Physics Letters A 375 (2011) 990–993

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Ghost telescope and ghost Fourier telescope with thermal light

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ARTICLE INFO

Article history:
Received 20 October 2010
Received in revised form 31 December 2010
Accepted 5 January 2011
Available online 8 January 2011
Communicated by P.R. Holland

Keywords:
Ghost imaging
Coherence
Telescope

ABSTRACT

As important observation tools, telescopes are very useful in remote observations. We report a proof-of-principle experimental demonstration of ghost telescope scheme and show that, by measuring the intensity correlation of two light fields and only changing the position of the detector in the reference path, ghost telescope and ghost Fourier telescope can be obtained even if a single-pixel detector is fixed in Fresnel region of the object. Differences between conventional telescope and ghost telescope are also discussed.

1. Introduction

In imaging science, telescope and microscopy, respectively, are two important observation tools at macro-level and micro-level. Using classical coherent light, we can obtain Fourier-transform diffraction pattern of an object on the focal plane of a Fourier lens, which is called Fourier telescope in remote imaging. While the real-space image of the object can also be realized by using an imaging lens (or lens group) and classical incoherent light, which is usually called telescope. Apparently, the above two imaging methods are based on the first-order correlation of light fields, thus we "see" an image only when we look at the object, which means that detection and imaging is not divided in the conventional imaging process. Further, in order to obtain the above two imaging styles, we use different sources and different optical detection system. In recent years, ghost imaging has provided a new imaging method to nonlocally image an object and has drawn much attention in the field of quantum optics [1]. Both entangled source and thermal light source can be used to realize ghost imaging and Fourier-transform ghost diffraction [1–21]. Compared with conventional imaging, ghost imaging, based on the high-order correlations of light fields, for the first time leads to the separation of detection and imaging. Based on the specific characteristic of ghost imaging, when a single-pixel detector is always fixed in the test path, a new type of telescope and Fourier telescope with thermal light are investigated via the intensity correlation of two light fields between the test path and the reference path.

2. Experimental results and theory

Here, Fig. 1 presents the proof-of-principle experimental setup of ghost telescope and ghost Fourier telescope with thermal light. The pseudo-thermal light source S is obtained by passing a neodymium doped yttrium aluminum garnet laser beam, with the wavelength $\lambda = 532$ nm and the source's transverse size $D = 4.0$ mm, into a slowly rotating ground glass disk and then is divided by a beam splitter (BS) into a test and a reference paths. In the test path, the light goes through a single thin lens with the focal length f_1 and a double-slit (with slit width $a = 0.2$ mm and center-to-center separation $d = 0.6$ mm) then to a single-pixel detector D_t. In the reference path, the light propagates through

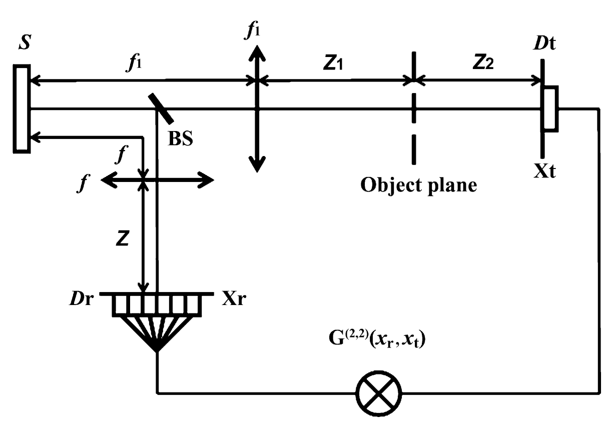

Fig. 1. Experimental setup for ghost telescope and ghost Fourier telescope with thermal light.

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doi:10.1016/j.physleta.2011.01.008

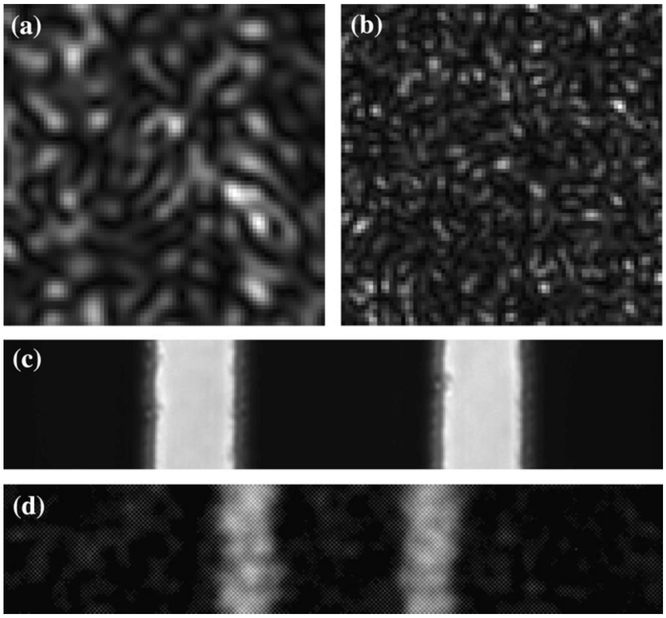

Fig. 2. Ghost imaging of the double-slit reconstructed via intensity correlation measurements with $z = 406.3$ mm (averaged 5000 observations). (a) and (b), respectively, are the instantaneous single-shot intensity distributions on the object plane and on the detection plane in the reference path when the object is removed and a CCD camera is positioned on the object plane; (c) the image of the double-slit; and (d) ghost imaging of the double-slit.

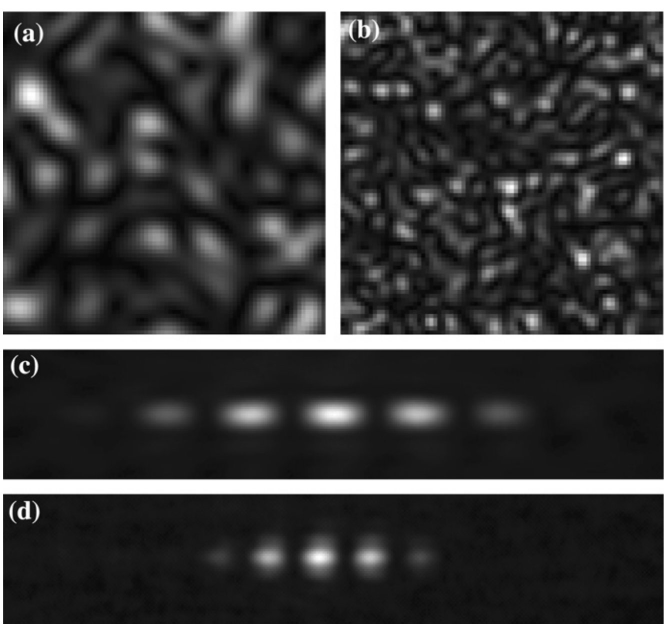

Fig. 3. Fourier-transform ghost diffraction of the double-slit reconstructed via intensity correlation measurements with $z = 562.5$ mm (averaged 5000 observations). (a) and (b), respectively, are the instantaneous single-shot intensity distributions on the detection plane in the test path and on the detection plane in the reference path when the object is removed from the test path and the single-pixel detector is replaced by a CCD camera; (c) standard Fourier-transform pattern of the object by a single-lens f_s–f_s system ($f_s = 400$ mm) illuminated by a laser; and (d) Fourier-transform ghost diffraction of the double-slit.

another single thin lens with the focal length f and then to a CCD camera D_r. Moreover, the experimental parameters listed in Fig. 1 are as follows: $f_1 = 400$ mm, $f = 250$ mm, $z_1 = 800$ mm, and $z_2 = 400$ mm. Experimental results are shown in Fig. 2 and Fig. 3. For comparison, Fig. 2(c) presents the double-slit's image obtained by a thermal light source and Fig. 3(c) displays the diffraction pattern of the object illuminated by a laser. By measuring the intensity correlation between two paths used in Ref. [10], ghost imaging of the double-slit appears in Fig. 2(d). When the distance between the lens f and the CCD camera D_r is increased, as depicted in Fig. 3(d), Fourier-transform ghost diffraction pattern of the double-slit is also obtained.

To understand the experimental results, we consider the correlation function of intensity fluctuations between the two paths [5–8]

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

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.

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

$$h_r(x_r, x_1) \propto \exp\left\{ \frac{j\pi}{\lambda f}\left(1 - \frac{z}{f}\right) x_1^2 - \frac{2j\pi}{\lambda f} x_r x_1 \right\} \tag{2}$$

and the impulse response function for the test path is

$$h_t(x_t, x_2) \propto \int dx' \exp\left\{ \frac{j\pi}{\lambda f_1}\left(1 - \frac{z_1}{f_1}\right) x_2^2 - \frac{2j\pi}{\lambda f_1} x' x_2 \right\} t(x') \times \exp\left\{ \frac{j\pi}{\lambda z_2} (x_t - x')^2 \right\}, \tag{3}$$

where $t(x)$ is the transmission function of the object.

Assuming the thermal source is fully spatially incoherent and the intensity distribution is uniform with a constant I_0, then $G^{(1,1)}(x_1, x_2)$ can be represented by a Dirac δ function,

$$G^{(1,1)}(x_1, x_2) \propto I_0 \delta(x_1 - x_2). \tag{4}$$

If the source's transverse size is large enough, substituting Eqs. (2)–(4) into Eq. (1), the correlation function can be expressed as

$$\Delta G^{(2,2)}(x_r, x_t) \propto \left| \int dx_2 \int dx'\, t(x') \exp\left\{ \frac{2j\pi}{\lambda}\left(\frac{x_r}{f} - \frac{x'}{f_1}\right) x_2 \right\} \times \exp\left\{ \frac{j\pi}{\lambda}\left[\frac{z_1}{f_1}\left(\frac{1}{z_1} - \frac{1}{f_1}\right) - \frac{z}{f}\left(\frac{1}{z} - \frac{1}{f}\right) \right] x_2^2 \right\} \times \exp\left\{ \frac{j\pi}{\lambda z_2}(x_t - x')^2 \right\} \right|^2, \tag{5}$$

when

$$z = \left(\frac{f}{f_1}\right)^2 z_1 + f - \frac{f^2}{f_1}, \tag{6}$$

namely the quadratic term including x_2 in Eq. (5) is zero, then Eq. (5) can be represented as

$$\Delta G^{(2,2)}(x_r, x_t) \propto \left| t\left(\frac{f_1}{f} x_r\right) \exp\left\{ \frac{j\pi}{\lambda z_2}\left(x_t - \frac{f_1}{f} x_r\right)^2 \right\} \right|^2, \tag{7}$$

thus as shown in Fig. 2(d), ghost imaging of the object can be achieved. If

$$z = \left(\frac{f}{f_1}\right)^2 (z_1 + z_2) + f - \frac{f^2}{f_1}, \tag{8}$$