Photon interference of second- and third-order correlation generated by two fluorescence sources

Siqiang Zhang¹, Faizan Raza¹, Irfan Ahmed¹², Wei Li¹, Kaichao Jin¹ 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 Physics, City University of Hong Kong, Hong Kong SAR, People’s Republic of China

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

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Abstract

We demonstrate the second- and third-order temporal correlation of two independent pseudo-thermal fluorescence (FL) sources. The two distinguishable sources become indistinguishable following the delay in Feynman’s path. The second- and third-order correlation demonstrates the strong bunching amplitude surrounded by variable oscillations and interfering side bands (beats). Specifically, three-photon bunching is overlapped by two-photon bunching, and further decomposed into multiple lower order correlation functions. Here, the strong interference arises from source and path indistinguishable terms (varying time offset, laser frequency and the bandwidth of FL sources); The support for this idea comes from Feynman’s path integral theory and sub wavelength interference for such kind of sources with appropriate detection schemes. Such phenomena may serve as modulation and carrier for quantum communication channels.

1. Introduction

The correlation and interference phenomenon provide a solid foundation for the establishment and development of the coherence and the quantum theory of light [1]. Dirac considered superposition comes only from the single photon in the single photon interference [2]. But in case of generation of twin/paired photon, a similar statement can be established for interference of two photons, in which superposition comes from jointly measured pair of photon (analogous definition of Dirac) sharing the same energy level such as photons generated from multi-wave mixing (MWM) under phase matching condition [3–5]. However, Paul considered the Dirac’s statement to be limited to first-order coherence [6]. Since then [7, 8], second-order temporal and spatial coherence from two independent sources (coherent, pseudo thermal, laser-photon etc) is extensively studied using ‘Hong-Ou-Mandel (HOM) dip’ or ‘Shih-Alley dip’ interference phenomenon [9–11]. But up to our information till date, no one has come up with third-order temporal coherence from two independent sources of pseudo thermal fluorescence (FL) light. Continuing with the development of second-order coherence, recently, Kim et al observed cosine modulation in the spatial second-order coherence function in a HOM interferometer with entangled photon pairs [9, 12] and self-coherence within the same inputs being essential for the interference. Similarly, Saleh observed beating fringes, a byproduct of interference with frequency mismatch [13, 14]. Based on recent development of the second-order interference between thermal and laser light [15, 16] and concept of sub wavelength interference using join detection schemes, we will study the second- and third-order temporal interference between pseudo thermal fluorescence light sources, which is employed to superposition theory in Feynman’s path integral. The support for this idea comes from unified interpretation of second-order subwavelength interference based on Feynman’s path integral theory from coherent and thermal sources [17–21] or quantum dotted light sources [22, 23] along with their indistinguishability [21, 24]. This study might help to create hope for quantum communication via classical channel.
In this paper we discuss the second- and third-order temporal correlation by treating multi-order fluorescence as two independent pseudo-thermal sources. We analyze two- and three-photon bunching and quantum beating effect at different frequency bandwidth, frequency deference and relative time delay of two sources. Our results demonstrated strong interference effect between two nondegenerate fluorescence sources based on the indistinguishability of different paths.

2. Theoretical model

Figure 1 illustrates the employed joint detection schemes for calculating second- and third-order correlation from two fluorescence sources. Figure 1(a) shows the two sources joint detection system, in which fluorescence source named ‘Sf’ produces two photons named as A and B via beam splitter. Similarly, another source named ‘Sf’ is employed via beam splitter and produces A and B photon. The photon A from both sources can be either detected by detector D1 or D2. Similarly, the photon B from both sources can be detected by either detector D1 or D2. Source and path indistinguishable terms are displayed in figures 1(a2) and 1(a3), respectively. Following these indistinguishable schemes, the coincidence count (CC) will produce second-order temporal correlation or ‘two-photon bunching’ along with interference side peaks or ‘beats’. Such phenomenon mainly depends on the time offset in the detector and frequency of the sources. The third-order temporal correlation or ‘three-photon bunching’ can be obtained by applying detection scheme illustrated in figure 1(b1), here two independent FL sources pass through two beam splitters (BS1 and BS2). The CCC produces the center peak (three-photon bunching) along with multiple interference side peaks (beat frequency) depending on the frequency of the FL sources. The source and path indistinguishability for this detection scheme is illustrated in figures 1(b2) and 1(b3). We can model the intensity of second- and fourth-FL sources using diagonal density matrix elements via their perturbation chains. The fourth-order FL signal can be generated using two input beams in a three level system ($|0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle$). The fourth-order FL signal can be described by the perturbation chain

$$\rho^{(4)}_{00} \to \rho^{(1)}_{00} \to \rho^{(2)}_{00} \to \rho^{(3)}_{00} \to \rho^{(4)}_{00}.$$  

The transition pathways density-matrix element can be written as

$$\rho^{(4)}_{22} = G_1 G_2 / [(\Gamma_{10} + i\Delta_1)\Gamma_{00} + (\Gamma_{20} + i\Delta_2)\Gamma_{22}].$$  

The bandwidth of fourth-order FL signal can be written as

$$\Gamma_{22} = \Gamma_{10} + \Gamma_{20} + \Gamma_{00} + \Gamma_{12}.$$  

![Figure 1](image-url)
3. Interference of second-order correlation

It is surprising that two pseudo-thermal FL sources are interfering due to Feynman’s path integral theory caused by the beam splitter. Following Feynman’s path integral theory, there could be four different cases to trigger two-photon coincidence count, so the second-order interference of FL sources shown in figure 1 (a1) follows the path depicted in figures 1 (a2) and (a3). First case happens when both photons (A and B) come from the SF source following beam splitter. Second case happens when both photons come from SF. In third case photon A comes from SF and photon B comes from Sb. The fourth case is opposite of third case. In the first case, there are two different alternatives to trigger a two-photon coincidence counter, which are A → D1, B → D2 and A → D2, B → D1, respectively. A → D1 is short path for photon, photon A goes to D1 and other symbols are defined similarly. In the second case, both photons are emitted by Sb. Similarly, there should be two alternatives. However, there is only one alternative since these two alternatives are identical. In the third case, there are two alternatives, which are A → D1, B → D2 and A → D2, B → D1, respectively. The fourth case is similar as the third one. Before the Feynman’s path, all photons coming from both sources are distinguishable, once both sources follow Feynman’s path caused by single beam splitter, all photons become indistinguishable along with their alternative paths, therefore one can define the jth detected two-photon probability distribution as [25]

\[
P_j^{(2)}(r_1, t_1, r_2, t_2) = \sum_j P_j^{(2)}(r_1, t_1, r_2, t_2) = \exp\left[ -i(k_{\alpha\beta} \cdot r_{\alpha\beta} - \omega_{\alpha\beta} t_{\alpha\beta}) \right],
\]

where \(\ldots\) is ensemble average by taking all the detected two-photon probability distributions into consideration. The four lines on the right hand side of equation (2) correspond to four different cases mentioned above, respectively. Since the two pseudo-thermal FL sources are independent, then \(\exp\left[ -i(k_{\alpha\beta} \cdot r_{\alpha\beta} - \omega_{\alpha\beta} t_{\alpha\beta}) \right],\) \(\exp\left[ -i(k_{\alpha\beta} \cdot r_{\alpha\beta} - \omega_{\alpha\beta} t_{\alpha\beta}) \right],\) \(\exp\left[ -i(k_{\alpha\beta} \cdot r_{\alpha\beta} - \omega_{\alpha\beta} t_{\alpha\beta}) \right],\) and \(\exp\left[ -i(k_{\alpha\beta} \cdot r_{\alpha\beta} - \omega_{\alpha\beta} t_{\alpha\beta}) \right],\) all terms can be equal to 0. Equation (2) can be simplified as

\[
P_j^{(2)}(r_1, t_1, r_2, t_2) = \exp\left[ -i(k_{\alpha\beta} \cdot r_{\alpha\beta} - \omega_{\alpha\beta} t_{\alpha\beta}) \right],
\]

where \(k_{\alpha\beta}, r_{\alpha\beta}\) and \(\omega_{\alpha\beta}\) are the wave and position vectors of the photon emitted by S\(\alpha\) and detected at D\(\beta\), and \(r_{\alpha\beta}\) is the distance between S\(\alpha\) and D\(\beta\). \(\omega_{\alpha\beta}\) and \(t_{\alpha\beta}\) are the frequency and time for the photon emitted by S\(\alpha\) and detected at D\(\beta\)(\(\alpha = f\) and \(F, \beta = 1\) and 2). Second order correlation between two independent thermal sources can be written as
where $t_{12} = t_1 - t_2$, $\Delta \omega$ and $\omega_i$ (where $i = \text{F}$ for F) represents the bandwidth and frequency of the pseudo-thermal FL source, respectively. The three detectors $D_1$, $D_2$, and $D_3$ are placed at equal distance $r_{ps}$ to observe the photon counting at each individual detector, equation (5) can be simplified by assuming bandwidth of both FL sources to be equal i.e $\Delta \omega_f = \Delta \omega_p = \Delta \omega$, therefore, equation (5) can be simplified as

$$P^{(2)}(t_{12}) \propto 2 + \sin c^{2} \frac{\Delta \omega(t_{1} - t_{2})}{2} [1 - \cos(t_{1} - t_{2})(\omega_f - \omega_p)].$$

From above equation, one can predict that, the term $\cos(t_{1} - t_{2})(\omega_f - \omega_p)$ is responsible for introducing interference caused by frequency beat $(\omega_f - \omega_p)$ and time offset difference $(t_{1} - t_{2})$ caused by path difference hitting coincident counter. If we remove the beam splitter, there will be no interference.

4. Interference of third-order correlation

To observe interference among photons in third-order correlation from two sources, we will employ the scheme illustrated in figure 1 (b). Two independent FL sources are incident on the two beam splitter (BS1 and BS2) and signals are detected at three single photon detectors $D_1$, $D_2$, and $D_3$. The distance between the source and detection planes are all same. For simplicity, the polarization (linear) and intensities of these two FL sources are assumed to be the same. The possible eight combinations of $j$th detected three-photon probability distributions can be written as

$$P_{ij}(t_{12}, t_{23}, t_{3}) = e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3} + e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3} + e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3} + e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3}.$$ (7a)

Here $\varphi_{jA}$, $\varphi_{jB}$ and $\varphi_{jC}$ are the initial phases of photons A, B and C emitted by source $S_j$ in $j$th detected three photon, respectively. There is an extra phase $\pi/2$ for the photon reflected by the beam splitter comparing to that transmitting through the same beam splitter. $K_{i3}$ is short for $K_{i}(t_{23}, t_{3})$, which has same meaning defined in two photon case.

$$P_{ij}(t_{12}, t_{23}, t_{3}) = e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3} + e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3} + e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3} + e^{i(\varphi_{jA} + \pi/2)}K_{i1}e^{i(\varphi_{jB} + \pi/2)}K_{i2}e^{i(\varphi_{jC} + \pi/2)}K_{i3}.$$ (7b)

Similarly, for third-order correlation, $\varphi_{jA}$, $\varphi_{jB}$ and $\varphi_{jC}$ is the initial phase of photons A, B and C emitted by another source $S_j$ in the $j$th detected three photon, respectively. Rest of the definitions remain same.
\[ P_3(h_{12}, t_{23}, h_3) = e^{i(h_{12} + \pi/2)K_{12}} e^{i(h_{23} + \pi/2)K_{23}} e^{i(h_3 + \pi/2)K_3} + e^{i(h_{12} + \pi/2)K_{12}} e^{i(h_{23} + \pi/2)K_{23}} e^{i(h_3 + \pi/2)K_3} + e^{i(h_{12} + \pi/2)K_{12}} e^{i(h_{23} + \pi/2)K_{23}} e^{i(h_3 + \pi/2)K_3} + e^{i(h_{12} + \pi/2)K_{12}} e^{i(h_{23} + \pi/2)K_{23}} e^{i(h_3 + \pi/2)K_3} + e^{i(h_{12} + \pi/2)K_{12}} e^{i(h_{23} + \pi/2)K_{23}} e^{i(h_3 + \pi/2)K_3}. \]
By solving above eight equations (7a)–(7h), third-order correlation function can be written as

\[ p^{(3)}(t_{12}, t_{23}, t_3) = \left\{ \begin{align*} &3 + \sin c^2 \frac{\Delta \omega \phi(t_1 - t_2)}{2} + \sin c^2 \frac{\Delta \omega \phi(t_1 - t_3)}{2} \\
&\quad + \sin c^2 \frac{\Delta \omega \phi(t_2 - t_3)}{2} + 2 \sin c^2 \frac{\Delta \omega \phi(t_2 - t_3)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_1 - t_2)}{2} \cos (t_1 - t_2)(\omega_F - \omega_F) \\
&\quad + 2 \sin c^2 \frac{\Delta \omega \phi(t_1 - t_3)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_3)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_2 - t_3)}{2} \cos (t_2 - t_3)(\omega_F - \omega_F) \\
&\quad + 2 \sin c^2 \frac{\Delta \omega \phi(t_2 - t_3)}{2} \sin c \frac{\Delta \omega \phi(t_2 - t_3)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_3 - t_1)}{2} \cos (t_3 - t_1)(\omega_F - \omega_F) \\
&\quad + 2 \sin c^2 \frac{\Delta \omega \phi(t_3 - t_1)}{2} \sin c \frac{\Delta \omega \phi(t_3 - t_1)}{2} \\
&\quad + \frac{\Delta \omega \phi(t_3 - t_1)}{2} \cos (t_3 - t_1)(\omega_F - \omega_F) \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_1 - t_2)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_2)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_1 - t_3)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_3)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_2 - t_3)}{2} \sin c \frac{\Delta \omega \phi(t_2 - t_3)}{2} \\
&\quad + \frac{\Delta \omega \phi(t_3 - t_1)}{2} \cos (t_3 - t_1)(\omega_F - \omega_F) \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_1 - t_2)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_2)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_1 - t_3)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_3)}{2} \\
&\quad \times \sin c \frac{\Delta \omega \phi(t_2 - t_3)}{2} \sin c \frac{\Delta \omega \phi(t_2 - t_3)}{2} \\
&\quad + \frac{\Delta \omega \phi(t_3 - t_1)}{2} \cos (t_3 - t_1)(\omega_F - \omega_F) \right\} \right\}.
\] (8)

by applying bandwidth condition \((\Delta \omega \phi = \Delta \omega \phi = \Delta \omega)\), above equation can be redefined as

\[ p^{(3)}(t_{12}, t_{23}, t_3) = 2 + \sin c^2 \frac{\Delta \omega \phi(t_1 - t_2)}{2} \left[ 1 + \cos (t_1 - t_2)(\omega_F - \omega_F) \right] \\
+ \sin c^2 \frac{\Delta \omega \phi(t_2 - t_3)}{2} \left[ 1 + \cos (t_2 - t_3)(\omega_F - \omega_F) \right] \\
+ \sin c^2 \frac{\Delta \omega \phi(t_3 - t_1)}{2} \left[ 1 + \cos (t_3 - t_1)(\omega_F - \omega_F) \right] \\
+ \sin c^2 \frac{\Delta \omega \phi(t_1 - t_2)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_2)}{2} \sin c \frac{\Delta \omega \phi(t_1 - t_3)}{2} \\
\times \left[ 1 + \cos (t_1 - t_2)(\omega_F - \omega_F) + \cos (t_2 - t_3)(\omega_F - \omega_F) \right] \\
+ \cos (t_3 - t_1)(\omega_F - \omega_F) \right\},
\] (9)

where \(t_{12} = t_1 - t_2, t_{23} = t_2 - t_3, t_{13} = t_3 - t_1\).

5. Results and discussions

Here, we investigated the second-order temporal intensity correlation by exciting two multi-order pseudo-thermal fluorescence sources on beam splitter (scheme displayed in figure 1(a1)). The FL signals generated from two independent FL sources are divided into two beams using beam splitters (BS1). Two beams following the BS are recorded at detectors (D1 and D2) and then sent to coincidence counter that calculates the second-order correlation \(G^{(2)}(t_{12})\) using equation (6). In figures 2(a1)–(a5), bandwidth of two FL sources \(S_F (\omega_F = 1 \text{ MHz})\) and \(S_F (\omega_F = 2 \text{ MHz})\) are kept equal, and \(t_1\) time offset is fixed at 0 \(\mu\)s. The bandwidth \(\Delta \omega\) of both source \(S_F\) and \(S_F\) is varied from 1 MHz (figure 2(a1)) to 10 MHz (figure 2(a5)). By this consideration, equation (5) is simplified to equation (6). According to equation (6), as we increase the bandwidth of FL sources, the linewidth of correlation changes from broad to sharp as shown in figures 2(a1)–(a5). The transition of correlation line shape from broad to sharp can be explained from change in decoherence rate of FL sources \((\Gamma_{FL} = \Gamma_{10} + \Gamma_{11})\). When bandwidth of FL source is \(\Delta \omega = 1 \text{ MHz}\), decoherence rate \(\Gamma_{11}\) is low which corresponds to broad peak.
when the frequency difference between two pseudo-thermal FL sources $S_f$ and $S_F$ is fixed at $\omega_f - \omega_F = 1\, \text{MHz}$. (b1)–(b5) Calculated correlation function of two photons by increasing bandwidth $\Delta \omega$ of pseudo-thermal FL source from 0 MHz to 10 MHz, when frequency difference between two sources $S_f$ and $S_F$ is fixed at $\omega_f - \omega_F = 8\, \text{MHz}$. (c1)–(c5) Calculated third-order temporal correlation function of three photons by varying bandwidth $\Delta \omega$ from 0 MHz to 10 MHz.

Figure 2. (a1)–(a5) calculated second-order temporal correlation function of two photons by varying bandwidth $\Delta \omega$ of pseudo-thermal FL source from 0 MHz to 10 MHz when the detector $D_s$ is off. The frequency difference between two pseudo-thermal FL sources $S_f$ and $S_F$ is fixed at $\omega_f - \omega_F = 1\, \text{MHz}$. (b1)–(b5) Calculated correlation function of two photons by increasing bandwidth $\Delta \omega$ of pseudo-thermal FL source from 0 MHz to 10 MHz, when frequency difference between two sources $S_f$ and $S_F$ is fixed at $\omega_f - \omega_F = 8\, \text{MHz}$. (c1)–(c5) Calculated third-order temporal correlation function of three photons by varying bandwidth $\Delta \omega$ from 0 MHz to 10 MHz.

In figure 2(a1)) and when $\Delta \omega$ is increased to 10 MHz then decoherence rate $\Gamma_{21}$ increases, which produces sharp correlation peak as shown in figure 2(a5). To study the relationship between bandwidth and oscillation, we increase the frequency $\omega_f$ of source $S_f$ to 10 MHz and increase the bandwidth $\Delta \omega$ of both source $S_f$ and $S_F$ from 1 MHz (figure 2(b1)) to 10 MHz (figure 2(b5)) under the condition $\Delta \omega_f = \Delta \omega_F = \Delta \omega$. Figure 2(b) shows calculated theoretical results of $G^{(2)}(t_{12})$ from equation (6) measured at $t_1$ time offset 0 $\mu$s. The coincidence counter produces the second-order correlation in which the number of the oscillation (sides bands) decreases with increase in FL source bandwidth as displayed in figures 2(b1)–(b5). The amplitude of correlation oscillation precisely follows the bell shape as predicted by equation (6) along with strong indistinguishable oscillations. As we increase the bandwidth of the FL source to 10 MHz, the linewidth of correlation gets narrower, which correspond to same phenomenon of decreasing linewidth of second-order correlation. Similarly, in case of third-order correlation (figure 2(c)) calculated using equation (9), the linewidth of correlation function is determined by $\sin^{-2}[\Delta \omega(t_1 - t_2)]$, when the bandwidth $\Delta \omega$ is set at 1 MHz, the linewidth of correlation signal is broad as demonstrated in figure 2(c1). As $\Delta \omega$ is increased to 10 MHz, linewidth of correlation curve becomes narrow as illustrated in figure 2(c5).

Figure 3(a) shows theoretical results of $G^{(2)}(t_{12})$ from equation (5) for two-photon bunching measured by changing $t_1$ time offset from $-2$ to 2 $\mu$s by fixing bandwidth ($\Delta \omega_f = 5\, \text{MHz}$ and $\Delta \omega_F = 1\, \text{MHz}$) and frequency ($\omega_f = 15\, \text{MHz}$ and $\omega_F = 1\, \text{MHz}$) of FL sources. One can observe that by changing $t_1$ time offset from $-2$ $\mu$s (figure 3(a1)) to 2 $\mu$s (figure 3(a5)), the peak amplitude of correlation curve shifts from $t_1$ time offset $-2$ $\mu$s sensed at coincidence counter. Similarly, third-order correlation $G^{(3)}(t_{123}, t_{13})$ can be calculated using equation (8) under same condition as in figure 3(a). In figure 3(b1), multiple side peaks are observed surrounding the strong center peak. These multiple peaks result from interference between two FL sources governed by the time beat term $[1 - \cos(\theta(t_1 - t_2)(\omega_f - \omega_F))]$ from equation (8). Figures 3(b1)–(b5) demonstrate the strong bunching peak surrounded by variable oscillation with the shifted peak from mean position (0 $\mu$s). This time shifting of strong indistinguishable bunching amplitude with variable side bands suggests the strong interference mechanism of three photons coming from two independent FL sources following Feynman’s path. Here the interference solely depends on the frequency beat $(\omega_f - \omega_F)$ between two FL sources following the Feynman’s path and the time offset $(t_1 - t_2)$ introduced in the detection of photons at $D_1$.

In figure 4, we investigated the second- and third-order correlation of two- and three-photon, respectively, from two FL sources by changing the frequency $\omega_f$ of the once $S_f$ source from 1 MHz (low) to 62 MHz (high) and fixing frequency $\omega_F$ of other source $S_F$ at low that is 1 MHz. One can notice from figures 4(a1)–(a6), as the frequency $\omega_f$ of $S_f$ source is increased, interference generated from source and path indistinguishable terms
increases, which gives rise to side peaks. Mathematically, interference side peaks and central peak amplitude arise from the term \[1 - \cos(t_1 - t_2)(\omega_f - \omega_p)\] and \[\sin^2[\Delta \omega(t_1 - t_2)/2]\] of equation (5), respectively [26, 27]. However, the number of side peak precisely depends on the difference of frequencies (beat) among the FL sources i-e \[1 - \cos(t_1 - t_2)(\omega_f - \omega_p)\]. The same phenomenon is observed in third-order correlation function. As \(\omega_f\) increases to 62 MHz, oscillation factor in equation (8) i-e \[1 + \cos(t_1 - t_2)(\omega_f - \omega_p) + \cos(t_2 - t_3)(\omega_f - \omega_p) + \cos(t_1 - t_3)(\omega_f - \omega_p)\], presenting positive correlation with interference, their amplitude and linewidth precisely follow the shape as in second-order correlation. As the frequency of the FL source is further increased, the bunching effect and strong interference are observed as shown in figures 4(b1)–(b6). From figures 4(b1)–(b3) and (a1)–(a3), the bunching dominates due to very small oscillation factor which results from small frequency difference \(\omega_f - \omega_p\) at the condition of low frequency \(\omega_f\). Whereas at high frequency \(\omega_f\) of input FL source the interference increases dramatically as shown in figures 4(a3)–(a6) and (b3)–(b6). Based on these observations, one can conclude that beating is strongly dependent on frequency difference of FL sources.

At present, our group is conducting the experimental research on second- and third-order correlation in atomic-like ensemble. In addition to the work presented in current paper, we have investigated the third-order correlation coming from nonlinear interaction among three multi-order fluorescence signals generated from a pseudo-thermal source [28]. Also, we have demonstrated the third-order correlation (resulting from path indistinguishability) of single multi-order fluorescence signal generated from a pseudo-thermal light source [29]. Currently, we are exploring the second- and third-order correlation from two and three independent pseudo-thermal fluorescence sources experimentally in our lab but the experiments are still in its initial stages.
6. Conclusion

In conclusion, we demonstrated the second- and third-order correlation from two independent pseudo-thermal fluorescence (FL) sources. The correlation curves demonstrated strong bunching amplitude and beats. Three-photon bunching was overlapped by two-photon bunching, and was decomposed further into multiple lower order correlation functions. The interference generated from source and path indistinguishability was recorded at joint detection scheme. By controlling time offset in joint triggering, photon bunching can be controlled. By increasing frequency of one SF source from 1 to 62 MHz, interference among photons also increases significantly. We believed that the results presented in our manuscript may have potential applications in quantum communication through classical channel through beating effect.

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ORCID iDs

Yanpeng Zhang @ https://orcid.org/0000-0002-0954-7681

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