Optics Communications 382 (2017) 415–420

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The influence of the positive and negative defocusing on lensless ghost imaging

Xue Zeng, Yanfeng Bai*, Xiaohui Shi, Yang Gao, Xiquan Fu

College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China

ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form
5 July 2016
Accepted 9 July 2016

Keywords:
Ghost imaging
Defocusing length
Imaging resolution
Fidelity

ABSTRACT

Lensless ghost imaging with fully spatially incoherent source is investigated theoretically and experimentally. The effects of positive and negative defocusing on lensless ghost imaging are studied by using classical optical theory and a fully spatially incoherent source. Based on the numerical calculation and experimental results, we find that the negative defocusing has a stronger influence on imaging resolution when compared with that from the positive defocusing. To explain this phenomenon, the analytical expression of point spread function with the positive and negative defocusing is presented.

1. Introduction

Ghost imaging which usually called correlated imaging is a method to nonlocally image an object through spatial intensity correlation measurement. Firstly, it was realized by using the entangled photon pairs generated by spontaneous parametric down-conversion (SPDC) in 1995 [1,2]. One of two entangled photons travels through a reference optical imaging system, and the other propagates through a test optical imaging system with an object located. One can reconstruct the image of the object as a function of the transverse position of the reference photon by measuring the coincidence rate of these photon pairs at the reference and test detector. Since then, the observation of this phenomenon was studied theoretically and experimentally with entangled photons [3–5] for the great potential applications in quantum metrology, lithography, and holography [6–10]. These results have evoked many controversies about whether it is necessary to realize correlated imaging by using quantum entanglement. Soon Bennink et al. presented that it is not necessary by their experimental results and believed that ghost imaging with classical light is just a point-by-point, shot-by-shot projection [11]. Gatti et al. demonstrated theoretically that ghost imaging with truly incoherent light can be realized [12]. Based on classical statistical optics, coincidence interference with a complete incoherent light and without lenses was studied by Cheng and Han [13]. Soon, Valencia et al. confirmed experimentally that ghost imaging can be realized with quasi-thermal light [14], and the group of Lugiato performed the experiment of ghost imaging and ghost diffraction with classical quasi-thermal light [15]. In recent years, because ghost imaging with classical thermal light provided more potential applications than that under an entangled source, classical correlated imaging has been studied extensively, both theoretically and experimentally [16–24]. Especially, Karmakar et al. firstly demonstrated lensless ghost imaging with sunlight [25].

Lensless imaging system has attracted much interest in recent years because the correlation result can be obtained without the use of a lens anywhere in this system [16,17]. Note that the group of Cheng investigated theoretically the effects of the source parameters, detector size and defocusing length on imaging quality in a lensless ghost diffraction system [26], while the results in a lensless ghost imaging system were not mentioned. As we all know, the two imaging systems are similar except that the test detector is used as a bucket detector in a lensless ghost imaging system (while the detector is treated as a pixel-like detector in a lensless ghost diffraction system). In this paper, intrigued by this work, we theoretically and experimentally study the effects from the defocusing length on imaging resolution in a lensless ghost imaging system with incoherent light source. Based on classical optical theory, the analytical expression describing the point spread function (PSF) of lensless ghost imaging system with defocusing effect is derived. The resolution of ghost imaging is dependent on the width of PSF. It is shown theoretically and experimentally that the influence of positive defocusing and negative defocusing are quite different, and the effect from the negative defocusing is bigger. One can obtain good imaging resolution by controlling the defocusing length. This result can also be

* Corresponding author.
E-mail address: yfbai@hnu.edu.cn (Y. Bai).

http://dx.doi.org/10.1016/j.optcom.2016.07.023
0030-4018/

understood by the changes of spatial longitudinal and transverse coherent length.

2. Model and equations

The lensless imaging system is shown in Fig. 1, the light source is divided into two beams by a beam splitter (BS). And then the two beams propagate through a test path and a reference path to test detector D_1 and reference detector D_2, respectively. The test path contains an unknown object (maybe a double slit) with transmission function $t(y)$, which is different from reference path of free space. It should be noticed that the test detector D_1 is used as a pixel-like detector in lensless ghost diffraction, so it cannot give the image of the object. While the test detector D_1 is used as a bucket detector to collect all light passing through the object in lensless ghost imaging. The distance between the source and the reference detector, the source and the object, the object and the test detector are z, z_1, and z_2, respectively.

Using a correlator to measure the intensity correlation function, the coincident counting rate is proportional to the second-order correlation function $G^2(u_1, u_2)$ [10,16]:

$$G^2(u_1, u_2) = \langle E(u_1)E(u_2)E^*(u_2)E^*(u_1)\rangle = \langle I_1(u_1)\rangle\langle I_2(u_2)\rangle + G(u_1, u_2), \quad (1)$$

where u_1 and u_2 are the transverse position of detectors D_1 and D_2, respectively. $\langle I_i(u_i)\rangle$ denotes intensity distribution on the ith detector (i=1, 2), and the first item on the right of Eq. (1) is the background. The brackets mean an average over all realizations of the field. $G(u_1, u_2)$ indicates the correlation function of intensity fluctuations depending on both paths. Here we have [13,16]

$$G(u_1, u_2) = \left|\int \Gamma(x_1, x_2)h_1(x_1, u_1)h_2^*(x_2, u_2)dx_1dx_2\right|^2, \quad (2)$$

where x_i is the location of the source plane, $\Gamma(x_1, x_2)$ represents the first-order correlation function of the source. $h_1(x_1, u_1)$ and $h_2(x_2, u_2)$ are the impulse response functions of the test and reference path, respectively. For a lensless imaging system, $h_1(x_1, u_1)$ and $h_2(x_2, u_2)$ take the forms [13]:

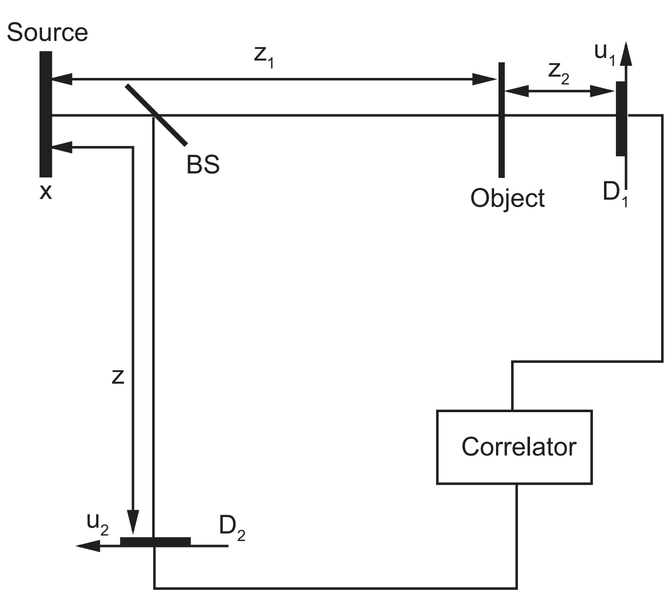

Fig. 1. The scheme for lensless ghost imaging.

$$h_1(x_1, u_1) = \left(\frac{-1}{\lambda^2 z_1 z_2}\right)^{-1/2} \int \exp\left[\frac{-i\pi}{\lambda z_1}(y - x_1)^2\right]t(y) \times \exp\left[\frac{-i\pi}{\lambda z_2}(u_1 - y)^2\right]dy, \quad (3)$$

$$h_2(x_2, u_2) = \left(\frac{-i}{\lambda z}\right)^{-1/2} \exp\left[\frac{-i\pi}{\lambda z}(u_2 - x_2)^2\right], \quad (4)$$

where λ is the wavelength of light source. For the fully spatially incoherent light source, the first-order correlation function has the form [13]

$$\Gamma(x_1, x_2) = \exp\left(-\frac{x_1^2 + x_2^2}{2a^2}\right)\delta(x_1 - x_2), \quad (5)$$

where a is the transverse size of the source. Substituting Eqs. (3)–(5) into Eq. (2), we can obtain the correlation function of intensity fluctuation $G(u_1, u_2)$ as

$$G(u_1, u_2) = \frac{1}{\lambda^3 z z_1 z_2}\int dx_1\, dx_2\, dy\, dy' t(y)t(y') \times e^{-\alpha x_1^2}e^{-\alpha x_2^2}e^{i\beta_0[(u_2-x_1)^2-(u_2-x_2)^2]} \times e^{i\beta_1[(y-x_2)^2-(y'-x_1)^2]}e^{i\beta_2[(u_1-y)^2-(u_1-y')^2]}, \quad (6)$$

where $\alpha = \frac{1}{a^2}$, $\beta_0 = \frac{\pi}{\lambda z}$, $\beta_1 = \frac{\pi}{\lambda z_1}$ and $\beta_2 = \frac{\pi}{\lambda z_2}$. After integrating over u_1, Eq. (6) can be simplified as

$$G(u_2) = \frac{\beta_0\beta_1\beta_2}{\pi^3}\int dy|t(y)|^2\, h(y, u_2), \quad (7)$$

its integral kernel $h(y)$ can be considered as the PSF of lensless ghost imaging system [27,28], and $h(y)$ takes the form:

$$h(y) = \frac{\pi}{\sqrt{2\alpha}\,\beta_1\Delta_{PSF}}\exp\left[-\frac{y^2}{\Delta_{PSF}^2}\right], \quad (8)$$

where the width of PSF can be written as

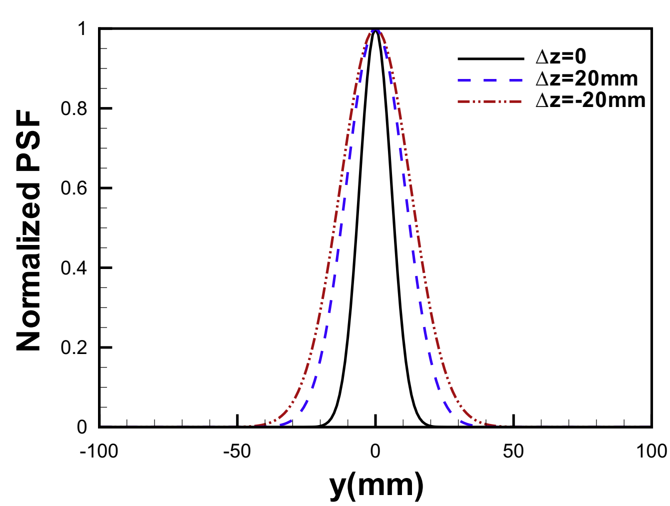

Fig. 2. The normalized PSF of the lensless ghost imaging system for different defocusing lengths: $\Delta z = 0$ (the solid curve), $\Delta z = 20$ mm (the dash curve), and $\Delta z = -20$ mm (the dashdotdot line).