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Ghost imaging of Gaussian Schell pulse beams propagation in the slant non-Kolmogorov turbulent channels

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ABSTRACT

Lensless ghost imaging with Gaussian Schell-mode pulse beam through a slant non-Kolmogorov turbulent atmosphere channel has been studied, based on the optical coherent theory and the extended Huygens–Fresnel integral. The analytical ghost-imaging formulas have been derived by the approximation of the form of spatial–temporal coherence function of the laser field in the product of the spatial and temporal coherence function, and the quadratic approximation of the wave structure function. Based on these formulas, we find that the image quality is influenced by the turbulence strength, the propagation distance, the zenith angle of communication channel, the fractal constant of the non-Kolmogorov power spectrum of atmospheric turbulence, the pulse duration of source and the coherent parameters of the partially coherent light.

1. Introduction

Ghost imaging, also known as coincidence images or “correlated” imaging or “two-photon” imaging, was first implemented with position-momentum entangled photons [1]. An object is imaged by placing it in the path of one photon of an entangled pair. This signal photon, as it has come to be called, is then allowed to fall onto a spatially nonresolving bucket detector. As its name implies, the bucket detector collects all the signal photons that make it past the object. The idler photons, on the other hand, are incident upon a spatially resolving detector. A sharp image is obtained in the coincidence counts of the two detectors. The term “ghost image” was coined for this phenomenon based on the fact that the image was formed without directly obtaining any spatially resolved image information from the object itself [2]. It was soon shown that ghost imaging relied solely on the spatial correlations of the two light fields. The same effect was reproduced by using randomly but synchronously directed twin beams of classical light [3]. The only benefit of using entangled photons was found to be that imaging could be performed both in the near and far fields, without having to change the source [4]. This is a direct consequence of the fact that entangled photons have strong correlations in both position and momentum, which correspond to correlations in the near and far fields, respectively. In the case of ghost imaging with an entangled source, the choice of whether to measure in the image plane or the diffraction pattern is left to the observer, instead of being determined by the source.

The possibility of using classic light for ghost imaging was first pointed out in Ref. [3] and later several efforts have been made in order to compare quantum and classic ghost imaging [4–6]. Ghost imaging with thermal and pseudo-thermal light are revealed in Refs. [7–10]. Cai and Zhu [11,12] discussed Ghost imaging with scalar partially coherent light and the influence of the degree of coherence of the illumination beam on the image. Since then numerous papers on various theoretical, numerical and experimental aspects of ghost imaging were published [13–20]. Recently, Ghost imaging with thermal light in atmospheric turbulence are studied based on the extended Huygens–Fresnel integral in Refs. [21–23] and Ghost imaging with partially coherent light in the presence of turbulent atmosphere in both arms of the arrangement is predicted in Refs. [24,25].

In this paper we theoretically formulate lensless ghost imaging with Gaussian Schell-mode pulse beams in non-Kolmogorov turbulence. In Section 2, we derive general expressions relating to ghost imaging by means of Gaussian Schell-pulse beams and then use this formulation for developing analytic formulas for ghost imaging in non-Kolmogorov turbulent channel (Section 3). Finally, we summarize the findings in Section 4.

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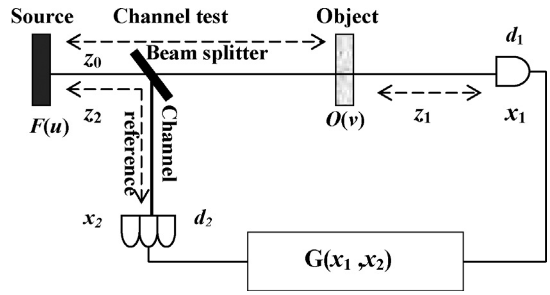

Fig. 1. Geometry of a lensless ghost imaging system in atmospheric turbulence.

2. Ghost imaging with Gaussian Schell-beams

Let's consider the lensless ghost imaging (LGI) scheme [13] shown in Fig. 1 a partially coherent pulse source E_s is split into two beams by the beams splitter. For the sake of simplicity, we will only consider the one-dimensional case. The two beams propagate through two different channels. There is an unknown object $O(v)$ located in the channel one, and the detector d_1 used in this channel is a bucket detector. The distance between the source and the object, the source and the reference detector, the object and the test detector d_2 are z_0, z_1 and z_2 respectively. A correlator is used to measure the correlation function $G(x_1, x_2)$ of the intensity fluctuations.

In the turbulent channel, based on the extended Huygens–Fresnel integral [26], the field $E_1(x_1, t)$ in the detector d_1 (see Fig. 1) can be written as

$$E(x_1,t)=\frac{1}{i\lambda\sqrt{z_0z_1}}\iint \mathrm{d}u\mathrm{d}vE_s(u,t)\exp\left[\frac{ik}{2z_0}(v-u)^2+\psi(v,u)\right]O(v)\exp\left[\frac{ik}{2z}(x_1-v)^2+\psi(x_1,v)\right] \quad (1)$$

where $k=2\pi/\lambda$ is the wave number, λ is the wavelength, $O(v)$ denotes the transmission function of the object, $E_s(u, t)$ denotes the source field and $E_s(u,t)=E_s(u)E(t)$, $E(t)=\exp[-(t/T_1)^2-i\omega_0 t]$, T_1 is the duration of a single pulse in source plane [27], ω_0 is the central frequency, $\psi(v,u)$ and $\psi(x_1,v)$ are the complex phase which represent the random part of a spherical wave propagating through the atmosphere from the source to the object $O(v)$ and from the object to the detector d_1, respectively. Similar to the channel one, the field at d_2 is given by

$$E(x_2,t)=\frac{1}{\sqrt{i\lambda z_2}}\int \mathrm{d}uE_s(u,t)\exp\left[\frac{ik}{2z_2}(x_2-u)^2+\psi(x_2,u)\right] \quad (2)$$

Based on the optical coherent theory, in the one dimensional case, the time-dependent correlation function containing the imaging of the object is [12,13]

$$G(x_1,x_2,t)=\langle I(x_1,t)I(x_2,t)\rangle-\langle I(x_1,t)\rangle\langle I(x_2,t)\rangle \quad (3)$$

here $I(x_1, t)$ and $I(x_2, t)$ denote the time-dependent intensities in the channel one and two, respectively. The brackets denote an average over all realizations of the field.

Assuming the complex phase $\psi(x_1,v)$, $\psi(x_2,u)$ and $\psi(v,u)$ obey the Gaussian statistics with a zero-average mean, applying the Gaussian moment theorem, and according to the form of spatial–temporal coherence function of the laser field in the product of the spatial and temporal coherence function [28], we have the intensity correlation

$$\begin{aligned}\langle I(x_1,t)I(x_2,t)\rangle &= \frac{1}{\lambda^3 z_0z_1z_2}\iint\iint\iint \langle E_s(u_1)E_s^*(u_1')E_s(u_2)E_s^*(u_2')\rangle\,\mathrm{d}u_1\mathrm{d}u_1'\mathrm{d}u_2\mathrm{d}u_2'\mathrm{d}v\mathrm{d}v'\\
&\times\langle E_s(t,z_0)E_s^*(t,z_0)\rangle\langle\exp[\psi(u_1,v)+\psi^*(u_1',v')]\rangle_a\langle E_s(t,z_1)E_s^*(t,z_1)\rangle_t\langle\exp[\psi(v,x_1)+\psi^*(v',x_1)]\rangle_a\\
&\times\langle E_s(t,z_2)E_s^*(t,z_2)\rangle_t\langle\exp[\psi(u_2,x_2)+\psi^*(u_2',x_2)]\rangle_a\exp\left\{\frac{ik}{2z_0}[(v+v')-(u_1+u_1')][(v-v')-(u_1-u_1')]\right\}\\
&\times O(v)O^*(v')\exp\left\{\frac{ik}{2z_1}[(v^2-v'^2)-2x_1(v-v')]\right\}\exp\left\{\frac{ik}{2z_2}[(u_2^2-u_2'^2)-2x_2(u_2-u_2')]\right\}\end{aligned} \quad (4)$$

where $\langle\cdots\rangle_t$ denotes the temporal ensemble average of turbulent atmosphere, and $\langle\cdots\rangle_a$ denotes the spatial ensemble average of turbulent atmosphere.

The last term of Eq. (3) can be expressed as

$$\begin{aligned}\langle I(x_1,t)\rangle\langle I(x_2,t)\rangle &= \frac{1}{\lambda^3 z_0z_1z_2}\iint\iint\iint \langle E_s(u_1)E_s^*(u_1')\rangle\langle E_s(u_2)E_s^*(u_2')\rangle\,\mathrm{d}u_1\mathrm{d}u_1'\mathrm{d}u_2\mathrm{d}u_2'\mathrm{d}v\mathrm{d}v'\\
&\times\langle E_s(t,z_0)E_s^*(t,z_0)\rangle_t\langle\exp[\psi(u_1,v)+\psi^*(u_1',v')]\rangle_a\langle E_s(t,z_1)E_s^*(t,z_1)\rangle_t\langle\exp[\psi(v,x_1)+\psi^*(v',x_1)]\rangle_a\\
&\times\langle E_s(t,z_2)E_s^*(t,z_2)\rangle_t\langle\exp[\psi(u_2,x_2)+\psi^*(u_2',x_2)]\rangle_a\exp\left\{\frac{ik}{2z_0}[(v+v')-(u_1+u_1')][(v-v')-(u_1-u_1')]\right\}\\
&\times O(v)O^*(v')\exp\left\{\frac{ik}{2z_1}[(v^2-v'^2)-2x_1(v-v')]\right\}\exp\left\{\frac{ik}{2z_2}[(u_2^2-u_2'^2)-2x_2(u_2-u_2')]\right\}\end{aligned} \quad (5)$$