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Multipath effect constraint of pseudo-thermal light source in ghost imaging

Xiaonan Zhu, Xiquan Fu *, Bowen Wang, Xiaohui Shi, Suqin Nan

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

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ABSTRACT

Multipath effect in communication system is important to the quality of signals. The influence of the multipath effect on the performance of ghost imaging is investigated numerically and experimentally. The reflected light from ground glass is used as the light source to trigger the multipath effect, and we compare it with the traditional ghost imaging using transmitted light from ground glass as the light source. To compare the influence of the multipath effect, ghost imaging using reflected light from the aluminized ground glass under different distances is presented. The multipath effect is affected by the complexity of mutual interference, and it has both constructive and destructive influence on the quality of ghost imaging. The strong multipath effect increases the resolution, but it also reduces the signal-to-noise ratio of the reconstructed images.

1. Introduction

An increasing number of people have been devoted into the field of quantum ghost imaging (QGI) in last two decades, because of its tremendous prospect for quantum communication and quantum sensing. The initial work used the quantum nature of two-photons entanglement generated by spontaneous parametric down-conversion (SPDC) to realize nonlocal correlated imaging, which retrieved an unknown object by measuring second-order intensity correlation function between the test arm and the reference arm experimentally [1,2]. Before long, it was found that the classical light source, which was based on statistical optics, can also realize ghost imaging (GI) [3–8]. Very recently, the spatial light modulator (SLM) and digital micro-mirror device (DMD) are used in computational ghost imaging (CGI), it can be realized with only one single-pixel detector, which greatly simplified the settings of GI [9–12]. Additionally, many different schemes of GI have been reported, such as high-order GI [13], compressive GI [14], differential GI [15], normalized GI [16], polarimetric GI [17], far-field GI [18] and 3D GI [19].

The multipath effect is an important concept in communication systems, such as GPS system [20] or OFDM system [21]. It is a propagation phenomenon that leads to the constructive or destructive interference, and this phenomenon is caused by the reflection and refraction in propagation medium. In GI, the multipath effect is a kind of mismatch, which exists in the light source and the optical path, the mismatch of the optical paths in ghost imaging have been widely studied [22–24]. As far as we known, the multipath effect of light source in GI has been rarely studied. So it is necessary to make a clear analysis of its influence. Because the multipath effect of pseudo-thermal light source in practical applications is extensive and complex, we introduce the multipath effect into the GI system from the perspective of reflection and refraction inside the light source, for simplicity. Based on earlier studies [25], the signal-to-noise ratio (SNR) is an important factor affecting the quality of GI, and it is also the main contributing factor of the multipath effect. Therefore, the research about the influence of multipath effect on the quality of GI is meaningful. Noted that as early as 1963, Bennett verified the aluminized ground glass (GG) surfaces had a Gaussian reflectance curve, the scatter plates of this material make excellent reflection filters and slightly weakens the energy passed in desired wavelength region [26]. Therefore, we use the aluminized ground glass to investigate the diversity of multipath effect in following scheme.

In this paper, the influence of multipath effect of pseudo-thermal light source on the imaging quality of lensless ghost imaging (LGI) is studied numerically and experimentally. The reflected light from the ground glass is used to produce the multipath effect, and we investigate the imaging quality at different distances for the observation of different degrees of multipath effect. Besides, a layer of aluminum is coated on the smooth surface of the GG to investigate the diversity of multipath effect. Our simulations and experiments indicate that the multipath effect has both constructive and destructive influence on the performance of ghost imaging, and one can get an eclectic result between high resolution and low noise by the proper regulation of the multipath effect. In addition, using the reflected light from rotating ground glass (RGG) to implement GI can cut down reflector that is used to convert the direction of the light path in some cases, such as multiple light path system [27].

* Corresponding author.
E-mail address: fuxq@hnu.edu.cn (X. Fu).

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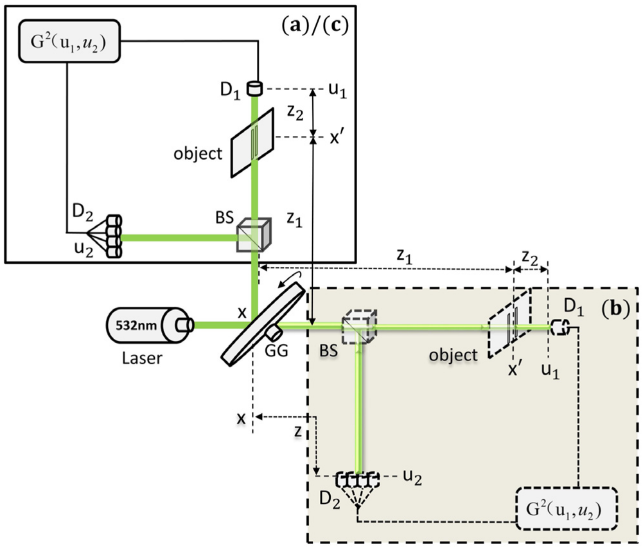

Fig. 1. Setup of lensless ghost imaging with pseudo-thermal light: (a) using reflected light from ground glass; (b) using transmitted light from ground glass; (c) using reflected light from aluminized ground glass (replacing the ground glass with an aluminized ground glass and the other settings remain the same with (a)).

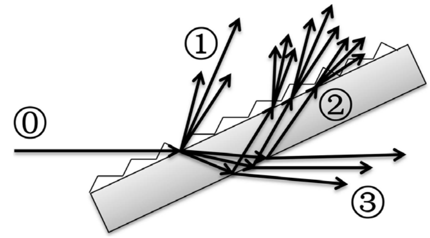

Fig. 2. Details of part of light passing through the ground glass. ⓪ is the incident light, ① is the reflected light from rough outer surface of the ground glass, ② is the reflected light from smooth inner surface of the ground glass, and ③ is the transmitted light from the ground glass.

2. Model and analytical results

We study the multipath effect in GI by analyzing the details of the reflection and refraction inside the light source. Firstly, we study the property of the reflected light from RGG in GI, the schematic diagram is illustrated in Fig. 1(a) (the solid line of Fig. 1). To generate a pseudo-thermal light, a laser with wavelength of 532 nm illuminates the rough surface of a slowly RGG, and the angle between the direction of light source and the GG plane is 45°. Fig. 2 shows the details of part of the light passing through the GG, the reflected light is divided into the test path and the reference path by a non-polarizing beam splitter. In the test arm, the beam propagates through an object and then detected by a bucket detector D_1 to collect light passing through the object, the object is located at a distance of z_1 from the source, and the distance between the detector and the object is z_2. In the reference arm, a CCD camera D_2 which does not see the object is located at the distance of z from the source.

In the framework of Fig. 1(a), the second-order correlation function $G^2(u_1, u_2)$ can be retrieved by measuring the spatial correlation function of the intensities detected by D_1 and D_2[14]

$$G^2(u_1,u_2) = \langle E(u_1)E(u_2)E^*(u_1)E^*(u_2)\rangle = \langle I_1(u_1)\rangle\langle I_2(u_2)\rangle + \langle \Delta I_1(u_1)\Delta I_2(u_2)\rangle, \tag{1}$$

where $E(u_1)$ is the optical field in the test detector and $E(u_2)$ is the optical field in the reference detector. $u_i (i = 1, 2)$ is the transverse position of the ith detector, $I_i(u_i)$ is the intensity distribution on the ith detector, and $\langle \Delta I_1(u_1)\Delta I_2(u_2)\rangle$ is the correlation function of intensity fluctuations depending on both paths. We have already known that the first term $\langle I_1(u_1)\rangle\langle I_2(u_2)\rangle$ on the right-hand side of Eq. (1) is called the background term which only contributes a background. The second term $\langle \Delta I_1(u_1)\Delta I_2(u_2)\rangle$ contains all the information of the object to be tested, and it is defined as intensity fluctuation correlation function $G(u_1, u_2)$[14]

$$G(u_1,u_2) = \left| \int G^{1,1}(x_1,x_2) h_1(x_1,u_1) h_2^*(x_2,u_2) \mathrm{d}x_1 \mathrm{d}x_2 \right|^2, \tag{2}$$

where x_i $(i = 1, 2)$ represents the location of the source plane, $G^{1,1}(x_1, x_2)$ is 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 function of the test system and the reference system separately [15]

$$h_1(x_1,u_1) = \int \frac{e^{-ikz_1}}{i\lambda z_1} \exp\left[\frac{-i\pi}{\lambda z_1}(x'-x_1)^2\right] t(x') \times \frac{e^{-ikz_2}}{i\lambda z_2} \exp\left[\frac{-i\pi}{\lambda z_2}(u_1-x')^2\right] \mathrm{d}x', \tag{3}$$

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

where $t(x')$ represents the transmission function of object, and the intensity distribution of incident light ⓪, as shown in Fig. 2 is:

$$G_0^{1,1}(x_1,x_2) = G_0 \exp\left(-\frac{x_1^2+x_2^2}{4a^2}\right), \tag{5}$$

where G_0 is a normalized constant and a is the transverse size of the source. Fig. 2 shows the details of part of the light passing through the ground glass, in which ⓪ is the incident light, ① is the reflected light from rough outer surface of the ground glass, ② is the reflected light from smooth inner surface of the ground glass, and ③ is the transmitted light from the ground glass. In GI with reflected light from GG, the light source used for imaging consists of ① and part of ②, in which ①is the primary source and ② is the secondary source. Besides, the rest of the ② was reflected back to GG. Suppose that the GG is an ideal object whose absorptivity is nonexistent, and its reflectivity is P_R, then the transmittance is $(1 - P_R)$. It should be noted that P_R is assumed to be uniform on different positions of ground glass, therefore we can get the intensity distribution of ① by adding the incoherent term and multiplying the reflection coefficient based on Eq. (3) [28]

$$G_1^{1,1}(x_1,x_2) = G_0 P_R \exp\left(-\frac{x_1^2+x_2^2}{4a^2}\right) \delta(x_1-x_2). \tag{6}$$

To compare the performance of GI using transmitted or reflected light from RGG, we implement the classical GI scheme as the transmitted version. For consistency, the angle between the direction of light source and the GG plane is also 45°. The corresponding settings are plotted in Fig. 1(b) (the dashed line of Fig. 1). In the transmitted version, section ③ (shown in Fig. 2) is the only light source, and the relationship between the primary source and the secondary source does not exist in this case. We assume that the light source is fully spatially incoherent, then its intensity distribution is Gaussian type as follows [9]

$$G_3^{1,1}(x_1,x_2) = G_1 \exp\left(-\frac{x_1^2+x_2^2}{4a^2}\right) \delta(x_1-x_2). \tag{7}$$

Under the theory of geometrical optics, we can obtain ⓪ − ① = ② + ③, and ② takes the form

$$G_2^{1,1}(x_1,x_2) = \left[G_0 - \left(G_0 P_R + G_1\right) \delta(x_1-x_2)\right] \exp\left(-\frac{x_1^2+x_2^2}{4a^2}\right), \tag{8}$$