, Phys. Rev. Lett. 102, 063603 (2009).
29 E. Pamaricco, B. Sanguinetti, N. Gisin, R. Thew, H. Zbinden, G. Schreiber, A. Thomas, and W. Sohler, New J. Phys. 11, 13042 (2009).
30 F. Wolfgramm, Y. A. de I. Astiz, F. A. Beduini, A. Ceré, and M. W. Mitchell, Phys. Rev. Lett. 106, 053602 (2011).
31 J. Fekete, D. Rieländer, M. Cristiani, and H. de Riedmatten, Phys. Rev. Lett. 110, 220502 (2013).
32 Z.-Y. Zhou, D.-S. Ding, Y. Li, F.-Y. Wang, and B.-S. Shi, J. Opt. Soc. Am. B 31, 128 (2014).
33 K. Liu, J. Guo, C. Cai, S. Guo, and J. Gao, Phys. Rev. Lett. 110, 220501 (2014).
34 Y. Jeronimo-Moreno, S. Rodriguez-Bevabides, and A. B. U’Ren, Laser Physics 20, 1211 (2010).
35 R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B 31, 97 (1983).
36 A. Kuzmich, W. P. Bowen, A. D. Boszer, A. Boca, C. W. Chou, L. M. Duan, and H. J. Kimble, Nature 423, 731 (2003).
37 M. A. Zentile, D. J. Whiting, J. Keaveney, C. S. Adams, and I. G. Hughes, Opt. Lett. 40, 200 (2015).