X-ray ghost imaging with a laboratory source

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Abstract: We describe an experiment demonstrating ghost imaging with an incoherent low brightness X-ray tube source. We reconstruct the images of 10 μm and 100 μm slits with very high contrast. Our results advance the possibilities that the high-resolution method of ghost diffraction will be utilized with tabletop X-ray sources.

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References and links
1. Introduction

Ghost imaging (GI) and Ghost diffraction (GD) are imaging techniques, in which the reconstruction of objects is achieved by using the spatial intensity correlations between two beams. In many schemes, this is done by introducing spatial intensity fluctuations into the input beam, which is split into two beams with identical intensity fluctuations. One of the beams propagates through the object and it is collected by a single-pixel detector while the second beam does not interact with the object and it is collected by a multi-pixel detector. The image is reconstructed from the instantaneous spatial-second-order intensity correlation function that is measured for various realizations of the intensity fluctuations at the input [1].

The thermal light sources are implemented either by using a coherent source together with optical components with a small speckle size such as a rotating glass [1–3] or a spatial light modulator, or by using true thermal light sources [4]. The advantage of the former approach is the ability to control the resolution and the contrast of the apparatus by choosing the speckle size and their variation rate [2, 3]. The techniques have been studied extensively in the optical regime [1–20] and recently GI with atoms [21] and temporal GI [5] have been demonstrated.

Since the use of X-ray lenses for imaging is very limited because of their small magnification and aperture size, lensless techniques are widely used in this regime [22–25]. However, despite that nanometer scale resolution has been achieved with coherent X-ray radiation, which is generated by X-ray free-electron lasers [22], X-ray imaging with low brightness incoherent sources utilize mainly direct absorption measurements and no magnification or small magnification is used. Consequently, although the phase information of objects could enhance the contrast of images, this quantity is almost never measured in systems based on incoherent sources, and the resolution of those systems is not smaller than the pixel size of the camera. Both GI and GD are promising for X-ray imaging since they require neither coherent bright sources nor lenses and can lead to high-resolution and high-contrast imaging techniques that can be implemented with low-cost X-ray sources [26].

X-ray GI and GD have been demonstrated experimentally with synchrotron radiation generated by large accelerators [27, 28]. In the GI experiment the intensity fluctuations of the synchrotron were used, while in the GD experiment, the authors used spatially coherent radiation and a diffuser with a moving porous gold film. While those important demonstrations advance significantly the extension of GI and GD into the X-ray regime, the sources that were used are not tabletop sources.

We note that GI and GD techniques can be implemented also by using photon pairs that are created by using parametric down conversion [2, 6, 7]. However, X-ray parametric down-conversion with reasonable signal-to-noise ratio has been reported only with synchrotron sources [29, 30].

Here we make another step in the direction of utilizing tabletop sources for high-resolution X-ray imaging and demonstrate experimentally thermal GI with an X-ray tube.
source. We describe experiments that show the possibility to reconstruct images by using incoherent X-ray sources. Although the source in incoherent, we implement the thermal source by using a rotating copy paper. This is because the intensity fluctuations of the source are weak and fast. We note that this scheme works since the divergence of X-ray beams is much weaker than the divergence of optical beams due to the very short wavelength.

2. Experimental system and procedure

The experiments are conducted by using the Rigaku Smartlab X-ray diffraction system with a 9 kW rotating Cu anode system, which radiates at 8.05 keV (1.54 Å). The schematic of the experimental setup of the GI experiments is shown in Fig. 1. The beam is collimated and monochromatized by parabolic multilayer mirror and a Ge(220) channel-cut monochromator. The estimated divergence angle is about 0.1 mrad. The relative spectral bandwidth $\Delta E / E$ is about $10^{-4}$.

We introduce the intensity fluctuations by using a diffuser made from a copy paper, where the average speckle size is about 1 μm. We split the beam into two beams by using a highly ordered pyrolytic graphite (HOPG) crystal in Bragg geometry, where we choose the (004) reflection and the corresponding Bragg angle is 27.5°. We choose to implement the beam splitter with the HOPG because, as we show below, its rocking curve is much broader than the width of the angular distribution of the intensity fluctuations and because its reflection efficiency is nearly 50%. The HOPG is mounted 100 mm from the diffuser.

Fig. 1. Schematic of the ghost imaging experimental setup. A copy paper diffuser is mounted on a rotation stage. A highly oriented pyrolytic graphite crystal splits the beam into a transmitted beam (reference arm) and a reflected beam (test arm). The spatial resolution of the reference arm is realized via a scanning slit. The object is mounted very close to the single-pixel detector and the distances between the two detectors and the highly oriented pyrolytic graphite are equal.

For detectors, we use a fast silicon drift detector (SDD) and an avalanche photo-diode (APD). The reflected beam propagates through the object and it is collected by one of the detectors, which we denote as the test detector. The transmitted beam propagates directly into the detection system, which includes a scanning slit and a second detector that we denote as the reference detector. The input average flux before the diffuser is $2 \times 10^8$ photons/s. The diffracted average flux and the transmitted average flux are $\sim 1 \times 10^7$ photons/s and $\sim 2 \times 10^7$
photons/s, respectively (about $6 \times 10^7$ photons/s are absorbed in the HOPG crystal). The scanning slits and the objects are mounted very close to the detectors and centered with respect to the centers of the beams.

The objects we test in this work are one-dimensional 10 μm and 100 μm slits. The resolution of the scans is 2 μm and 10 μm, for 10 μm and 100 μm slits, respectively. The properties of the objects and the scanning slits are summarized in Table 1. We summarize the parameters of the measurements in Table 2. We denote the distances between the detectors and the beam splitter as $d_r$.

### Table 1. Properties of GI objects and scanning slits

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<tr>
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<tbody>
<tr>
<td>Object</td>
<td>10</td>
<td>Tungsten</td>
<td>20</td>
<td>$1.77 \times 10^{-3}$</td>
</tr>
<tr>
<td>Object</td>
<td>100</td>
<td>Stainless steel</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Scanning slit</td>
<td>2</td>
<td>Tungsten</td>
<td>20</td>
<td>$1.77 \times 10^{-3}$</td>
</tr>
<tr>
<td>Scanning slit</td>
<td>5</td>
<td>Gold and stainless steel</td>
<td>25.4, 12.7</td>
<td>$2.12 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

### Table 2. Parameters of GI measurements

<table>
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<tbody>
<tr>
<td>10</td>
<td>150</td>
<td>5</td>
<td>37,500</td>
<td>21,800</td>
<td>1.066x10^9</td>
<td>3.6x10^3</td>
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<tr>
<td>100</td>
<td>550</td>
<td>1.5</td>
<td>8,000</td>
<td>10,000</td>
<td>6.125x10^7</td>
<td>2.4x10^7</td>
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Denoting $x_{ref}$ and $x_{test}$ as the coordinates across the reference and the test detectors, respectively, we write the normalized second-order intensity correlation function as [2]:

$$G^{(2)}(x_{ref}, x_{test}) = \frac{\langle I_{ref}(x_{ref})I_{test}(x_{test}) \rangle - \langle I_{ref}(x_{ref}) \rangle \langle I_{test}(x_{test}) \rangle}{\langle I_{ref}(x_{ref}) \rangle \langle I_{test}(x_{test}) \rangle}. \quad (1)$$

where the indices $I_{ref}$, $I_{test}$ are the average intensities (the count rate divided by the effective area of the detector) at the reference and test detectors, respectively. The $\langle \rangle$ indicates an ensemble average over the realizations, where each of the realizations refers to a different position on the copy paper and therefore represents different intensity fluctuations.

To reconstruct the images of the objects we calculate the normalized second-order intensity correlation function from the measurements of the intensities of both detectors at various positions of the scanning slit before the reference detector. For each position of the scanning slit we rotate the diffuser continuously at a constant velocity. The parameters for each of the measurements are summarized in Table 2. We apply a minimal threshold to the coincidence counts of each realization to enhance the visibility of the image [18]. We obtain the average intensities of the two detectors by averaging over the intensities of all the realizations.

### 3. Results and discussions

Figure 2 shows the results for GI and the comparison with scanning electron microscopy (SEM) measurements. The SEM curves are obtained by integrating over two dimensional data from the SEM measurements in Fig. 3. GI and SEM measurements of the 10 μm slit are shown in panel (a) and of the 100 μm slit are shown in panel (b). The respective GI measured widths of the slits in panels (a) and (b) are $10 \pm 1$ μm and $100 \pm 5$ μm. The respective SEM measured widths of the slits in panels (a) and (b) are $10.662 \pm 0.078$ μm and $101.24 \pm 1.25$ μm. The measured slit widths of the GI and the SEM measurements are in agreement. The contrast between the edges of the slits and the slit centers in the GI measurements are much higher than in the SEM measurements.
To get a deeper insight on our technique including its limitations and future opportunities, we discuss the parameters of the diffuser and of the beam splitter. The first parameter that affects the quality of the image is the magnitude of the intensity fluctuations that are introduced by the diffuser. Unlike the optical regime, X-ray scattering is weak in general, thus we need to verify that the scattering by the diffuser is strong enough to introduce intensity fluctuations, which are higher than the background noise. Furthermore, since we use a low brightness source, the measurement time of each realization should be such that the statistical error is smaller than the intensity fluctuations that we introduce with the diffuser.

Another important parameter is the temporal rate of the variation of the intensity fluctuations. It has been shown that this rate should be slower than the response time of the detector [2, 3, 18]. However, since in this work we use fast detectors with a time resolution below 1 µsec, we overcome this challenge very easily.

A typical trace of the normalized intensity fluctuations is shown in Fig. 4(a). Each realization represents a different position on the surface of the diffuser. A 2-µm tungsten slit...
is mounted in front of the detector at a distance of 350 mm from the diffuser. The integration time at each realization is 10 sec. The measured standard deviation of the intensity fluctuations introduced by the diffuser is 0.97%. The measured standard deviation of the source without a diffuser is 0.22%. The conclusion is that for sufficiently long averaging times the intensity fluctuations of the diffuser become dominant, which allows its use for GI with X-rays.

The next important requirement is that the acceptance angle of the beam splitter is much larger than the angular spread of the intensity fluctuations that the diffuser introduces. This is because the beam splitter is based on Bragg diffraction, which is angular dependent. Thus, if the acceptance angle of the beam splitter is not wide enough, the reflected beam contains only intensity fluctuations that are within the angular acceptance of the beam splitter, while the transmitted beam contains the entire range of the fluctuations. Consequently, the intensity fluctuations of the two beams are not identical and the contrast is highly reduced.

The angular acceptance angles of the copy paper diffuser in the horizontal and vertical directions are shown in Figs. 4(b) and 4(c), respectively. The results are obtained by Fourier transforming the visible microscope image of the paper. The axes are scaled to reflect the angular acceptance of the copy paper diffuser by using the relation for small angles \( \theta_i = k_i / k \), where \( k_i \) is the coordinate along the x and y axes of the Fourier transform of the microscope image, and \( k = 4.078 \times 10^{10} \) \( 1/m \) is the wave vector of the X-ray source. We find that the full-width at half-maximum (FWHM) of the angular distribution of the fluctuations introduced by the copy paper diffuser is smaller than 0.002°. The rocking curve of the HOPG beam splitter is shown in Fig. 4(d). The HOPG angular acceptance angle at the FWHM is...
0.72°. It is clear from Fig. 4 that the HOPG complies with the requirement that the rocking curve will be much larger than the angular spread of the intensity fluctuations.

We note that the horizontal and vertical directions in Figs. 4(b) and 4(c) exhibit different shapes and widths. The effective speckle size at the object plane can be estimated as θ\text{iz}, where z is the distance between the diffuser and the object. The calculated effective speckle sizes for the GI measurements in Figs. 2(a) and 2(b) are then approximately 4.4 µm and 9.6 µm, respectively. We note that the actual effective speckle size may be smaller due to resolution limitations of the optical microscope. Since the resolution of GI is limited by the speckle size, which has to be smaller than the object [2, 3, 13], we expect the that the reconstruction of the 100 µm slit in Fig. 2(b) would be better than the reconstruction of the 10 µm slit in Fig. 2(a), where most of the speckles are larger than the imaging resolution. The results shown in Fig. 2(a) are not influenced due to the large number of realizations taken to obtain this image.

4. Conclusion

We report the observation of ghost imaging in the X-ray regime with an incoherent low-brightness laboratory system. We demonstrated the ghost imaging effect with 10 µm and 100 µm slits at scanning resolutions of 2 µm and 10 µm, respectively.

It is most likely that by mounting the object far from the test detector it will be possible to measure ghost diffraction with laboratory X-ray sources. In this scheme, the diffraction pattern of the object is reconstructed from the measurements of the correlation function [26]. In this case the resolution of the image is limited by the largest k-vector of the beam and by the near field speckle size and not by the pixel size of the multi-pixel detector [20]. We therefore expect that the resolution of ghost diffraction will be much better than the pixel size of the state-of-the-art cameras. Hence, this approach can lead to the development of high-resolution incoherent X-ray imaging techniques. Moreover, since in ghost diffraction, the diffraction pattern depends on variations of the refractive index of the object and not just on its absorption, the approach can lead also to high-contrast imaging techniques. This is because the phase inhomogeneity that is introduced by objects is in many cases much stronger than the amplitude variations [25].

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