Experimental observation of three-photon interference between a two-photon state and a weak coherent state on a beam splitter

著者（英）	Tingyu Li, Saburo Sakurai, Katsuyuki Kasai, Lirong Wang, Masayoshi Watanabe, Yun Zhang
journal or publication title	Optics Express
volume	26
number	16
page range	20442-20449
year	2018-08-06
URL	http://id.nii.ac.jp/1438/00009074/

doi: 10.1364/OE.26.020442

Research Article | Vol. 26, No. 16 | 6 Aug 2018 | OPTICS EXPRESS 20442
Optics EXPRESS

Experimental observation of three-photon interference between a two-photon state and a weak coherent state on a beam splitter

Tingyu Li,[1] Saburo Sakurai,[2] Katsuyuki Kasai,[3] Lirong Wang,[4,5,6] Masayoshi Watanabe, [2] and Yun Zhang [2,7]

[1] *College of Information and Computer, Taiyuan University of Technology, Taiyuan, 030024, Shanxi, China*
[2] *Department of Engineering Science, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182-8585, Japan*
[3] *Advanced ICT Research Institute, National Institute of Information and Communications Technology, 588-2, Iwaoka, Nishi-ku, Kobe, Hyogo, 651-2492, Japan*
[4] *State Key laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan, 030006, China*
[5] *Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, 030006, China*
[6] *wlr@sxu.edu.cn*
[7] *zhang@ee.uec.ac.jp*

Abstract: We experimentally demonstrated a three-photon interference on a beam splitter between a weak coherent state and a two-photon state produced by a spontaneous parametric down conversion. It indicates that a combined three-photon probability amplitude, which is formed by the two-photon state and one-photon from the coherent state, can be used to interfere with another three-photon probability amplitude from the coherent state. The observed three-photon coincidence rate showed that the interference depended on not only the relative phase between the two interference field but also the amplitude of the weak coherent state. This may introduce another free parameter for preparing quantum state, such as high N00N state, with quantum interference.

OCIS codes: (270.0270) Quantum optics; (270.4180) Multiphoton processes; (190.4410) Nonlinear optics, parametric processes.

References and links

1. T. B. Pittman and J. D. Franson, "Generation of entangled photon holes using quantum interference," Phys. Rev. A **74**, 041801 (2006).
2. R. B. Jin, J. Zhang, R. Shimizu, N. Matsuda, Y. Mitsumori, H. Kosaka, and K. Edamatsu, "High-visibility nonclassical interference between intrinsically pure heralded single photons and photons from a weak coherent field," Phys. Rev. A **83**, 031805 (2011).
3. K. H. Hong, J. Jung, Y. W. Cho, S. W. Han, S. Moon, K. Oh, Y. S. Kim, and Y. H. Kim, "Limits on manipulating conditional photon statistics via interference of weak lasers," Opt. Express **25**, 10610-10621 (2017).
4. X. Li, L. Yang, L. Cui, Z. Y. Ou, and D. Yu,"Observation of quantum interference between a single-photon state and a thermal state generated in optical fibers," Opt. Express **16**, 12505 (2008).
5. T. F. da Silva, G. B. Xavier, G. C. Amaral, G. P. Temporao, and J. P. von der Weid, "Quantum random number generation enhanced by weak-coherent states interference," Opt. Express **24**, 19574 (2016).
6. Y. J. Lu, and Z. Y. Ou, "Observation of Nonclassical Photon Statistics due to Quantum Interference," Phys. Rev. Lett. **88**, 023601 (2002).
7. M. Koashi, K. Kono, T. Hirano, and M. Matsuoka, "Photon antibunching in pulsed squeezed light generated via parametric amplification," Phys. Rev. Lett. **71**, 1164(1993).
8. M. Koashi, K. Kono, M. Matsuoka, and T. Hirano, "Probing the two-photon phase coherence of parametrically down-converted photons by a local oscillator," Phys. Rev. A **50**, 3605 (1994).
9. D. Wu, K. Kawamoto, X. M. Guo, K. Kasai, M. Watanabe, and Y. Zhang, "Observation of two-photon interference with continuous variables by homodyne detection," Eur. Phys. J. D **71**, 260 (2017).
10. D. Stoler, "Photon antibunching and possible ways to observe it," Phys. Rev. Lett. **33**, 1397 (1974).
11. J. W. Pan, Z.-B. Chen, C.-Y. Lu, H. Weinfurter, A. Zeilinger, and M. Zukowski, "Multiphoton entanglement and interferometry," Rev. Mod. Phys. **84**, 777 (2012).

#332829 https://doi.org/10.1364/OE.26.020442
Journal © 2018 Received 28 May 2018; revised 4 Jul 2018; accepted 11 Jul 2018; published 26 Jul 2018

12. H. Kim, H. S. Park, and S. K. Choi, "Three-photon N00N states generated by photon subtraction from double photon pairs," Opt. Express **17**, 19720 (2009).
13. Z. Y. Ou, *Multi-Photon Quantum Interference* (Springer,New York, 2007).
14. P. Chen, C. Shu, X. Guo, M.M.T. Loy, and S. Du, "Measuring the biphoton temporal wave function with polarization-dependent and timer-resolved two-photon interference," Phys. Rev. Lett. **114**, 010401 (2015).
15. N. Tischler, A. Buse, L. G. Helt, M. L. Juan, N. Piro, J. Ghosh, M. J. Steel, and G. Molina-Terriza, "Measurement and Shaping of Biphoton Spectral Wave Functions," Phys. Rev. Lett. **115**, 193602 (2015).
16. F. A. Beduini, J. A. Zielinska, V. G. Lucivero, Y. A. de Icaza Astiz, and M. W. Mitchell, "Interferometric measurement of the biphoton wave function," Phy. Rev. Lett. **113**. 183602 (2014).
17. T. Kobayashi, R. Ikuta, S. Yasui, S. Miki, T. Yamashita, H. Terai, T. Yamamoto, M. Koashi and N. Imoto, "Frequency-domain Hong-Ou-Mandel interference," Nature Photonics **10**, 441 (2016).
18. A. J. Menssen, A. E. Jones, B. J. Metcalf, M. C. Tichy, S. Barz, W. S. Kolthammer, and I. A. Walmsley, "Distinguishability and many particle interference," Phys. Rev. Lett. **118**, 153603 (2017).
19. S. Agne, T. Kauten, J. Jin, E. Meyer-Scott, J. Z. Salvail, D. R. Hamel, K. J. Resch, G. Weihs, and T. Jennewein, "Observation of genuie three-photon interference," Phys. Rev. Lett. **118**, 153602 (2017).
20. H. H. Lu, J. M. Lukens, N. A. Peters., O. D. Odele, D. E. Leaird, A. M. Weiner, and P. Lougovski, "Electro-Optic Frequency Beam Splitters and Tritters for High-Fidelity Photonic Quantum Information Processing," Phys. Rev. Lett. **120**, 030502 (2018).
21. K. Azuma, K. Tamaki, H. K. Lo, "All-photonic quantum repeaters," Nature Commun. **6**, 6787 (2015).
22. I. Walmsley, "Quantum interference beyond the fringe," Science **358**, 1001(2017).
23. Y. S. Ra, M. C. Tichy, H. T. Lim, C. Gneiting, K. Molmer, A. Buchleitner, and Y. H. Kim, "Reversed interplay of quantum interference and which-way information in multiphoton entangled states," Phy. Rev. A **96**, 023845 (2017).
24. T. Giordani, F. Flamini, M. Pompili, N. Viggianiello, N. Spagnolo, A. Crespi, R. Osellame, N. Wiebe, M. Walschaers, A. Buchleitner, F. Sciarrino, "Experimental statistical signature of many-body quantum interference," Nature Photonics **12**, 173 (2018).
25. R. B. Jin, R. Shimizu, K. Wakui, H. Benichi, and M. Sasaki, "Widely tunable single photon source with high purity at telecom wavelength," Opt. Express **21**, 10659 (2013).
26. R. B. Jin, M. Fujiwara, R. Shimizu, R. J. Collins, G. S. Buller, T. Yamashita, S. Miki, H. Terai, M. Takeoka, and M. Sasaki, "Detection-dependent six-photon Holland-Burnett state interference," Sci. Rep. **6**, 36914/1-7 (2016).
27. Y. S. Kim, O. Kwon, S. M. Lee, J. C. Lee, H. Kim, S. K. Choi, H. S. Park, and Y. H. Kim, "Observation of Young's double-slit interference with the three-photon N00N state," Opt. Express **19**, 24957 (2011).
28. M. Matsuoka and T. Hirano, "Quantum key distribution with a single photon frem a squeezed coherent state," Phys. Rev. A **67**, 042307 (2003).
29. Y. J. Lu, L. B. Zhu, and Z. Y. Ou, "Security improvement by using a modified coherent state for quantum cryptography," Phys. Rev. A **71**, 032315 (2005).
30. H. Wang and T. Kobayashi, "Phase measurement at the Heisenberg limit with three photons," Phys. Rev. A **71**, 021802 (2005).
31. T. Kobayashi, D. Yamazaki, K. Matsuki, R. Ikuta, S. Miki, T. Yamashita, H. Terai, T. Yamamoto, M. Koashi, and N. Imoto, "Mach-Zehnder interferometer using frequency-domain beamsplitter," Opt. Express **25**, 12052–12060 (2017).
32. I. Afek, O. Ambar, and Y. Silberberg, "High-NOON states by mixing quantum and classical light," Science **328**, 879 (2010).
33. Y. H. Xue, T. Y. Li, K. Kasai, Y. Okada-Shudo, M. Watanabe and Y. Zhang, "Controlling quantum interference in phase space with amplitude," Sci. Rep. **7**, 2291 (2017)
34. Y. Zhang, T. Furuta, R. Okubo, K. Takahashi, and T. Hirano, "Experimental generation of broadband quadrature entanglement using laser pulses," Phys. Rev. A **76**, 012314 (2007).
35. R.-B. Jin, K. Wakui, R. Shimizu, H. Benichi, S. Miki, T. Yamashita, H. Terai, Z. Wang, M. Fujiwara, and M. Sasaki,, "Nonclassical interference between independent intrinsically pure single photons at telecommunication wavelength ," Phys. Rev. A **87**, 063801 (2013).

1. Introduction

Photon interference between a two-photon state (or squeezed state) from spontaneous parametric down conversion (SPDC) and a weak coherent state is of fundamental interest in quantum optics [1–5]. Because of its involvement of the special sources and potential applications in quantum information, a case of interference between two-photon state has been attracting much attention [6–9]. The two-photon interference was initially investigated as an alternative method to produce photon anti-bunching [7, 10]. Later, it has been used as the core of many quantum information protocols [11, 12]. The principle of two-photon interference has been widely understood as a superposition of two probability amplitudes from the weak coherent state and the two-photon state respectively [13]. Up to now, the phenomenon was demonstrated experimentally

Optics EXPRESS

with an optical parametric amplifier (OPA) or beam splitter and the light sources can be employed either a pulse laser or a continuous wave laser [6–9]. As one of most important applications, a complex wave function, which provides complete knowledge of a state, for two-photon state has also been measured [14–16]. To meet practical applications in quantum information technology, the interest for photon interference is recently extending to the investigation of frequency conversion of single photon and multi-photon interference [17–19]. The frequency conversion of single photon provides an unique avenue for the link between quantum memory and quantum communications [20, 21]. Extending the study of multi-photon interference is critical for our understanding and fundamental tests of quantum mechanics as well as for developments of technique in quantum information applications [22–27].

The above-mentioned concept of two-photon interference is modified from Dirac's famous statement of photon interference: *each photon interferes only with itself; different photons never interfere with each other.* When the probability of more than two-photon state is investigated, the situation becomes complex since we have to consider the contribution from combinations between the weak coherent state and the two-photon state [28, 29]. Hence, the multi-photon interference results become surprisingly richer than two-photon state interference and a number of features of multi-photon interference are remaining mysterious. Thus, multi-photon interference plays an essential role in the understanding of particle interference. On the other hand, the multi-photon interference also has great relevance to practical applications in quantum information processing, quantum metrology, and quantum state engineering. For example, interference with two photons and single-photon by an asymmetric Mach-Zehner interferometer was proposed for phase measurement below the Heisenberg limit [30, 31]. Relying on multi-photon interference and post-selection technique, lots of methods on generation of high N00N state, which lies at the core of super-resolving phase measurements, have been proposed and experimentally demonstrated [22, 32]. Thus the practical applications also require to further investigate the principle of muliti-photon interference.

In this paper, we report a three-photon interference between a two-photon state and a weak coherent state on a beam splitter. It indicates that the two-photon state and one-photon from the coherent state can be used to combine a three-photon probability amplitude. Three-photon interference occurs between the combined three-photon probability amplitude and that from the coherent state. The measured three-photon coincidence rate depends on not only the relative phase between the two interference field but also the amplitude of the weak coherent state.

2. Model

To understand the interference principle, let us consider a scheme, in which a weak coherent state is interfered with a squeezed state from SPDC on a beam-splitter. Three photon coincidence is measured at one of outputs of beam splitter. We assume that each light beam is in a single mode and neglect the contribution from more than three photons, the two state can be expanded in photon number (Fock) state and represented by

$$|s\rangle \approx |0\rangle - \frac{s}{\sqrt{2}}|2\rangle, \text{ for squeezed state} \tag{1}$$

$$|\alpha\rangle \approx |0\rangle + a|1\rangle + \frac{\alpha^2}{\sqrt{2}}|2\rangle + \frac{\alpha^3}{\sqrt{6}}|3\rangle, \text{ for weak coherent state} \tag{2}$$

respectively. We assume that s is a real small positive number, so the norm of state (1) is close to one. The coherent state has a complex amplitude $|\alpha|e^{i\theta}$ and its norm is also close to one when $|\alpha| \ll 1$. We only corcent concern on the case of three-photon probability, so the output state of beamsplitter can be described as [13]

$$|\Psi_{out}\rangle = \frac{(\alpha^2 - 3s)\alpha}{4\sqrt{3}}(|0,3\rangle + |3,0\rangle) + \frac{(\alpha^2 + s)\alpha}{4}(|2,1\rangle + |1,2\rangle). \tag{3}$$

Optics EXPRESS

The normalization of coefficients are not considered, since only three-photon probability is measured in our experiment. As can be seen, if we set $\alpha^2 = -s$, the coefficient in front of $|2,1\rangle + |1,2\rangle$ is zero and a three-photon N00N state will be obtained. The complete cancellation of the coefficient of $|2,1\rangle$ and $|1,2\rangle$ terms or the enhancement of the coefficient of $|0,3\rangle$ and $|3,0\rangle$ can be understood three-photon interference between $|0,3\rangle$ and $|2,1\rangle$ input terms [30, 32]. This was understood that a two-photon from squeezed vacuum state combines with a single-photon from the coherent light to form a three-photon probability amplitude. This probability amplitude can be used to interfere with another three-photon probability amplitude from the coherent light. Here, we extend this concept to three-photon interference between a weak coherent state and two-photon state. The three-photon coincidence (R_{30} or R_{03}), which corresponds the coefficient of term $|0,3\rangle + |3,0\rangle$ in Eq. (3), of one output of beamsplitter is given by,

$$R_{30} \propto |\alpha|^6 - 6s|\alpha|^4 \cos 2\theta + 9s^2|\alpha|^2, \tag{4}$$

in which 2θ is the relative phase between two interference fields. Equation (4) is a cubic polynomial for parameter of $|\alpha|^2$ when a fixed squeezed state ($|s|$=constant) is employed. When $2\theta = (2n+1)\pi$ ($n = 0, 1, 2, \ldots$), the cubic's inflection point is the only critical point. So, this predicts that the measured three-photon coincidence will monotonically increase with a increasing of intensity of coherent state. On the other hand, the polynomial has two critical points for $2\theta = 2n\pi$. Thus, the three-photon coincidence will have a local maximum and a local minimum with the incresment of intensity of coherent state. To give an explanation of this, let's introduce a combined three-photon probability amplitude formed by a two-photon state from squeezed state and a one-photon state from cohernet state. This combined three-photon probability amplitude is relative to both the probability amplitude of the one-photon state and the relative phase between two probability amplitudes of two-photon state and one-photon state, so the measured three-photon probability depends on not only the relative phase between two interference fields but also the amplitude of interference field. Especially, this interference indicates oscillation with the amplitude of interference field when multi-photon interference is considered [33].

To further understand the obtained three-photon probability, we normalized the measured three-photon probability to that of the input coherent state (when the squeezed parameter $s = 0$ is taken).

$$\mathfrak{R}_{30} = 1 - 6\beta \cos 2\theta + 9\beta^2 = \begin{cases} (1-3\beta)^2 & 2\theta = 2n\pi \\ (1+3\beta)^2 & 2\theta = (2n+1)\pi, \end{cases} \tag{5}$$

where $\beta = s/|\alpha|^2$ gives the relative strength of two fields. Equation (4) presents the typical relative phase dependent feature for interference effect. Obviously, the normalized three-photon probability is always larger than unit indicating the constructive interference for $2\theta = (2n+1)\pi$. On the other hand, the three-photon probability becomes complex for $2\theta = 2n\pi$. When $|\alpha|^2$ is very small ($|\alpha|^2 < 1.5s$), the normalized three-photon probability is larger than unit irrespective of the relative phase. Only when $|\alpha|^2$ is enough large, the normalized three-photon probability becomes less than one and a completely destructive interference occurs at $|\alpha|^2 = 3s$.

3. Experimental setup

For the interference experiment, a layout of the setup is shown in Fig. 1. It is similar to our previous experiment for controlling quantum interference in phase space with amplitude [33]. A cw mode-locked Ti: Sapphire laser, operating at 798 nm with a pulse duration of 2 ps and a pulse repetition rate of 82 MHz, was employed as primary source. Most of the laser power was sent to a single-pass-through second harmonic generator (SHG) to produce an efficient 399 nm light as a pumping field for generation of the two-photon state with a parametric down converter (PDC). In our SHG system, a 15-mm-long type-I LBO crystal was used as a nonlinear material. In particular, an average power of about 100 mW for ultraviolet light was generated when the

Optics EXPRESS

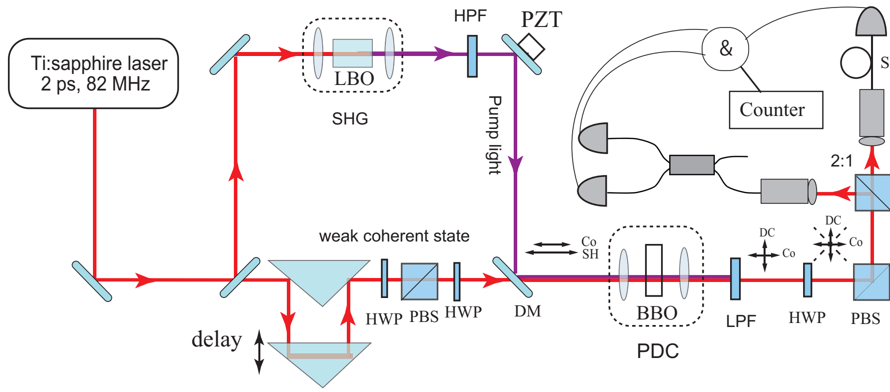

Fig. 1. Experimental setup for three-photon interference in phase space. SHG: second harmonic generation, HPF: high-pass filter, HWP: half-wave plate, PBS: polarizing beam splitter, LPF: low pass filter, PDC: parametric down converter, SMF: single-mode fiber

fundamental input power was about 700 mW. A smaller remainder portion of the laser power as the weak coherent state was combined with pump light and injected into the PDC. Before they combined, the intensity of the weak coherent state was adjusted by a half-wave plate and a polarizer, then its polarization was changed by another half-wave plate. To ensure the coherent light had reached th PDC simultaneously with the pump pulses, a pair of movable prisms were employed for temporally delaying it. The relative phase between the coherent light and the pump light was also finely adjusted and stabilized by a mirror, which was mounted on a piezoelectric translator (PZT). Both the pump light and the coherent light have the same polarization, so that the coherent light experiences no parametric interaction. After the pump was eliminated by a low pass filter, the polarization of orthogonally polarized weak coherent state and two-photon state was rotated by a half-wave plate(HWP). To maximally utilize the two-photon state, the rotation angle of HWF was setted for reflect most of two-photon state and small part of coherent state on the coming polarizing beam splitter (PBS), which worked as a beam splitter (95:5). Then the output was further separated by a 2:1 beam splitter. One of the outputs was coupled into a single 50:50 single-mode fiber beam splitter (Thorlabs FC830-50B-FC) and the other port was coupled into a single-mode fiber. Finally, all of the collected photons were sent to three single photon counting modules (SPCM, Perkin Elmer, SPCM-AQRH14) and the three-photon number probability of the interfered beam was investigated with a three-fold coincidence counter, which consisted of a electronical coincidence circuit and a photon counter.

We note that the mixing of two beams in interference was not done in the traditional method with a beam splitter. We injected the coherent beam and pump beam with the same polarization and mixed the coherent state and the produced orthogonal two-photon state by the PBS. This method has several advantages. First, interference requires the temporal and spatial mode matching between the weak coherent state and the two-photon state. This can be checked by operating the system as an optical parametric amplifier when the coherent beams was injected as an ordinary ray in crystal. Second, it also can avoids mechanics phase fluctuations since two beams pass through the same optical components.

The PDC for producing the two-photon state consisted of a 3-mm-long type I beta barium borate (BBO) crystal. The two-photon state with a squeezing parameter of $s = 0.13$ at pump power of 40 mW was estimated by the measured parametric gain when the PDC was operating as an optical parametric amplifier, that is, the coherent beam was injected into the PDC as an ordinary ray [34]. In the above pump condition, the two-photon coincidence count rate for the two-photon state was 3.5 kcps, while average counting rates of two SPCMs were 18.5 kcps and 18.8 kcps,

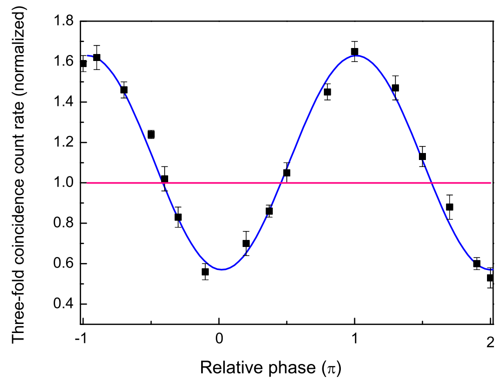

Fig. 2. Three-photon interference for delay τ=0 versus relative phase between pump and injected coherent light. The solid curve is 1-Vcos θ, where V=0.53 is the expected visibility. The plotted data give mean and standard error for five independence measurements. The red line gives a non-interference standard measuring at delay of τ=5 ps.

including the dark count rate, respectively. The following intensity of injection coherent state was referenced to the two-photon coincidence count rate by recording the two-photon coincidence of injection coherent state without pump field. The intensity of the coherent state was varied by changing attenuation, which consisted of a half-wave plate (HWP) and a PBS, in the coherent light beams.

4. Experimental result and discussion

Figure 2 shows the observed three-photon coincidence rate as a function of relative phase between the two-photon state and the weak coherent state when the measured two-photon probability of coherent state is about twice that of the two-photon state. The measured coincidence rate is normalized to that of when the temporal overlap between two fields is mismatched, meaning that three-photon interference does not occur. In experimant, it was realized by two steps. In the first step, the normalization standard was obtained by recording the three-fold coincidence when temporal overlap between two-photon state and coherent state was mismatched. In the second step, The three-photon interference was investigated by measuring the three-fold coincidence when temporal overlap between two-photon state and coherent state was matched and the relative phase between the two-photon state and coherent state was scanned. The plotted data give an average value of five measurements and each measurement corresponds accumulation of three-fold coincidence during 60 second. The solid curve in Fig. 2 is plotted using $1 - V \cos 2\theta$, where $V = 0.53$ is the expected visibility. The sinusoidal behavior in good agreement with the measured data reveals three-photon interference as predicted by Eq. (4). Once again, what happens is that the two-photon combines with a single-photon in the coherent state to form a three-photon probability amplitude. This combined probability amplitude interferes with another three-photon probability amplitude from the coherent state. The imperfect visibility might have originated from the significant spectrum difference, in where the spectrum of two-photon state is much wider than that of coherent state. In our experiment, a ps pulse laser train usally produces two-photon state with a spectrum bandwidth of several-hundred GHz. On the other hand, the ps pulse has a spectrum bandwidth of several GHz. Another main cause of degradation of visibility are the contribution of higher than three photon state. This indicates that the present experiment with squeezing parameter of s=0.13 is not low enough to reduce higher photon contribution. We estimated this contribution from the couting rates for three-fold coincidence to be about 10 %. It

Optics EXPRESS

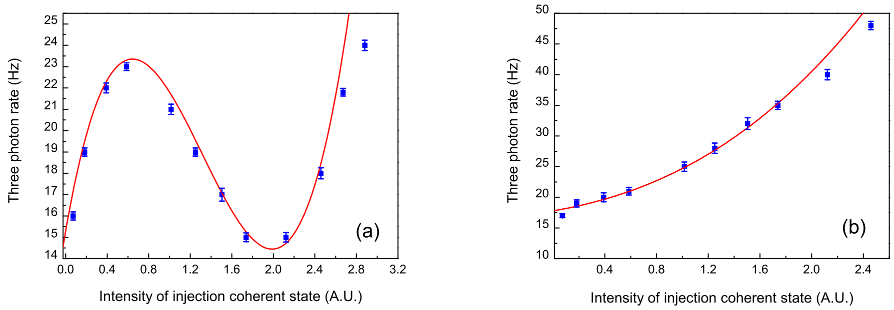

Fig. 3. Three-photon rate for delay τ=0 versus intensity of the coherent state. (a) The relative phase is fixed at destructive interference. (b) The relative phase is fixed at constructive interference. The solid curves show the cubic equations of $A(y^3 \pm 6y^2 + 9y + B)$. The plotted data give mean and standard error for five independence measurements.

is possible to improve the visibility by reducing the pump power. Unfortunately, the obtained three-fold coincidence will be dramatically decreased [35]. Other possible causes are including spatial mis-alignement and temporal mismatching between two-photon state and coherent state. A narrower frequency filter always be helpful for observation of a higher visibility interference, but it also reduce the measured coincidence rate.

To further understand the combined three-photon probability amplitude and the three-photon interference, the three-photon coincidence is measured when the intensity of the coherent state is varied at a fixed pump power. The intensity of the coherent state is scaled by comparing the two-photon coincidence counting rate of coherent state with that of produced two-photon state by pump fields. Figure 3(a) and (b) give the recorded three-photon coincidence rate when the relative phase is fixed at destructive interference and constructive interference, respectively. With an increment of the intensity of the coherent state, the three-fold coincidence rate for the destructive interference phase indicates an oscillation characteristics while it is monotonically increasing for the constructive interference phase. It can be understood as follow: For a given pump power, the generated two-photon state has a fixed two-photon probability amplitude. At a small coherent injection, whole one-photon probability amplitude of coherent input were used up to form the combined three-photon probability amplitude since the two-photon probability amplitude from the two-photon state is sufficient. Hence, the combined three-photon probability amplitude is determined by the intensity of the coherent state. In this regime, the one-photon probability amplitude is larger than the three-photon probability amplitude of coherent state so the interference can not indicate the elimination of the three-photon probability even at the destructive phase. At further increasing the intensity of the coherent state, however, there is a maximum value for the combined three-photon probability amplitude since it is limited by the probability amplitude of the two-photon state rather than the one-photon probability amplitude of coherent state. When the two three-photon probability amplitudes become comparable, the destructive interference begins to indicate the elimination of the three-photon probability and a complete elimination finally occurs. Then the measured three-photon probability increases with the increment of the intensity of the coherent state since the three-photon probalibilty of the coherent state becomes significantly larger than that of the combined probability. On the other hand, the constructive interference results for three-photon interference give monotonically increasing since the three-photon probability amplitude from both the combination between one-photon and two-photon and the coherent state are increasing with the increment of intensity of coherent state. The measured data are fitting with cubic equation of $A(y^3 \pm 6y^2 + 9y + B)$ (the

Optics EXPRESS

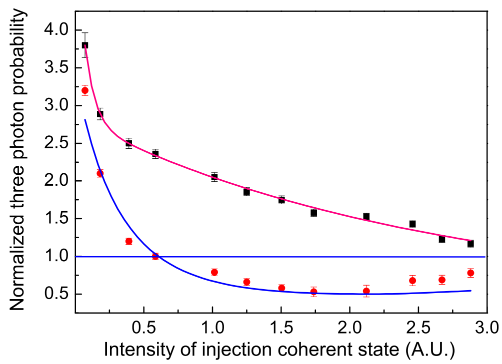

Fig. 4. Normalized three-photon probability versus intensity of the coherent state. The red curve and black squares show the constructive interference. The blue curve and red circles give the destructive interference. The plotted data give mean and standard error for five independence measurements.

form of Eq. (4)), where $a(y = ax)$ uses to scale the measured data, A and B come from a fit to the data. A well agreement is achieved when $a = 1.5$ for both the constructive and destructive interference.

It is more clear by normalizing the measured three-photon probability to that of the corresponding coherent state. Figure 4 gives the normalized three-photon probability as a function of intensity of the input coherent state. For constructive interference, the normalized three-photon probability is always more than unit. It, however, becomes less than unit from a special value, which usually relatives to the pump power, for destructive interference. The normalized three-photon probability with a value more than unit at small injected coherent state indicates that the combined three-photon probability amplitude from the two-photon state and one photon of coherent state is larger than that of corresponding coherent state. When the two three-photon probability amplitudes are comparable, three-photon interference can be clearly observed. At a larger injected coherent state, the three-photon probabilities for both constrictive interference and destructive interference are approaching to that of the coherent state.

5. Conclusion

In conclusion, we experimentally observed a three-photon interference between a two-photon state and a coherent state on a beam splitter. It was found that the destructive interference is oscillated with the intensity of interference coherent state. This is the first experiment on observation of photon interference with the combined photon-probability amplitude. This idea can be used to interpret multi-photon interference, which is crucial for generation of high N00N state. This experiment can also be applied to quantum metrology and quantum spectroscopy in future.

Funding

JSPS KAKENHI (17K05071,17K05072); National Natural Science Foundation of China (NSFC) (61728502, 61575116); Program of State Key Laboratory of Quantum Optics and Quantum Optics Devices (KF201812); Program for Sanjin scholars of Shanxi Province.

Acknowledgments

We are grateful to Prof. T. Hirano at Gakushuin University for his lots of supports.