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Lens ghost imaging with thermal light: From the far field to the near field

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For a fixed 2-f reference path, we demonstrate both theoretically and experimentally that based on the spatial correlation between two light fields, ghost imaging in spatial domain (GI) and Fourier-transform ghost interference (FRT) can be obtained by only increasing the transverse size of the thermal source D. Both explanation of the transformation from GI to FRT and their potential applications are also discussed.

1. Introduction

With respect to the classical area of imaging, the field of quantum imaging aims to devise novel techniques for optical imaging, by exploiting the quantum nature of light [1]. After the introduction of entangled photon pairs into the research of ghost imaging [2–7], ghost imaging with thermal light was also realized in lensless and lens optical systems both theoretically and experimentally [5–22]. However, except for the lensless ghost imaging scheme described in Ref. [14] and experimental study of momentum correlation of a pseudothermal light in Ref. [11], almost ghost imaging system was investigated in the near field (namely the object, relative to the source, is in Near-contact or Fresnel regions), and GI (FRT) was realized by setting a different reference path. For example the lens ghost imaging schemes discussed in Refs. [3,4,9], when the reference path contains a 2-f optical system, we can obtain FRT while GI is realized if the reference path is an imaging system. Also, because the thermal source in ghost imaging system acts as a phase conjugated mirror, the correlated imaging equation with thermal light is similar to Gaussian thin-lens equation in geometrical optics, thus the whole imaging system is equivalent to imaging in the near field [10]. In some practical applications, especially for active long range ghost imaging, the object is located in Fraunhofer region (in the far field) of the source via free propagation of light field. In order to obtain a reference light field correlated with that located in the test path and convenient operation in practical applications, the reference path is usually proposed as a miniaturized and fixed 2-f optical system. Although the ghost imaging scheme mentioned in Ref. [11] is also investigated in the far field, the symmetrical imaging approach is hard to be applied to long range ghost imaging. Moreover, for the Fourier-transform ghost interference schemes mentioned in Refs. [3,4], what will happen as the object is located in the far field of the thermal source? To understand the above questions, in this Letter, lens ghost imaging with thermal light both in the far and in the near fields are investigated by modulating the thermal source's transverse sizes.

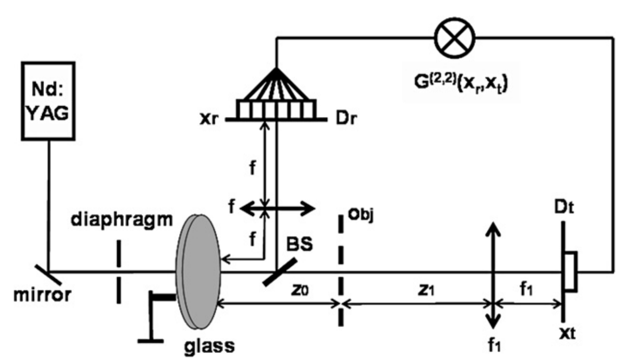

Fig. 1. Schematic of lens ghost imaging with thermal light in the near and far fields.

2. Experimental results and theory

The schematic of experimental setup discussed in this Letter is sketched in Fig. 1. Similar to some lens ghost imaging schemes [3,4], the test detector shown in Fig. 1 is also a single pointlike detector and fixed on the Fourier-transform plane of the object. Different from previous lens ghost imaging systems, now the refer-

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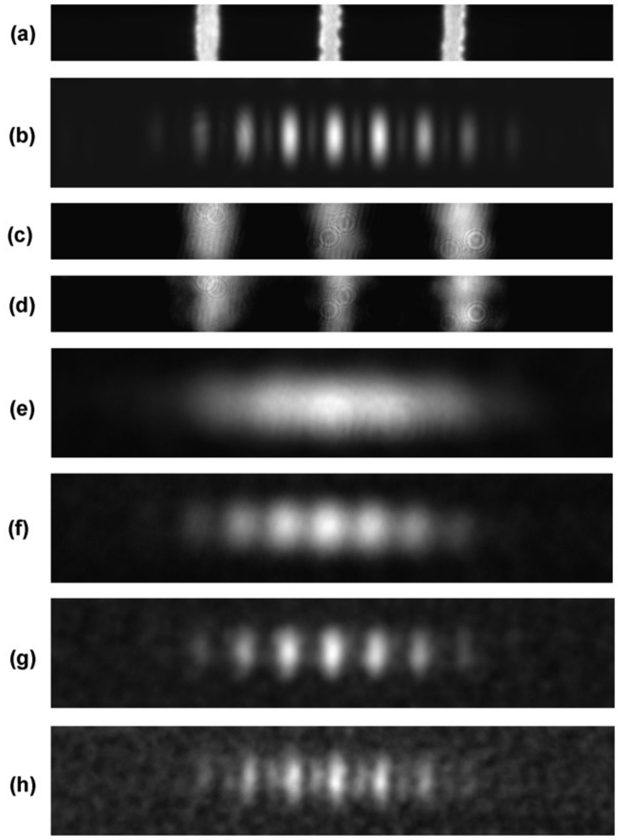

Fig. 2. Images obtained via intensity correlation measurements in different source's transverse sizes using the schematic of Fig. 1 (averaged 5000 speckle frames). (a) The object; (b) Standard Fourier-transform pattern of the object by a single-lens 2-f system ($f = 250$ mm) illuminated by a laser; (c) $D = 0.3$ mm ($\Delta x \approx 0.44$ mm); (d) $D = 0.6$ mm ($\Delta x \approx 0.22$ mm); (e) $D = 1.0$ mm ($\Delta x \approx 0.13$ mm); (f) $D = 1.6$ mm ($\Delta x \approx 0.08$ mm); (g) $D = 3.0$ mm ($\Delta x \approx 0.04$ mm); and (h) $D = 4.0$ mm ($\Delta x \approx 0.03$ mm). The receiving area of the test detector is 0.60 mm × 0.60 mm for (c)–(d) while 0.01 mm × 0.01 mm for (e)–(f).

ence detector is always fixed on the Fourier-transform plane of the thermal source. In the experiment, the pseudo-thermal source is obtained by passing a neodymium doped yttrium aluminum garnet (Nd: YAG) laser beam, with the wavelength $\lambda = 532$ nm and laser pulse width $\Delta\tau = 5$ ns, into a slowly rotating ground glass disk. The transverse sizes of the light spot on the disk can be controlled by a diaphragm and the light is divided by a beam splitter (BS) into a test and a reference paths. In the test path, the light goes through a three-slit (slit width $a = 0.2$ mm, slit height $h = 1.0$ mm and center-to-center separation $d = 1.0$ mm), a thin lens of focal length f_1 and then is focused onto a single pointlike detector D_t. In the reference path, a CCD camera D_r is fixed on the focal plane of another thin lens with focal length f. The exposure time window for the two detectors is set to be 1 ms in order to ensure the detection of the signals with 5 ns pulsed width. In the experiment, the experimental parameters listed in Fig. 1 are as follows: $z_0 = 250$ mm, $z_1 = 400$ mm, $f_1 = 150$ mm and $f = 250$ mm. By increasing the transverse size of the diaphragm to obtain different source's transverse sizes D, as shown in Fig. 2, GI and FRT can be transformed, which appears puzzled compared with the results described in Refs. [3,4,9]. Furthermore, as D is increased, the transverse coherence lengths on the object plane are decreased and the spatial resolution of the real-space images and diffraction patterns will be enhanced, which is in agreement with the results discussed in Ref. [9].

To understand the experiment, we consider the correlation function of intensity fluctuations between two paths [12,13]:

$$\Delta G^{(2,2)}(x_r, x_t) = \left| \int dx_1 \int dx_2\, G^{(1,1)}(x_1, x_2) h_r^*(x_r, x_1) h_t(x_t, x_2) \right|^2, \tag{1}$$

where $G^{(1,1)}(x_1, x_2)$ is the first-order correlation function on the source plane, and $h_t(x_t, x_2)$ is the impulse function in the test path whereas $h_r^*(x_r, x_1)$ denotes phase conjugate of the impulse function in the reference path.

Suppose the light source is fully spatially incoherent, then

$$G^{(1,1)}(x_1, x_2) = I_0 \delta(x_1 - x_2), \tag{2}$$

where I_0 is a constant, and $\delta(x)$ is Dirac delta function.

For the schematic shown in Fig. 1, under the paraxial approximation, and when the effective apertures of the lenses in the optical system are large enough, then the impulse response function of the reference system is

$$h_r(x_r, x_1) \propto \exp\left\{ -\frac{2j\pi}{\lambda f} x_r x_1 \right\}, \tag{3}$$

and the impulse response function for the test path is

$$h_t(x_t, x_2) \propto \int dx' \exp\left\{ \frac{j\pi}{\lambda z_0} (x' - x_2)^2 \right\} t(x') \times \exp\left\{ -\frac{2j\pi}{\lambda f_1} x_t x' + \frac{j\pi}{\lambda f_1} \left(1 - \frac{z_1}{f_1}\right) x_t^2 \right\}, \tag{4}$$

where $t(x)$ is the transmission function of the object. Substituting Eqs. (2)–(4) into Eq. (1), the correlation function can be expressed as

$$\Delta G^{(2,2)}(x_r, x_t) \propto \left| \int dx_2 \int dx' \exp\left\{ \frac{2j\pi}{\lambda} \left(\frac{x_r}{f} - \frac{x'}{z_0} \right) x_2 \right\} t(x') \times \exp\left\{ \frac{j\pi}{\lambda z_0} x_2^2 + \frac{j\pi}{\lambda z_0} x'^2 - \frac{2j\pi}{\lambda f_1} x_t x' \right\} \right|^2. \tag{5}$$

When the object, relative to the thermal source, is positioned in the far field (namely $z_0 \geqslant \frac{2D^2}{\lambda}$), then the quadratic term including x_2 in Eq. (5) is approximately a constant (namely $\exp\{\frac{j\pi}{\lambda z_0} x_2^2\} \approx 1$). But considering the effect of axial correlation depth of light field for a circular-shaped source [14,15,17,23], even if

$$z_0 \geqslant \frac{2D^2}{6.7\lambda}, \tag{6}$$

where D is the source's transverse size, then the quadratic term including x_2 in Eq. (5) can still be ignored. After the integral of x_2, Eq. (5) can be represented as

$$\Delta G^{(2,2)}(x_r, x_t) \propto \left| \int dx' \exp\left\{ \frac{j\pi}{\lambda z_0} x'^2 - \frac{2j\pi}{\lambda f_1} x_t x' \right\} t(x') \times \sin c\left\{ \frac{D}{\lambda z_0} \left(\frac{x_r z_0}{f} - x' \right) \right\} \right|^2, \tag{7}$$

where $\sin c(x) = \frac{\sin(\pi x)}{\pi x}$. From Eq. (7), GI can be obtained and the resolution of GI is determined by the source's transverse size or the distance between the object plane and the thermal source plane (namely $\Delta x \approx \frac{\lambda z_0}{D}$), which accords with the results depicted in Fig. 2(c)–(d). On the contrary, as the transverse size D is increased, then the condition in Eq. (6) is deviated. When

$$z_0 \ll \frac{D^2}{\lambda}, \tag{8}$$

namely the object is located in the near field relative to the thermal source. After some calculations, Eq. (5) can be rewritten as

$$\Delta G^{(2,2)}(x_r, x_t = 0) \propto \left| \widetilde{T}\left[\frac{-2\pi}{\lambda f} x_r\right] \right|^2, \tag{9}$$

where $\widetilde{T}(q)$ is Fourier transformation of $t(x)$. Apparently, Eqs. (8)–(9) validly explain the results depicted in Fig. 2(e)–(h) and the cases described in Refs. [3,4]. Thus, from Eqs. (6)–(9), even if a 2-f optical system is fixed in the reference path, both GI and FRT can be obtained by only increasing the thermal source's transverse sizes, which is in accordance with the experimental results displayed in Fig. 2.

3. Discussion and conclusion

Generally speaking, GI depends on the spatial correlation between two light fields placed on the object plane and the reference detection plane (called "Type-I correlation") while FRT is determined by the spatial correlation between two light fields located in the test detection plane and the reference detection plane (named "Type-II correlation"). For the optical systems discussed in Refs. [3,4], above two types of spatial correlations can be realized by only changing the role of the lens L in the reference path. If the lens L is used to image a light field (such as $2f$-$2f$ setup or f-$2f$-f setup), GI can be achieved because of Type-I correlation, which is similar to the lensless ghost imaging in Refs. [8, 15]. Correspondingly, as a result of Type-II correlation, we can obtain FRT when the lens L is used to realize Fourier transformation of a light field (f-f setup). However, here the reference detector is always fixed on the Fourier-transform plane of the thermal source (namely in the far field). When the transverse sizes of the source D are small enough so that the object fixed in the test path is also located in the far field, we can only obtain GI because of Type-I correlation and the effect of axial correlation depth of light field (ACDF) [17], which has similarly been proved in lensless ghost imaging system [14,15] and the lens ghost imaging system in Ref. [11] (where both detection planes are located at the focal plane of the lens, so they are located in the far field of the thermal source, which is equivalent to the far-field imaging system via free space propagation of light field in Ref. [14]). As the increase of D, then the object, relative to the thermal source, is in the near field, thus Type-I correlation is absent. However, FRT can be realized due to Type-II correlation. Thus only increasing D, the transformation from GI to FRT can be realized. Similarly, for the case discussed in Ref. [20], if the source's transverse sizes are further reduced, GI can also be obtained. Based on the above analysis and discussion, so ghost imaging modes are closely related to the thermal source's transverse sizes and the source should be stressly taken into consideration in ghost imaging systems. Actually, from Eqs. (6) and (8), similar to the effect of the source's transverse sizes on ghost imaging modes, FRT and GI can also be transformed by only increasing the distances between the object plane and the thermal source plane. Furthermore, the transformation of FRT and GI originates from the effect of ACDF and such effect is a general phenomenon for ghost imaging, which can be obtained by increasing the distances between the object plane and the source plane or decreasing the source's transverse sizes [17].

Moreover, for thermal light, the resolution of both GI and FRT recovered by the intensity correlation measurement can be explained by the uncertainty relation involving the product of conditional variances in position $(\Delta(x_1 - x_2))$ and momentum $(\Delta(p_1 - p_2))$ [6,7]. For the schematic depicted in Fig. 1, the best resolution of optical system depends on the Abbe–Rayleigh Diffraction Limit cased by the constrained transverse sizes of thermal source. For GI, as D is decreased, the uncertainty $\Delta(p_1 - p_2)$ will reduce, thus the resolution of GI is decayed but its visibility will be enhanced (Fig. 2(c)–(d)), which has also been demonstrated experimentally in Refs. [14,21,22]. Especially when $\Delta(p_1 - p_2) = 0$, then the radiation coming from the same mode of the electromagnetic field and passing through the same optical path, would have identical intensity fluctuations [8], so ghost images with good visibility can be achieved but the image's resolution will be very low. Similar results can also be obtained for FRT (see Fig. 2(e)–(h)).

In conclusion, by only increasing the transverse sizes of the thermal source, one can obtain both GI and FRT even if the reference path is a fixed 2-f optical system and the test detector is a single pointlike detector. As an application, when a fixed and small optical system is set as the reference path of ghost imaging, the image of an object which is far from the source can still be reconstructed even if a single pointlike detector is used to collect the information from the object, which is very useful to long-distance imaging.

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