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Ghost imaging and its visibility with partially coherent elliptical Gaussian Schell-model beams

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ABSTRACT

The performances of the ghost image and the visibility with partially coherent elliptical Gaussian Schell-model beams have been studied. In that case we have derived the condition under which the goal ghost image is achievable. Furthermore, the visibility is assessed in terms of the parameters related to the source to find that the visibility reduces with the increase of the beam size, while it is a monotonic increasing function of the transverse coherence length. More specifically, it is found that the inequalities of the source sizes in x and y directions, as well as the transverse coherence lengths, play an important role in the ghost image and the visibility.

1. Introduction

Being different from the conventional lens imaging, ghost imaging (GI) is an indirect imaging technique, in which the image of an unknown object can be acquired by means of measurements of the intensity correlation rather than the intensity distribution [1]. In a general lensless setup for GI, a source beam is divided into two beams, propagating in two different paths, respectively. One beam traverses through the test arm in which an object is located, and then be detected by a bucket detector with no spatial resolution, this clearly means that no image is formed depending on this path alone. Another one is referred to as the reference arm that directly collects the information about the source but is spatially resolved by a point-like (single-pixel) detector. Therefore, neither image is available in the output of the high spatial-resolution detector, since the illumination never interacts with the object. But spatial information about the object can be retrieved through correlating the intensities from the two detectors. In general, making using of the same scheme, it is also promising for some other applications, such as the ghost diffraction, the Fourier transform or fractional Fourier transform and ghost interference, relying on the choice of the controllable parameters including those associated with the source beam.

The pioneering work on GI that the first experimental demonstration, performed based on two-photon light (biphotons) generated in spontaneous parametric down-conversion, lied the foundation of the researches concentrating on it [2,3]. Afterwards, it was proved by subsequent demonstrations that the same phenomenon is in existence with classical correlated light, thermal or pseudo-thermal light [4–7], not strictly restricted to the frame of quantum optics. Furthermore, many experimental confirmations were carried out to verify the validity in view of classical light [8,9]. Since the classical cases provide more potential applications and are more simply realizable in comparison with quantum source, much work has been devoted to GI with various initial lights, including the completely incoherent beams, and the partially coherent beams [10–12]. In particular, it is claimed that the visibility of image is strongly affected by the source size and the transverse coherence length. More recently, the treatment for scalar beams on GI has been extended to the electromagnetic domain by taking the effect of the degree of polarization into account [13–16]. And it was concluded by saying that the visibility enhances with the increase of the degree of polarization. Besides, the temporal counterparts for GI were also examined [17,18], in which it was reported that the temporal intensity correlation function of the two ends of detectors is just presented by the fractional Fourier transform of the object. However, it is to be noted that so far most attempts are confined to the incident beams with circular symmetry intensity distribution, never processing the beams with non-circular intensity distribution. Thus further investigations with

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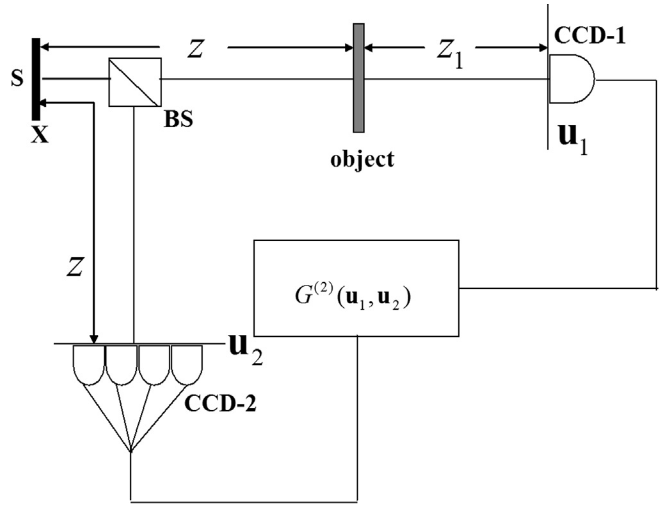

Fig. 1. Lensless geometries for ghost imaging with partially coherent elliptical Gaussian–Schell model beams.

more general form of incident beams are needed to enrich the context of GI.

In this paper, we theoretically consider the GI with a representative beam belonging to the class of non-circular intensity distribution, the partially coherent elliptical Gaussian Schell-model (EGSM) beam to examine the dependences of the image quality and its visibility on the closely relevant parameters about the beam source.

2. Ghost imaging with the partially coherent elliptical Gaussian Schell-model beams

The representative experimental scheme for lensless GI is shown in Fig. 1. Here we have set the distance from the beam source to the object z and the length of the reference arm z_2 to be the same ($z = z_2$), therefore, the scheme becomes a direct ghost imaging system. The same system can be used to study the ghost diffraction only need to set $z < z_2$. The spatial information of the object can be retrieved through the measurements of the intensity correlation from the two detectors, by scanning the point-like detector transversely. Then let us begin by reviewing some basic results of the theory of intensity correlation function for analysis, which is governed by [19,12]

$$G^{(2)}(\mathbf{u}_1, \mathbf{u}_2) = \langle I(\mathbf{u}_1)I(\mathbf{u}_2)\rangle = \langle I(\mathbf{u}_1)\rangle\langle I(\mathbf{u}_2)\rangle + \langle \Delta I(\mathbf{u}_1)\Delta I(\mathbf{u}_2)\rangle, \tag{1}$$

where $\mathbf{u}_i$ $(i = 1, 2)$ is the spatial argument of the ith detector, and the angular brackets denote the ensemble average. In the total results of intensity correlation, only the second term on the right-hand side of Eq. (1) plays an important role in the GI as it contains the information of the object, while the first term contributes only to the background, namely, it cannot be used to implement correlated imaging.

According to the definition of intensity fluctuation, it is expressed as

$$\Delta I(\mathbf{u}_i) = I(\mathbf{u}_i) - \langle I(\mathbf{u}_i)\rangle, \tag{2}$$

where $I(\mathbf{u}_i)$ is the instantaneous intensity and is given by the expression

$$I(\mathbf{u}_i) = E^*(\mathbf{u}_i)E(\mathbf{u}_i), \tag{3}$$

here the star denotes the complex conjugate.

Making an assumption that the fluctuations of the field obey the Gaussian statistics, and using the moment theorem for complex Gaussian random process [19], it is readily shown that the term of intensity fluctuations takes the form

$$\langle \Delta I(\mathbf{u}_1)\Delta I(\mathbf{u}_2)\rangle = \left|W(\mathbf{u}_1, \mathbf{u}_2)\right|^2, \tag{4}$$

which means that the cross-spectral density function, comprised by $W(\mathbf{u}_1, \mathbf{u}_2) = \langle E^*(\mathbf{u}_1)E(\mathbf{u}_2)\rangle$, can be interpreted as a description of the correlation between the field's intensity fluctuations at the outputs of text arm and reference arm.

The cross-spectral density function of the output plane is related with that in the plane of the source by [19]

$$W(\mathbf{u}_1, \mathbf{u}_2) = \iint\iint W^{(0)}(\mathbf{r}_1, \mathbf{r}_2)h_1(\mathbf{u}_1, \mathbf{r}_1)h_2^*(\mathbf{u}_2, \mathbf{r}_2)\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2. \tag{5}$$

And accordingly, for the average intensity it is taken to be

$$\langle I(\mathbf{u}_i)\rangle = \iint\iint W^{(0)}(\mathbf{r}_1, \mathbf{r}_2)h_i(\mathbf{u}_i, \mathbf{r}_1)h_i^*(\mathbf{u}_i, \mathbf{r}_2)\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2. \tag{6}$$

Among the above equations the function $h_i(\mathbf{u}_i, \mathbf{r}_1)$ represents the response function of the two optical paths having the forms

$$h_1(\mathbf{u}_1, \mathbf{r}_1) = \frac{1}{\lambda^2 z z_1}\iint \exp\left[-\frac{ik}{2z}(\mathbf{r}_1 - \mathbf{v}_1)^2 - \frac{ik}{2z_1}(\mathbf{v}_1 - \mathbf{u}_1)^2\right]H(\mathbf{v}_1)\mathrm{d}\mathbf{v}_1, \tag{7}$$

and

$$h_2(\mathbf{u}_2, \mathbf{r}_2) = -\frac{i}{\lambda z}\exp\left[-\frac{ik}{2z}(\mathbf{r}_2 - \mathbf{u}_2)^2\right], \tag{8}$$

where $H(\mathbf{v}_1)$ is the transmission function of the object to be imaged. In general, the spatial information about the object can take any form of transparency, without restrictions on the determinate object. For the sake of convenience in our following calculations, we take a soft circular aperture as example to be the imaged, whose transmission function is expressible in the form [20]

$$H(\mathbf{v}_1) = \frac{1}{C_0}\sum_{n=1}^{N}\frac{(-1)^{n-1}}{N}\binom{N}{n}\exp\left(-\frac{n\mathbf{v}_1^2}{a_0^2}\right). \tag{9}$$

The coefficient $C_0 = \sum_{n=1}^{N}\frac{(-1)^{n-1}}{N}\binom{N}{n}$ normalizes the intensity distribution of the soft circular aperture, and a_0 is the radius of the aperture (Fig. 2).

Now we will consider a partially coherent EGSM beam as the initial source, which is statistically stationary, at least in a wide-sense, whose cross-spectral density function is characterized by [21]

$$W^{(0)}(x_1', y_1', x_2', y_2') = \exp\left(-\frac{x_1'^2 + x_2'^2}{4w_{0x}^2} - \frac{y_1'^2 + y_2'^2}{4w_{0y}^2}\right) \times \exp\left[-\frac{(x_1' - x_2')^2}{2\sigma_{0x}^2} - \frac{(y_1' - y_2')^2}{2\sigma_{0y}^2}\right], \tag{10}$$

where w_{0i} and σ_{0i} denote the source size and the transverse coherence length of the i component of the source, respectively. Here the nondiagonal elements of the transverse spot width matrix and the transverse coherence width matrix have been supposed to be zero so that the variables x_i' and y_i' can be handled separately.