

Video Article

Measurement of X-ray Beam Coherence along Multiple Directions Using 2-D Checkerboard Phase Grating

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Abstract

A procedure for a technique to measure the transverse coherence of synchrotron radiation X-ray sources using a single phase grating interferometer is reported. The measurements were demonstrated at the 1-BM bending magnet beamline of the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). By using a 2-D checkerboard $\pi/2$ phase-shift grating, transverse coherence lengths were obtained along the vertical and horizontal directions as well as along the 45° and 135° directions to the horizontal direction. Following the technical details specified in this paper, interferograms were measured at different positions downstream of the phase grating along the beam propagation direction. Visibility values of each interferogram were extracted from analyzing harmonic peaks in its Fourier Transformed image. Consequently, the coherence length along each direction can be extracted from the evolution of visibility as a function of the grating-to-detector distance. The simultaneous measurement of coherence lengths in four directions helped identify the elliptical shape of the coherence area of the Gaussian-shaped X-ray source. The reported technique for multiple-direction coherence characterization is important for selecting the appropriate sample size and orientation as well as for correcting the partial coherence effects in coherence scattering experiments. This technique can also be applied for assessing coherence preserving capabilities of X-ray optics.

Video Link

The video component of this article can be found at <https://www.jove.com/video/53025/>

Introduction

The third-generation hard X-ray synchrotron radiation sources, such as the APS at ANL, Lemont, IL, USA (<http://www.aps.anl.gov>), have had tremendous impacts on the development of X-ray sciences. A synchrotron radiation source generates a spectrum of electromagnetic radiations, from infrared to X-ray wavelengths, when charged particles, such as electrons, are made to move near the speed of light in a circular orbit. These sources have very unique properties such as high brightness, pulsed and pico-second timing structure, and large spatial and temporal coherence. X-ray beam spatial coherence is an important parameter of the third and fourth generation synchrotron sources and the number of experiments making use of this property has dramatically increased over the past two decades¹. The future upgrades of these sources, such as the planned Multi-bend achromat (MBA) lattice for the APS storage ring, will dramatically increase the beam coherent flux (<http://www.aps.anl.gov/Upgrade/>). The X-ray beam can be tuned using a crystal monochromator to achieve higher temporal coherence. The transverse coherence of synchrotron sources is significantly higher than that of laboratory based X-ray sources because of the low electron-beam emittance and long propagation distance from the source to the experimental station.

Normally, Young's double-pinhole or double-slit experiment is used to measure the spatial coherence of the beam through the inspection of the visibility of the interference fringes². To obtain the complete Complex Coherence Function (CCF), systematic measurements are needed with the two slits placed at different positions with various separations, which is, especially for hard X-rays, cumbersome and impractical. Uniformly Redundant Array (URA) can also be used for beam coherence measurement by employing it as a phase shifting mask³. Although the technique can provide the full CCF, it is not model-free. More recently, interferometric techniques based on Talbot effect were developed using the self-imaging property of periodic objects. These interferometers make use of the interferogram visibility measured at a few self-imaging distances downstream of the grating for obtaining the beam transverse coherence⁴⁻⁹. Measurements of transverse coherence using two grating system is also reported⁷.

Mapping the transverse beam coherence, simultaneously along vertical and horizontal directions was first reported by J. P. Guigay *et al.*⁵. Recently, scientists in the Optics Group, X-ray Science Division (XSD), of APS have reported two new techniques to measure beam transverses coherence along more than two directions simultaneously using two methods: one with a checkerboard phase grating⁸, and the other with a circular phase grating⁹.

In this paper the measurement and data analysis procedures are described for obtaining the transverse coherence of the beam along the 0°, 45°, 90°, and 135° directions relative to the horizontal direction, simultaneously. The measurements were carried out at the 1-BM beamline of APS with a checkerboard $\pi/2$ phase grating. The details of this technique listed in the protocol sections include: 1) planning of the experiment; 2) preparation of the 2-d checkerboard phase grating; 3) experiment setup and alignment at the synchrotron facility; 4) performing coherence measurements; 5) data analysis. In addition, the representative results are shown to illustrate the technique. These procedures can be carried out at many synchrotron beamlines with minimum changes on the grating design.

Protocol

1. Planning of the Experiment

1. Identify the synchrotron beamline. Contact beamline scientist to find the appropriateness of the experiment at that beamline.
NOTE: Experiments reported in this manuscript were performed at the 1-BM-B beamline, which is dedicated to optics and detectors testing, under XSD of APS.
2. Submit a user proposal and beam time request.
3. Work out the details of the experiment with the beamline scientist and specify the required instruments including motorized stages for the grating and detector alignment, 2-dimensional detector (CCD or CMOS), long translation stage covering the least and farthest distances needed between the detector and the phase grating.
4. Prepare for the beam time by following the instructions provided in the relevant website. Complete the safety trainings and necessary experimental safety assessment form.

2. Preparation of the 2-D Checkerboard Phase Grating

1. Determine the period of the grating, p , which is related to the period of the interferogram pattern, p_θ , along different transverse direction angle θ . The visibility values, $V_\theta(d)$, of the interferogram along different θ angle oscillate as a function of the grating-to-detector distance, d . For a 2-D checkerboard $\pi/2$ phase grating, $V_\theta(d)$ peaks at distances,

$$d_{n,\theta} = \frac{(2n-1)p_\theta^2}{2\lambda}, (1)$$

with $n = 1, 2, 3, \dots$ and λ the photon wavelength. The interferogram pattern has a characteristic period of $p_\theta = p/\sqrt{2}$ along the diagonal direction of the square blocks and a period of $p_\theta = p/2$ along the edge of the square blocks. The choice of p thus relies on the following criteria.

2. Make sure at least several $V_\theta(d)$ peaks are within the largest grating-to-detector distance, or the space limit of the experimental station, $d_{\max}$. To satisfy $d_{n,\theta} < d_{\max}$, it follows

$$p_\theta < \left(\frac{2\lambda d_{\max}}{2n-1} \right)^{\frac{1}{2}}, (2)$$

For $n = 5$, $d_{\max} = 1$ m, $\lambda = 0.06888$ nm (18 keV), it gives $p_\theta < 3.9$ μ m.

3. Within $d_{\max}$, make sure that the height of the $V_\theta(d)$ peak at the largest distance $d_{n,\theta}$ is less than a factor γ of that of the first $V_\theta(d)$ peak at $d_{1,\theta}$ in order to have an accurate Gaussian decay function fitting. Hence, $\gamma = V_{\theta,n}(d) / V_{\theta,1}(d)$ which is the ratio of the n^{th} peak visibility to the first peak. For an X-ray source following Gaussian intensity distribution with the coherence length, ξ_θ , the period of a $\pi/2$ phase grating needs to satisfy

$$p_\theta > \sqrt{\frac{2\ln \gamma}{n(1-n)}} \xi_\theta, (3)$$

for instance, with $\gamma = 10\%$, $\xi_\theta = 5$ μ m and parameters above, it gives $p_\theta > 2.4$ μ m.

4. Ensure that the period of the interferogram pattern, p_θ , is a few times larger than the spatial resolution of the detector by choosing the correct detector systems.
5. Determine the thickness, T , of the grating required for a phase shift of, φ , at the X-ray photon wavelength, λ , using

$$T = \frac{\varphi \lambda}{2\pi \delta}, (4)$$

where δ is the refractive index decrement of the phase shifting material. For example, the refractive index decrement for Au is 9.7×10^{-6} for 18 keV. The Au thickness for $\varphi = \pi/2$ phase grating is thus 1.8 μ m.

6. Fabricate the phase grating by electroplating Au into a patterned polymer mold on a silicon nitride (Si_3N_4) window.
NOTE: The procedure for preparation of silicon nitride (Si_3N_4) window substrate and fabrication of the grating structure are presented below.
 1. Prepare the substrate by first releasing the Si_3N_4 membrane to form the X-ray transparent window.
 2. Acquire silicon (Si) wafers with low stress (<250 MPa) Si_3N_4 deposited on both sides of the wafer from a vendor.
 3. Load the wafer into a magnetron sputtering deposition system to deposit Cr and Au to act as an electroplating base.
 4. Deposit 5 nm of Cr then 30 nm of Au on one side of the wafer, following manufacturer's directions.
NOTE: The deposition processes from the system manufacturer will include information such as deposition rate.
 5. Unload wafer from deposition tool. Use the side of the wafer deposited with Cr and Au for grating fabrication.
 6. Determine the total size of the grating and then design a photolithography mask to pattern membranes slightly larger. Use the design to acquire a photolithography mask by purchasing from a vendor or fabricate the photolithography mask.
 7. Spin a 3- μ m thick layer of photoresist on the back side of the wafer where there is no Cr and Au coating. Expose the resist with a UV lithography tool for 20 sec using the designed photolithography mask. Develop the exposed resist in aqueous alkaline developer solution for 30 sec then rinse with deionized water and dry with flowing N_2 .
 8. Load the wafer into a reactive ion etching (RIE) tool with patterned photoresist facing the chamber. Use CF_4 plasma to etch the exposed Si_3N_4 following tool instructions.

9. Evacuate the etching chamber and input etch recipe into RIE tool. Run the recipe until the Si_3N_4 layer is etched completely and the Si layer is exposed in the pattern.
 10. Etch the exposed Si on the wafer backside by submerging into 30% KOH solution heated to 80 °C for about 8 hr. Etch rate is approximately 75 $\mu\text{m/hr}$ using the stated recipe.
 11. After Si etch is finished, rinse with deionized water and dry with flowing N_2 . The sample is ready for grating fabrication.
7. Fabricate the electroplating mold for the phase grating using the following steps.
 1. Design the square checkerboard grating pattern and compensate for pattern biasing by reducing the exposed square pattern size by 100-250 nm. Include a $>50\text{-}\mu\text{m}$ wide frame around the grating pattern for thickness confirmation later in the process.
 2. Load the sample into a resist spin coater and deposit poly (methyl methacrylate) (PMMA) positive resist solution on the grating side of the sample. Run the resist spin coater to form a 2 to 3.5- μm thick resist film depending on desired final grating thickness.
NOTE: Spin curves with information on spin speed versus film thickness are provided by the PMMA solution vendor or can be determined empirically.
 3. Load the wafer into a 100 keV electron beam lithography system.
 4. Calibrate tool for exposure with a large exposure current greater than 10 nA.
 5. Expose the PMMA resist using a 100 keV e-beam lithography tool to create the grating pattern, where areas exposed will be removed in the development step. Use an exposure dose range of 1,100-1,250 $\mu\text{C}/\text{cm}^2$ depending on resist thickness.
 6. Unload the sample from the tool.
 7. Develop the exposed resist by submerging in a 7:3 (by volume) isopropyl alcohol (IPA): deionized water solution for 30-40 sec with gentle swirling. Rinse with IPA, and then dry with flowing N_2 . Ensure the PMMA was fully developed by looking at exposed area with an optical microscope.
 8. Load the sample into a RIE tool with PMMA pattern facing the chamber.
 9. Evacuate the etching chamber and input descum etch recipe into RIE tool. The descum process is a short (<30 sec) O_2 plasma based etch to remove any residual PMMA from the exposed grating area.
 8. Finish the Au grating by electroplating into the fabricated mold using the following steps.
 1. Make sure the electroplating mold thickness by scanning the probe of a profilometer across the frame included for thickness confirmation.
 2. Submerge the sample into the Au-sulfite electroplating solution heated to 40 °C. The electroplating setup is composed of a beaker filled with the electroplating solution, a constant current DC power supply, and a Pt mesh anode.
 3. Determine the plating area of the sample by calculating the exposed Au in the exposed pattern, then calculate current for the desired current density, which is the primary variable used to set the deposition rate.
 4. Calculate plating time to reach desired grating thickness using the plating rate determined by the applied current density.
 5. Turn on the DC power supply to apply the determined current on the sample, acting as a cathode, and plate for approximately half the total plating time.
 6. Measure the plating thickness using the same method used in step 2.8.1.
 7. Turn on the DC power supply to electroplate Au into the PMMA mold and electroplate to the desired grating thickness, taking into account the plated height measured in step 2.8.6.
 9. Remove the polymer mold using a heated solvent by submerging the sample. Then inspect with an optical microscope and a scanning electron microscope (SEM) to confirm grating period, duty cycle, and grating thickness.
NOTE: Have two 2-D checkerboard phase gratings (one for the experiment and one as a spare) ready, a few days before the experiment begins.

3. Experiment Setup and Alignment at the Synchrotron Facility

1. Request the beamline scientist to set the X-ray beam energy or wavelength to the desired value that matches the phase grating. Routinely used X-ray energies at the APS 1-BM beamline are between 6 and 28 keV. In this case, tune the photon energy to 18 keV.
2. Select the desired objective lens for the detector system. Here, use a Coolsnap HQ2 CCD detector with $1,392 \times 1,040$ imaging pixels of $6.45 \times 6.45 \mu\text{m}^2$ pixel size. To resolve the smallest interference pattern, use an EC plan Neofluar 10 $\times$ objective. The effective pixel size of the detector system including the magnification effect of microscopic objective is thus 0.64 μm . The estimated spatial resolution is about 2 μm , which is mainly due to the point spread function of the detector system.
3. To set the rough focusing of the detector system, place the scintillator (lutetium-yttrium oxyorthosilicate, 150- μm thick) at the 'working distance' from the lens (~ 5.2 mm for the used system). At first, set the focus under ambient light by monitoring the images acquired under 'continuous mode' as the scintillator position is adjusted using a pico-motor.
4. Move the 2-D detector into the X-ray beam, by using vertical and horizontal stages align the center of the detector to the beam center.
5. Place a 'phase sample', for example a piece of Styrofoam, into the X-ray beam. Perform the fine focusing of the detector system by observing the scattering pattern from the phase sample and adjusting the scintillator position until the highest image sharpness.

4. Performing Coherence Measurements

1. Place the 2-D checkerboard grating into the X-ray beam where the coherence of the beam is to be measured. In this case it is at 34 meters from the bending magnet source.
2. Adjust the plane of the 2-D checkerboard phase grating to be perpendicular to the direction of the X-ray beam propagation.
3. Center the grating to the X-ray beam by using the motorized stages and looking at the images acquired under detector continuous mode.
4. Rotate the grating around the X-ray beam propagation direction (y) so that the diagonal direction of the checkerboard pattern is along the desired transverse beam direction. In this case, align the diagonal directions of the checkerboard (preferred measuring directions) in the horizontal and vertical directions of the beam. Fine tune the grating rotations around the other two axes (x and z) to ensure its perpendicularity to the X-ray beam, which is achieved by maximizing the interferogram periods in both the horizontal and vertical directions.

5. Move the detector system as close as physically possible to the phase grating along the beam propagation direction. In this study, use a distance of 43 mm.
6. Calculate the smallest period in the interference pattern. The $\pi/2$ checkerboard grating with period $p = 4.8 \mu\text{m}$ will generate an interference pattern with $p_\theta = 3.4 \mu\text{m}$ and $p_\theta = 2.4 \mu\text{m}$ (smallest period) along the diagonal and the non-diagonal directions of the checkerboard pattern, respectively. Estimate the number of data points needed in-between $V_\theta(d)$ peak positions given by Equation (1) to obtain a smooth curve.
7. Select the appropriate exposure time for each interferogram, four seconds in this case.
8. Record interferograms with the same exposure time (e.g., 4 sec) at different grating-to-detector distances. Choose the exposure time based on the beam intensity level. Starting from the minimum grating-to-detector distance (43 mm), move the detector downstream of the X-ray by small intervals (10 mm determined based on step 4.6) and record an interferogram at each detector position until the maximum possible grating-to-detector distance (750 mm).
9. Acquire dark-frame images with the same exposure time (4 sec) but turn off the X-ray beam and keep all other experimental conditions the same.

5. Data Analysis

NOTE: There is currently no standard software available for the data analysis.

1. Using the selected image processing program, read in the dark-frame image(s) and the data image. Correct the data image by subtracting the (averaged) dark-frame image.
2. Fourier transform the dark-frame corrected image, which produces visible harmonic peaks in the horizontal ($\theta = 0^\circ$), vertical ($\theta = 90^\circ$) as well as $\theta = 45^\circ$ and $\theta = 135^\circ$ directions.
3. Crop the 0th order harmonic image centered at the 0th order peak. The length and width of the image equal to the distances between the 0th and 1st order peaks along the horizontal and vertical directions, respectively. Similarly, obtain the 1st order harmonic images of the same length and width along the transverse direction of interest.
4. Inverse Fourier Transform (IFT) the cropped harmonic images. Ratio of the mean of the amplitudes of the IFT image from the 1st order harmonic image along any transverse direction to that of the IFT image from the 0th order harmonic image gives the visibility along that direction.
Note that this process is valid if few high-frequency components exist in the measured interferogram. Otherwise, one can use the corresponding harmonic peak intensities of the Fourier transform images from step 5.4 instead. Due to the beam divergence, the harmonic peak positions will change gradually at different grating-to-detector distances. Therefore, a correction to p'_θ at each distance or a peak finding process is needed.
5. Repeat step 5.1-5.4 for all the measured images at different grating-to-detector distances and save the visibility value of each image.
6. Plot the visibility $V_\theta(d)$ as a function of the grating-to-detector distance. Identify data points at $V_\theta(d)$ peaks. Note that the full curve was measured just to better identify the peak positions given by Equation (1). Manually select peak data points as well as adjacent data points on either side of each peak.
7. Draw Gaussian fitting function for the selected data points. Extract standard deviation, σ_θ , of the Gaussian fitting function.
8. Obtain the transverse coherence length, ξ_θ , using

$$\xi_\theta = \frac{\lambda \sigma_\theta}{p_\theta} \quad (5)$$

Representative Results

While detailed experimental and simulation results could be found elsewhere⁸, this section only shows selected results to illustrate the above measurement and data analysis procedures. **Figure 1** represents the experiment setup at the APS 1-BM-B beamline. The beam size is defined by a $1 \times 1 \text{ mm}^2$ slit placed upstream of the Double Crystal Monochromator (DCM) and 25 m from the bending magnet source. The DCM is tuned to output photon energy of 18 keV. The X-ray beam passes through several Beryllium windows (1 mm total thickness) placed at different locations along the beam path.

Figure 2(a) shows the central portion of the scanning electron microscope image of the 2-D checkerboard phase grating fabricated at the Center for Nanoscale Materials (CNM) in ANL. The grating period is $p = 4.8 \mu\text{m}$. The whitish squares are the Au blocks formed on the Si_3N_4 membrane. The grating is placed in the X-ray beam such that it is perpendicular to the beam direction and the diagonals of the square gold blocks are parallel to the horizontal and vertical directions, as shown in **Figure 2(b)**. Such an orientation serves two purposes: (i) it ensures a higher visibility along the primary directions, which are along the horizontal and vertical directions, and (ii) it reduces the effect of fabrication uncertainty of the grating period along the primary directions⁸.

Interferograms were recorded at different grating-to-detector distances, d , covering at least five $V_\theta(d)$ peaks in each transverse direction as defined in Equation (1). **Figure 3** shows the central portion of the measured interferograms at (a) $d_{1,0^\circ} = 83 \text{ mm}$ and (b) $d_{4,0^\circ} = 579 \text{ mm}$, which correspond to the first and fourth peak positions along $\theta = 0^\circ$ direction ($p_\theta = 3.4 \mu\text{m}$). At these Talbot distances 2-D checkerboard pattern is replicated (self-imaging). The coherence property of the X-ray beam is embedded in the interferogram visibility, which is retrieved from the Fourier analysis of each recorded image.

The Fourier transform of the measured interferogram produces harmonic peaks which are representative of the periodic nature of the interferogram along different directions. As an example, **Figures 3(c)** and **(d)** are the FT images of **Figures 3(a)** and **(b)**, respectively, carried out by the Fast Fourier Transform (FFT). Due to the central symmetry of the FT image, four independent 1st order peaks are present along four directions, namely $\theta = 0^\circ, 45^\circ, 90^\circ$ and 135° as defined in **Figure 2(b)**. The periodicity (p_θ) in each direction can be determined from the peak position relative to the central 0th order peak. Take **Figure 3(c)** as an example, the 1st order harmonic peak along 0° direction reveals a periodic structure with $p_{0^\circ} = 3.4 \mu\text{m}$, which can be easily identified as the line-type structure in **Figure 3(a)**. The visibility is given by the ratio of the amplitude of the 1st order peak ($A_{\theta,1}$) to that of the 0th order peak ($A_{\theta,0}$), or $V_\theta = 2A_{\theta,1}/A_{\theta,0}$ ¹⁰. In practice the visibility was obtained following protocol steps 5.5-5.7 with the crop boxes shown in **Figures 3(c)** and **(d)**. Clearly the intensity of the 1st order peak at 0° is much smaller in **Figure 3(d)** than in **Figure 3(c)**, which indicates a reduced visibility at $d = 579 \text{ mm}$. This is also evidenced in the lack of periodic structure along 0° in **Figure 3(b)**.

Following protocol steps 5.8-5.12, **Figure 3(e)** shows the visibility evolution as a function of d . The Gaussian fitting to the selected data around $V_\theta(d)$ peaks gives $\sigma_{0^\circ} = 180 \text{ mm}$. The horizontal coherence length is thus $\xi_{0^\circ} = 3.6 \mu\text{m}$ following Equation (5).

Similar to **Figure 3**, **Figure 4** presents results along the $\theta = 45^\circ$ direction. The FT images [cf. **Figure 4(c)** and **(d)**] indicate a period of $p_{45^\circ} = 2.4 \mu\text{m}$. Therefore, $V_\theta(d)$ peaks for 45° appear at shorter distances ($d_{1,45^\circ} = 43 \text{ mm}$ and $d_{4,45^\circ} = 293 \text{ mm}$) in comparison with that for 0° . At this distance, for 45° , the interferograms are a mesh-type pattern [cf. **Figure 4(a)** and **(b)**]. The visibility evolution shown in **Figure 4(e)** gives the coherence length $\xi_{45^\circ} = 5.0 \mu\text{m}$. By applying the same data analysis procedure to all four available directions, the transverse coherence area of the X-ray beam is mapped.

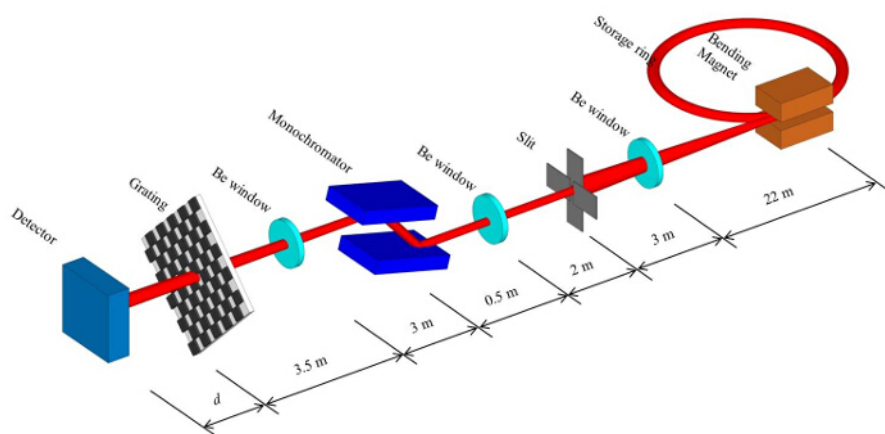


Figure 1. Experimental Setup. Schematic of the beamline setup at the 1-BM-B beamline of the APS. [Please click here to view a larger version of this figure.](#)

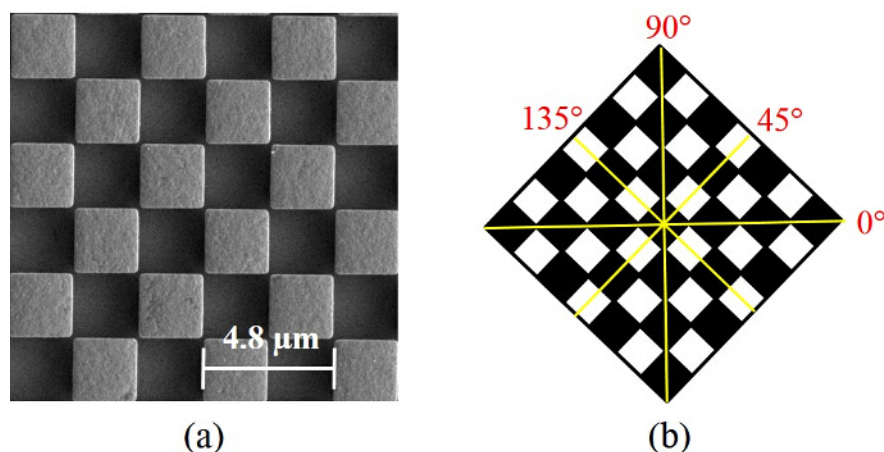


Figure 2. 2-D Checkerboard Grating. (a) SEM image of the checkerboard grating with a period of $4.8 \mu\text{m}$. (b) Grating orientation in the transverse plane perpendicular to the beam propagation direction (pointing into or out of the paper). The numbers in red indicate θ . [Please click here to view a larger version of this figure.](#)

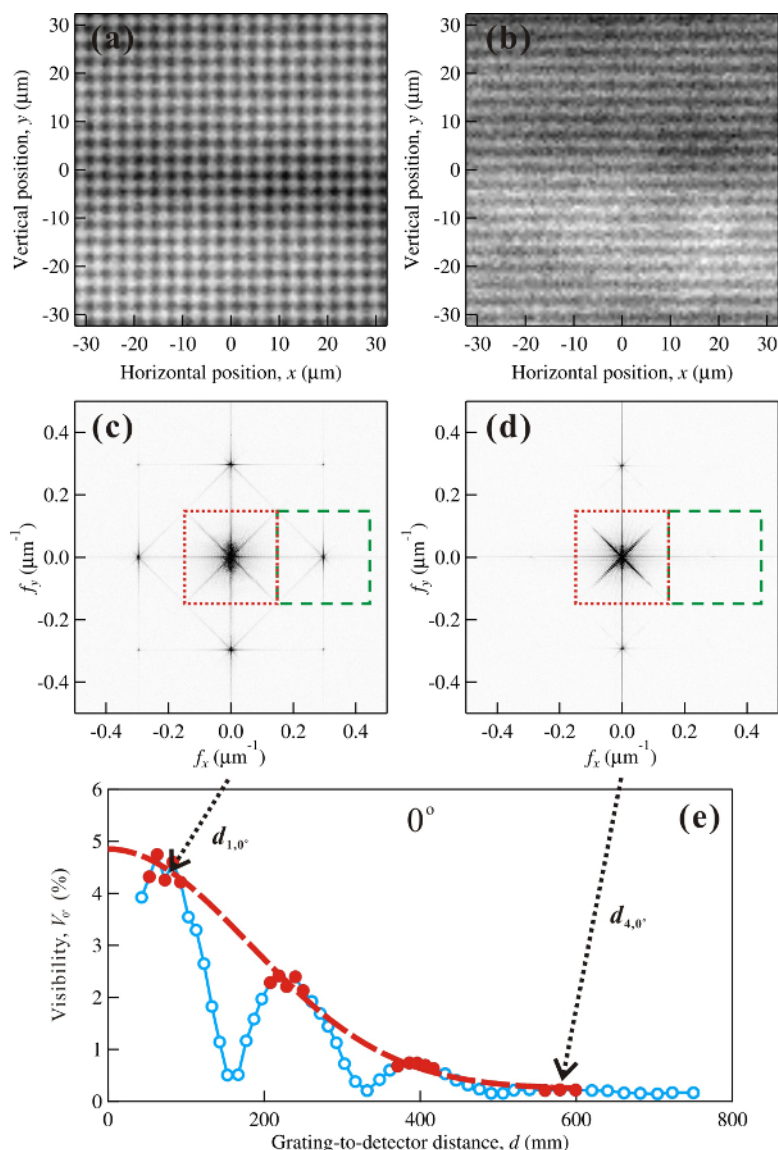


Figure 3. Visibility Measurement along 0° Direction. Interferograms recorded at $d_{1,0^\circ} = 83$ mm (a) and $d_{4,0^\circ} = 579$ mm (b), corresponding to the first and fourth $V_0(d)$ peak positions along 0° direction (Equation (1) with $p_{0^\circ} = 3.4$ μm), respectively. Their Fourier transform images are shown in (c) and (d), with the red dotted and green dashed regions indicating the 0^{th} and 1^{st} harmonic images, respectively. (e) The visibility evolution as a function of the grating-to-detector distance, d . The blue circles are all the experimental data, while the red bullets are data selected around each Talbot distances for the Gaussian envelope fitting (red dashed curve). [Please click here to view a larger version of this figure.](#)

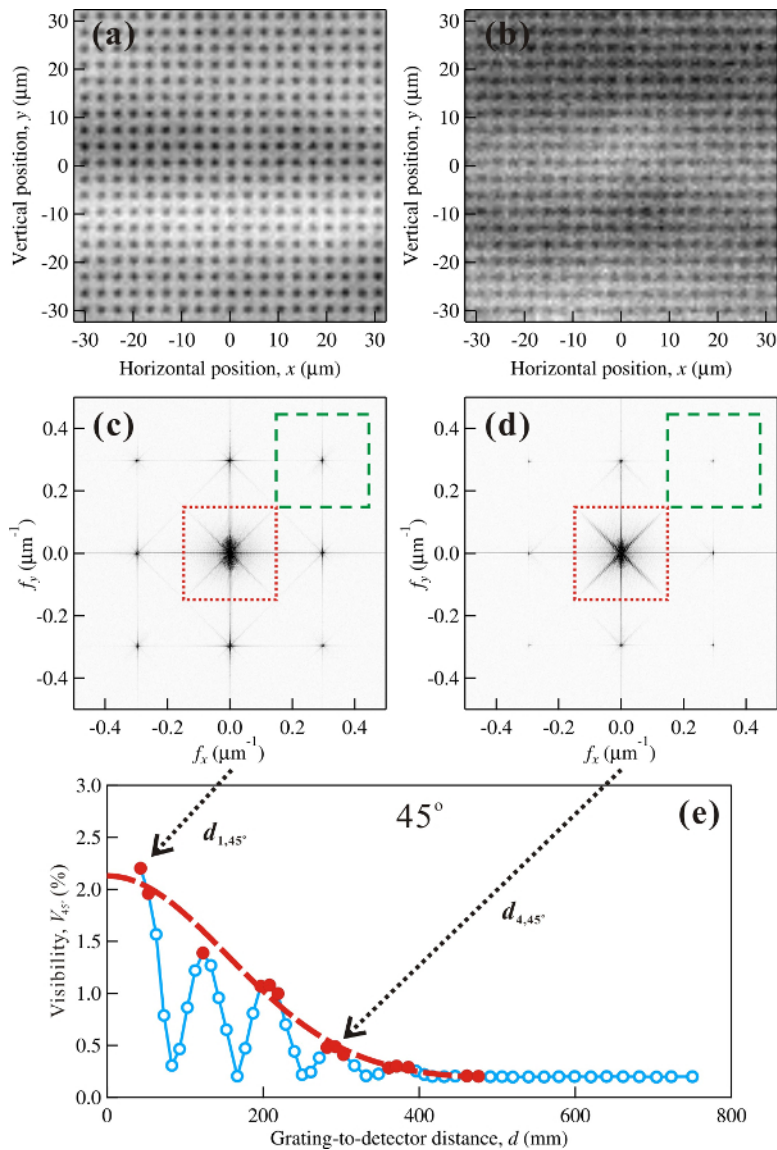


Figure 4. Visibility Measurement along 45° Direction. Interferograms recorded at $d_{1,45^\circ} = 43$ mm (a) and $d_{4,45^\circ} = 293$ mm (b), corresponding to the first and fourth $V_{45^\circ}(d)$ peak positions along 45° direction (Equation (1) with $p_{45^\circ} = 2.4$ μm), with their FT images shown in (c) and (d), respectively. (e) The visibility evolution as a function of d . See Figure 3 caption for details. [Please click here to view a larger version of this figure.](#)

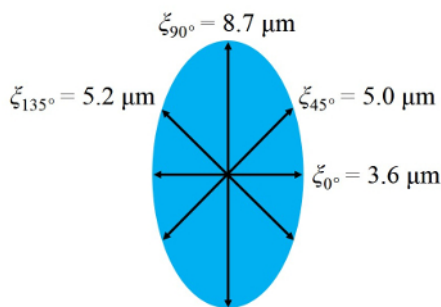


Figure 5. Coherence Area Map. Coherence area visualized using the measured transverse coherence lengths along four directions. [Please click here to view a larger version of this figure.](#)

Discussion

Figure 5 shows the estimated transverse coherence length along all four directions. Clearly, the 90° direction has higher ξ_θ compared to 0° direction. Since the beamline optics has negligible effect on the beam coherence at the grating relative location, the measured coherence area is

inversely proportional to the source size area. The presented X-ray beam coherence measurement technique maps this accurately which can be shown as an ellipse with its major axis along the vertical direction (cf. **Figure 5**). It is important to note that with a well characterized grating only the interferograms at the self-imaging distances or few images around the self-imaging distance are needed to obtain the coherence length. One of the limitations of this technique is that transverse coherence measurement at a particular energy requires a grating optimized for that energy.

The technique relies on the accurate measurement of the distance between the grating and the detector, especially, when the experiment is performed using the grating with smaller periods and at lower energies, for example, at 8 keV. Along the diagonal of the square blocks of the checkerboard grating, effects of grating period mismatch on the visibility curve are negligible, and higher visibilities are obtained. Therefore, the choice of the grating orientation depends on the preferred directions along which the transverse coherence measurement needs to be performed.

Compared to the technique described in reference 3, the presented method does not need the assumption of any shape model to obtain the CCF curve. A single phase grating was used instead of a two-grating interferometer system⁷ (including a phase grating and an amplitude grating, of which the fabrication is challenging for hard X-ray applications). The use of a single grating enables the quick setup and alignment while providing the same coherence information as the two-grating interferometer system. Going beyond the work described in references 4-6, the single grating interferometer maps the coherence length along four different directions simultaneously. The technique is also capable of resolving local variations in the coherence of the beam wavefront over a small area.

The transverse coherence information of the X-ray beam provided by the technique is very important not only for designing the experiments but also as a priori knowledge for the data analysis. As the coherence brightness of the synchrotron and XFEL sources continuously increases the X-ray optics needed to preserve this source coherence has to be evaluated and the technique described here can be a great tool for measuring transverse coherence of the (local) beam wavefront.

Disclosures

The authors have nothing to disclose.

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