Subwavelength Fourier-transform imaging without a lens or a beamsplitter*

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The fourier-transform patterns of an object are usually observed in the far-field region or obtained in the near-field region with the help of lenses. Here we propose and experimentally demonstrate a scheme of Fourier-transform patterns in the Fresnel diffraction region with thermal light. In this scheme, neither a lens nor a beamsplitter is used, and only one single charge coupled device (CCD) is employed. It means that dividing one beam out of a light source into signal and reference beams is not as necessary as the one done by the use of a beamsplitter in usual ghost interference experiments. Moreover, the coincidence measurement of two point detectors is not necessary and data recorded on a single CCD are sufficient for reconstructing the ghost diffraction patterns. The feature of the scheme promises a great potential application in the fields of X-ray and neutron diffraction imaging processes.

Keywords: thermal light, Fourier imaging, intensity correlation

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1. Introduction

The first ghost imaging experiment was realized by Pittman *et al.*[1] with entangled photon pairs of spontaneous parametric down-conversion in 1995. In the ghost imaging process, one beam out of a light source is divided by a beamsplitter into signal and reference beams. The signal beam goes through an object and is detected by a bucket detector. The reference beam directly propagates to a spatial distribution detector, such as a charge coupled device (CCD) or a point detector scanning on the observing plane. Neither of the two detectors can reveal the spatial distribution of the object alone. However, one can obtain the object image from the coincidence measurement of the two beams. Lately, the ghost imaging was realized with two correlated light beams[2] and thermal light.[3–6]

There are two kinds of (quantum and classical) interpretation to the ghost imaging. The quantum theory explains that the ghost imaging results from the two-photon (multiphoton) probability amplitude interference.[7] However, the classical theory argues that the ghost imaging can be interpreted by the intensity fluctuation correlation between the signal and reference light beams[4] or semiclassical photon detection theory.[8] Besides the ghost imaging, ghost diffraction and subwavelength interference were also implemented with entangled photon pairs and thermal light.[9–15] Noise is the key factor which effects image quality, and some groups have analyzed the ghost imaging.[16,17] In the last few years, numerous new techniques have been developed to improve the imaging quality and signal-to-noise ratio, such as computational ghost imaging,[18,19] compressive ghost imaging,[20] differential ghost imaging,[21] and high-order ghost imaging.[22–25]

In usual thermal light ghost diffraction experiments, either beamsplitters or lenses and even both are indispensable optical components. The usage of these optical devices limits applications of the ghost imaging in some important fields such as X-ray, electron and neutron diffraction images. Therefore, a desirable goal is to realize the ghost imaging without either a lens or a beamsplitter, and even both. In 2004, Cheng *et al.*[26] proposed a scheme with a classical incoherent light source to realize lensless Fourier-transform ghost imaging at the Fresnel distance. In 2007, they experimentally demonstrated a proposal with a thermal light source and showed that the Fourier-transformation diffraction pattern can be constructed from the intensity correlation between the signal and reference beams measured at the Fresnel distance.[15] In 2010, the same group implemented a ghost diffraction experiment without a beamsplitter.[27] In their setup, the ground glass attached by a random pin-hole was used to simulate a thermal light source and two focus lenses were placed in the signal and reference beams to make sure that the measured light comes from the same point of the ground glass. Cao *et al.*[28] proposed a scheme of the double-slit interference with thermal light and demonstrated that the visibility and resolution of the interference pattern can be enhanced by using the higher-order

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correlation of the diffracted light. It is interesting that neither lens nor beamsplitters are required in the scheme and the higher-order correlations are extracted from the data recorded by a single CCD detector placed on the observing plane in the Fraunhofer diffraction region. We notice that Wang *et al.*[29] conducted a Fraunhofer diffraction experiment to realize the subwavelength two-photon Airy disk which can avoid the influence propagation. In this paper, we experimentally demonstrate that the Fourier-transformation image of an object illuminated by thermal light can be observed in the Fresnel diffraction region without a lens and a beamsplitter.

2. Model and method

Our experimental setup is depicted in Fig. 1. The thermal light is produced by a He–Ne laser wath a 632.8 nm wavelength and a rotating ground glass disk (GGD). The angular velocity of the GGD is kept at $\omega = \pi$ rad/s. A double slit is placed right after the GGD. The width of each slit is $a = 0.5$ mm, and the distance between the centers of the two slits is $d = 1.5$ mm. The thermal light shines on the double slit and the diffracted light behind the double slit propagates freely to the detecting plane, and then is recorded by a single CCD detector. The CCD is located at $z = 20$ cm behind the double slit. As is well known, the bound between the Fresnel diffraction and the Fraunhofer diffraction is determined by the diffraction distance $z_0 \approx d^2/\lambda$, where d is the size of the object, and λ is the wavelength of the light source. The low bound of our experiment for the Fourier-transform imaging is $z_0 = 3.5$ m when the GGD is moved out. Thus, the CCD in the setup illustrated in Fig. 1 is placed in the Fresnel diffraction region with respect to the double slit.

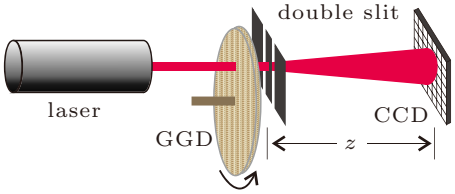


Fig. 1. Schematic of one beam second-order correlation measurement. The GGD and double slit are put as close as possible. The detecting plane (CCD) is placed in the Fresnel diffraction region for the double slit. The CCD is 1040×1392 array of 4.65×4.65 μm^2 pixels, and the measurement is performed with an exposure time of 100 μs.

If the GGD is taken away from the setup, only the projection of the double slit is observed on the CCD detection plane because the CCD is placed very close to the object. In Fig. 2(a), we show the intensity distribution of the transmitted light on the CCD plane without the GGD. Obviously, it is only the projection of the double slit with inevitable baffle edge diffraction. When the GGD is inserted in the light beam, the intensity distribution of the diffracted light measured on the CCD plane is shown in Fig. 2(b). It is seen that except for the random diffraction speckles, there is no information about the object. In this case, one cannot observe the diffraction pattern of the object by directly observing the intensity of the diffracted light.

The intensity correlation function of a field is defined as $G^{(2)}(\boldsymbol{x}_1, \boldsymbol{x}_2) = \langle I_1(\boldsymbol{x}_1) I_2(\boldsymbol{x}_2) \rangle$, where $I_i(\boldsymbol{x}_i)$ is the intensity of the field at location $\boldsymbol{x}_i$ and $\langle \cdots \rangle$ represents averaging over time. According to Ref. [26], the fluctuation of the intensity correlation function of the diffracted light can be related to the first-order correlation function of a light source by the integral

$$\begin{aligned} &\Delta G^{(2)}(\boldsymbol{x}_1, \boldsymbol{x}_2) \\ &= G^{(2)}(\boldsymbol{x}_1, \boldsymbol{x}_2) - \langle I_1(\boldsymbol{x}_1) \rangle \langle I_2(\boldsymbol{x}_2) \rangle \\ &= \left| \iint \mathrm{d}\boldsymbol{x}_1 \mathrm{d}\boldsymbol{x}_2 h_1^*(\boldsymbol{x}_1, \boldsymbol{x}_1') h_2(\boldsymbol{x}_2, \boldsymbol{x}_2') G^{(1)}(\boldsymbol{x}_1', \boldsymbol{x}_2') \right|^2, \end{aligned} \tag{1}$$

where $h_1(\boldsymbol{x}_1, \boldsymbol{x}_1')$ and $h_2(\boldsymbol{x}_2, \boldsymbol{x}_2')$ are the impulse response functions of optical systems for the signal and reference light beams transmitting from the light source to the observing planes, respectively. In Eq. (1), the first-order correlation function $G^{(1)}(\boldsymbol{x}_1', \boldsymbol{x}_2')$ is defined as $\langle E^*(\boldsymbol{x}_1') E(\boldsymbol{x}_2') \rangle$, where $E(\boldsymbol{x}_i')$ is the amplitude of the electrical field on the light source plane at location $\boldsymbol{x}_i'$. As shown in Fig. 1, the light beam coming out of the light source is not divided into two parts, so-called signal and reference beams, in usual ghost diffraction schemes.[15] It means that in our scheme, the signal and reference light beams are the same, and both of them experience the same optical system. Correspondingly, the impulse response functions have the identical expression

$$h_1(\boldsymbol{x}, \boldsymbol{x}') = h_2(\boldsymbol{x}, \boldsymbol{x}') = \frac{\mathrm{e}^{\mathrm{i}kz}}{\mathrm{i}\lambda z} \mathrm{e}^{-\mathrm{i}\frac{k(\boldsymbol{x}-\boldsymbol{x}')^2}{2z}} T(\boldsymbol{x}'), \tag{2}$$

where $k = 2\pi/\lambda$ is the wave number and $T(\boldsymbol{x}')$ is the transmission function of the object. Here we have assumed that the object is placed as close as possible to the GGD and the detection plane is in the Fresnel zone. Suppose that the light source is fully spatially incoherent. Then, its first correlation function can be written as

$$G^{(1)}(\boldsymbol{x}_1', \boldsymbol{x}_2') = I_0 \delta(\boldsymbol{x}_1' - \boldsymbol{x}_2'), \tag{3}$$

where $\delta(\boldsymbol{x})$ is the Dirac delta function, and I_0 is the intensity distribution of the light on the source plane. Here, we have assumed that the intensity distribution of the incoherent thermal light on the source plane is uniform. Substituting Eqs. (2) and (3) into Eq. (1), we obtain

$$\Delta G^{(2)}(\boldsymbol{x}_1, \boldsymbol{x}_2) = \left| \frac{2\pi I_0}{\lambda^2 z^2} \widetilde{T^2}\left(\frac{k}{z} (\boldsymbol{x}_2 - \boldsymbol{x}_1) \right) \right|^2, \tag{4}$$

where $\widetilde{T^2}(\cdot)$ is the Fourier transformation of $T^2(\boldsymbol{r})$. This result shows that a well-defined Fourier-transform diffraction pattern of the object can be extracted from the intensity correlation fluctuation (Eq. (1)).

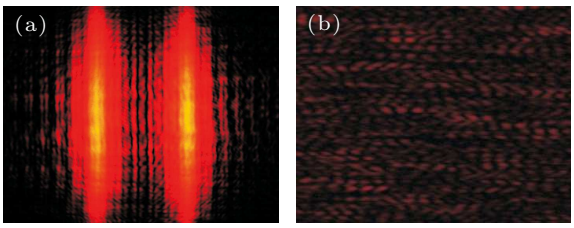


Fig. 2. Intensity distribution of the diffraction field from the double slit illuminated by (a) the coherent light and (b) the incoherent thermal light.

In a real experiment, the light intensity on the source plane may not be completely uniform. To remove the effects induced by the variation of the light intensity on the source plane, instead we consider the normalized correlation function $g^{(2)}(\boldsymbol{x}_1,\boldsymbol{x}_2)=\langle I(\boldsymbol{x}_1)I(\boldsymbol{x}_2)\rangle/(\langle I(\boldsymbol{x}_1)\rangle\langle I(\boldsymbol{x}_2)\rangle)$. From Eq. (4), we find the relation $g^{(2)}(\boldsymbol{x}_1,\boldsymbol{x}_2)\propto|\widetilde{T^2}(k(\boldsymbol{x}_2-\boldsymbol{x}_1)/z)|^2$. It means that a diffraction pattern of the object can be extracted from the normalized intensity correlation function although the diffraction pattern $|\widetilde{T^2}(k\boldsymbol{x}/z)|^2$ is not directly observed on the CCD plane under our experiment conditions.

In usual ghost diffraction experiments, the intensity correlation between the signal and reference beams is directly measured by the coincidence counts of two point detectors scanning on the observing planes. In the following, we will show that the Fourier transformation can be reconstructed from the data recorded by a single CCD even in the Fresnel diffraction region. In Eq. (4), we notice that the Fourier-transformation patterns extracted from the intensity correlation fluctuation depends on the scanning direction and step of the two point detectors on the observing planes of the signal and reference beams. In Ref. [10], the subwavelength interference pattern is obtained with an entangled light source when the detectors synchronously scan along the same direction. In Ref. [13], however, it is shown that the subwavelength interference pattern can be constructed with a thermal light source only when the two detectors scan along the opposite direction with the same step. Here we consider the intensity correlation at two points $(x,-x)$ of the CCD plane.

We take the data recorded on one row of the CCD plane as the measured results of the two point detectors. Then the center of the row of the CCD is regarded as the origin and the pair points $(x,-x)$ are taken from the two opposite directions along the row. The $I(x)$ and the product $I(x)I(-x)$ calculated from each row of the two-dimensional data as shown in Fig. 2(b) are averaged over 10000 frame measured results. Finally, we obtain the two-dimensional normalized diffraction pattern as shown in Fig. 3(a). The highest contrast ratio of the resulting pattern is 31.1%, which approaches the theoretical limit of 33.3%.[13] Figure 3(b) shows the one-dimensional diffraction patterns, obtained directly from one of the rows of Fig. 3(a). In Fig. 3(b), five primary peaks are observed clearly. The distance from the zeroth-order to the first-order interference peak in Fig. 3(b) is about 42.7 μm and is in agreement with the theoretical value of 42.2 μm that is expected from Eq. (4). The diffraction fringe spacing is much smaller in the Fresnel region than the fringe obtained in the Fraunhofer diffraction region.[28] For example, the minimum fringe spacing is 1.5 mm when the observing plane is placed at the lower bound distance $z=3.5$ m and the double-slit is illuminated with coherent light. From the above results, we see that the well-defined subwavelength Fourier-transform patterns in the Fresnel diffraction region is reconstructed just from the data recorded by a single CCD detector.

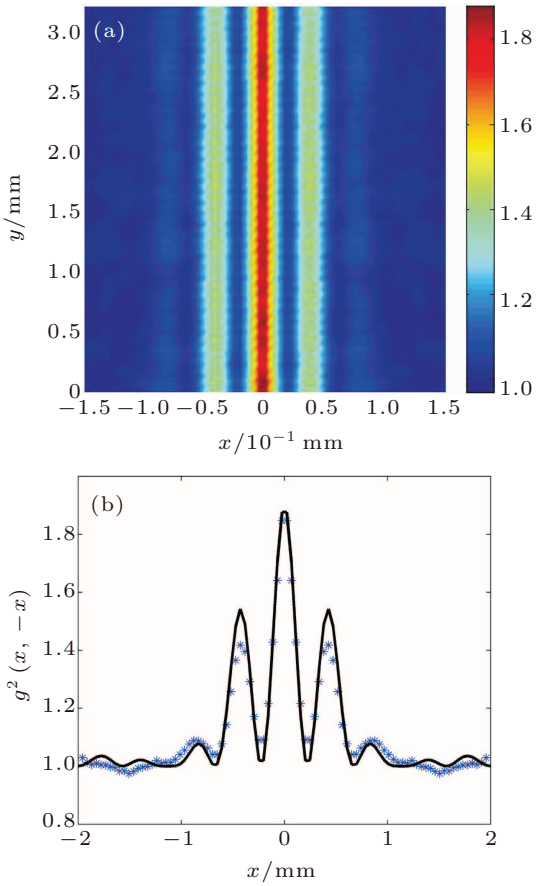


Fig. 3. Second-order correlation patterns in the Fresnel diffraction region. (a) $g^2(x,-x)$ on the CCD plane and (b) in one row of the CCD plane. The blue star represents the experimental intensity distribution and the black line represents the theoretical Fourier-transform image of the double slit.

Compared with usual ghost imaging schemes in which two point detectors are used, our scheme employs only a single CCD detector. Figure 4(a) shows a complete intensity correlation distribution of $g^{(2)}(x_1,x_2)$, and the subwavelength interference pattern can be obtained in the diagonal direction. The CCD detector can help us get sufficient data one time for reconstructing the Fourier imaging if the object possesses some symmetrical characteristics. For example, we can add all the rows of the second-order correlation obtained from one sample to reduce the total number of samples in our experi-

ment. Therefore, we can record only ten frames of the two-dimensional data (Fig. 2(b)) to obtain a second-order correlation diffraction pattern similar to Fig. 4(a), which is shown in Fig. 4(b), because our CCD array is 1040×1392 pixels and the ten frames are equivalent to 10400 samples obtained by two point detectors in usual ghost imaging experiments. Therefore, our proposal would save considerable time for the realization of the Fourier-transform imaging with a one-dimensional object.

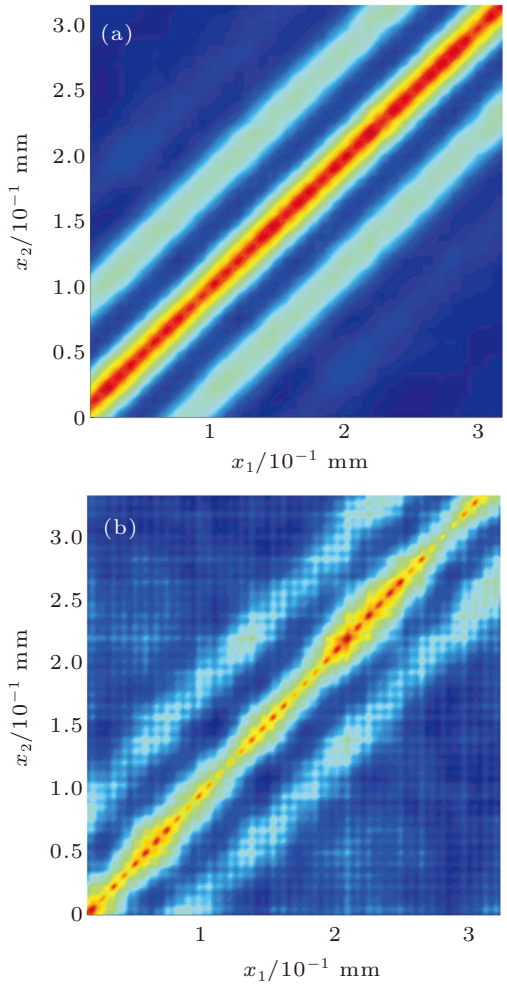


Fig. 4. Complete second-order correlation patterns in the Fresnel diffraction region. (a) $g^2(x,-x)$ with the same row of all frames; (b) $g^2(x,-x)$ with all the rows of ten frames.

3. Summary

In summary, we propose and experimentally demonstrate a scheme of the Fourier-transform diffraction in the Fresnel diffraction region. The scheme has several remarkable features. First, the subwavelength-resolution Fourier-transform diffraction pattern with thermal light can be constructed in the Fresnel diffraction region without a lens and a beamsplitter. The contrast ratio of the rebuilt pattern approaches the limitation of the ghost diffraction with thermal light. Second, the experimental setup is very simple and contains only one incoherent light source and a single CCD detector. It means that dividing one beam into signal and reference beams is not so necessary as the one done by the use of a beamsplitter in usual ghost diffraction experiments. These features promise a great potential application of our scheme in the fields of X-ray and neutron diffraction imaging processes, where suitable lenses or beamsplitters or even both of them are unavailable.

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