

Small angle X-ray scattering ghost imaging

Feixiang Wang¹, Wenqiang Hua^{1,2,*}, Changzhe Zhao^{1,2}, Haipeng Zhang¹, Shumin Yang^{1,2},
Xiuhong Li^{1,2}, Biao Deng^{1,2}, Honglan Xie^{1,2} and Tiqiao Xiao^{1,2,†}

¹Shanghai Synchrotron Radiation Facility, *Shanghai Advanced Research Institute*, Chinese Academy of Sciences, Shanghai 201204, China

²Shanghai Institute of Applied Physics, *Chinese Academy of Sciences*, Shanghai 201800, China
and *University of Chinese Academy of Sciences*, Beijing 100049, China



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Traditional small angle X-ray scattering (SAXS) techniques utilize a focused microbeam for spatial scanning to achieve spatially resolved imaging of the nanostructures of nonuniform materials. However, this method is notably inefficient regarding information acquisition, and its spatial resolution is constrained by the beam's focusing capabilities. We propose a proof-of-concept experiment using structured illumination to demonstrate a SAXS method capable of achieving high spatial resolution. This method leverages the experimental setup of real-space ghost imaging in intensity correlation measurements. It maps reciprocal space signals—specifically, small angle scattering signals—to real space, enabling small angle scattering imaging with enhanced spatial resolution without needing beam-focusing elements. Due to its inherent compatibility with compressed sensing, this method can significantly reduce the number of measurements. Successfully validated using synchrotron radiation X-rays, this approach theoretically applies to scattering imaging of photons and high-energy particles across various wavelength bands. It holds broad application prospects in the fields of nanomaterials and biomedicine.

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I. INTRODUCTION

Small angle X-ray scattering (SAXS) is a crucial technique for uncovering nanoscale structural information within materials [1]. It has been extensively applied in diverse fields such as biomacromolecules [2], nanoparticles [3], polymeric materials [4], mesoporous materials [5], catalysts [6], and alloys [7]. SAXS is particularly effective for analyzing amorphous materials and can detect structural features between 1 and 100 nm. However, conventional SAXS techniques typically use a beam size of several hundred micrometers. For nonuniform samples, the resulting two-dimensional reciprocal space scattering patterns represent superimposed signals from various components, leading to information overlap that complicates precise nanostructural analysis. Essentially, the primary challenge in spatially resolved SAXS measurements is the spatial aliasing of the SAXS signal, which limits its application in analyzing nonuniform samples.

Microbeam small angle X-ray scattering (μ SAXS) technology addresses this by focusing the beam below several tens of micrometers and employing spatial scanning [8–10]. This approach allows each measurement to illuminate only a tiny portion of the sample, facilitating the acquisition of spatial

information. The resolution is determined by the size of the incident beam. Over the past decade, the advancement of spatially resolved μ SAXS technology has opened fascinating opportunities across various fields [11,12]. Despite its success, μ SAXS faces significant challenges: (1) Focusing X-ray radiation, particularly at high photon energies, is challenging. The capability to utilize a small, focused beam across a broad photon energy range is limited to specific synchrotron radiation beamlines and X-ray free-electron lasers [13]. For bench-top sources, focusing is feasible only within a narrow photon energy range at the expense of substantial photon flux loss. (2) In practical μ SAXS applications, acquiring spatial information involves time-consuming point-by-point scanning of the sample, which can extend measurement times to several days for large samples or three-dimensional imaging. Prolonged exposure to the focused beam can also cause irreversible thermal damage to the sample, potentially distorting data and even necessitating premature experiment termination.

In this paper, we propose a proof-of-concept experiment that demonstrates a SAXS method with the potential for enhanced spatial resolution, addressing these challenges through structured illumination and spatial intensity correlation. Recent advancements in intensity correlation imaging techniques have explored many intriguing directions across a broad wavelength range, from radio waves to X-rays [14–20]. These techniques have extended to ultrasound [21], electrons [22], neutrons [23], and atoms [24], offering exciting prospects for future applications. Two distinct intensity spatial correlation imaging techniques have been demonstrated to date. Classical ghost imaging uses thermal or pseudothermal light and relies on semiclassical Hanbury Brown–Twiss (HBT) correlations to generate images.

*Contact author: huawq@sari.ac.cn

†Contact author: txiao@sari.ac.cn

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Based on the HBT experimental framework, the generalized concept of optical coherence has become a widely used and powerful research tool across various physics fields, with applications ranging from stellar interferometry to nuclear collisions [25]. Even for some processes based on incoherent transmissions, such as fluorescence emission or Compton scattering, it is also possible to effectively double the accessible range in Fourier space through a method known as incoherent diffraction imaging [26,27]. Ghost imaging, an indirect imaging technique, capitalizes on the second-order correlations of light field intensities recorded by two detectors. These detectors are illuminated by two spatially separated but mutually correlated beams. By finely adjusting the distance between the object and the detectors, ghost imaging can spatially resolve sample images using only a bucket detector, capturing fine details such as the distribution of absorption [18] and fluorescence information [28].

The success of ghost imaging hinges on the fact that the signals collected by the bucket detector are a spatial superposition of the sample signals within the illuminated area. Although in the two-dimensional SAXS scattering diagram, an individual pixel represents only a localized feature of the sample's reciprocal space, this pixel corresponds to the superposition of all spatial information across the entire sample. Theoretically, the local scattering features in the SAXS pattern also have the potential to resolve the spatial distribution of the scattering sources. This characteristic is expected to be integrated with the dual-path ghost imaging technique, providing an alternative method for precisely analyzing the nanostructure of nonuniform samples.

In this paper, we have developed a speckle-modulated illumination-based SAXS ghost imaging method that enables the reconstruction of the real-space distribution of the scattering source from the two-dimensional reciprocal space signal, i.e., small angle scattering signals. This method not only achieves direct high spatial resolution imaging of arbitrary features in small angle scattering but also enables the extraction of equivalent microbeam μ SAXS signals from any localized region within the sample. The primary advantage of this method is its ability to provide spatial resolution information without the need for focusing, thereby eliminating the reliance on focusing devices typically required in conventional μ SAXS techniques. Furthermore, due to its inherent adaptability to compressed sensing measurements, this approach can significantly reduce the number of measurements required compared to traditional scanning techniques.

II. EXPERIMENTAL METHOD

Figure 1 presents a schematic diagram of the proposed SAXS ghost imaging method. The data acquisition process utilized in this study follows a two-step measurement method for virtual beam splitting based on classical ghost imaging [16]. The two-step data acquisition procedure of SAXS ghost imaging first involves exposing the X-ray beam to a mask with nonuniform transmission, resulting in fluctuations in the beam intensity. The configured spatial modulation mask, made from foam copper, has a thickness of 0.5 mm, a porosity of 80 PPI (points per inch), and an average pore diameter of 50 μ m. Downstream from the mask, a scatterless pinhole

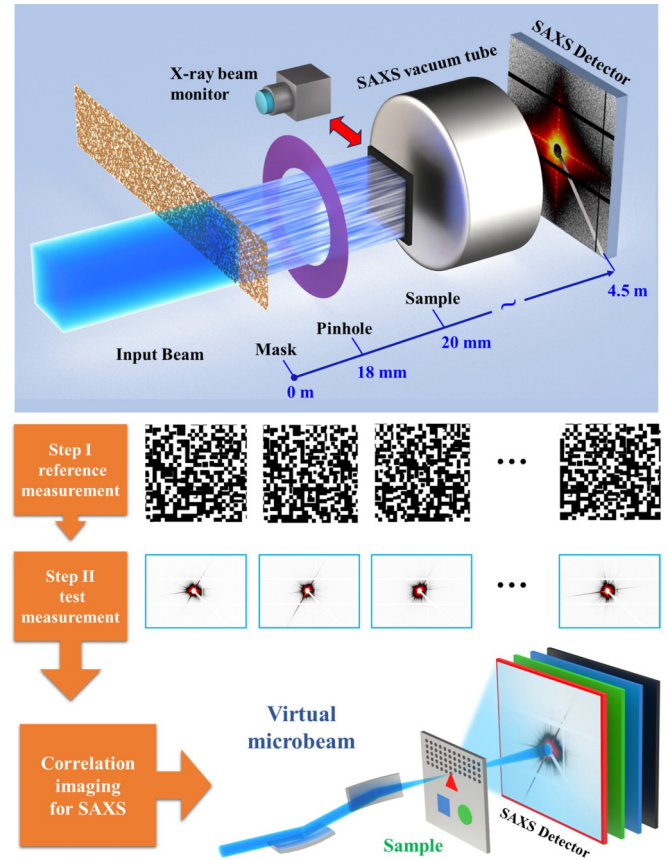


FIG. 1. Diagram of experimental installation and data acquisition procedure of SAXS spatial correlation imaging. Step I: measure the intensity patterns induced by the mask in the absence of the object. Step II: measure the SAXS information in the presence of the object.

with a diameter of 300 μ m is positioned to block scattering signals from the mask, thereby preventing interference with the target signals of the sample. Thus the effective beam size is confined to a circular area with a diameter of 300 μ m. Step I, the reference arm, involves scanning different areas of the mask and measuring the fluctuations in beam intensity introduced by the mask on the sample plane. This process employs a zigzag raster scanning with a step of 400 μ m, which is slightly larger than the spot size. Concurrently, these fluctuations are precisely replicated in step II, which is crucial for the subsequent image reconstruction process. Step I is completed without the sample, moving a high-resolution imaging system (Hamamatsu, C11440-36U, paired with a Navitar zoom 6000 microscope objective, with an effective pixel size of 1.3 μ m and a 1920×1200 array of pixels) into the plane where the sample would be in step II for recording. In step II, this imaging system is removed, and the sample is positioned at the original location of its scintillator. Using the same scanning parameters as in step I, the mask is scanned, and the two-dimensional scattering signals from the sample are recorded using a SAXS detector (Dectris, Pilatus 2M, with a pixel resolution of 172 μ m and a 1475×1679 pixels array).

We obtained two data sets after completing measurements of the entire experimental setup. The first set includes the

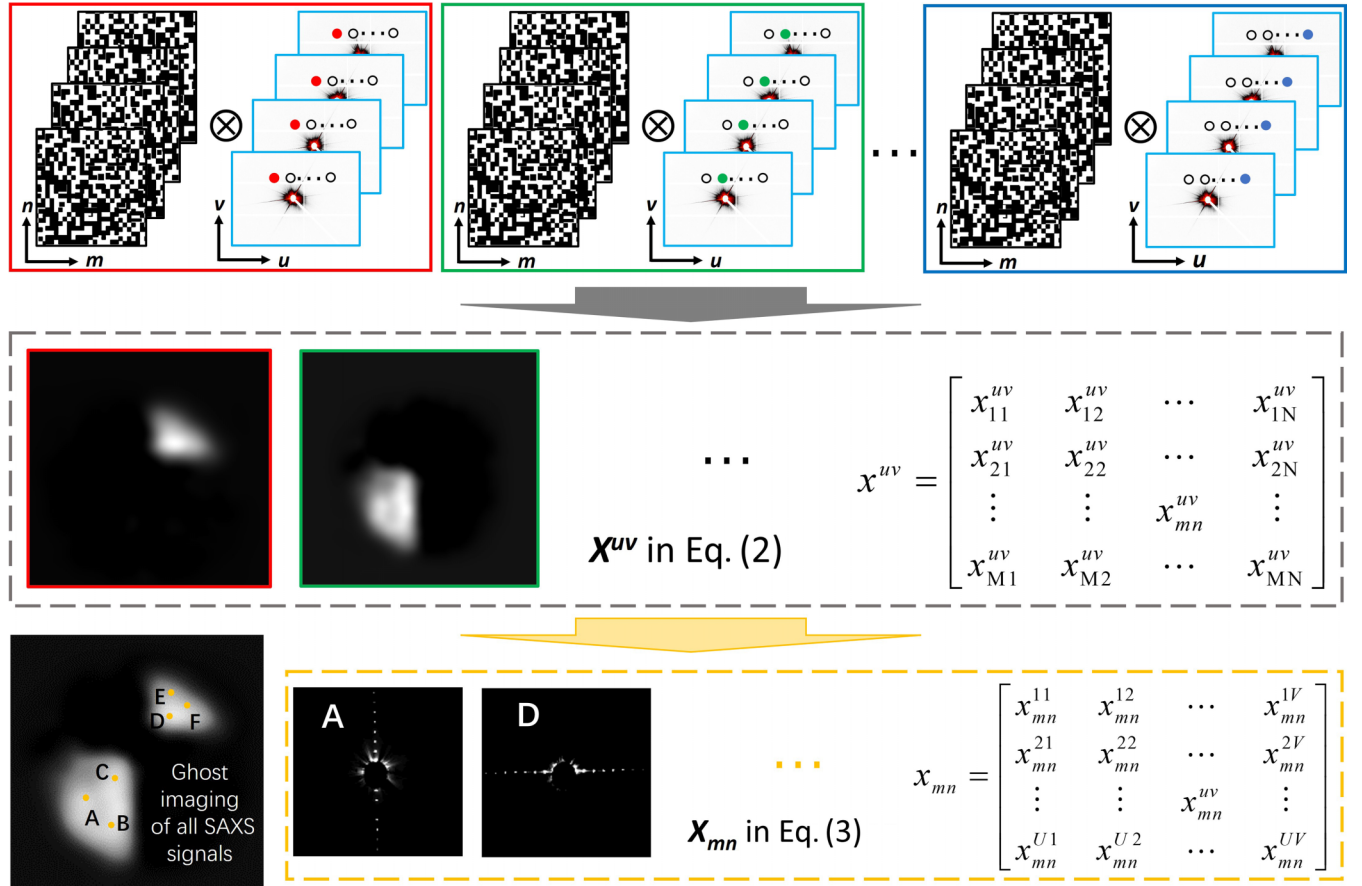


FIG. 2. SAXS ghost imaging data processing diagram.

mask patterns measured in step I, and the second comprises the SAXS patterns produced by the sample when illuminated by structured light, measured in step II. To reconstruct high-resolution SAXS signals, specifically the two-dimensional SAXS signals within localized small areas at the pixel level of the sample, we performed the following reconstruction procedure for each pixel point [with coordinates denoted as (u, v)] in the original SAXS pattern data. According to the object-image relationship [18], the correlation between the intensity fluctuations measured by the two detectors constitutes a standard real-space mapping reconstruction. Using the vector T^{uv} , which encompasses many realizations, denotes the intensities of the corresponding scattering signals measured at the SAXS detector coordinates (u, v) . We use another vector x^{uv} to represent the distribution of the scattering source in real space corresponding to the signal T^{uv} . The mask patterns are represented by the matrix A , for which every row is a single realization. The vector T^{uv} is equal to the product of the matrix A and the vector x^{uv} :

$$Ax^{uv} = T^{uv}, \quad (1)$$

Given that the gradients of natural images typically exhibit sparsity, we utilized a compressed sensing algorithm based on the “total variation minimization by augmented Lagrangian and alternating direction algorithms” (TVAL3) protocol [29]. This algorithm can effectively reconstruct the vector x^{uv} by minimizing the augmented Lagrangian with respect to the L_2

norm:

$$\min_{x^{uv}} \sum_i \|D_i x^{uv}\|_2 + \frac{\mu}{2} \|Ax^{uv} - T^{uv}\|_2^2 \text{ such that } x^{uv} \geq 0, \quad (2)$$

Here, $D_i x^{uv}$ is the i th component of the discrete gradient of the vector x^{uv} , and μ is the penalty parameter of the model. Here, the value is set to 2^{11} . Figure 2 presents the data processing diagram, detailing the steps involved in the analysis. Upon completing the calculations for all pixel points on the SAXS detector, we obtained a total of $U \times V$ matrices. Leveraging the duality between real space and reciprocal space, these matrices are recombined based on the spatial coordinates [denoted as (m, n)] of the high-resolution camera at the sample location. This recombination enables the acquisition of high-resolution scattering signals for any pixel at the sample location, as detailed below:

$$x_{mn} = \begin{bmatrix} x_{mn}^{11} & x_{mn}^{12} & \cdots & x_{mn}^{1V} \\ x_{mn}^{21} & x_{mn}^{22} & \cdots & x_{mn}^{2V} \\ \vdots & \vdots & x_{mn}^{uv} & \vdots \\ x_{mn}^{U1} & x_{mn}^{U2} & \cdots & x_{mn}^{UV} \end{bmatrix}. \quad (3)$$

The validation experiments were conducted at the time-resolved ultrasmall angle X-ray scattering station (10U1) of the Shanghai Synchrotron Radiation Facility, using an X-ray energy of 10 keV and a beam diameter slightly larger than

300 μm . In the experimental setup, the high-resolution imaging system in the reference arm is positioned alongside the sample and can switch flexibly between steps I and II via a translational motor, thereby enhancing the efficiency and accuracy of the experiment. In steps I and II, the exposure times for a single image are 0.5 and 1 s, respectively.

III. RESULTS AND DISCUSSION

A standard sample typically used in SAXS experiments, consisting of two horizontal and two vertical one-dimensional planar transmission gratings with specific spatial distribution characteristics, was chosen to demonstrate the method. These gratings, each with a period of 210 nm, were fabricated on a low-stress 100-nm-thick Si_3N_4 membrane using photolithography technology (Crestec CABL-9500C). An 80-nm-thick gold layer was subsequently deposited on the grating structure using electron beam evaporation, improving both the optical properties and durability of the grating. Each grating area measures exactly $300 \times 300 \mu\text{m}$, and the total size of the sample significantly exceeds that of the incident light beam. Detailed views are provided in the microscope photo shown in Fig. 3(a) and the electron microscope photos in Figs. 3(b) and 3(c).

During step I of the experiment, 500 mask patterns were recorded following the established experimental protocols. The characteristics of the light field generated by a typical spatial modulation mask are depicted in Fig. 3(d). Given the dimensions of the light beam, the mask image was uniformly cropped to 480×480 pixels. The autocorrelation function [30] of the mask is presented in Fig. 3(e), and the one-dimensional horizontal and vertical projections are also depicted therein. The autocorrelation function exhibits almost isotropy, with the FWHM of the curve being 40.3 ± 1.3 and $36.4 \pm 1.3 \mu\text{m}$ for the horizontal and vertical axes, respectively. The grating is then installed into the optical path, initiating data recording for step II. However, the precise location of the incident beam within the grating sample has not yet been determined. The same scanning procedure recorded a set of 500 two-dimensional SAXS images. After completing the data acquisition for the two described steps, the spatial mapping vector of the scattering sources for each pixel on the SAXS detector was reconstructed using Eq. (2). Subsequently, these data were combined based on Eq. (3) to obtain high-resolution SAXS signals from the single-pixel area at the sample location, equivalent to the μSAXS signal obtained through microfocusing probe technology.

It is noteworthy that for SAXS ghost imaging, through simple matrix addition operations, it is possible to reconstruct the SAXS signal from the single-pixel area at the sample location and any spatial coordinate combination within the sample. Similarly, if the scattering signals from several pixel regions in the original SAXS pattern are aggregated, and then the spatial distribution vector is reconstructed with respect to this aggregated signal, the resulting vector should represent the spatial distribution of all scattering sources that generated the aggregated signal. For instance, all signals captured by the two-dimensional scattering detector in step II were aggregated. Following this, the aggregated signal, which corresponds to the total scattering intensity of the sample,

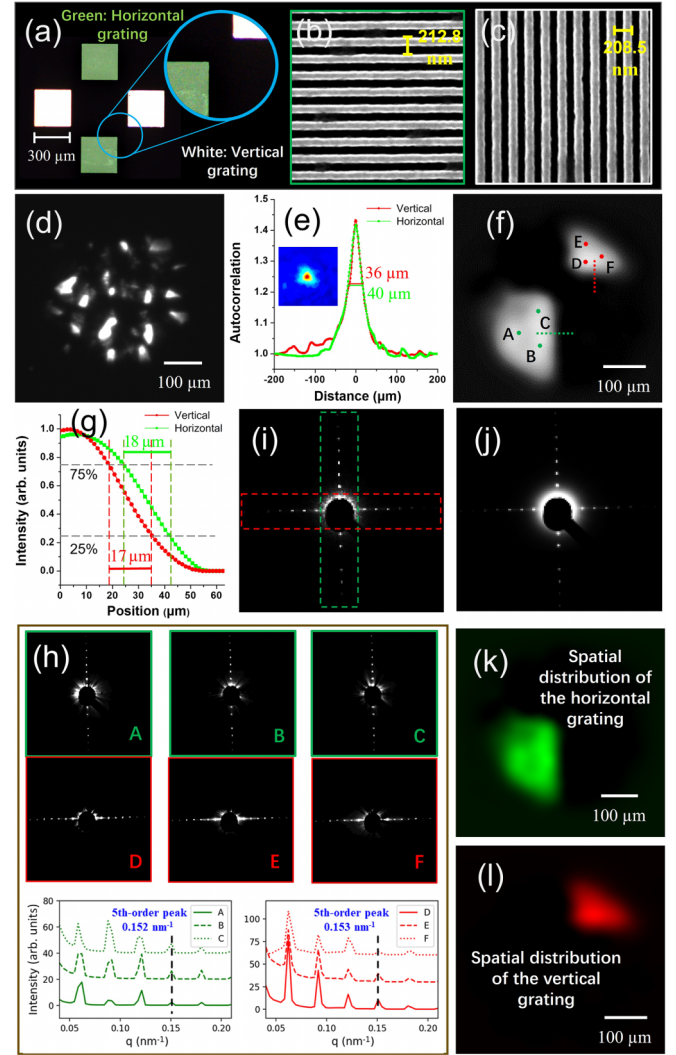


FIG. 3. SAXS ghost imaging results of the grating sample. (a) Microscopic images of the sample. [(b), (c)] The electron micrographs of the horizontal grating and the vertical grating. (d) A typical spatial modulation mask. (e) The cross-sectional curve of the autocorrelation function of the mask. (f) The spatial map reconstructed for the total scattering signal of the sample using the proposed method. (g) The normalized intensity curves corresponding to the green and red dashed lines in (f). (h) The equivalent microbeam probe SAXS patterns reconstructed for the green and red dots in (f) using the SAXS ghost imaging method, along with their corresponding I - q plots post-transformation. (i) The SAXS pattern resulting from the superposition of scattered signals across all sample pixels. (j) The average SAXS image derived from all input mask measurements in step II. [(k), (l)] The spatial distribution of the horizontal grating and vertical grating reconstructed by the proposed method.

underwent reconstruction for the spatial distribution of the scattering sources. This resulted in obtaining the sample area characteristics as illustrated in Fig. 3(f). Due to the sharp edges of the grating sample, two cross sections, horizontal and vertical, are selected at the edge of the sample as indicated by the horizontal green dashed line and the vertical red dashed line in Fig. 3(f). Estimating the half-width of the slope of these cross sections can equivalently assess the spatial resolution

of SAXS ghost imaging. The half-widths of the slope for the horizontal and vertical cross sections are 18.2 ± 1.3 and 16.9 ± 1.3 μm , respectively, as shown in Fig. 3(g). This indicates that the spatial resolution of the presented method is superior to the lateral coherence length (FWHM of the autocorrelation function) of the mask [30–32].

Although the imaging results indicate that the incident light beam illuminated two adjacent grating areas, it is still impossible to uniquely determine which area the X-ray specifically struck due to the presence of two similar positions in the diagonal direction within the sample. As detailed in the preceding sections, the SAXS signal from any pixel within the sample, equivalent to that of a microbeam probe, can be reconstructed using the methodology introduced herein. For instance, three pixels were randomly selected for analysis in the two grating regions, as indicated by the green dots A, B, and C and the red dots D, E, and F in Fig. 3(f). Using Eq. (3), the equivalent microbeam probe SAXS patterns for each green and red dot were reconstructed. Moreover, the corresponding I - q plots derived from these patterns are depicted in Fig. 3(h).

The reconstruction results indicate that the green-tagged pixels are located within the horizontal grating area, and the SAXS ghost imaging patterns for these three pixels are nearly identical, all exhibiting the scattering pattern of the horizontal grating. This observation is consistent with the theoretical predictions. Similarly, the red-tagged pixels all exhibit the scattering patterns characteristic of vertical gratings. In the I - q curves of each pixel point, the fifth-order diffraction peak of the horizontal grating is located at 0.152 ± 0.01 nm, while that of the vertical grating is situated at 0.153 ± 0.01 nm, from which the period of the horizontal grating can be calculated to be $d = 2\pi/q = 2\pi/(0.152/5) \text{ nm}^{-1} = 206.7 \pm 1.3$ nm; by the same token, the period of the vertical grating can be calculated to be 205.3 ± 1.3 nm, which is consistent with the results from electron microscopy (212.8 ± 0.3 nm, 208.5 ± 0.3 nm). In the I - q curves of the various pixel points, the proportional relationships of the diffraction peak values for different orders are slightly different, which may imply that the uniformity of the grating sample varies at different points. In the proposed SAXS ghost imaging method, the sum of all reconstructed virtual microfocusing SAXS signals is calculated, specifically by adding up the signals at all (m, n) coordinates in Eq. (3). The result is a SAXS pattern that simulates the incidence of a large beam spot, as depicted in Fig. 3(i). The average SAXS image derived from all input mask measurements in step II is also equivalent to the result obtained from direct incidence of a large beam spot, as shown in Fig. 3(j), due to the randomness of the mask. The close similarity between Figs. 3(i) and 3(j) indicates the correctness of the reconstruction results. However, Fig. 3(j) exhibits a higher level of noise compared to Fig. 3(i), which can be attributed to the noise robustness of SAXS ghost imaging as supported by the principles of compressed sensing theory [33,34]. For the SAXS image set collected in step II, the areas outlined by the green and red squares in Fig. 3(i) were selected. The scattering signals from these two regions were individually accumulated and reconstructed using Eq. (2), yielding the spatial mapping vectors of the corresponding scattering sources, as illustrated in Figs. 3(k) and 3(l). The reconstruction results vividly reveal the spatial distribution of the horizontal and vertical gratings,

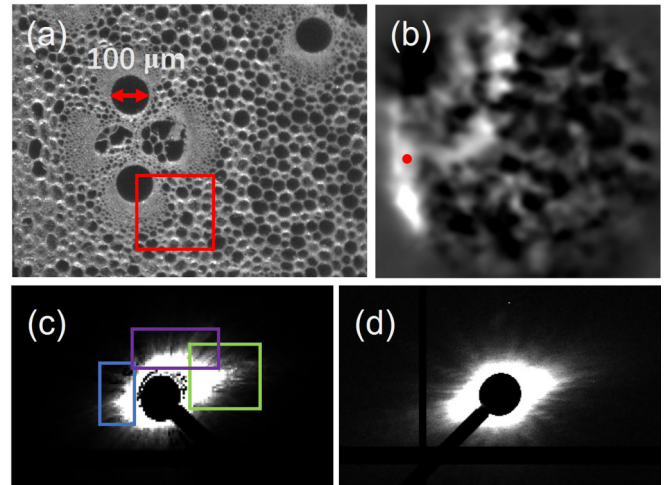


FIG. 4. SAXS ghost imaging results of the bamboo sample. (a) Microscopic images of a thin-section sample of bamboo xylem. (b) The spatial map reconstructed for the total scattering signal of the sample using the proposed method. The equivalent microbeam probe SAXS pattern reconstructed for the red dot in (b) through the SAXS ghost imaging method is shown in (c), and the scattering pattern obtained by the μ SAXS method in the microbeam mode is depicted in (d).

enabling precise identification of the incident X-ray position in the original sample, as indicated in Fig. 3(a). These results fully validate the correctness and effectiveness of the SAXS ghost imaging concept.

Figure 4 presents an example of a biological sample, comparing the high-resolution virtual microbeam SAXS signals reconstructed using the proposed SAXS ghost imaging method with the result obtained by the traditional microbeam μ SAXS approach. The sample is a thin section of bamboo xylem, depicted in the microscopic image of Fig. 4(a). After acquiring 500 pairs of raw data, the signals from all pixel points on the SAXS detector were accumulated. The distribution of the sample scattering source spatial mapping vectors reconstructed using Eq. (2) is shown in Fig. 4(b). This figure distinguishes the vascular bundle structure (the peripheral areas of the larger circular conduits) and the thin-walled cell structure (the smaller circular areas in the image) within the bamboo. A schematic diagram of the imaging area is annotated in Fig. 4(a). In Fig. 4(b), the red dot indicates a typical pixel point representing the vascular bundle structure; the equivalent microbeam probe SAXS pattern reconstructed using the proposed method is shown in Fig. 4(c). Subsequently, utilizing the microbeam scattering experimental station of BL10U1 [35], the imaging mode was adjusted to the microbeam probe mode with the focused beam spot size set to 10 μm . Positioning the focused beam at the location corresponding to the vascular bundle structure depicted in Fig. 4(c), the microbeam μ SAXS signal was acquired, as depicted in Fig. 4(d). Upon comparison, it is evident that the equivalent microbeam small angle scattering characteristics of the vascular bundle structure pixel, reconstructed by SAXS ghost imaging, are remarkably similar to the scattering patterns obtained by the μ SAXS technique. For certain studies, SAXS patterns from minute regions are crucial as they provide rich

nanostructural information about the cellulose microfibrils in the bamboo cell walls, such as porosity and orientation details. Normalized cross correlation (NCC) is employed to assess the similarity between Figs. 4(c) and 4(d) [36]. An NCC value of 1 indicates perfect positive correlation between two signals, signifying maximum similarity. Conversely, an NCC value closer to 0 suggests a lack of correlation between the signals, indicating lesser similarity. In view of the different beam stop and pixel gaps in the SAXS detector array within the image, three square regions were selected away from these locations to encompass as many scattering patterns as possible, as shown in Fig. 4(c). The regions enclosed by the blue, green, and purple rectangles exhibit NCC values of 0.8876, 0.8816, and 0.9223 between the two images in Figs. 4(c) and 4(d), respectively. This indicates a high degree of similarity between the SAXS patterns obtained by the two methods.

The differences observed in the scattering patterns displayed in Figs. 4(c) and 4(d) can be attributed to the differing spatial resolutions of the two methods. The spatial resolution of the traditional μ SAXS method is approximately equal to the size of the focused beam spot, which is challenging to reduce further. Conversely, the spatial resolution of SAXS ghost imaging can theoretically reach the pixel size of the reference arm speckle image. Additionally, the transition from the SAXS ghost imaging mode to the μ SAXS mode involves introducing focusing optical elements, which leads to a drift in the incident beam spot position. Consequently, there is an error in the positioning of the focused beam spot relative to the original coordinates, and the SAXS signals from similar structures within the sample are similar but not identical.

This research confirms that the SAXS spatially correlated ghost imaging method can effectively map the sample's two-dimensional SAXS signals—the characteristic signals in reciprocal space—to real space under large beam spot sizes. This method achieves precise reconstruction of the spatial distribution of the corresponding scattering sources, effectively mapping the reciprocal space information of the sample's nanostructure onto an image at the micrometer scale. Moreover, this method also reconstructs the equivalent microbeam probe SAXS signals with high spatial resolution at any spatial coordinate within the sample. For example, this imaging method not only spatially resolves the scattering sources for local SAXS feature signals, as demonstrated in Figs. 3(k) and 3(l), but it can also accurately compute the two-dimensional SAXS signals produced by any single pixel or selected area within the sample, as shown in Figs. 3(h) and 3(i). This capability offers significant advantages for studying samples with unknown structures, enabling researchers to analyze and compare subtle differences in SAXS signals on a point-by-point basis. Compared to traditional μ SAXS scanning imaging techniques, the proposed method mitigates the risk of radiation damage, particularly under experimental conditions where the focusing performance of the light source is insufficient, demonstrating significant application potential.

Despite many aspects not covered in this paper, especially the quantitative relationship between the volume of correlation imaging data and the quality of compressed sensing imaging, numerous ghost imaging studies have substantiated that compressed sensing algorithms can significantly reduce the necessary amount of measurement data. Correlative studies indicate that imaging quality is significantly affected only when the amount of data is reduced below a certain critical threshold [28]. Additionally, the limits of spatial resolution for SAXS ghost imaging methods have not yet been clearly revealed. Observations from Figs. 3(k) and 3(l) show that the sample's boundaries exhibit a blurred diffusion phenomenon. This boundary diffusion effect suggests that it may similarly impact the equivalent microbeam SAXS scattering signals reconstructed by Eq. (3), leading to a blending of the scattering correlation imaging signals from adjacent pixel points within the sample, making them difficult to separate entirely. The blurring effect is directly related to the modulation pattern of the mask. The spatial resolution of SAXS ghost imaging is close to the full width at half maximum of the autocorrelation function of the mask modulation pattern. By refining the speckle grain size on the mask and optimizing the fluctuation intensity of the light field, the quality of scattering correlation imaging can be significantly enhanced.

IV. CONCLUSION

This method has expanded the application scope of ghost imaging technology from super-resolution imaging of real-space information to super-resolution imaging in reciprocal space, equivalent to that of a microbeam probe, opening possibilities for high spatial resolution SAXS imaging experiments using laboratory X-ray sources with high emittance. The method is also easily transferable to small angle electron scattering, small angle neutron scattering, and wide angle X-ray scattering (X-ray diffraction), providing a glimpse of the possibility of revolutionizing the current scattering methods widely used in research in materials science and biomedicine. Further generalization of our results will lead to applications to extend the capabilities and impact of SAXS ghost imaging to more areas.

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[1] W. Ehrenberg and A. Franks, Small-angle X-ray scattering, *Nature (London)* **170**, 1076 (1952).

[2] G. L. Hura, H. Budworth, K. N. Dyer, R. P. Rambo, M. Hammel, C. T. McMurray, and J. A. Tainer, *Comprehensive*

- macromolecular conformations mapped by quantitative SAXS analyses, *Nat. Methods* **10**, 453 (2013).
- [3] K. Tsukimura, Y. Miyoshi, T. Takagi, M. Suzuki, and S. I. Wada, Amorphous nanoparticles in clays, soils and marine sediments analyzed with a small angle X-ray scattering (SAXS) method, *Sci. Rep.* **11**, 6997 (2021).
 - [4] H. M. Lai, P. H. Geil, and G. W. Padua, X-ray diffraction characterization of the structure of zein-oleic acid films, *J. Appl. Polym. Sci.* **71**, 8 (1999).
 - [5] X. Wang, L. He, J. Sumner, S. Qian, Q. Zhang, H. O. Neill, Y. Mao, C. Chen, A. Al-Enizi, and A. Nafady, Spatially confined protein assembly in hierarchical mesoporous metal-organic framework, *Nat. Commun.* **14**, 973 (2023).
 - [6] M. Povia, J. Herranz, T. Binninger, M. Nachtegaal, A. Diaz, J. Kohlbrecher, D. F. Abbott, B. J. Kim, and T. J. Schmidt, Combining SAXS and XAS to study the operando degradation of carbon-supported Pt-nanoparticle fuel cell catalysts, *ACS. Catal.* **2018**, 7000 (2018).
 - [7] X. Y. Liu *et al.*, Self-assembled soft alloy with Frank-Kasper phases beyond metals, *Nat. Mater.* **23**, 570 (2024).
 - [8] M. Georgiadis, A. Schroeter, Z. Gao, M. Guizar-Sicairos, and M. Rudin, Nanostructure-specific X-ray tomography reveals myelin levels, integrity and axon orientations in mouse and human nervous tissue, *Nat. Commun.* **12**, 2941 (2021).
 - [9] F. Schaff, M. Bech, P. Zaslansky, C. Jud, M. Liebi, M. Guizar-Sicairos, and F. Pfeiffer, Six-dimensional real and reciprocal space small-angle X-ray scattering tomography, *Nature (London)* **527**, 353 (2015).
 - [10] M. Liebi, M. Georgiadis, A. Menzel, P. Schneider, J. Kohlbrecher, O. Bunk, and M. Guizar-Sicairos, Nanostructure surveys of macroscopic specimens by small-angle scattering tensor tomography, *Nature (London)* **527**, 349 (2015).
 - [11] Y. Yu, D. Yu, B. Sadigh, and C. A. Orme, Space- and time-resolved small angle X-ray scattering to probe assembly of silver nanocrystal superlattices, *Nat. Commun.* **9**, 4211 (2018).
 - [12] T. Hu, W. Q. Hua, G. J. Zhong, Y. D. Wang, and T. Q. Xiao, Nondestructive and quantitative characterization of bulk injection-molded polylactide using SAXS microtomography, *Macromolecules* **53**, 6498 (2020).
 - [13] G. E. Ice, J. D. Budai, and J. W. L. Pang, The race to X-ray microbeam and nanobeam science, *Science* **334**, 1234 (2011).
 - [14] V. H. Tang, A. Bouzerdoum, and S. L. Phung, Compressive radar imaging of stationary indoor targets with low-rank plus jointly sparse and total variation regularizations, *IEEE Trans. Image Process.* **29**, 4598 (2020).
 - [15] L. Zanutto, R. Piccoli, J. Dong, D. Caraffini, and L. Razzari, Time-domain terahertz compressive imaging, *Opt. Express* **28**, 3795 (2020).
 - [16] H. Yu, R. Lu, S. Han, H. Xie, G. Du, T. Xiao, and D. Zhu, Fourier-transform ghost imaging with hard X rays, *Phys. Rev. Lett.* **117**, 113901 (2016).
 - [17] H. Zhang *et al.*, Megapixel X-ray ghost imaging with a binned detector in the object arm, *Chin. Opt. Lett.* **20**, 033401 (2022).
 - [18] D. Pelliccia, A. Rack, M. Scheel, V. Cantelli, and D. M. Paganin, Experimental X-ray ghost imaging, *Phys. Rev. Lett.* **117**, 113902 (2016).
 - [19] G. Douga, K. Yay, E. Kisiel, M. Wojcik, D. Sheyfer, M. Highland, I. Fisher, S. Hruszkewycz, and Z. Islam, Dark-field x-ray microscopy with structured illumination for three-dimensional imaging, *arXiv:2405.12799v2*.
 - [20] J. Li, S. Chen, D. Ratner, T. Blu, P. Pianetta, and Y. Liu, Nanoscale chemical imaging with structured X-ray illumination, *Proc. Natl. Acad. Sci. USA* **120**, 49 (2023).
 - [21] Q. B. Lu, L. Ding, Y. Y. Zhou, M. H. Lu, W. Cao, and Y. F. Chen, Ultrasonic holographic ghost imaging, *Phys. Rev. Appl.* **17**, 034052 (2022).
 - [22] S. Li, F. Cropp, K. Kabra, T. J. Lane, G. Wetzstein, P. Musumeci, and D. Ratner, Electron ghost imaging, *Phys. Rev. Lett.* **121**, 114801 (2018).
 - [23] Y. H. He, Y. Y. Huang, Z. R. Zeng, Y. F. Li, J. H. Tan, L. M. Chen, L. A. Wu, M. F. Li, B. G. Quan, and S. L. Wang, Single-pixel imaging with neutrons, *Sci. Bull.* **66**, 133 (2021).
 - [24] R. I. Khakimov, B. M. Henson, D. K. Shin, S. S. Hodgman, R. G. Dall, K. G. H. Baldwin, and A. G. Truscott, Ghost imaging with atoms, *Nature (London)* **540**, 100 (2016).
 - [25] G. Baym, The physics of Hanbury Brown-Twiss intensity interferometry: From stars to nuclear collisions, *Acta Phys. Pol. B* **29**, 1839 (1998).
 - [26] A. Classen, K. Ayyer, H. N. Chapman, R. Röhlberger, and J. von Zanthier, Incoherent diffractive imaging via intensity correlations of hard X-rays, *Phys. Rev. Lett.* **119**, 053401 (2017).
 - [27] F. Trost *et al.*, Imaging via correlation of X-ray fluorescence photons, *Phys. Rev. Lett.* **130**, 173201 (2023).
 - [28] Y. Klein, O. Sefi, H. Schwartz, and S. Shwartz, Chemical element mapping by X-ray computational ghost fluorescence, *Optica* **9**, 63 (2022).
 - [29] C. Li, W. Yin, H. Jiang, and Y. Zhang, An efficient augmented Lagrangian method with applications to total variation minimization, *Comput. Optim. Appl.* **56**, 507 (2013).
 - [30] W. L. Gong and S. S. Han, Experimental investigation of the quality of lensless super-resolution ghost imaging via sparsity constraints, *Phys. Lett. A* **376**, 1519 (2012).
 - [31] J. Du, W. Gong, and S. Han, The influence of sparsity property of images on ghost imaging with thermal light, *Opt. Lett.* **37**, 1067 (2012).
 - [32] J. Chen, W. Gong, and S. Han, Sub-Rayleigh ghost imaging via sparsity constraints based on a digital micro-mirror device, *Phys. Lett. A* **377**, 1844 (2013).
 - [33] D. L. Donoho and Y. Tsaig, Fast solution of ℓ_1 -norm minimization problems when the solution may be sparse, *IEEE Trans. Info. Theory* **54**, 4789 (2006).
 - [34] E. J. Candès and M. B. Wakin, An introduction to compressive sampling, *IEEE Signal Process. Mag.* **25**, 21 (2008).
 - [35] W. Hua, M. Song, K. Liao, P. Zhou, and X. Li, A new experimental station for microbeam X-ray scattering at the SSRF BL10U1 beamline, *J. Appl. Crystallogr.* **57**, 446 (2024).
 - [36] J. C. Yoo and T. H. Han, Fast normalized cross-correlation, *Circuits, Syst. Signal Process.* **28**, 819 (2009).