X-ray ptychography using a distant analyzer

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Abstract: Ptychography has offered unparalleled high resolution in hard X-ray imaging. However, the imaging quality relies on the interaction between the object and the illumination to be well described by a mathematical model in the reconstruction algorithm. Here, we demonstrate at X-ray wavelengths a method that allows for reconstruction of the object exit wavefield without the need for the knowledge of this interaction. The incident field interacts with the object, and the exit wavefield propagates freely to the plane of an analyzer. As we translate the analyzer and measure diffraction patterns, the propagated wavefield can be reconstructed and the object exit wavefield determined by numerical backpropagation. The method broadens the impact and application of ptychography as it offers information inaccessible to conventional ptychography as well as working distances of tens of millimeters.

OCIS codes: (100.5070) Phase retrieval; (180.7460) X-ray microscopy; (340.7440) X-ray imaging; (340.6720) Synchrotron radiation.

References and links
1. H. M. L. Faulkner and J. M. Rodenburg, “Movable aperture lensless transmission microscopy: a novel phase retrieval algorithm,” Phys. Rev. Lett. 93, 023903 (2004).
2. P. Thibault, M. Dierolf, A. Menzel, O. Bunk, C. David, and F. Pfeiffer, “High-resolution scanning x-ray diffraction microscopy,” Science 321, 379–382 (2008).
3. A. M. Maiden and J. M. Rodenburg, “An improved ptychographical phase retrieval algorithm for diffractive imaging,” Ultramicroscopy 109, 1256–1262 (2009).
4. P. Thibault, M. Dierolf, O. Bunk, A. Menzel, and F. Pfeiffer, “Probe retrieval in ptychographic coherent diffractive imaging,” Ultramicroscopy 109, 338–343 (2009).
5. M. Guizar-Sicairos and J. R. Fienup, “Phase retrieval with transverse translation diversity: a nonlinear optimization approach,” Opt. Express 16, 7264–7278 (2008).
6. S. O. Hruszkewycz, M. V. Holt, C. E. Murray, J. Bruley, J. Holt, A. Tripathi, O. G. Shpyrko, I. McNulty, M. J. Highland, and P. H. Fuoss, “Quantitative nanoscale imaging of lattice distortions in epitaxial semiconductor heterostructures using nanofocused X-ray Bragg projection ptychography,” Nano Lett. 12, 5148–5154 (2012).
7. M. Guizar-Sicairos, M. Holler, A. Diaz, J. Vila-Comamala, O. Bunk, and A. Menzel, “Role of the illumination spatial-frequency spectrum for ptychography,” Phys. Rev. B 86, 100103 (2012).
8. P. Godard, G. Carbone, M. Allain, F. Mastroianni, G. Chen, L. Capello, A. Diaz, T. H. Metzger, J. Stangl, and V. Chamard, “Three-dimensional high-resolution quantitative microscopy of extended crystals,” Nat. Commun. 2, 568 (2011).
9. B. E. Warren, “X-ray Diffraction,” Courier Corporation (1969).
10. F. Zhang, G. Pedrini, and W. Osten, “Phase retrieval of arbitrary complex-valued fields through aperture-plane modulation,” Phys. Rev. A 75, 043808 (2007).
11. I. Johnson, K. Kefmian, O. Bunk, C. David, M. Dierolf, J. Gray, D. Renker, and F. Pfeiffer, “Coherent diffractive imaging using phase front modifications,” Phys. Rev. Lett. 100, 155503 (2008).
1. Introduction

Ptychography is an amplitude- and phase-sensitive technique based on coherent diffractive imaging that offers quantitative structural images with nanoscale resolution [1, 2]. For ptychography, the object of interest is typically translated to scan a coherent illumination at overlapping positions. The incident illumination is transversely confined to provide a signal that can be adequately sampled at the detector. Diffraction patterns are measured and used in iterative algorithms to reconstruct the incident illumination and the transmissivity function of the object [3–5]. Convergence of the reconstruction in conventional ptychography hinges upon the knowledge of a mathematical model that can accurately describe the interaction between the incident field and the object. The interaction is most commonly approximated as a product of the incident field and the object transmissivity under the assumptions that the incident field is time-invariant and that the object is relatively thin and the multiple-scattering effects are negligible. Significant deviations from such a model affect the resolution and signal-to-noise ratio of the reconstruction.

An example in which this interaction model could be inadequate is ptychography in Bragg diffraction geometry, which is sensitive to both the shape of crystalline areas and crystallographic strain along the momentum transfer. For the case in which this strain component exhibits only moderate variations in the measurement’s field of view or when the lattice bending is out of the reflection plane, such ptychographic reconstructions have been successfully obtained.
under the aforementioned approximations [6], i.e., the exit wavefields can be well represented by the product of the object and the incident field, which is the subset of the divergent incident beam that fulfills the Bragg condition. However, in cases of significant strain variations or prominent lattice bending, the angular spectral portion of the incident focused beam that is in Bragg condition can vary significantly from one position of the scan to another. Under such conditions, the interaction cannot be expressed as a multiplication of the object with a constant incident field, rendering conventional ptychography unsuitable. The use of a small-pinhole illumination provides a broad angular spectrum [7] and is therefore not a viable alternative. Although reconstruction of full 3D datasets removes these limitation by measuring a rocking curve at each point [8], current implementations cannot account for the dynamical theory of diffraction for perfect crystals [9], or the multiple scattering effects as the diffracted beam interacts with strong features outside the probed volume. Therefore, in cases when these effects are significant, conventional ptychography algorithms are also unsuitable.

In this work, we demonstrate an X-ray ptychography method that allows us to faithfully reconstruct the object exit wavefield after an arbitrary interaction of the object with a coherent beam. We circumvent the need for a mathematical model describing this interaction by reconstructing the object exit wavefield using a ptychography experiment with a scanning distant analyzer, taking advantage of the fact that the interaction between the propagated exit wavefield and the analyzer is well approximated by the multiplicative relation. We refer to this technique as X-ray tele-ptychography.

In addition to the motivation to extend the applicability of ptychography in the Bragg regime to systems with strong inhomogeneous strain, the method does not require translating the object of interest and provides a large working distance, both significant assets when performing in situ experiments. Different from conventional ptychography, our approach provides the object exit wavefield and does not disentangle the incident illumination from the object influence. However, for situations in which the assumptions of conventional ptychography are not applicable to the extent where the reconstruction quality and quantitativeness are compromised, a high-quality reconstruction of the exit wavefield provides a first step towards nanoscale characterization of the sample.

Compared to previous works that detect the exit wavefield by scanning a phase plate [10, 11], our method does not require a confined illumination and preserves the capability of a customizable and extended imaging region on the sample. While a similar approach has been shown in optical wavelength microscopy [12], it is not trivial to establish the method at the X-ray wavelengths, as in synchrotron beamlines the wavefront is often distorted and fluctuates in time due to imperfections and vibrations of the conditioning optical elements. Here, we explore the applicability and advantages of X-ray tele-ptychography for nanoscale imaging and quantify the coherence requirements, the sensitivity to the conditioning of the incident beam, and the relation between the imaging resolution and the effective field of view due to diffraction effects.

We describe the X-ray tele-ptychography setup in Section 2. In Section 3, we provide the experimental validation and, in Section 4, we characterize the performance of the method as a function of working distance and for the case of a typical versus planar incident wavefront. Section 5 summarizes and discusses the potential and applications of our method.

2. Method

In X-ray tele-ptychography, as illustrated in Fig. 1, the region of interest of the object is illuminated and the exit wavefield, \( \psi_{\text{obj}} \), is the function to be characterized. At a distance \( D \) downstream of the object, an analyzer mounted on a high-precision stage is translated across the propagated exit wavefield, \( \psi_{\text{prop}} \). The field after the analyzer for the \( j \)-th scanning position,
Fig. 1. Overview of the tele-ptychography setup. The area of interest of the object is illuminated, and an exit wavefield $\psi_{\text{obj}}$ is generated by an interaction between the incident beam and the object. This interaction can in principle be unknown. An analyzer downstream of the object is translated across the propagated exit wavefield, $\psi_{\text{prop}}$. The field after the analyzer, $\psi_{\text{ana}}$, propagates to the detector and diffraction patterns, $I$, are recorded. Standard ptychography algorithms are used to reconstruct $\psi_{\text{prop}}$ and the analyzer transmissivity function.

$\psi_{\text{ana}}(j)$, is well expressed as a product of $\psi_{\text{prop}}$ and the analyzer transmissivity and is spatially confined by the analyzer to provide a field that can be adequately sampled by the detector. At each scanning point, an intensity pattern, $I(j)$, is measured. Sufficient overlap between neighboring $\psi_{\text{ana}}(j)$ is ensured in order to obtain a well-conditioned ptychography dataset. Using standard ptychography reconstruction algorithms, phase and amplitude of $\psi_{\text{prop}}$ and the analyzer transmissivity are quantitatively reconstructed. Subsequently, the exit wavefield of interest, $\psi_{\text{obj}}$, is recovered by numerically backpropagating the reconstructed $\psi_{\text{prop}}$.

3. Experiment

To experimentally demonstrate and validate X-ray tele-ptychography, we performed experiments at the cSAXS beamline (X12SA), Swiss Light Source, Paul Scherrer Institut (PSI), Switzerland. For the purpose of comparison and validation, an object that works well with conventional ptychography was chosen. The incident beam was defined to $300 \times 300 \, \mu\text{m}^2$ by a crossed pair of slits located 8 m upstream of the object, as shown in Fig. 1. A photon energy of 6.2 keV, i.e., wavelength $\lambda = 0.2 \, \text{nm}$, was defined with a double-crystal Si(111) monochromator. As a test object, we used a gold Fresnel zone plate (FZP) [13], manufactured in the Laboratory for Micro- and Nanotechnology, PSI, Switzerland. The analyzer was a tungsten pinhole with 2.5 $\mu\text{m}$ diameter and 20 $\mu\text{m}$ thickness, positioned at approximately $D = 3.15 \, \text{mm}$ downstream of the object. It was translated across the propagated wavefield, scanning over a square field of view (FOV) of $10 \times 10 \, \mu\text{m}^2$ on concentric rings with a radial step size of 0.5 $\mu\text{m}$ and $5n$ scanning positions on the $n$th ring [14]. The distance $D$ was determined through numerical propagation. Diffraction patterns were recorded 7.2 m downstream the pinhole with 0.2 s exposure time using a Pilatus detector with $172 \times 172 \, \mu\text{m}^2$ pixel size [15]. In this case, $I(j)$ is the measured far-field intensity pattern, $|\mathcal{F}\{\psi_{\text{ana}}(j)\}|^2$, where $\mathcal{F}\{\cdot\}$ is the Fourier transform. One measured diffraction pattern is shown on a base 10 logarithmic scale in Fig. 1 with the pattern dimension $192 \times 192$ pixels and the scale bar $20 \, \mu\text{m}^{-1}$.

Figures 2(a) and 2(b) show the reconstruction of $\psi_{\text{prop}}$ and the pinhole transmissivity, respectively, which was carried out using the difference-map algorithm followed by maximum

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likelihood refinement [4,16]. Before backpropagation, the reconstructed $\psi_{\text{prop}}$ was apodized 25 pixels along each edge of the $230 \times 230$ pixels window with a quarter period of a cosine function, reminiscent of a Hanning filter, to ameliorate edge artifacts along the image boundaries that may arise due to numerical propagation. The pixel size was $43.6 \times 43.6$ nm$^2$. Figure 2(c) shows the reconstructed backpropagated wavefield, $\psi_{\text{obj}}$

As cross validation, the same object was measured using conventional ptychography, which is suitable for this sample because its interaction with the incident field can be represented by the multiplicative approximation. For this, the pinhole was placed upstream of the object such that it created a confined illumination, which was incident on the object. The object, mounted on a high-precision scanning stage, was translated and illuminated at different scanning positions. The same scanning parameters outlined for the previous experiment were used. The object reconstruction is shown in Fig. 2(d), which compares well to the reconstruction obtained from tele-ptychography in Fig. 2(c). The increase in noise, seen as ripples in the tele-ptychography reconstruction, may be attributed to the method being more sensitive to temporal fluctuations of the incident beam which could be caused by hardware instabilities, e.g. vibration of upstream optical components. This fluctuation exists because the illumination deviates from a perfect plane wave and its spatial structure changes over time, causing $\psi_{\text{prop}}$ also to vary over time,

Fig. 2. (a) Reconstruction of the propagated exit wavefield, $\psi_{\text{prop}}$, and (b) the pinhole transmissivity using tele-ptychography. (c) The field at the object plane, $\psi_{\text{obj}}$, was recovered by backpropagating the reconstructed $\psi_{\text{prop}}$ in (a) from plane $z_2$ to $z_1$, as shown in Fig. 1. (d) For comparison the same object was also measured using conventional ptychography. The scanning FOV was $10 \times 10$ µm$^2$. The hue and brightness encode the phase and amplitude, respectively. The brightness was obtained by normalizing the amplitude to its mean plus two times its standard deviation. Although this causes slight saturation of the brightness, it improves visibility of faint features. The scale bars are 1 µm for all images.
conflicting with the method’s assumption of a time-invariant wavefield. In contrast, for conventional ptychography, this time-variant effect is ameliorated as the pinhole serves as a spatial filter and thus largely removes the spatial structure of the incident beam. The reconstructed phase shift of the FZP is \(-0.73\pi \pm 0.05\pi\) using tele-ptychography and \(-0.73\pi \pm 0.04\pi\) using conventional ptychography. This phase shift was determined by fitting the histogram of the phase to a Gaussian mixture model with two components and obtaining the mean and standard deviation of the difference between the two phase distributions. Both reconstructions reasonably approximate the expected phase shift for the FZP, which has a nominal zone height of 1 \(\mu m\) and would induce a \(-0.80\pi\) phase shift assuming Au density 19.3 g/cm\(^3\). The differences between the reconstructed and the nominal values are within the expected deviation of the height and density of the FZP.

One practical advantage of tele-ptychography is that it offers a flexible working distance. To explore the effects of varying working distances, we imaged gold particles electroplated on a silicon nitride membrane at \(D\) varying from 9.65 mm to 15.65 mm with 0.5 mm intervals, with similar experimental parameters as previously described. Each scan comprised a 30×30 \(\mu m^2\) scanning FOV and 1 \(\mu m\) radial step size. Figure 3(a) shows the reconstructed \(\psi_{prop}\), which was backpropagated by 9.65 mm to give the reconstructed gold particles, shown in Fig. 3(b). Figures 3(c) and 3(d) show the reconstruction of \(\psi_{prop}\) and \(\psi_{obj}\), respectively, for \(D = 15.65\) mm. Through these reconstructions, we demonstrate the method’s ability to image at working dis-

Fig. 3. Gold particles imaged using tele-ptychography. The reconstructed wavefields, \(\psi_{prop}\), are shown in (a) and (c) for \(D = 9.65\) mm and \(D = 15.65\) mm, respectively. The object exit wavefields obtained through backpropagation are given in (b) and (d), clearly showing the particles. The scanning FOV was 30×30 \(\mu m^2\). The hue and brightness encode the phase and amplitude respectively, brightness is adjusted as described in Fig. 2 caption. The scale bars are 1 \(\mu m\) for all images.
We have shown experimentally that tele-ptychography allows for the reconstruction of object exit wavefield without the need for an object-beam interaction model using a practical setup that allows for flexible working distances and does not require translating the object. To offer practical considerations for the implementation of tele-ptychography, in this section we discuss imaging requirements and characterization of the system performance and image resolution.

4.1. Coherence requirement

The required transverse coherence area increases with longer working distance. Here, we show an analysis assuming a kinematic interaction. As illustrated in Fig. 4, diffracted contributions interfere from a larger region of \( \psi_{\text{obj}} \) than the pinhole diameter \( \xi \), resulting in a required transverse coherence of \( \xi + 2\Delta \), where \( \Delta \) is the range that covers the main diffraction contribution of the object. This range is given in the near field by the first Fresnel zone radius, \( \Delta_{nf} = \sqrt{\frac{\lambda D}{2}} \) [17]. Conversely, in the far field \( \Delta_{ff} = \frac{\lambda D}{(2r_{\text{obj}})} \), where \( r_{\text{obj}} \) is the radius of the finest object feature or the image resolution. With the Fresnel number defined by \( N_F = \frac{r_{\text{obj}}^2}{\lambda D} \), it can be shown that the transition occurs, i.e., \( \Delta_{nf} = \Delta_{ff} \), at Fresnel number \( N_F = 0.25 \). When the analyzer is placed in the far field, the required coherence length is equal to \( \Delta_{ff} \), which depends on the object feature size, \( r_{\text{obj}} \). In both the near-field and far-field cases, a larger coherence length is needed as \( D \) increases to ensure the quality and resolution of the reconstruction. For the experiment described in Fig. 3, to image features of size \( r_{\text{obj}} = 85 \, \text{nm} \) at \( \lambda = 0.2 \, \text{nm} \) with \( D = 9.65 \, \text{mm} \) and \( 15.65 \, \text{mm} \), we calculated \( N_F = 0.004 \) and 0.002, respectively, indicating that the pinhole was placed in the far field regime. Therefore, the coherence requirement was \( \xi + 2\Delta_{ff} \), where \( \xi = 2.5 \, \mu \text{m} \) and \( \Delta_{ff} = 11 \, \mu \text{m} \) and \( 18 \, \mu \text{m} \) for \( D = 9.65 \, \text{mm} \) and \( 15.65 \, \text{mm} \), respectively. The coherent area of our illumination beam was at least \( 30 \times 300 \, \mu \text{m}^2 \) (H \( \times \) V), therefore strictly providing sufficient coherence only for \( D \lesssim 11.7 \, \text{mm} \). As a result, the image resolution degrades as \( D \) gets larger because the coherence requirement is no longer fully satisfied.

4.2. Image resolution

Because of diffraction effects, the required scanned area increases with the distance between the exit plane of the object and the analyzer. Hence another important consideration for the method is the relation between the image resolution, \( r_{\text{obj}} \), and the scanning FOV. For \( D = 12.75 \, \text{mm} \), with \( r_{\text{obj}} = 85 \, \text{nm} \) and \( \lambda = 0.2 \, \text{nm} \), \( 2\Delta_{ff} = 30 \, \mu \text{m} \), which corresponds to the scanning FOV in Fig. 3. In other words, in this case, the central point of \( \psi_{\text{obj}} \) has sufficient information for

![Fig. 4. Diffracted contributions interfere from a larger region of \( \psi_{\text{obj}} \) at a pinhole with diameter \( \xi \), resulting in a required transverse coherence of \( \xi + 2\Delta \).](image-url)
the reconstruction of \( r_{\text{obj}} = 85 \) nm features through backpropagation. However, as \( D \) increases, \( 2\Delta r \) exceeds 30 \( \mu \text{m} \) and the scanning FOV required for image retrieval increases as well. The increase in scanning FOV is reflected in the increase of scanning time, during which fluctuations need to be controlled, and the increased radiation dose imparted to the specimen. Consequently, it tends to be advantageous to minimize the scanning FOV for any given imaging demand.

Figure 5 shows the deteriorating image resolution as \( D \) increases for a fixed scanning FOV. A polynomial fitting is shown by the dashed line for each curve to aid the visualization of the trend. The image resolution was determined using Fourier shell correlation (FSC) [18, 19] after image registration [20] between neighboring images in the sequence of varying \( D \), and the first intersection of the FSC curve with the 1/2-bit threshold [18] was used as the resolution estimate. Gray lines indicate the estimates mentioned above, i.e., when coherence may become insufficient and when the scanning FOV may become insufficient for high-resolution imaging.

4.3. Beam conditioning

As previously described, for tele-ptychography, a combination of spatial structure and temporal variation in the incoming wavefront can limit the technique performance. In order to experimentally quantify this effect in a realistic scenario, we explored the sensitivity of the method to beam conditioning. For this purpose, we performed experiments using an incident beam with spatial structure caused by beamline components versus a beam that approximates a plane wave. The latter is created by decreasing the entrance slit openings from \( 300 \times 300 \mu \text{m}^2 \) to \( 50 \times 50 \mu \text{m}^2 \). With a smaller slit opening, the object is illuminated by the central lobe of the slit far field diffraction pattern, providing an illumination with reduced spatial structure of the incident beam, at the cost of a reduction of the flux. As a result, the intensity changed from roughly \( 1.3 \times 10^6 \) photons per diffraction pattern to \( 5.1 \times 10^5 \) photons, with an exposure time of 0.2 s in both configurations. We have used this strategy in the past to provide a diffraction-limited wavefront for optics characterization [21].

The experiment in Fig. 3, done with a slit opening of \( 300 \times 300 \mu \text{m}^2 \), was repeated with the same scanning parameters but with a slit opening of \( 50 \times 50 \mu \text{m}^2 \). Figure 5 shows dependence of reconstructed image resolution versus \( D \) for both cases. As the spatial structure of the beam is significantly reduced with the smaller slit opening, temporal variations due to vibrations become less significant, giving noticeable improvement in resolution.

Fig. 5. Image resolution determined using FSC for different distances \( D \) is compared for slit openings \( 300 \times 300 \mu \text{m}^2 \) and \( 50 \times 50 \mu \text{m}^2 \). The latter reduces significantly the incident flux while providing an incident field that is close to a plane wave. The first gray line shows the distance above which the coherence requirement is not strictly satisfied; the second gray line gives the threshold above which the scanning FOV gradually becomes insufficient.
4.4. Dose consideration

In X-ray tele-ptychography, the whole region of interest is continuously illuminated while a small fraction of the deposited dose is used for detection through an analyzer, rendering the method better suited for radiation-tolerant specimens. The dose delivered on the sample for the measurements in Fig. 3 was approximately 5 MGy [22]. Nonetheless, with this dose, the method still allows for the characterization of many materials and even for 3D imaging by measuring several 2D images. For comparison, from the work on Bragg ptychography in [8], we calculate a dose on the order of 450 MGy for 2D imaging and 4.5 GGy for the full 3D scan. Many factors are at play to determine the required imaging dose and its effect on the sample, including the desired resolution, the feature contrast, the sample material, the focusing scheme, and the scanning step size. As the sample materials and aims are different between [8] and the work presented here, the point is only to illustrate that the imaging dose required for tele-ptychography does not detract from its practical application and potential.

5. Conclusion

We have introduced a ptychographic approach that allows us to quantitatively characterize an exit wavefield with nanoscale resolution. X-ray tele-ptychography offers several advantages in terms of experiment practicality. The method offers a significantly large working distance, as shown in Fig. 5, which is only limited by practical considerations and can be further extended following the guidelines for scanning FOV and coherence outlined in Section 4. Furthermore, the sample is not translated in tele-ptychography, allowing the use of bulky chambers for in situ environmental or mechanical tests that are not always amenable to precision scanning. In particular, this approach serves as a means to study samples in environments that cannot be well characterized, including situations in which the exact position of potentially scattering windows or other obstructions is an issue.

Caveats of the method in comparison to conventional ptychography include a larger required transverse coherence length and the increased sensitivity to beam conditioning. We have shown that the time-variant spatial structure of the incident illumination may negatively affect the reconstruction and that this problem can be mitigated by having a diffraction-limited wavefront. We have also demonstrated that, as the propagation distance increases, a larger scanning FOV is needed to capture the diffracted high spatial frequency contributions of the wavefield.

The great potential of tele-ptychography arises from its advantage of being independent of a priori assumptions on the interaction between the illumination and the object. This offers new opportunities in nanoscience, including a step towards the nanoscale characterization of highly strained crystals and their defects in or close to Bragg conditions and the use of probes, such as electrons and photons in the visible range, for which multiple, potentially inelastic scattering effects may present a challenge. By reconstructing the object exit wavefield, the contribution of the object response and the incident illumination is not decoupled. Nonetheless, development of further analysis techniques could provide a physically meaningful object description. In the cases of thick crystalline samples in Bragg geometry, with an object exit wavefield, the physical characteristic of the object could potentially be recovered by including the dynamical scattering theory in the reconstruction.

For objects that exhibit significant multiple-scattering effects, the limitation by the multiplicative approximation can be overcome by a recently proposed multi-slice approach [23, 24], where the thick object is divided into thin slices that individually satisfy the product approximation. This is an example where extending the mathematical model is possible, provided the number and separation of slices are known. Other complications may also render a simple interaction model insufficient. For instance, when the object has a flat and smooth surface that is almost parallel to the propagation direction of the beam, surface reflection caused by this
grazing incidence can be problematic to the reconstruction algorithm that assumes a planar object. In the case of spatially sparse objects, one can take advantage of compressed sensing approaches to reconstruct a longitudinally sectioned image from an exit wavefield [25]. For weakly interacting objects, one could obtain 3D reconstructions from exit wavefields at different orientations using principles of diffraction tomography [26, 27]. Moreover, this technique could potentially be applied in the future to characterize a complex interaction between the beam and the sample if measurements with and without the sample and under different illumination conditions are available.

In short, we have experimentally demonstrated at X-ray wavelengths a technique that allows ptychographic reconstruction at a position distant from the object. This method provides a way to recover an object exit wavefield in situations where conventional ptychography is not applicable by circumventing the need to model the interaction between the illumination and the object. While not providing direct information about the object, tele-ptychography is applicable in forward and Bragg geometry and provides a reliable technique for nanoscale characterization of the exit wavefield. In cases where conventional ptychography is at its limits of applicability, tele-ptychography offers a faithful reconstruction of the exit wavefield, paving the way for a comprehensive study of the object.

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