Ghost imaging with pure phase object

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Abstract: Ghost imaging has attracted a great deal of attentions due to it´s nonlocal characteristic and imaging resolution breaking the limitation of diffraction. A study about the relationship between the pure phase object ghost imaging and the fluctuation of the source was reported. That the intensity fluctuations of the source can affect the information of the pure phase object which we get from the ghost image was demonstrated theoretically and experimentally: the more severely the intensity of the source fluctuates, the more information of the pure phase object we can recover from the ghost image. Moreover, the increase of the intensity fluctuations could lead to the growing deviation of the object information of ghost images which obtained from different samples.

Key words: ghost imaging; intensity fluctuation; pure phase

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纯相位物体的鬼成像

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摘　要： 鬼成像因为其具有的非定域特性和突破衍射极限的高分辨率引起了人们的广泛关注。研究了光源的强度波动对纯相位物体的鬼成像的影响。用理论分析和仿真实验证明了光源的强度波动可以影响鬼成像中纯相位物体的信息：光源的强度波动越大，可以从鬼像中得到的物体信息就越多。同时，发现了随着光源强度波动的增大，不同的采样样本得到的纯相位物体的鬼成像中物体信息的差别越大。

关键词： 鬼成像；　强度波动；　纯相位

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0 Introduction

Ghost imaging was first demonstrated by Pittman et al[1]. by using an entangled source, which was regarded as the reason of the special nonlocal characteristic for a long time. And it attracted a great deal of attentions due to it′s resolution was higher than the classical imaging techniques[2–3]. Ryan S. Bennink et al[4], also got a ghost image by using two classically correlated beams and they claimed that the classical light couldn′t get the image of the pure phase object in 2002. After this experiment demonstrated, the nature of ghost imaging has been interpreted in two different ways: (1) Shih et al [5–7], hold the view that the two-photon interference is the cause of the ghost image (2) Shapiro et al[8–10], think we can reconstruct the image with the intensity fluctuations of the light. Quantities of theoretical and experimental studies were demonstrated that many features of the ghost image with entangled source could reproduced by a classical pseudothermal light[11–15]. However, for the phase-only object cannot affect the amplitude of the field, Ryan S. Bennink et al. thought the image of a pure phase object couldn′t be reconstructed by the classical correlation of intensity fluctuations. In 2004, M. Bache demonstrated the classical intensity correlation contained the amplitude and phase of the object by using a two-photon state source in the ghost imaging setup, but he didn′t report whether the intensity fluctuations of thermal light contained the phase of the object in the same ghost imaging setup.

In this article we used a pseudothermal light as the source and the object was pure phasic. We used classical correlation theory and simulation experiment to demonstrate that by using intensity fluctuations of the source we could reconstruct the information of the pure phase object and interpreted how the intensity fluctuations affected the pure phase object ghost image.

1 Ghost imaging with thermal light

1.1 Thermal lensless ghost imaging

The laser light is rendered spatially incoherent by passing through a rotating ground glass and the diffuse light is divided into two by a 50–50 beam-splitter. The transmitted light propagates to the "bucket" detector(D1) at a distance of d_1+d_2 after passing through a phase-only object located in front of it, and we name this path for the test arm. The reflect light freely propagates to a CCD detector (D2) at a distance of $d=d_1+d_2$, and we call this path for the reference arm. The ´bucket´ detector just outputs the total intensities of the test arm. In our simulation experiment, the exposure time of the detectors is much less than the coherence time of light, and the two samples′ interval is greater than the coherence time of the light. So we can consider that the optical field is steady during a sampling time, and the fields obtained in different samples are completely independent.

The output pulses of both detectors are sent to a coincidence circuit for counting the joint-detection events of the pair of pulses. Then we can get the second-order intensity correlation function, which contains the information of the object.

1.2 Pure phase object reconstruction

With the experiment setup showed in Fig.1, in order to reconstruct the pure phase object whose transmission function is $t(x,y)$, the second-order correlation of the pure phase object at the coordinate (x,y) is defined as:

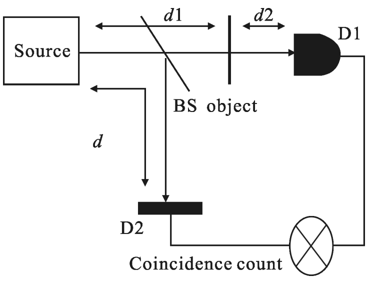

Fig.1 Schematic setup for pseudothermal lensless ghost imaging

$$G^{(2)}(x,y)=\langle BI(x,y)\rangle \tag{1}$$

Where $I(x,y)$ is obtained by measuring the intensities impinge on the CCD plane at the coordinate (x,y) is the intensities measured by the "bucket" detector behind the object:

$$B=\int \mathrm{d}x\mathrm{d}y I(x,y)t(x,y) \tag{2}$$

In this article, we choose the limpid rectangle phase grating as shown in Fig.2 as the phase-only object.

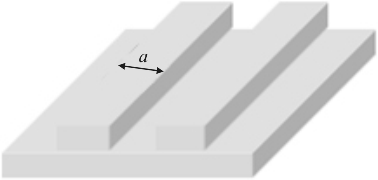

Fig.2 Limpid rectangle phase grating

The transmission of the phase grating is:

$$t(x,y)=\begin{cases}1, & \frac{2k-1}{2}a<x\leqslant\frac{2k+1}{2}a,\ k=-2,0,2\\ -1, & \frac{2k-1}{2}a<x\leqslant\frac{2k+1}{2}a,\ k=-1,1\\ 0, & \text{others}\end{cases} \tag{3}$$

Where a is the cycle length of the grating. We can obtain the ghost image of the limpid rectangle phase grating by substituting Eq.(2-3) into (1). The second-order correlation of the outputs of the detectors can be written[17] as follows:

$$G^{(2)}(x,y)=\langle B\rangle\langle I(x,y)\rangle+\langle\Delta B\Delta I(x,y)\rangle \tag{4}$$

Where ΔB is the total intensity fluctuations on the "bucket" detector. $\Delta I\ (x,y)$ is the intensity fluctuations on a pixel area on the CCD detector. The first term just give raise to a featureless background, while the second term leads to the ghost image.

For more intuitive, in the rest of this article we use the standard deviation $\sigma(I(x,y))$, which obtained by duplicating the experiments independently N times to donate the intensity fluctuations $\Delta I(x,y)$ on one pixel area on the CCD detector plane. For the fields are mutually independent, we can donate the total intensity fluctuations on the "bucket" detector:

$$\sigma(B)=\sigma(\sum I(x,y)t^2(x,y)) \tag{5}$$

Then we can calculate $\sigma\ (B)=\sqrt{M}\ \sigma\ (I(x,y))$, where M is the proportion of the object area divided by the pixel area. For the pure phase cannot change the intensity of the light, we can easily find $B=MI(x,y)$.

1.3 Ghost imaging simulation

In our simulation experiment, we chose the case in which the phase grating cycle length a was 150 μm, the wavelength was 532 nm, the distance d_1 was 160 mm, d_2 was 200 mm, d was 360 mm, the proportion was 25, the mean intensities illuminate on each pixel $\langle I(x,y)\rangle$ were and we repeated the independent experiment 10000 times with each value of the intensity fluctuations on one pixel area $\sigma(I(x,y))$.

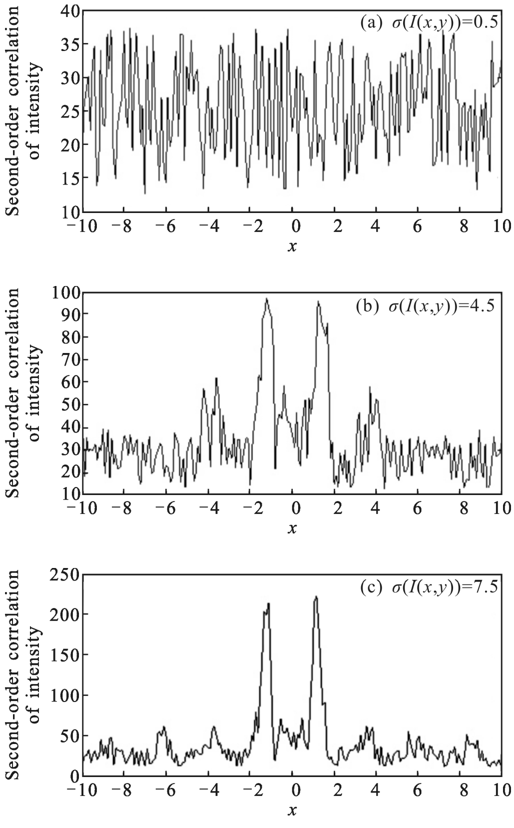

Fig.3 Images of the phase grating with different value of intensity fluctuations

As shown in Fig.3, with the increasing of theintensity fluctuations, the image information of the phase grating was enhanced in the ghost image. In Fig.3(a) when the intensity fluctuations were very weak, we couldn′t obtain the image of the phase grating on the CCD detector plane. In Fig.3(b) the intensity fluctuations reached to the value of 4.5, the image of the phase grating began to appear and the construct was found to be 61.9%. In Fig.3(c) when the intensity fluctuations reached to the value of 6.3, the construct was found to be 79.1%. We found that as the increasing of the intensity fluctuations, the image of the phase grating went sharper.

To make better understanding of the relationship between the intensity fluctuations and the contrast of the image. We used to donate the contrast of the image. We could obtain the contrast by Eq.(4):

$$C=\frac{\langle \Delta B\Delta I(x,y)\rangle-\langle B\rangle\langle I(x,y)\rangle}{\langle \Delta B\Delta I(x,y)\rangle+\langle B\rangle\langle I(x,y)\rangle}=\frac{\sqrt{M}\ \sigma^2(I(x,y))-M\langle I(x,y)\rangle^2}{\sqrt{M}\ \sigma^2(I(x,y))+M\langle I(x,y)\rangle^2} \tag{6}$$

In Fig.4 the solid line is the theoretical contrast with the change of $\sigma(I(x, y))$ and the blue dots represent the experimental data, and the result showed that when the intensity- fluctuations were very weak below $\sqrt{5}$, the contrast was below zero, which meant the background noise was too high compared with the image of phase grating. when the intensity fluctuations reached to the neighborhood of the value of $\sqrt{5}$, the image of the object gradually appeared. As the intensity fluctuations grew, the contrast increased rapidly until the intensity fluctuations reached to the value of 5.6, from then on, the contrast increased slightly and converged to 1 eventually. We concluded that the intensity fluctuations contained information of the pure phase object. And the deeper of the intensity fluctuated, the more information of the pure phase object we could get in the ghost image. However, we found in Fig.3 that the increase of the intensity fluctuations enhanced the deviation between the experimental data and the theoretical curve. In order to explore the reason, we only considered the second term of Eq.(4), which contributed to the ghost image:

$$G(x,y)=\langle \Delta B\Delta I(x,y)\rangle \tag{7}$$

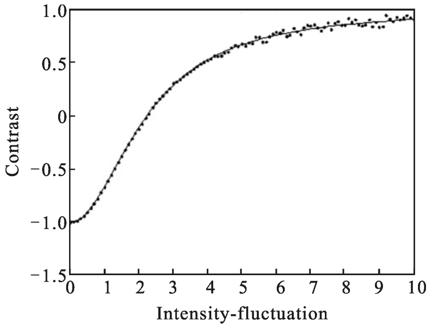

Fig.4 Analysis on contrast variation over intensity fluctuation under thermal light ghost imaging system

We used the standard deviation to represent the fluctuations of the object information of the ghost image:

$$\Delta G(x,y)=\sqrt{\langle[\Delta B\Delta I(x,y)]^2\rangle-[G(x,y)]^2} \tag{8}$$

We clearly observed from Fig.5 that deviation between the samples was growing with the increase of the intensity fluctuations. And we could enlarge the number of the samplings to decrease the deviation of the ghost image information between the experimental data and the theoretical curve according to reference[18].

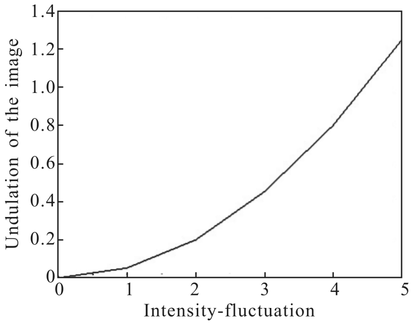

Fig.5 Trend of the undulation of the ghost image versus intensity fluctuation without background noise

2 Conclusion

In summary we concluded that the intensity fluctuations have effect on the thermal lensless ghost imaging with pure phase object. The contrast of the pure phase ghost imaging could be significantly enhanced by the increasing intensity fluctuations. We concluded that the information of the phase −only object could be increased with the growing intensity fluctuations. We confirmed this idea by forming a simulation experiment. We further found the increasing intensity fluctuations would cause greater deviation in the image of the phase grating, which could be decreased by enlarging the measurement times. Finally, we have demonstrated that the classical intensity fluctuations contain the information of the pure phase object by making theoretical analysis and simulation experiment.

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