High-order Ghost Imaging of Reference Beam

Anning Zhang (张安宁)[1,2*], Wenping Li (李文萍)[1], Lianjie Zhao (赵连洁)[1], Hui Ye (叶 惠)[2], Yan Liu (刘 延)[2], Xiaogang Wei (魏小刚)[1], and Zenbin Wang (王增斌)[1]

[1]*Beijing Institute of Aerospace Control Devices, Beijing 100854, China*

[2]*Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, and Institute of Physics and Department of Physics, Hunan Normal University, Changsha 410081, China*

**Corresponding author: anzhang@hunnu.edu.cn*

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In this letter, we focus on the high-order quantum image of reference beam. We successfully reduce the noise of reference beam, and achieve a clear high-order quantum image of reference beam. The experimental results convince that the more information from the reference beam, the better visibility will be achieved.

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In 1995, Pittman *et al.* demonstrated the first ghost image experiment used entangled photon pairs[1]. In 2002, Bennink *et al.* reported an experiment in which a demonstrably classical-state source yielded a ghost image[2]. Valencia *et al.*[3] demonstrated pseudo-thermal light ghost image that laser light rendered spatially incoherent by passing through a rotating ground glass. Nowadays, the pseudo-thermal light ghost image has attracted a lot of attention due to its potential practical applications[4−13] as well as the interpretation of its underlying physical process[14−23]. However, the pseudo-thermal light ghost image always lies on a noisy background and not exceed one-third visibility. Recently, high-order intensity correlations have been utilized to improve the contrast of a thermal ghost image[24−32]. Chen *et al.* demonstrated the high-order ghost imaging with pseudo-thermal light[31]. In Ref. [31], the visibility of $g^{n,1}$ image is enhanced,but the image $g^{1,m}(m > 1)$ is even worse in the experiment. Theorists also discussed the ghost imaging visibility by the third-order correlation and forth-order correlation[24−26], and the visibility of $g^{1,m}(m > 1)$ image can also be enhanced.

In this letter, we focus on the high-order ghost image of reference beam. We find a way to normalize the noise of the reference beam and show a more clear $g^{1,m}(m > 1)$ high-order ghost image than previous work. We experimentally demonstrate the visibility of $g^{1,m}(m > 1)$ image can be enhanced as the same trend as $g^{n,1}(n > 1)$ case.

In a Nth-order intensity correlation measurement, the thermal light beam is divided into N parts, each of which passes through an optical system and then is registered by a detector. The Nth-order intensity correlation function g^N is given by

$$g^N(x_1, \cdots, x_N) = \frac{\langle I_1(x_1) \cdots I_N(x_N)\rangle}{\langle I_1(x_1)\rangle \cdots \langle I_N(x_N)\rangle}, \qquad (1)$$

where $I_j(x_j)$ is the instantaneous intensity at the transverse position x_j, and I_j also is the instantaneous intensity at the detector j in our high-order ghost image experiment. $\langle\cdots\rangle$ stands for ensemble averaging.

In our experiment, we use a conventional lensless pseudo-thermal ghost imaging setup shown in Fig. 1. The pseudo-thermal light is generated by a rotating ground glass plate. The BE is a beam Expander which used to control the speckle size on the rotating ground glass plate.

Then, pseudo-thermal light passes through an ordinary beam splitter. One output from the beam splitter illuminates a slit followed by a bucket detector charge-coupled device (CCD1), while the other output is detected directly by a camera (CCD2). In our experiment, we use CCD1 as the bucket detector detects n beams of one intensity distribution passing though the slit. That is to say, we envisage that the n object beams have the same instantaneous intensity. And for the instantaneous intensity of all object beams,we have $I_1(x_1) = I_2(x_2) = \cdots = I_n(x_n) = I_{\rm B}$, which $I_{\rm B}$ is the instantaneous intensity at the bucket detector CCD1. B is an abbreviation of the bucket detector.

Moreover, we assume that the $N - n$ reference beams also have the same instantaneous intensity. And for the instantaneous intensity of all reference beams, we have $I_{n+1}(x_{n+1}) = I_{n+2}(x_{n+2}) = \cdots = I_N(x_N) = I_{\rm c}$, which $I_{\rm c}$ is an instantaneous variable intensity detected by one pixel in CCD2. And $I_{\rm c}(x, y)$ is the intensity distribution at CCD2. C is an abbreviation of the Camera.

Then, the Nth-order intensity correlation function g^N is simplified as

$$g^{n,N-n}(B, C(x, y)) = \frac{\langle I_{\rm B}^n I_{\rm c}^{N-n}(x, y)\rangle}{\langle I_{\rm B}\rangle^n \langle I_{\rm c}(x, y)\rangle^{N-n}}, \qquad (2)$$

where $g^{n,N-n}(B, C(x, y))$ is the Nth-order intensity correlation for a bucket detector and CCD2. In this letter, $g^{n,N-n}$ is the abbreviation for $g^{n,N-n}(B, C(x, y))$, B and C are an abbreviation of the bucket detector and the

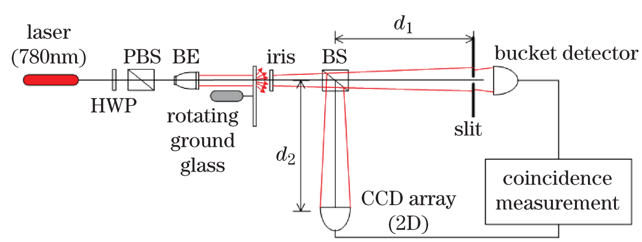

Fig. 1. Experimental setup for the high-order lensless ghost imaging.

camera.

In our experiment, the laser wavelength is 780 nm, and the beam diameter D is 1.2 mm. The laser beam is projected onto a rotating ground-glass plate at a speed of roughly 1 mrad/s in order to generate a pseudo-thermal light source. After passing through a conventional beam splitter (BS), one beam is transmitted though the object (slit) with a width of roughly 0.8 mm, and is detected by the bucket detector (CCD1). The other beam is reflected into the reference arm, and detected by the camera (CCD2). The object is a single slit which is very close to CCD1. The distance $d1$ between BS and the object is equal to $d2$ that between BS and CCD2, $d1 = d2 = 90$ cm. In our experiment, CCD1 and CCD2 are MTV-1881EX, which is 600×800 pixels CCD, and each pixel size is 9 μm.

In our experiment, we take 9000 frames and achieve the high-order ghost images which are shown in Figs. 2 and 3. In figures, $L^{n,m} = g^{n,m}/g^{n,m}_{\max}$.

The visibility of $L^{n,1}(g^{n,1})$ is increasing depended on n, but the visibility of $L^{1,m}(g^{1,m})$ is worse and uncorrelated with m. In Chen's opinion, the image is blurred in the case of $L^{1,m}(g^{1,m})(m > 1)$. Actually, each pixel of CCD is probably disturbed by the different noise, quantum efficiency, dark current and so on. Normally, these can be neglected in the conventional imaging process and the $g^{n,1}$ ghost imaging process, but would induce huge noise in the $g^{n,m}(m > 1)$ ghost imaging process. In Fig. 4, we calculate the white noise of each pixel in a reference beam by $R^{0,m} = g^{0,m}/g^{0,m}_{\max}$. All information of Fig. 4 is from a reference beam and independent with the object beam. So we have to reduce the influence from CCD2 pixels in

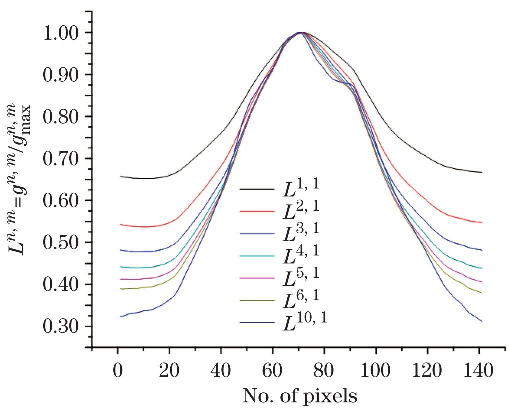

Fig. 2. High-order ghost image $L^{n,1}$.

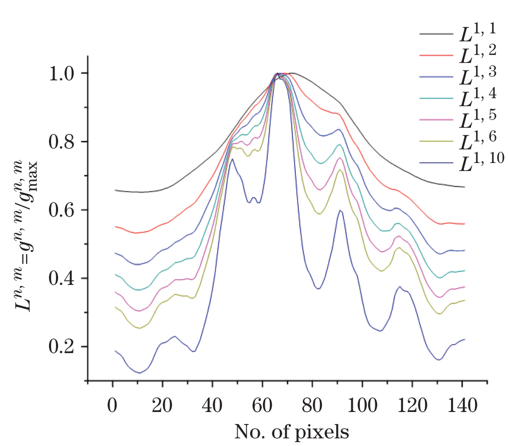

Fig. 3. High-order ghost image $L^{l,m}$.

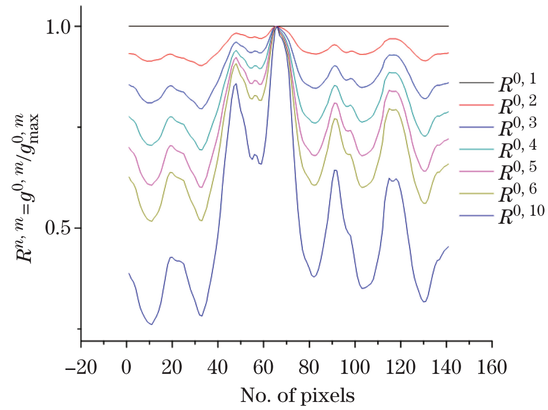

Fig. 4. Noise of reference beam for a different $R^{0,m}$.

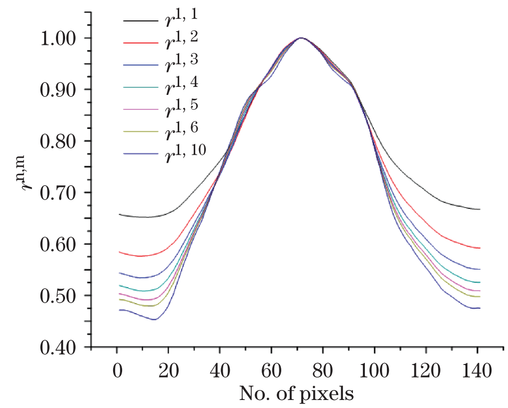

Fig. 5. High-order ghost image $r^{1,m}$ after normalizing the reference CCD2.

the $g^{1,m}(m > 1)$ ghost imaging process.

In our experiment, we could use

$$r^{n,N-n} = \frac{g^{n,N-n}/g^{n,N-n}_{\max}}{g^{0,N-n}_{\max}/g^{0,N-n}_{\max}} \qquad (3)$$

to normalize the different noise in each pixel of CCD2 and show a more clear $g^{1,m}(m>1)$ high-order ghost image.

After normalizing the different noise of each pixel of CCD2, we turn Fig. 3 to 5.

As shown in Fig. 5, the visibility of $r^{1,m}(g^{1,m})$ has a similar trend with $L^{n,1}(g^{n,1})$.

In conclusion, we experimentally realize a high-order ghost imaging of reference beam. Compared to previous work in which the $g^{1,m}(m > 1)$ ghost image was blurred in noise, we normalize the different noise from each pixel of reference CCD, and comfirm that the image visibility can be improved along with the increase of order n or m. It would be benefit to realize the high-order ghost image with more than one reference detector.

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