Physics Letters A 380 (2016) 684–688

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Second-order spatial correlation in the far-field: Comparing entangled and classical light sources

Erfeng Zhang *, Weitao Liu, Huizu Lin, Pingxing Chen

College of Science, National University of Defense Technology, Changsha 410073, PR China

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 11 December 2015
Accepted 13 December 2015
Available online 17 December 2015
Communicated by A. Eisfeld

Keywords:
Coherence
Photon statistics and coherence theory
Foundations of quantum mechanics
Measurement theory

ABSTRACT

We consider second-order spatial correlation with entangled and classical light in the far-field. The quantum theory of second-order spatial correlation is analyzed, and the role of photon statistics and detection mode in the second-order spatial correlation are discussed. Meanwhile, the difference of second-order spatial correlation with entangled and classical light sources is deduced.

1. Introduction

Quantum optics was considered to be born in 1956 with the work of Hanbury Brown and Twiss [1,2]: To measure the diameters of stars, they measured the cross-correlations in the photocurrent fluctuations recorded by two separated detectors. Such phenomenon can be explained by the classical theory with the fluctuating electric field. Meanwhile, Glauber proposed quantum formulation of optical coherence theory in 1963 which can explain the phenomenon of Hanbury Brown–Twiss (HBT) experiments [3,4].

As a hot aspect of quantum coherence theory in recent years, second-order spatial correlation attracts more and more attentions due to its novel physical peculiarities, and many potential applications in practice, such as ghost imaging, ghost interference and so on [5–14]. In 1995, the second-order spatial correlation effect was observed experimentally using entangled photon pairs generated by spontaneous parametric down-conversion (SPDC) [5,6]. Later, the second-order cross-correlation of entangled light source with a large number of photons was formulated [7]. Then, Abouraddy et al. discussed the role of entanglement in second-order spatial correlation, and found that entanglement is a prerequisite for achieving the spatial correlation effect [8]. However, it was soon discovered that second-order spatial correlation can also be achieved with some classical light sources, and many features of the spatial correlation with entangled light can be mimicked by these classical light sources [9–14]. Meanwhile, the difference in the fundamental physics of second-order spatial correlation with entangled and classical light sources is still a very lively debate [15–18].

Recently, the spatial correlation effects of statistically independent light sources have been studied [19–21]. In this paper we consider second-order spatial correlation of statistically dependent and independent light sources, entangled and classical light, in the far-field with the configurations described in Refs. [19–21]. Based on the quantum coherence theory, second-order spatial correlation of entangled and classical light is studied. The difference of second-order spatial correlation in the far-field with different light sources: entangled and classical light is analyzed. In addition, as a key issue of second-order correlation function, the difference of the visibility in second-order correlation functions with entangled and classical light sources is deduced, and the effects influencing the visibility are analyzed. These analytical results will contribute to understand the difference of second-order spatial correlation with entangled and classical light sources.

2. Second-order correlation function with entangled and classical light

In this section, we consider M identical sources located at positions $\vec{R}_1$ to $\vec{R}_M$ as shown in Fig. 1. Two detectors measure the light field at the Fourier plane of the light source, then the electric field at position $\vec{r}_N$ $(N = 1, 2)$ can be written as

* Corresponding author.
E-mail address: efzhang@163.com (E. Zhang).

http://dx.doi.org/10.1016/j.physleta.2015.12.014
0375-9601/

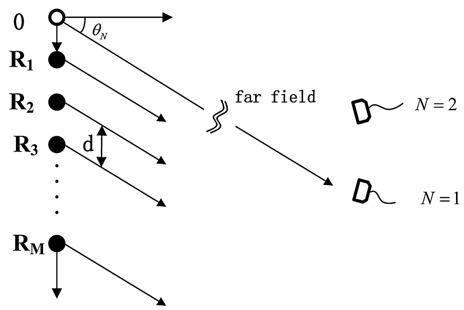

Fig. 1. Setup to measure second-order spatial correlation in the far-field. M identical sources are located at positions $\vec{R}_1$ to $\vec{R}_M$, and separated by a distance d. Two detectors measuring the photons scattered by the light sources are located at positions $\vec{r}_1$ and $\vec{r}_2$ in the far-field, respectively.

$$E_N^{(+)}(\vec{r}_N) \propto \sum_{m=1}^{M} e^{i\phi_{mN}} a_m, \tag{1}$$

where a_m denotes the annihilation operator at the position $\vec{R}_m$, and ϕ_{mN} denotes the optical phase accumulated by a photon emitted at $\vec{R}_m$ $(m = 1, 2, \cdots, M)$ and the position $\vec{r}_N$ relative to a photon emitted at the origin:

$$\phi_{mN} = -k\frac{\vec{r}_N \cdot \vec{R}_m}{r_N} = -mkd\sin\theta_N, \tag{2}$$

where k denotes the wave vector of the light source. In this situation, second-order correlation function in the far-field can be obtained [3,4]:

$$G(\vec{r}_1, \vec{r}_2) = \mathrm{Tr}[\rho E_1^{(-)}(\vec{r}_1) E_2^{(-)}(\vec{r}_2) E_2^{(+)}(\vec{r}_2) E_1^{(+)}(\vec{r}_1)], \tag{3}$$

where ρ denotes the density matrix describing the M sources.

2.1. Quantum description of entangled and classical light

The starting point of our analysis is the quantum description of entangled and classical light sources. The state of entangled light is considered as a pure state [7]:

$$|\psi\rangle_e = \prod_{m=1}^{M} \sum_{n=0}^{\infty} c_n |n, \vec{R}_m\rangle_S |n, \vec{R}_m\rangle_I, \tag{4}$$

where the subscript e denotes entangled light, $|n, \vec{R}_m\rangle_{S/I}$ is the Fock state with n photons at point $\vec{R}_m$ of the beam S/I, and c_n is the probability amplitude of Fock state with n photons. In the entangled light case, we consider two situations: (1) The beams S and I are in different polarizations, and the light from entangled light source is divided into two beams with different polarizations. Then, the two detectors detect the photons of the two beams with different polarizations; (2) The beams S and I are in the same polarizations, and the light from entangled light source is divided into two beams, measured by two detectors. Meanwhile, the state of classical light can be described as a mixed state [22]:

$$\rho_c = \prod_{m=1}^{M} \sum_{n=0}^{\infty} p_n |n, \vec{R}_m\rangle\langle n, \vec{R}_m|, \tag{5}$$

where the subscript c denotes classical light, and p_n is the probability of the Fock state with n photons $|n, \vec{R}_m\rangle$.

2.2. Second-order correlation function in the far-field

The physical picture of second-order correlation function in the far-field can be explained by the two-photon quantum paths [23,24]. It can be obtained from Eq. (1) that each of the two detectors measures a photon which has been scattered from any of the M identical sources. Thus, we can obtain M^2 two-photon quantum paths which is shown in Fig. 2. Furthermore, we can sort the M^2 two-photon quantum paths to two different types: a. the two photons are scattered by only one light source, which leads to the M quantum paths in the first line of Fig. 2; b. the two photons are emitted by two different light sources, corresponding to the $M(M-1)$ quantum paths depicted in the second line of Fig. 2. Given an initial state, there are two basic rules for calculating the second-order spatial correlation function: 1. If the two-photon quantum paths processes lead to the same final states, then these processes are indistinguishable. To obtain the probability, one must add the probability amplitudes of these processes and take the absolute square. 2. If the processes lead to different final states, then these processes are distinguishable. The probability can be obtained to add the probabilities of these processes.

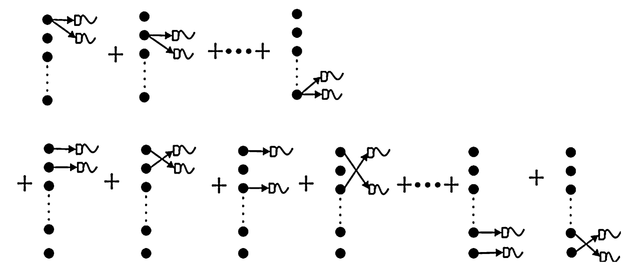

Fig. 2. Schematic representation for the two-photon quantum paths of the M identical sources. There are two types of two-photon quantum paths: a. the first line, the two photons are scattered by only one light source; b. the second line, the two photons are emitted by two different light sources.

In the situation of entangled light, second-order correlation function in the far-field can be written as

$$\begin{aligned} G_e(\vec{r}_1, \vec{r}_2) &= \left| E_1^{(+)}(\vec{r}_1) E_2^{(+)}(\vec{r}_2) |\psi\rangle_e \right|^2 \\ &\propto \left| \sum_{m=1}^{M} e^{i(\phi_{m1}+\phi_{m2})} a_m^S a_m^I |\psi\rangle_e \right|^2 \\ &\quad + \left| \sum_{\substack{m,j=1 \\ m\neq j}}^{M} e^{i(\phi_{m1}+\phi_{j2})} a_m^S a_j^I |\psi\rangle_e \right|^2, \end{aligned} \tag{6}$$

where the first term in the right hand of Eq. (6) gives the M quantum paths depicted in the first line of Fig. 2, and the second term is the $M(M-1)$ quantum paths depicted in the second line of Fig. 2. In the situation that the beams S and I of entangled light are in different polarizations, the two detectors detect the photons of the two beams with different polarizations, then we can obtain

$$\begin{aligned} G_{ed}(\vec{r}_1, \vec{r}_2) \propto{}& [M^2 K(\phi_{11}+\phi_{12}) - M] \cdot \left| \sum_{n=0}^{\infty} c_n^* c_{n+1}(n+1) \right|^2 \\ &+ M\langle n^2\rangle_e + M(M-1)\langle n\rangle_e^2, \end{aligned} \tag{7}$$

where the subscript ed denotes entangled light with the two beams in different polarizations, and $\langle n^q\rangle_e, (q = 0, 1, 2, \cdots)$ denotes $\sum_{n=0}^{\infty} n^q |c_n|^2$. Moreover, the function $K(\phi_{11}+\phi_{12})$ is an anti-correlation term:

$$K(\phi_{11}+\phi_{12}) = \frac{\sin^2[M(\phi_{11}+\phi_{12})/2]}{M^2\sin^2[(\phi_{11}+\phi_{12})/2]}. \tag{8}$$

However, when the beams S and I of entangled light are in the same polarizations, the two detectors detect the photons with the same polarizations, it results to