Optics Communications 358 (2016) 88–91

Contents lists available at ScienceDirect

Optics Communications

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

Ghost telescope imaging system from the perspective of coherent-mode representation

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ARTICLE INFO

Article history:
Received 2 June 2015
Received in revised form
31 August 2015
Accepted 5 September 2015
Available online 18 September 2015

Keywords:
Ghost imaging
Coherent-mode representation
Imaging quality

ABSTRACT

We firstly analyze ghost telescope imaging system based on the coherent-mode representation theory of partially coherent fields. It is shown that the distribution of the eigenvalues of the source's coherent-mode representation and the decomposition coefficients of the object imaged can affect the quality of ghost imaging. According to the distribution of the decomposition coefficients, we analyze the most suitable position of the detectors to obtain good imaging quality. The results are also suitable for inhibiting the influence from the defocusing effect.

1. Introduction

Ghost imaging, also known as correlated imaging or coincidence imaging, is a nonlocal imaging technique which is used to obtain the information or the diffraction pattern of an object by using the intensity correlation of two light beams. The first ghost imaging experiment was implemented by Pittman et al. and Strekalov et al. with entangled beams [1,2]. Then, a series of theoretical and experimental results showed that both classical thermal sources and quantum entangled beams could be used for ghost imaging [3–8]. Having remarkable application value is one of the important reasons why ghost imaging attracted attention from international researchers over the last decade. Thus how to effectively improve the imaging quality has become a focus of study. Recently, a method based on compressive sensing was proposed to improve the efficiency of correlated imaging and imaging quality [9–12]. Meanwhile, the high-order ghost imaging has been developed to improve the visibility [13–16]. In addition, the computational ghost imaging which uses only a single-pixel detector has potential applications in remote sensing [17–20], and ghost imaging through atmospheric turbulence has also been studied [21–24].

Telescope, as an important observation tool, is very useful in remote observation. The first ghost telescope imaging system was proposed by Han, and the difference between conventional telescope and ghost telescope was discussed [25]. It is well known that the general correlation function of intensity fluctuations is based on a two-dimensional integral representation [7]. However, it is noted that a one-dimensional summation coherent-mode representation was proposed to analyze ghost imaging, and the results showed that this theory is particularly suitable for evaluating the imaging quality. Three kinds of correlated imaging schemes ($2-f$, $f-2f$ and lensless ghost diffraction imaging systems) were analyzed under the coherent-mode representation [26]. As far as we know, ghost telescope imaging system from the perspective of coherent-mode representation has not been investigated. In this paper, we analyze the possibility that the coherent-mode representation can be used to study ghost telescope imaging system. The theoretical analysis and numerical results show that the coherent-mode representation can be applied to ghost telescope imaging system, and it is very helpful for understanding the imaging magnification and analyzing imaging quality in ghost telescope imaging system. At the same time, one can choose a suitable position of the detector to inhibit the effect from the defocusing effect by analyzing the distribution change of the decomposition coefficients of the object imaged.

2. Theoretical analysis

Fig. 1 presents a simplified scheme for ghost telescope imaging system. The pseudo-thermal source S is prepared by passing a laser beam ($\lambda = 532$ nm) into a slowly rotating ground glass, then it is divided into the test path and the reference path by a beam splitter (BS). In the test path, the beam passes through a signal thin lens (with the focal length f_1) and a double slit then to a single-pixel detector D_t. The lens is located at a distance f_1 from the light source and the detector is located at a distance z_1 from the lens.

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http://dx.doi.org/10.1016/j.optcom.2015.09.020
0030-4018/

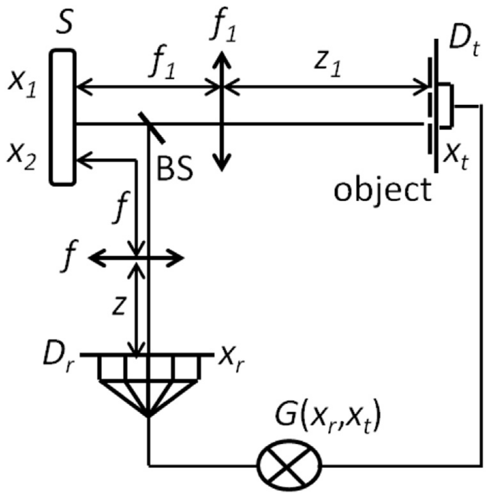

Fig. 1. A simplified scheme for ghost telescope imaging system.

The distance between the detector and the object can be ignored. In the reference path, a signal thin lens with the focal length f is located at the distance f from the light source. A CCD camera D_r is located at the distance z from the lens.

By measuring the correlation function of intensity fluctuations between two different detectors D_t and D_r, we can retrieve the information about the object imaged [3],

$$G(x_r, x_t) = \langle \Delta I_r(x_r) I_t(x_r) \rangle$$

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

where $\Delta I_i(x_i) = I_i(x_i) - \langle I_i(x_i) \rangle$ (i=r or t), $\Gamma(x_1, x_2)$ is the second-order spatial correlation function of the source, $h_t(x_1, x_t)$ and $h_r(x_2, x_r)$ are the impulse response functions for the test path and the reference path, respectively. Here

$$h_t(x_1, x_t) \propto \exp\{\frac{j\pi}{\lambda f_1}\left(1 - \frac{z_1}{f_1}\right)x_1^2 - \frac{2j\pi}{\lambda f_1}x_t x_1\} t(x_t), \tag{2}$$

$$h_r(x_2, x_r) \propto \exp\{\frac{j\pi}{\lambda f}\left(1 - \frac{z}{f}\right)x_2^2 - \frac{2j\pi}{\lambda f}x_r x_2\}, \tag{3}$$

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

From the optical coherence theory [27], and the previous results [26], we know

$$G(x_r, x_t) = \left| \sum \beta_n f_n^*(x_t) g_n(x_r) \right|^2, \tag{4}$$

where

$$f_n(x_t) = \int dx_1\, h_t(x_t, x_1)\phi_n(x_1), \tag{5}$$

$$g_n(x_r) = \int dx_2\, h_r(x_r, x_2)\phi_n(x_2), \tag{6}$$

β_n are the corresponding eigenvalues, ϕ_n are the eigenfunctions of the homogeneous Fredholm integral equation,

$$\beta_n = \left(\left(\frac{\pi}{a + b + c} \right)^{1/2} \frac{b}{a + b + c} \right)^n, \tag{7}$$

$$\phi_n(x) = \left(\frac{2c}{\pi} \right)^{1/4} \frac{1}{\sqrt{2^n n!}} H_n\left(x\sqrt{2c}\right) e^{-cx^2}, \tag{8}$$

where $H_n(x)$ are the Hermite polynomials, $a = \frac{1}{4\sigma_s^2}$, $b = \frac{1}{4\sigma_g^2}$, and $c = \sqrt{a^2 + 2ab}$. σ_s is the source's transverse size, and σ_g is the transverse coherence width of the source. Substituting Eqs. (2), (3), (5) and (6) into Eq. (4), we obtain

$$G(x_r) = \left| \int dx_t \sum_n \beta_n f_n^*(x_t) g_n(x_r) \right|^2 = \left| \sum_n \beta_n F_n^* g_n(x_r) \right|^2$$

$$\propto \left| \sum_n \beta_n F_n^* \int dx_2 \exp\left\{ \frac{j\pi}{\lambda f}\left(1 - \frac{z}{f}\right)x_2^2 - \frac{2j\pi}{\lambda f}x_r x_2 \right\} \phi_n(x_2) \right|^2, \tag{9}$$

$$F_n = \int dx_1\, dx_t\, h_t(x_1, x_t)\phi_n(x_1). \tag{10}$$

According to Eq. (5) in Ref. [26] and Eq. (10), we have

$$\sum_n F_n \phi_n^*(x_1) \propto \int dx_t \exp\{\frac{j\pi}{\lambda f_1}\left(1 - \frac{z_1}{f_1}\right)x_1^2 - \frac{2j\pi}{\lambda f_1}x_t x_1\} t(x_t), \tag{11}$$

from Eq. (11), one can obtain

$$T\left(\frac{2\pi}{\lambda f_1}x_1\right) \propto \sum_n F_n \phi_n^*(x_1) \exp\left\{ \frac{j\pi}{\lambda f_1}\left(\frac{z_1}{f_1} - 1\right)x_1^2 \right\}, \tag{12}$$

then

$$t^*\left(\frac{x_r f_1}{f}\right) \propto \sum_n F_n^* \int dx_1 \exp\left\{ \frac{j\pi}{\lambda f_1}\left(1 - \frac{z_1}{f_1}\right)x_1^2 - \frac{2j\pi}{\lambda f}x_1 x_r \right\} \phi_n(x_1), \tag{13}$$

where $T(x)$ is the Fourier transform of $t(x)$. Comparing Eq. (9) with Eq. (13), we can easily find that if $\beta_n = \beta_0 (n = 1, 2\ldots)$ and

$$\frac{1}{f}\left(1 - \frac{z}{f}\right) = \frac{1}{f_1}\left(1 - \frac{z_1}{f_1}\right), \tag{14}$$

the correlation function of intensity fluctuations is the same as $\left|t\left(\frac{x_r f_1}{f}\right)\right|^2$, i.e., one can obtain an image with magnification f/f_1 perfectly, which is different from the conclusion in Ref. [26]. In other words, one can clearly understand the magnification which is determined by the ratio of two lenses' focal length f/f_1 from Eqs. (9) and (13). As we know, the eigenvalues are decreasing in partly coherent fields ($\beta_0 > \beta_1 > \cdots > 0$), and this will greatly affect the imaging quality. According to the above discussion, we know that the images are determined by the distribution of β_n, F_n, and whether Eq. (14) is satisfied.

3. Results of the simulation

From Ref. [26], one can obtain high quality ghost imaging when the distribution of eigenvalues is wider than that of decomposition coefficients. In this section, we attempt to verify whether this conclusion is satisfied in ghost telescope imaging system.

Here, we choose a double-slit with the slit width 0.2 mm and the distance between the two slits 0.6 mm as the object imaged. From the above discussion, we know that the distribution of β_n, F_n, and whether the parameters z, z_1, f and f_1 obey Eq. (14), will affect the imaging quality. From Eq. (7), we can know that the distribution of β_n only depends on the parameter $q = \sigma_g/\sigma_s$. According to Eqs. (2), (8) and (10), the parameters z_1, f_1, σ_g and σ_s will influence the distribution of F_n, thus change the imaging quality.