The role of four-photon bunching in fourth-order correlation of thermal light in the photon counting regime

This content has been downloaded from IOPscience. Please scroll down to see the full text.
(http://iopscience.iop.org/0953-4075/48/7/075401)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
This content was downloaded by: fengwen
IP Address: 117.32.153.148
This content was downloaded on 18/03/2015 at 01:33

Please note that terms and conditions apply.
The role of four-photon bunching in fourth-order correlation of thermal light in the photon counting regime

Feng Wen1, Xun Zhang1, Chenzhi Yuan2, Huaibin Zheng1,3, Xin Yao1, Zepei Li3 and Yanpeng Zhang1

1 Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Shaanxi Key Lab of Information Photonic Technique, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China
2 Department of Electronic Engineering, Tsinghua University, Beijing, 100084, People’s Republic of China
3 School of Science, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China

E-mail: huaibinzhang@mail.xjtu.edu.cn and ypzhang@mail.xjtu.edu.cn

Received 18 July 2014, revised 24 January 2015
Accepted for publication 28 January 2015
Published 17 March 2015

Abstract
We theoretically discuss the fourth-order spatial correlation and four-photon bunching properties of pseudo-thermal light in the photon counting regime. It is found that four-photon bunching has the maximum correlation. If they all come from the same spatial cell in phase space, then fourth-order spatial correlation can be decomposed into not only auto-correlation and cross-correlation of second- and third- order, but the pure correlations among four photons as well, which is just the four-photon bunching. In addition, we also show that the contribution from four-photon bunching leads to the enhancement of the resolution and visibility in fourth-order ghost imaging. More precisely, the contribution from four-photon bunching to fourth-order spatial correlation is equal to the sum of all contributions from two-photon bunching and three-photon bunching when three reference detectors are scanned along the identical orientation and speed. On the other hand, the sum of all contributions from two-photon bunching and three-photon bunching to fourth-order spatial correlation will exceed the contribution from four-photon bunching, when two of three reference detectors are scanned in the same orientation and the speed of one reference detector is twice that of the other; meanwhile, the other two reference detectors are moved with opposite orientation but identical speed.

Keywords: photon statistics and coherence theory, quantum fluctuations, interference

(Some figures may appear in colour only in the online journal)

1. Introduction

Five decades ago, by measuring the second-order intensity fluctuations correlation from stars, Hanbury Brown and Twiss (HBT) found that the angular size of far stars can be obtained, and the phenomenon of two-photon bunching, where two photons have a tendency to arrive in pairs, was also discovered [1, 2]. Immediately, quantum theory of the higher-order coherence of light was introduced [3]. Since then, HBT interferometry has been applied in many areas of physics [4–12], and HBT experiments initiated and established a number of key concepts in modern quantum theory. However, the quantum or classical nature of the HBT phenomenon was still debated [13], for example, the spatial HBT-type experiment, given the name of ‘ghost’ imaging, was considered as a manifestation of nonclassical behavior at first [14–16]. However, ghost imaging experiments with chaotic thermal light is also demonstrated [17–23], where
nontrivial correlation of thermal light is confirmed. On the other hand, the contribution of the second-order intensity fluctuations correlation to two-photon correlation is universally accepted. Due to the difficulty in producing multi-photon entangled states, multi-photon imaging with thermal light is an exciting area for real applications. More recently, third-order ghost imaging with thermal light has been theoretically studied [24, 25] and experimentally demonstrated [26]. Furthermore, a higher-order intensity correlation experiment to study ghost imaging and interference is also conducted [27].

In addition to the earlier works [28, 29], in this paper, we will discuss the fourth-order spatial correlation and four-photon bunching properties of pseudo-thermal light in the near field, and analyze the role of four-photon bunching in the fourth-order correlation. In the first, fourth-order spatial correlation can be decomposed into multiple second- and third-order cross-correlations plus the four-photon bunching, and the contribution from four-photon bunching to the fourth-order spatial correlation peak is equal to all contributions from two-photon bunching and three-photon bunching when three reference detectors are scanned along the identical orientation and speed. On the other hand, the sum of all contributions from two-photon bunching and three-photon bunching to the fourth-order spatial correlation peak will exceed the contribution from four-photon bunching when two of three reference detectors are scanned in the same orientation and the speed of one reference detector is twice that of the other. Meanwhile, the other two reference detectors are moved with opposite orientation but identical speed.

2. Fourth-order spatial correlation and four-photon bunching

2.1. Basic theory

To consider the spatial properties of fourth-order correlation with fully incoherent light, we consider the setup shown in figure 1, where a laser beam is projected onto slowly rotating ground glass (GG), and the scattered beam is separated into four daughter beams by three 50/50 non-polarizing beam splitters (BS). These four daughter beams are injected into four single photon detectors via four different detection channels, including three reference arms and one test arm. In the test arm, the daughter beam reflected by BS1 is collected by a bucket detector D1. In the reference arm, the daughter beams are detected by three point-like detectors, respectively. Then, the four measured instantaneous intensities are seed into the coincidence circuit, where the fourth-order coincidence measurements are performed.

In the fourth-order spatial coincidence counting process, two important quantities, the fourth-order intensity correlation $g^{(4)}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4)$ and intensity fluctuation correlation $\Delta g^{(4)}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4)$, are defined $g^{(4)} = \left\{ \prod_{i=1}^{4} E^{-}(r_i)E^{+}(r_i) \right\}$ and $\Delta g^{(4)} = \left\{ \sum_{i=1}^{4} \Delta E^{-}(r_i)\Delta E^{+}(r_i) \right\}$, respectively, where $\left\{ E^{-}(r_i)E^{+}(r_i) \right\}$ is the instantaneous intensity at $r_i$ and $\Delta E^{-}(r_i)$ is field fluctuation at $r_i$. And $\langle \ldots \rangle$ means ensemble average and $r_i (i = 1, 2, 3, 4)$ denotes the coordinates of four single photon detectors. So, $g^{(4)}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4)$ of pseudo-thermal field can be expressed as

$$G^{(4)} = \text{Tr} \left\{ \rho^{\text{abcd}} E^{-}(\mathbf{r}_1)E^{-}(\mathbf{r}_2)E^{-}(\mathbf{r}_3)E^{+}(\mathbf{r}_4) \right\} \rho^{\text{abcd}} = \sum \rho^{\text{abcd}} \left| \Xi^{\text{abcd}} \right|^2$$

$\Xi^{\text{abcd}}$ is the density matrix of the pseudo-thermal field, where $\rho^{\text{abcd}}$ is the probability of finding the pseudo-thermal radiation in the four-photon state $\left| \Xi^{\text{abcd}} \right\rangle$, and assumed to be a constant in the following analysis. The four-photon state $\left| \Xi^{\text{abcd}} \right\rangle = \prod_{m=a,b,c,d} \int d^2k_x \kappa(k_m)e^{ik_x x_m} \left| 0 \right\rangle$ is the tensor product of four independent photon states with spatial multi-mode, and $\kappa(k_m)$ is the spatial distribution function. $k_m$ is the transverse wave vectors in the x orientation and $x_{0m}$ is the creation positions of photon $m (m=a, b, c, d)$ from the source, and $\left\{ 0 \right| E^{(\text{a})}(x_1)E^{(\text{b})}(x_2)E^{(\text{c})}(x_3)E^{(\text{d})}(x_4) \right\} \left| \Theta^{\text{abcd}} \right\rangle$ is the four-photon spatial effective wave function.

Based on the above discussion, $G^{(4)}(x_1, x_2, x_3, x_4)$ of the pseudo-thermal field can be simplified into

$$G^{(4)}(x_1, x_2, x_3, x_4) = \sum_{a,b,c,d} \rho^{\text{abcd}} \left\{ \left| 0 \right| E^{(\text{a})}(x_1)E^{(\text{b})}(x_2)E^{(\text{c})}(x_3)E^{(\text{d})}(x_4) \right\} \left| x_2 \right| E^{(\text{b})}(x_1) \left| \Theta^{\text{abcd}} \right\rangle \right|^2. \quad (1)$$

After the ensemble average and consider propagation effect from the source to four single photon detectors shown in figure 2(a), $G^{(4)}(u_1, u_2, u_3, u_4)$ of four detectors can be expressed as
To have a clear feeling about equation (2), now we are turning to figure 2(a) and using the Klyshko advanced-wave picture (KAWP) [30] to explore the physical interpretation of equation (2). Generally, the four-photon coincidence counting process can be interpreted in terms of propagation channels (corresponding to probability amplitudes) for the four independent photons to trigger the four detectors. The S1 (row 1, column 1) illustrated in figure 2(a) can be intuitively interpreted via KAWP, where \( a, b, c \) and \( d \) originated from \( D_1, D_2, D_3, \) and \( D_4 \) and propagate back to the pseudo-thermal source and reflects without changing, then propagate forward to the detector \( D_1, D_2, D_3, \) and \( D_4 \), respectively, and trigger them timely. This process is precisely described by the first term in equation (2), and corresponds to the background detected by the four detectors and contains no correlation information. Next, as S2 (row 1, column 2) in figure 2(a), \( c \) propagates backwards to source and turns into \( d \) and then propagates forward to \( D_4, D_2, \) and \( D_3 \) changes into \( c \) and forward to detector \( D_1, D_2, D_3, \) and \( D_4, \) respectively. In this time, \( a, b, \) and \( c \) trigger \( D_1, D_2, D_3, \) and \( D_4 \), respectively, and this process corresponds to the second term in equation (2). Third, as S3 (row 2, column 1) in figure 2(a), \( b, c \) and \( d \) propagates backwards to source and turns into \( b, c \) and \( d \), respectively, and \( a \) is unchanged. That is to say, \( a, b, \) and \( c \) trigger \( D_1, D_2, D_3, \) and \( D_4, \) respectively, which correspond to the fifth term in equation (2). Finally, as illustrated in figure 2(a) S4 (row 2, column 2), \( a, b, \) and \( c \) are all changed by source, and turned into \( b, c, \) and \( d, \) which means that \( d, a, b, \) and \( c \) trigger \( D_1, D_2, D_3, \) and \( D_4, \) respectively, and correspond to the tenth term in equation (2). As presented in equation (2), there are 24 different terms describing 24 different propagation channels for independent four-photons triggering four detectors coincidently. Therefore, the probability of four-photons coincidence counting can achieve the maximum of 24 if the 24 probability amplitudes superpose coherently. Equivalently, 24 different propagation channels are all indistinguishable in principle, therefore, the four photons are emitted from the identical spatial cell [31] and are indistinguishable in principle.

To evaluate equation (2), by taking the spatial momentum distribution function \((\kappa (k_d))\) as a constant within the narrow spatial bandwidth, we can simplify the integral into

\[
G^{(4)}(u_1, u_2, u_3, u_4) = 1 + \Delta G^{(2)} + \Delta G^{(2)} + \Delta G^{(2)} + \Delta G^{(2)} + \Delta G^{(2)} + \Delta G^{(2)} + \Delta G^{(2)} + \Delta G^{(2)}
\]

where \( \Delta G^{(2)} \) is a constant within the spatial momenta. The \( \Delta G^{(2)} \) is the two-photon bunching terms. \( \Delta G^{(2)} = 2G^{(1)}(u_2, u_1)G^{(1)}(u_3, u_1) \) and \( \Delta G^{(2)} = 2G^{(1)}(u_2, u_1)G^{(1)}(u_4, u_1) \) and \( \Delta G^{(2)} = 2G^{(1)}(u_3, u_2)G^{(1)}(u_4, u_2)G^{(1)}(u_4, u_3) \) are the three-photon bunching terms. \( \Delta G^{(2)} = G^{(1)}(u_3, u_2)G^{(1)}(u_4, u_2)G^{(1)}(u_4, u_3) \) is the one-photon bunching terms.
$2G^{(1)}(u_2, u_1) G^{(1)}(u_3, u_2) G^{(1)}(u_4, u_3) G^{(1)}(u_4, u_1)$ are the four-photon bunching terms. With $G^{(1)}(u_i, u_j) = \int \left\{E^{(-)}(x_{im})E^{(+)}(x_{jn})\right\} g^{(1)}_j(x_{m}, u_i) \cdot g_j(x_{n}, u_j) \, dx_{m} \cdot dx_{n}$, and $u_1, u_2, u_3$ and $u_4$ are the transverse positions of detectors $D_1, D_2, D_3,$ and $D_4$.

It can be seen from equation (4) and figure 2(b) that the fourth-order intensity fluctuation correlation can be decomposed into four categories. First, the auto-correlation (the first term in equation (4)), corresponding to the process where the four photons are created at the surface of the source and detected at $D_1, D_2, D_3,$ and $D_4$ without any exchange. Second, the cross-correlation of two photons ($\Delta g_{12}^{(2)}, \Delta g_{13}^{(2)}, \Delta g_{14}^{(2)}$, and $\Delta g_{12}^{(2)}$), as shown in figure 2(b), corresponding to any two of the four-photon exchanges in their propagation channels. Third, cross-correlation of three photons ($\Delta g_{123}^{(3)}, \Delta g_{124}^{(3)}, \Delta g_{134}^{(3)},$ and $\Delta g_{1234}^{(3)}$ ), where any three of four photons can be converted to each other in their propagation channels. Fourth, cross-correlation of four photons ($\Delta g_{1234}^{(4)}$) corresponding to the four-photon exchange with each other. Those four categories correspond to the probability amplitude pathway of four-photon coincidence counting event S1, S2, S3 and S4 shown in figure 2(a), respectively. The cross-correlation of two-photon, and three-photon and four-photon describe the two-, three- and four-photon bunching process, respectively, and in the following we will discuss the role they play in the measurement of fourth-order intensity fluctuation correlation.

To go further, the impulse response functions describing the propagation effects from the source to four detectors are required. As in figure 1, four detection channels, including the three reference arms and test arm, contain nothing but free space propagation from source to three reference detectors and the test detector. Under the paraxial approximation, the impulse response function can be expressed as

\[
h(k_i, x_i, u_j) = \frac{e^{-i k_i z_j}}{i k_z j} \cdot \exp \left\{-i \pi (x_i - u_j)^2 \right\} \times (i = a, b, c, d; j = 1,2,3,4),
\]

where $\lambda$ is the wavelength and $z_j$ is the distance between the source and detectors, and we assumed that the distances from the source to four detectors are all equal in the following discussion. Therefore, the quantized field operators at the four detectors take the following form

\[
E_j^-(u_j) = \int dk_i h(k_i, u_j) a^+(k_i) \quad (j = 1,2,3,4),
\]

$u_j$ is the coordinate of the $j$th detector. Substituting equation (5) into $G^{(1)}(u_m, u_n)$, after some calculations, we obtain the first-order coincidence counts between four detectors,

\[
G^{(1)}(u_m, u_n) = \int d\mathbf{x}_m d\mathbf{x}_n \left\{E^{(-)}(x_{m}^{\ast})E^{(+)}(x_{n}^{\ast})\right\} h(k_p, x_p, u_m) h^\ast
\times \left(k_q, x_q, u_n\right) \cdot \sin (\Delta \theta / \lambda (u_m - u_n)),
\]

In the near-field limit, $\Delta \theta \sim 2\pi r z$ is the angular size of the source with respect to the detector plane, and $r$ is the radius of the light source.

2.2. Numerical results

For the sake of easily realizable future experiments, the standard pseudo-thermal source contains a He-Ne laser (632.8 nm), a focal lens (25.4 mm focal length) and a fast-rotating diffusing surface (GG). Focused by the lens, the diameter size of the beam spots on the GG are about 2 mm. A large number of sub sources are produced when the laser beam is projected onto the slowly rotating GG. In any sub sources, all photons have identical positions and momenta, so
the four photons cannot be distinguished in principle if they are emitted from the same sub sources. A pinhole is fixed 800 mm away from the GG to select a small portion of the spatial coherence area (about ~1 mm). The beam can be divided into four daughter beams with equal intensities in the four transmission paths, and the distances between the pinhole and the four single photon detectors are set to have an equal distance of 500 mm. Four single photon detectors measure the instantaneous intensity and count the four-photon coincidences by a coincidence circuit.

From equation (4), we can see that $g^{(4)}(n_1, n_2, n_3, n_4)$ has four independent variables $u_i$. In the first place, we scan $D_2$, $D_3$, and $D_4$ simultaneously and fix $D_1$ at the zero point, and figure 3(a) shows the simulation result. It demonstrated that $g^{(4)}(n_1, n_2, n_3, n_4)$ achieves 24 (its maximum value) when $D_2$, $D_3$, and $D_4$ scanned in the vicinity of the origin (within or on the surface of the ellipsoid $(\lambda \Delta \theta)^2$), and the correlation rapidly decreased from 24 to 0 as $D_2$, $D_3$, and $D_4$ scanned out of the region. According to equation (4), the peak is determined by the sum of two-photon bunching terms ($\Delta g^{(2)}_{12}$, $\Delta g^{(2)}_{13}$, $\Delta g^{(2)}_{14}$, $\Delta g^{(2)}_{23}$, and $\Delta g^{(2)}_{24}$), three-photon bunching terms ($\Delta g^{(3)}_{123}$, $\Delta g^{(3)}_{124}$, $\Delta g^{(3)}_{134}$, and $\Delta g^{(3)}_{234}$), and four-photon bunching terms ($\Delta g^{(4)}_{1234}$). From the principles of quantum mechanics, the four photons cannot be distinguished from each other if $D_2$, $D_3$, and $D_4$ are simultaneously scanned near the origin (they are all in the same phase cell $(\lambda \Delta \theta)^2$), leading to the 24 propagation channels which cannot be distinguished. Therefore, the constructive interference of distinguished propagation channels causes the maximum correlation value. In phenomenology, the physical meaning of the volume of the ellipsoid is the size of the coherent cell in phase space.

Then, we scan $D_3$ and $D_4$ simultaneously and set $D_1$ and $D_2$ at $[-2\lambda \Delta \theta, 2\lambda \Delta \theta]$. As shown in figure 3(b), it demonstrated that the peak (as shown in figure 3(a)) is decomposed into four lower peaks, corresponding to four lower-order spatial correlations. Specifically, the heights of the peaks at $[u_3 = -2\lambda \Delta \theta, u_4 = -2\lambda \Delta \theta]$ is 4, and the peaks at point $[u_3 = -2\lambda \Delta \theta, u_4 = -2\lambda \Delta \theta]$ is equal to 6. We take the peak at $[u_3 = -2\lambda \Delta \theta, u_4 = -2\lambda \Delta \theta]$ as an example. According to equation (4), the peak at $[u_3 = -2\lambda \Delta \theta, u_4 = -2\lambda \Delta \theta]$ is determined by the contribution from $\Delta g^{(2)}_{14}$, $\Delta g^{(2)}_{12}$, $\Delta g^{(2)}_{13}$, and $\Delta g^{(2)}_{23}$. It is just the third-order spatial correlations function among $D_1$, $D_3$, and $D_4$. On the one hand, from the quantum perspective, three photons ($a$, $c$, and $d$) are in the same phase space $[-2\lambda \Delta \theta]$ and are indistinguishable in principle in the coincidence measurement when $D_3$, and $D_4$ scanned at $[u_3 = -2\lambda \Delta \theta, u_4 = -2\lambda \Delta \theta]$. On the other hand, $b$ and $a$ (c and $d$) can be distinguished at the detection plane for the distance between $D_2$ and $D_1$ ($D_3, D_4$) is larger than $\lambda \Delta \theta$. So, the peak at $[u_3 = -2\lambda \Delta \theta, u_4 = -2\lambda \Delta \theta]$ corresponds to the
third-order spatial correlation among D1, D3 and D4. Similarly, at $\lambda \Delta \theta = -u_2/3$, two pairs of photon pairs (a and c) and (b and d) are located in $-2i/\Delta \theta$ and $2i/\Delta \theta$, respectively. So two pairs of photon pairs (a and c) and (b and d) cannot be distinguished at this point. The other two peaks can be explained very well in the same manner. In phenomenology, the $g^{(3)}(n_1, n_2, n_3, n_4)$ can be decomposed into multiple second- and third-order correlation functions if the four-photon probability amplitudes can be distinguished.

Now we concentrate on the properties of the four-photon bunching effect and the role they play in fourth-order correlation measurements. In such numerical simulations, the test detector $u_1$ is fixed at zero point and the transverse coordinate ($u_2, u_3$ and $u_4$) of the three reference detectors can be controlled with two different detection schemes [32]. In the first detection scheme, three reference detectors are scanned along the identical orientation and speed, so that the constraint condition $u_2 = u_3 = u_4$ is always guaranteed. As shown in figure 4(a), it is obvious that the visibility of correlation peak $G^{(4)}$ is ~60%, and the full width at half maximum (FWHM) is ~0.72 mm. In the second detection scheme, D2 and D3 are scanned along opposite orientations but the same speed to make $u_2 = 2u_3 - u_4$ always satisfied. Meanwhile, other D2 and D4 are scanned along the identical orientation, and the speed of D4 is twice that of D2, so that the condition $u_4 = 2u_2 - u_1$ is always satisfied. As shown in figure 4(b), the FWHM decreased to ~0.33 mm and the visibility of the correlation peak of $G^{(4)}$ increases to ~92%, which means both the resolution and visibility have significantly improved when the second detection scheme is adopted.

In the first detection, according to equation (4), the visibility of $g^{(3)}(n_1, n_2, n_3, n_4)$ is determined by the sum of $\Delta g_{12}^{(2)}, \Delta g_{13}^{(2)}, \Delta g_{14}^{(2)}, \Delta g_{123}^{(3)}, \Delta g_{124}^{(3)}, \Delta g_{134}^{(3)}$ and some terms of $\Delta g_{1234}^{(4)}$. In the second detection scheme, however, the extra terms ($g_{23}^{(2)}, g_{24}^{(2)}, g_{34}^{(2)}, g_{234}^{(3)}$ and remaining items in $g_{1234}^{(4)}$) will be introduced for the cross-correlation of three reference detectors. It is precisely the contribution of those extra terms that makes the latter more visible. On the other hand, the narrowing effect about the peak can also be attributed to the sum of the cross-correlation of three reference detectors ($g_{23}^{(2)}, g_{24}^{(2)}, g_{34}^{(2)}, g_{234}^{(3)}$ and remaining items in $g_{1234}^{(4)}$). Compared with the first detection scheme, two kinds of higher spatial resolution function $\sin c [2\pi \Delta \theta (u_2 - u_1)/\lambda]$ and $\sin c [3\pi \Delta \theta (u_2 - u_1)/\lambda]$ are introduced in the second detection scheme, which has a narrower width when $u_2$ is scanned, which means that we can enhance visibility and the resolution.
by scanning $D_2$, $D_3$ and $D_4$ in a way guaranteeing $u_4 = 2u_2 - u_1$ and $u_2 = 2u_1 - u_3$.

In order to intuitively interpret the relationship between four-photon bunching and two- three-photon bunching, as shown in figure 5, we have calculated the four-photon bunching terms ($\Delta g_{1234}^{(4)}$) and the sum of two-photon bunching and three-photon bunching terms ($\Delta g_{12}^{(2)}, \Delta g_{13}^{(2)}, \Delta g_{14}^{(2)}, \Delta g_{23}^{(2)}, \Delta g_{24}^{(2)}, \Delta g_{34}^{(2)}$ and $\Delta g_{1234}^{(3)}$). In the first detection scheme, as shown in figures 5(a) and (b), the contribution from four-photon bunching to the final correlation peak (figure 5(a)) is precisely equal to the sum of the two-photon bunching and three-photon bunching (figure 5(b)), if contribution from the terms ($\Delta g_{12}^{(2)}, \Delta g_{13}^{(2)}, \Delta g_{14}^{(2)}$) to the background are subtracted. For a comparison, we also give the solid curves in figure 5(b) where the contributions to the correlation peak will exceed the sum of all contributions from two-photon bunching and three-photon bunching terms, respectively. As expected, the photon bunching and the sum of two-photon bunching and three-photon bunching terms ($\Delta g_{12}^{(2)}, \Delta g_{13}^{(2)}, \Delta g_{14}^{(2)}$) is much higher than that of $\Delta g_{1234}^{(4)}$ (four-photon bunching). This is very different to the relation between figures 5(a) and (b), where the final correlation peak is exactly equal. The relatively higher peaks are due to the contribution from those cross-correlation fluctuations of the three reference detectors such as $\Delta g_{12}^{(2)}, \Delta g_{13}^{(2)}, \Delta g_{14}^{(2)}$, $\Delta g_{23}^{(2)}, \Delta g_{24}^{(2)}$, $\Delta g_{34}^{(2)}$ and some terms of $\Delta g_{1234}^{(3)}$ must be considered when the second detection scheme is processed.

3. Conclusion

In conclusion, we have theoretically discussed the fourth-order spatial correlation and four-photon bunching properties. We found that the four photons have the maximum correlation of 24 if the four photons all come from the same spatial cell, and the fourth-order spatial correlation can be decomposed into multiple second- and third-order cross-correlation plus the four-photon bunching. In addition, we also show that the contribution from four-photon bunching leads to higher resolution and enhanced visibility in fourth-order ghost imaging. Specifically, the contribution from four-photon bunching to the fourth-order spatial correlation peak is equal to all contributions from two-photon bunching and three-photon bunching in the first detection scheme. On the other hand, the sum of all contributions from two-photon bunching and three-photon bunching to the correlation peak will exceed the contribution from four-photon bunching in the second detection scheme.

Acknowledgments

This work was supported by the 973 Program (2012CB921804), NSFC (61078002, 61078020, 11104214, 61108017, 11104216, 61205112), RFDP (20110201110006, 20110201120005, 20100201120031), FRFCU (2012jdzh05, 2011jdzh07, xjj2011083, xjj2011084, xjj2012080, xjj2013089), and CPSF (2012M521773).

References