Observation of Anticorrelation with Classical Light in a Linear Optical System

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Two-photon anticorrelation is observed when laser and pseudothermal light beams are incident to the two input ports of a Hong-Ou-Mandel interferometer, respectively. The spatial second-order interference pattern of laser and pseudothermal light beams is reported. Temporal Hong-Ou-Mandel dip is also observed when these two detectors are at the symmetrical positions. These results are helpful to understand the physics behind the second-order interference of light.

Ever since the second-order interference of light was first observed by Hanbury Brown and Twiss (HBT) in 1956 [1], it has been an important tool to study the properties of light [2]. The second-order interference of light has been studied with photons emitted by different kinds of sources, such as entangled photon pair source [3], two independent single-photon sources [4–6], laser and single-photon source [7], laser and entangled photon pair source [8], two lasers [9–11], two thermal sources [12–17], etc. Many interesting results were obtained from those studies. For instance, Hong et al. were able to measure the time separation between two photons with time resolution millions of times shorter than the resolution of the detector and the electronics [3–15]. Pittman et al. got the ghost image of an object with entangled photon pairs [16]. Bennett et al. observed Hong-Ou-Mandel (HOM) dip by feeding photons emitted by single-photon source and laser into the two input ports of a HOM interferometer, respectively [7]. The second-order interference of photons coming from laser and thermal light beams seems to have not been studied, in which, something interesting may happen. In this letter, we will experimentally study the second-order interference of laser and pseudothermal light beams in a HOM interferometer, where two-photon anticorrelation and temporal HOM dip are observed when these two detectors are at the symmetrical positions.

Two-photon anticorrelation is defined as the two-photon coincidence count probability is less than the accidental two-photon coincidence count probability, which is equal to the product of these two single-photon probabilities [20]. It is convenient to employ the normalized second-order coherence function or the degree of second-order coherence [21],

\[ g^{(2)}(r_1,t_1;r_2,t_2) = \frac{G^{(2)}(r_1,t_1;r_2,t_2)}{G^{(1)}(r_1,t_1)G^{(1)}(r_2,t_2)}, \]

(1)

to discuss the second-order correlation of light. Where \( G^{(2)}(r_1,t_1;r_2,t_2) \) is the second-order coherence function at space-time coordinates \((r_1,t_1)\) and \((r_2,t_2)\). \( G^{(1)}(r_1,t_1) \) and \( G^{(1)}(r_2,t_2) \) are the first-order coherence functions at \((r_1,t_1)\) and \((r_2,t_2)\), respectively [22]. When \( g^{(2)}(r_1,t_1;r_2,t_2) \) is greater than 1, these two photon detection events are correlated. When \( g^{(2)}(r_1,t_1;r_2,t_2) \) is equal to 1, these two events are independent. When \( g^{(2)}(r_1,t_1;r_2,t_2) \) is less than 1, these two events are anticorrelated. In our experiments, we are able to observe two-photon anticorrelation when these two single-photon detection events are at the same space-time coordinate in a HOM interferometer, which can be expressed mathematically as \( g^{(2)}(0) < 1 \).

The experimental setup is shown in Fig. 1. A single-mode continuous wave laser with central wavelength at 780 nm and frequency bandwidth of 200 kHz is divided into two equal portions by a non-polarized beam splitter (BS1). One beam is incident to a rotating ground glass (RG) after passing through a convex lens (L1) to simulate thermal light [12]. The other beam is expanded by another identical lens (L2) to ensure that the intensity of the laser beam is approximately constant across the measurement range. The focus lengths of L1 and L2 are both 50 mm. The distance between L1 and RG is 83 mm. The distances between the lens and detector planes all equal 825 mm.

The measured normalized second-order coherence functions of laser and pseudothermal light beams in a HOM interferometer are shown by the blank squares in Fig. 2(b), where a periodic modulation of the second-order coherence function is obvious. \( x_1 - x_2 \) is the transverse relative position of these two detectors and \( g^{(2)}(x_1 - x_2) \) is the normalized second-order coherence function when these two detectors are at \( x_1 \) and \( x_2 \), respectively. The red line is theoretical fitting of the experimental results by employing Eq. (1) in the following. All the experimental results in Fig. 2 are measured by scanning the transverse position of D1 while keeping the position of D2 fixed. The measurement time for each dot is 120 s. The temporal second-order coherence length of the pseudothermal light is 90.8 µs and the two-photon coincidence time window is 12.2 ns. The diameter of the collecting single-mode fiber is 5 µm, which is much less than the pseudothermal light spatial second-order coher-
ence length, 1.37 mm. The intensities of the laser and pseudothermal light beams at the two input ports of the HOM interferometer are set to be equal. It is obvious that \( g^{(2)}(0) < 1 \) is observed in Fig. 2(b).

In order to confirm two-photon anticorrelation is observed when these two detectors are at the symmetrical positions, we have measured the spatial second-order coherence function of pseudothermal light by blocking the laser light in our experiments. It is well-known that the second-order coherence function of thermal light in a HBT interferometer will get its maximum when these two detectors are at the symmetrical positions [1]. Comparing the second-order coherence function in Fig. 2(b) with the one of pseudothermal light in Fig. 2(a), which is shown by the red circles, it is obvious that two-photon anticorrelation in Fig. 2(b) is observed when these two detectors are at the symmetrical positions. We also measure the spatial second-order coherence function of laser light in a HBT interferometer, which is shown by the black squares in Fig. 2(a). The measurements confirm that two photon detection events of single-mode continuous wave laser in a HBT interferometer are independent [22].

In order to study how \( g^{(2)}(0) \) changes with the ratio between the intensities of thermal and total light beams, we also measure \( g^{(2)}(0) \) when the laser and pseudothermal light beams have different intensities. The experimental parameters are the same as the ones above except the temporal second-order coherence length is shortened to be 8.6 ns by enlarging the size of the laser beam on the ground glass. The results are shown in Fig. 3, where \( P_t \) is the ratio between the intensities of thermal and total light beams. The red curve is theoretical fitting of the experimental results by employing Eq. (5), where only the last constant is changeable in the fitting process. The value of the measured \( g^{(2)}(0) \) changes between 0.74 and 1.99 as the ratio changes, which means these two photon detection events can be correlated, independent or anticorrelated.

Figure 4 shows the two-photon coincidence counts vary with time difference of these two photon detection events when \( g^{(2)}(0) \) gets its minimum in Fig. 3. CC is two-photon coincidence count for 270 s and \( t_1 - t_2 \) is the time difference between these two single-photon detection events within a two-photon coincidence count. It is obvious that two-photon coincidence count gets its minimum when \( t_1 \) equals \( t_2 \). As the value of \( |t_1 - t_2| \) increases, the coincidence count increases and finally becomes a constant when the time difference exceeds the second-order temporal coherence length of pseudothermal light.

Both classical and quantum theories can be employed to interpret our experimental results [22, 23]. We will employ two-photon interference theory to interpret our experiments, for light is intrinsically quantum mechanical and quantum theory is valid for both classical and nonclassical light [24]. If the same method is employed to interpret the same experiment with classical and nonclassical light, for instance, the interference of thermal light beams and of entangled photons in a HOM interferometer, one may get a unified interpretation, which might be helpful to understand the physics behind.

There are three different ways for two photons to trig-
order coherence function in Fig. 1 can be expressed as the other photon comes from laser light. The second way is a photon comes from pseudothermal light and the last way is both photons come from pseudothermal light. The second-order spatial coherence function of thermal light is

\[ g_2^{(2)} = g_2^{(2)}(r_1, t_1; r_2, t_2) = \frac{P_2^2}{P_1^2} \left( \frac{1}{P_1^2} \right) \left( A_{a1, l_1} + A_{a2, l_2} \right)^2 \]

where \( P_1 \) and \( P_2 \) are the probabilities of the detected photon coming from pseudothermal and laser light beams, respectively. It is same as the HOM dip in Ref. [18] except the difference increases, CC increases and finally becomes a constant. It is same as the HOM dip in our experiments. The visibility is 13.50% in our experiments.

FIG. 3: Anticorrelation. \( g_2^{(2)}(0) \) is the normalized second-order coherence function when these two single-photon detection events are at the same space-time coordinate in a HOM interferometer. \( P_t \) is the ratio between the intensities of the thermal light and total light beams. The red line is the theoretical curve of \( 3P_t^2 - 2P_t + 1.09 \). Please see text for detail.

FIG. 4: Temporal HOM dip. CC is two-photon coincidence count for 270 s and \( t_1 - t_2 \) is time difference between these two photon detection events within a two-photon coincidence count. When \( t_1 \) equals \( t_2 \), CC gets its minimum. As time difference increases, CC increases and finally becomes a constant. It is same as the HOM dip in Ref. [18] except the visibility is 13.50% in our experiments.

\[ g_2^{(2)}(x_1, x_2) = P_1^2 \left[ \frac{1}{P_1^2} \right] A_{a1, l_1} A_{a2, l_2} \left[ \frac{1}{P_1^2} \right] \left[ \frac{1}{P_1^2} \right] \]

With similar calculations as the one in Refs. [17, 20, 27], it is straightforward to get the normalized spatial second-order coherence function as

\[ g_2^{(2)}(x_1, x_2) = \left[ \frac{1}{P_1^2} \right] A_{a1, l_1} A_{a2, l_2} \left[ \frac{1}{P_1^2} \right] \left[ \frac{1}{P_1^2} \right] \]

where the temporal part has been ignored and one-dimensional case is calculated for simplicity. \( L_t \) is the diameter of pseudothermal light source and \( L_l \) is the diameter of laser light in the same plane as pseudothermal light source. \( \lambda \) is the central wavelength of the laser. \( z \) is the distance between the source and detector planes. \( d \) is the transverse distance between the midpoints of the pseudothermal light source and the image of the laser light source in the ground glass plane by BS2. The first term on the right-hand side of Eq. (3) corresponds to two photons both come from pseudothermal light. \( P_1^2 \) is the probability and the left part of this term is a typical second-order spatial coherence function of thermal light. The second term corresponds to both photons come from laser light. It expresses like this is due to \( g_2^{(2)}(x_1, x_2) \) always equals 1 for single-mode continuous wave laser in a
HBT interferometer. The third term corresponds to one photon comes from laser light and the other one comes from pseudothermal light. There is a cosine modulation of the second-order coherence function, which is a result of the second-order interference between laser and pseudothermal light.

$L_t$ equals $L_l$ in our experiments, for the distances between the lens and detection planes are all the same. When the intensities of these two beams are equal, Eq. (3) can be simplified as

\[ g^{(2)}(x_1, x_2) = 1 + \frac{1}{4} \sin^2 \frac{\pi L}{\lambda z} (x_1 - x_2) \]

\[ - \frac{1}{2} \cos \frac{2\pi d}{\lambda z} (x_1 - x_2) \sin \frac{2\pi L}{\lambda z} (x_1 - x_2), \]

where $L$ equals $L_t$ and $L_l$, respectively. It is easy to see $g^{(2)}(0) = 0.75$ from Eq. (1).

We can further calculate how $g^{(2)}(0)$ changes with the ratio between the intensities of pseudothermal and total light beams. Substituting $P_l = 1 - P_t$ and $x_1 = x_2$ into Eq. (3), it is straightforward to get

\[ g^{(2)}(0) = 3P_t^2 - 2P_t + 1. \]

When $P_t$ equals 1/3, $g^{(2)}(0)$ gets its minimum, 2/3, which is obviously less than 1.

Comparing the spatial second-order interference pattern of laser and pseudothermal light beams in Fig. 2(b) with the interference pattern of two pseudothermal light beams in a HOM interferometer in Ref. [17], these two interference patterns are similar and they will get their minimums when these two detectors are at the symmetrical positions, respectively. However, there is an important difference between these two situations. It is predicted [28] and experimentally verified [17, 29] that $g^{(2)}(0)$ equals 1 for two thermal light beams in a HOM interferometer. This conclusion is true no matter what is the ratio between the intensities of these two input thermal light beams. While in the case of interference of laser and pseudothermal light beams, $g^{(2)}(0)$ can get the value in the domain of [2/3, 2] for different ratios between the intensities of the pseudothermal and total light beams. When $P_t$ is in the region of (0, 2/3), $g^{(2)}(0)$ is less than 1 and these two photon detection events are anticorrelated. When $P_t$ equals 2/3, $g^{(2)}(0)$ equals 1 and these two events are independent. When $P_t$ is in the region of (2/3, 1), $g^{(2)}(0)$ is greater than 1 and these two photon detection events are correlated.

There is one more thing we would like to point out. Although we have observed $g^{(2)}(0) < 1$ and $g^{(2)}(\tau) < g^{(2)}(\tau)$ ($\tau = t_1 - t_2$ and $\tau \neq 0$) in our experiments, it does not mean we have observed sub-Possion distribution or photon antibunching. Sub-Possion distribution and photon antibunching are defined as $g^{(2)}(0) < 1$ and $g^{(2)}(0) < g^{(2)}(\tau)$ in a HBT interferometer, respectively.

These two effects can only be observed with non-classical light. $g^{(2)}(0) < 1$ and $g^{(2)}(0) < g^{(2)}(\tau)$ observed in our experiments are in a HOM interferometer. These two interferometers are different. Therefore, the experimental results in our experiments do not satisfy the definitions of sub-Possion distribution or photon antibunching.

In conclusion, we have observed the spatial second-order interference pattern of laser and pseudothermal light beams in a HOM interferometer, in which, two-photon antcorrelation is observed when these two detectors are at the symmetrical positions. Further more, temporal HOM dip is also observed when these two detectors are at the symmetrical positions. The theoretical interpretations based on two-photon interference theory agree with the experimental results very well. Two-photon antibunching with laser and pseudothermal light in a HOM interferometer can be interpreted by the destructive two-photon interference, which is the same interpretation as two-photon anticorrelation with entangled photon pairs in a HOM interferometer.

References

[1] R. Hanbury Brown, and R. Q. Twiss, Nature (London) 177, 27 (1956); 178, 1046 (1956).
[2] L. Mandel and E. Wolf, Optical Coherence and Quantum Optics (Cambridge University Press, Cambridge, U.K., 1995).
[3] L. Mandel, Rev. Mod. Phys. 71, S274 (1999).
[4] J. Beugnon, M. P. A. Jones, J. Dingjan, B. Darquié, G. Messin, A. Browaeys, and P. Grangier, Nature (London) 2006, 779 (2006).
[5] R. Kaltenbaek, B. Blauensteiner, M. Żukowski, M. Aspelmeyer, and A. Zeilinger, Phys. Rev. Lett. 96, 240502 (2006).
[6] P. Maunz, D. L. Moehring, S. Olmschenk, K. C. Younge, D. N. Matsukevich, and C. Monroe, Nature Phys. 3, 538 (2007).
[7] A. J. Bennett, R. B. Patel, C. A. Nicoll, D. A. Ritchie, and A. J. Shields, Nature Phys. 5, 715 (2009).
[8] I. Afek, O. Ambar, and Y. Silberberg, Science 328, 879 (2010).
[9] R. L. Pfleegor and L. Mandel, Phys. Rev. 159, 1084 (1967).
[10] R. Kaltenbaek, J. Lavoie, D. N. Biggerstaff, and K. J. Resch, Nature Phys. 8, 864 (2008).
[11] J. B. Liu and G. Q. Zhang, Opt. Commun. 284, 2658 (2011).
[12] W. Martienssen, and E. Spiller, Am. J. Phys. 32, 919 (1964).
[13] Z. Y. Ou, E. C. Gage, B. E. Magill, and L. Mandel, J. Opt. Soc. Am. B 6, 100 (1989).
[14] Y. H. Zhai, X. H. Chen, and L. A. Wu, Phys. Rev. A 74, 053807 (2006).
[15] A. Nevet, A. Hayat, P. Ginzburg, and M. Orenstein, Phys. Rev. Lett. 107, 253601 (2011).
[16] H. Chen, T. Peng, S. Karmakar, Z. D. Xie, and Y. H. Shih, Phys. Rev. A 84, 033835 (2011).
[17] J. B. Liu, Y. Zhou, W. T. Wang, R. F. Liu, K. He, F. L. Li, and Z. Xu, Opt. Express 16, 19209 (2013).
[18] C. K. Hong, Z. Y. Ou, L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).
[19] T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko, Phys. Rev. A 52, R3429 (1995).
[20] P. Graingier, G. Roger, and A. Aspect, Europhys. Lett. 1, 173 (1986).
[21] R. Loudon, The Quantum Theory of Light (3rd ed.) (Oxford Univ. Press, 2001).
[22] R. J. Glauber, Phys. Rev. 130, 2529 (1963); 131, 2766 (1963).
[23] E. C. G. Sudarshan, Phys. Rev. Lett. 10, 277 (1963).
[24] J. H. Shapiro and R. W. Boyd, Quantum Inf. Process, doi:10.1007/s11128-011-03656-5
[25] R. P. Feynman, and A. R. Hibbs, Quantum Mechanics and Path Integrals (McGraw-Hill, Inc., 1965).
[26] J. B. Liu, Y. Zhou, W. T. Wang, F. L. Li, and Z. Xu, submitted for publication (2013).
[27] Y. H. Shih, An Introduction to Quantum Optics: Photons and Biphoto Physics (CRC Press, 2011).
[28] S. Olivares and M. G. A. Paris, Phys. Rev. Lett. 107, 170505 (2011).
[29] G. Brida, I. P. Degiovanni, M. Genovese, A. Meda, S. Olivares, and M Paris, Phys. Scr. T153, 014006 (2013).

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