
HAMAMATSU PRESENTS
ANALYTICAL TALKS
WATCH NOW

Received: 26 January 2021 | Revised: 9 June 2021 | Accepted: 2 July 2021

DOI: 10.1111/jmi.13048

Journal of Microscopy RMS

INVITED REVIEW

A review of high-resolution microscopic ghost imaging with a low-dose pseudothermal light

Z. Sun[1] | **F. Tuitje**[1,2] | **C. Spielmann**[1,2]

[1] Abbe Center of Photonics, Institute of Optics and Quantum Electronics, Friedrich Schiller University, Jena, Germany

[2] Helmholtz Institute Jena, Fröbelstieg 3, Jena 07743, Germany

Correspondence
Zhe Sun, Abbe Center of Photonics, Institute of Optics and Quantum Electronics, Friedrich Schiller University, Max Wien Platz 1, 07743 Jena, Germany.
Email: zhe.sun@uni-jena.de

Summary

High-resolution imaging is an important issue in various fields of scientific researches and engineering applications. Pseudothermal ghost imaging is one of the subfields of quantum imaging, providing new capabilities beyond conventional imaging methods. Also, it can provide a new viewpoint of imaging physical mechanisms. In this review, we explain the major ideas of pseudothermal ghost imaging, restricting the very important case of high-resolution imaging. We analyse the strategies which can significantly improve the image quality in pseudothermal ghost imaging. It may apply for merging it with common optical imaging methods in the extreme ultraviolet (XUV) or X-ray spectral regime for driving the applications to a wider audience in bioscience and nano-physics.

KEYWORDS
ghost imaging, microscopic, pseudothermal light, resolution

Key points

1. Ghost imaging, based on multiplexing, can help overcome specific kinds of noise. It can offer a way to alleviate the irreversible damage to the sample, because the object does not interact with the CCD camera.
2. Pseudothermal light sources have a substantially higher flux, so the performance of the pseudothermal ghost imaging system can exceed those based upon parametric down-conversion sources.
3. XUV and X-ray radiography are invaluable tools for the analysis of biological samples and in nano-physics. The pseudothermal ghost imaging can easily be transferred into the XUV and X-ray regime without a lens, whereas parametric down-conversion is restricted to the visible and infrared range.
4. The main drawbacks of pseudothermal ghost imaging are longer acquisition times and the large number of measurements required for image recovery. At present, the resolution of microscopic ghost imaging has never reached the level of traditional microscopic imaging.

1 | INTRODUCTION

In the last years, we have witnessed tremendous progress in optical microscopy, due to the development of new techniques allowing 3D sample reconstruction and/or high-resolution imaging using short-wavelength illumination in lensless approaches. However, many of these advanced imaging methods have severe drawbacks such as the need for high flux illumination sources, irreversible radiation damage of the sample and limited access to large-scale facilities. Fortunately, ghost imaging, which is an unconventional imaging technique developed in the frame of quantum imaging relying on quantum or spatial intensity-fluctuation correlations to image objects, will allow us to overcome some of these limitations. Both correlated photon interference and classical intensity-fluctuation correlations could be employed for ghost imaging. Ghost images are obtained by correlating the total intensity of the transmitted or reflected light of an illuminated object with the spatially resolved intensity of a position-correlated reference beam that has never interacted with the object. Therefore, radiation damage of the sample can be alleviated by varying the intensity ratios between object- and reference-beam, which is the most severe limitation for enhancing the resolution in classical biological nanoscale imaging. This becomes especially true using short-wavelength radiation, such as the XUV and X-ray, for increasing the resolution or to get element-specific imaging.

For quantum ghost imaging in the XUV, further work on the development of a useful photon-pair source needs to be done. Spatially correlated pairs of photons generated by spontaneous four-wave mixing might be the preferred process in the XUV because the conditions for spontaneous parametric down-conversion can be hardly met in the XUV. Four-wave mixing has been successfully demonstrated for photon-pair generation at infrared wavelengths, but more work will be necessary to realise XUV ghost imaging. Especially, it is necessary to implement a high-flux XUV light source, where the strong absorption of all materials in XUV reduces the possibility of manipulating light fields. On the contrary, pseudothermal ghost imaging is very flexible regarding wavelength and light source. Nowadays, pseudothermal ghost imaging relying more on conventional light sources is widely studied and is heavily used in current applications. The source of pseudothermal light is conveniently a laser beam sends through a rotating ground-glass screen to randomised the spatial phase (see Figure 1). The intensity-fluctuation correlation between the two beams as shown in the setup is mainly limited only by their shot noise fluctuations. The propagation between the object and the bucket detector does not need to preserve coherence in the pseudothermal ghost imaging. This means that scattering or another noise sources don't deteriorate the image. This advantage can be widely used in the application of biological imaging through scattering tissue and can be further enhanced by using shorter wavelengths. This will allow realising ghost imaging not only with laser-driven XUV and X-ray sources, but also with synchrotrons and free-electron lasers (FEL). Because of their parameters, they will enable, for example, element-specific X-ray microscopic ghost imaging, which is very promising also for life science applications. Further into the higher penetrating depth of X-rays, it will be possible to investigate thicker samples. Because of the photon energy-dependent elements specific core-level excitation, we can also identify the chemical composition of a thick sample with high-spatial-resolution.

High-resolution microscopic ghost imaging with low-dose pseudothermal light is very promising, but the achieved resolution is not yet comparable to conventional high-resolution imaging, or lensless imaging techniques such as coherent diffraction imaging (CDI), which is the method of choice in the short wavelength range. With this short review, we want to motivate other researchers to further explore pseudothermal ghost imaging to address some of the above-mentioned limitations and pave the way for ultra-high-resolution microscopy with low-dose light sources. To be more specific in this paper, we provide a review of high-resolution microscopic ghost imaging with low-dose pseudothermal light and focuses on the algorithms and methods developed in context with XUV and X-ray sources in the last two decades. Furthermore, we describe how to combine the advanced algorithms and methods, to establish an alternating imaging approach in microscopy without radiation damage and/or lowering the requirements for labelling or other invasive preparation procedures.

2 | RAISE THE QUESTION

In 1995, Yanhua Shih's group experimentally demonstrated quantum ghost imaging by using spatially correlated pairs of photons and offered a novel approach toward imaging. However, it was soon realised that while ghost imaging was originally designed to exploit the quantum nature of light. It is also possible to be accomplished as a classical ghost imaging experiment. Unlike quantum ghost imaging, the classical version relies on pseudothermal light sources. Such sources are easily realised by passing a laser beam through a rotating ground-glass diffuser. With a diffuser at rest, a static speckle pattern is generated, resulting from the diffusive transmitted light that undergoes constructive and destructive interference in different

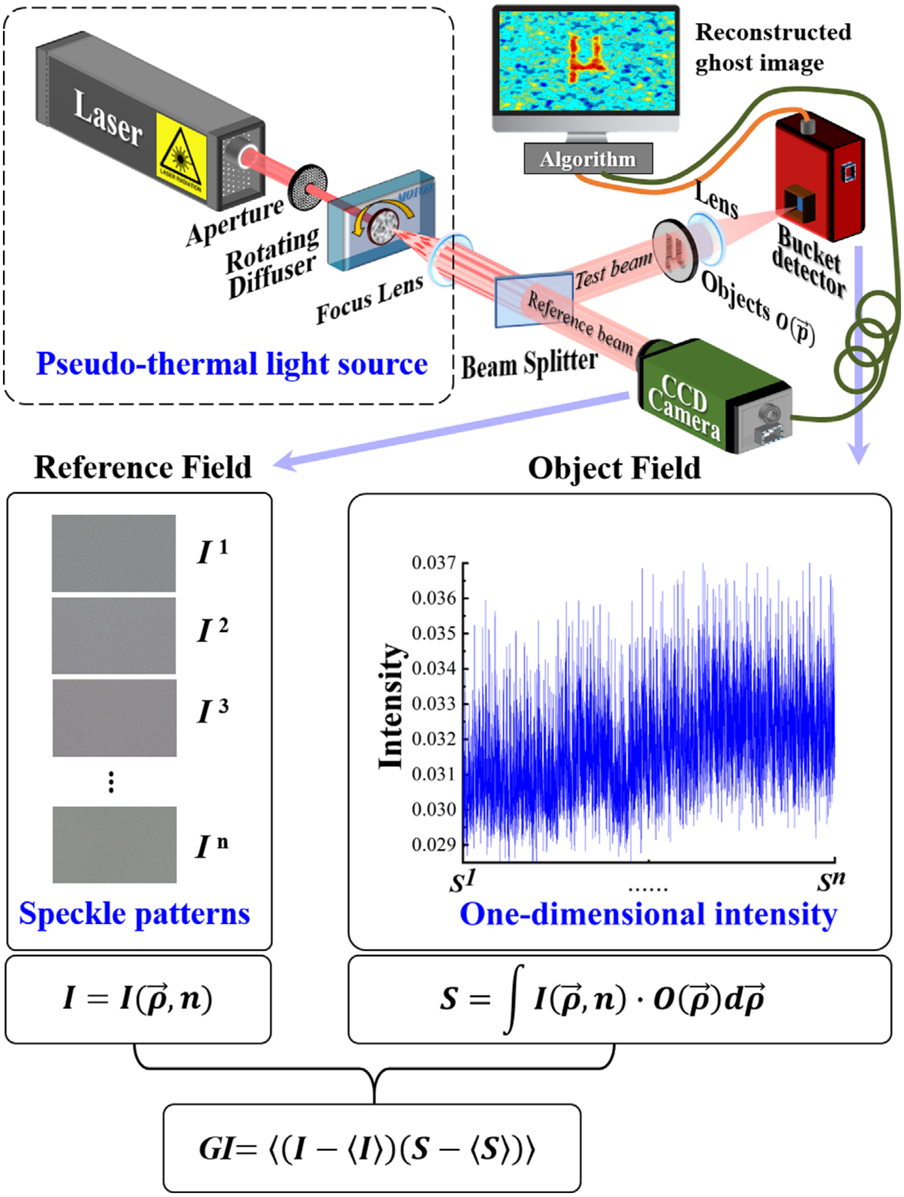

FIGURE 1 Schematic of pseudothermal ghost imaging. The collimated laser beam through a rotating ground-glass diffuser. The beam splitter copies the speckle patterns into the reference and object beams through the same distance free-space paths. The reference beam illuminates a high-spatial-resolution detector (CCD camera) whereas the test beam illuminates a single-pixel detector (bucket detector) through object transparency. $I = I(\vec{\rho}, \mathrm{n})$ is the intensity distribution of the signal speckle field. S is the total light intensity containing the object's information. $O(\vec{\rho})$ is the objective function and $\vec{\rho} = (x, y, z)$ is the space coordinate. n is the total number of iterations. The ghost image is retrieved by $GI = \langle (I - \langle I \rangle)(S - \langle S \rangle) \rangle$

spatial regions. Then the spatial structured illumination light field is split into two beams with nearly identical spatial properties. However, the so-called reference and object beam can have different intensities. The reference beam is recorded by the CCD while the object beam impinges upon the target object under a comparable distance. The scattered or transmitted light is then measured by the bucket detector, for example a photodiode. The signal from the bucket detector and the simultaneously recorded imaging with the CCD is stored rapidly in a computer. With advanced correlation algorithms, the unknown object can be retrieved from numerous simultaneously stored data sets. With the rapid development of classical ghost imaging relying on pseudothermal light sources, Shih's group[1] proposed the question of whether ghost imaging with 'classical' light sources, can provide the same accuracy as using light sources emitting spatially correlated pairs of photons. Since then, major efforts have been made to pursue high-resolution ghost imaging with pseudothermal light sources.

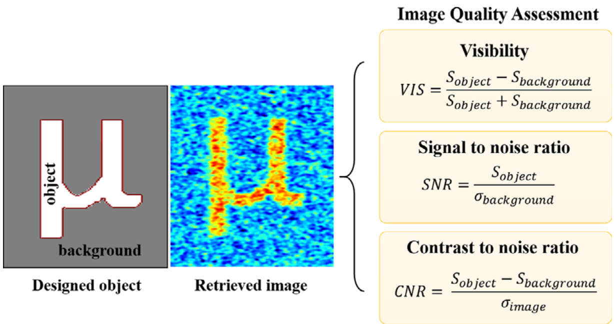

FIGURE 2 Common methods for the evaluation of image quality in ghost imaging. The S_{object} and $S_{\text{background}}$ are the fluctuating signals of the object and the background. The $\sigma_{\text{background}}$ is the square root of the standard deviation of the related noise. The CNR represents the noise and fluctuations in the fields. The σ_{image} is the root-mean-squared average of the corresponding noises in the image

3 | BRIEF REVIEW OF GHOST IMAGE QUALITY ASSESSMENT

Pseudothermal ghost imaging relies on correlating a measured 2-D intensity speckle pattern to a transmission or reflection scalar value of an object illuminated by the same speckle pattern (see Figure 1). The randomness of the rotating ground-glass diffuser in the pseudothermal ghost imaging will impose spatial field fluctuations. By varying the speckle pattern over time and simultaneously measuring the transmitted light through the object, a statistical reconstruction of the image is possible. The retrieved image quality directly depends on the number of iterations and the correlation between fluctuating patterns and bucket signals.

Visibility, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) have been used to characterise the image quality (see Figure 2). Among them, the visibility describes the relative difference between the bright and dark areas of the image. A pseudothermal ghost image always lies on a noisy background. Thus, the noise in the background of the retrieved image is one of the main drawbacks that affect the image quality. Unlike the visibility that contains no noise information, the SNR compares the level of a signal to the level of the background noise of the ghost image. To study the contrast compared to the overall noise in the image, the CNR is used to distinguish object signal and background noise.

4 | HIGH-QUALITY IMAGE RECONSTRUCTION STRATEGIES

The slightly lower theoretical possible contrast and resolution for the pseudothermal ghost imaging is outweighed by several advantages: First, the pseudothermal light sources have a substantially higher flux in most cases. With the rapidly fluctuating high-flux patterns, lots of independent images can be acquired, and subsequently, the image quality is improved by averaging. Second, the spatial resolution of an optical microscope linearly depends on the wavelength of the illuminating light source. Traditional imaging depends on an optical element with certain characteristics; this will be limited to a certain range of wavelengths. Fortunately, the pseudothermal ghost imaging can be transferred into the XUV and X-ray regime without a lens in principle, whereas parametric down-conversion is mainly restricted to the visible and infrared range due to the efficiency. Besides these advantages, over the last decade or so, there have been lots of strategies available that can significantly improve the image quality in pseudothermal ghost imaging, such as higher-order correlation, optimise the algorithm, speckle manipulation method and so on. These methods have shown incredible progress in improving image quality.

4.1 | High-order correlation

From very early developments of pseudothermal ghost imaging, there has been much research into ways to reduce both the data acquisition time and the image reconstruction time. The most classic idea based on multiplexing is high-order pseudothermal ghost imaging. Cao et al[2] have shown that high-order intensity correlation can dramatically enhance the visibility and resolution than low-order intensity correlation (see Figure 3). The pseudothermal light passes through the double slits to ensure that all the correlation terms play the same role while the intensity background is effectively reduced. The visibility in higher-order correlation measurements can be enhanced while the pattern resolution can also be improved under certain conditions.

4.2 | Speckle manipulation

In most of the earliest examples of traditional ghost imaging, the time-dependent speckle patterns whose coherence length are generated by passing the collimated laser beam through a rotating ground-glass diffuser as shown in Figure 1. As the ghost image quality highly depends on the characteristics of the speckle patterns.

With $x_0 = \pi\lambda f/\omega_0$, we can estimate the average speckle sizes δx_0 as a function of the wavelength λ, the focal length of the lens f and the beam waist ω_0, which can be easily changed. The image quality given by the CNR is proportional to the speckle size δx_0 according to previously

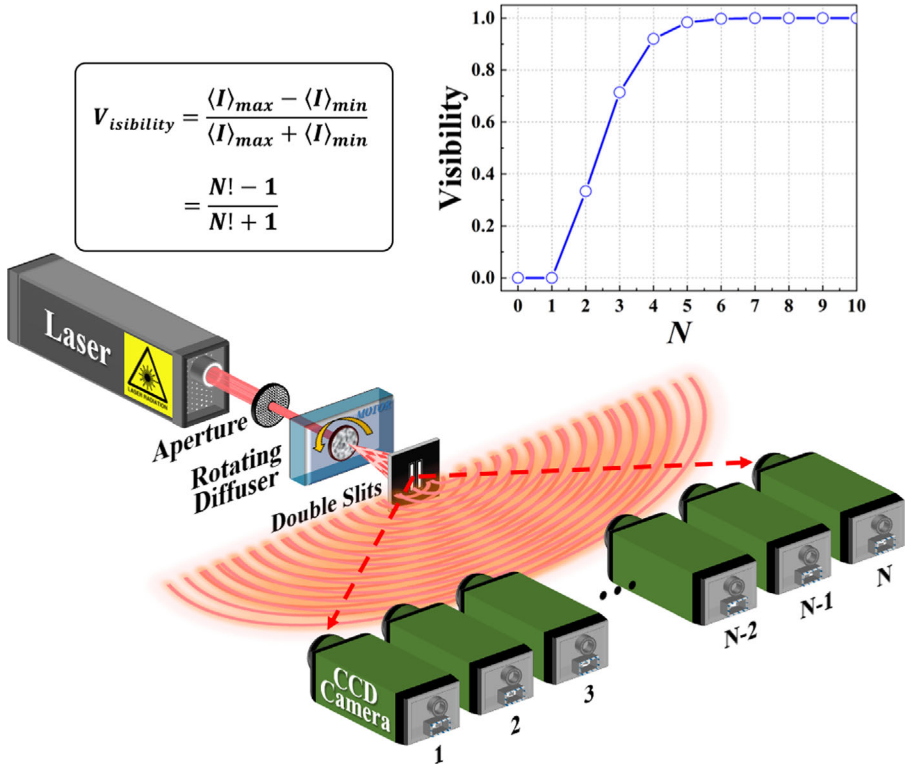

FIGURE 3 Experimental setup for double-slit interference with pseudothermal light by N_{th}-order correlation. The insert curve shows the maximum visibility increases toward unity with the order N for the N_{th}-order intensity correlation

published theoretical results. In Figure 4, we illustrate this scaling.

To enhance the image quality as described in Sun et al[3] With a specially designed speckle pattern, high-resolution and high CNR microscopy in pseudothermal ghost imaging was obtained. To be more specific, the role of speckle size, object size and detector noise on the maximum achievable CNR and resolution in microscopic ghost imaging was analysed. The scaling laws for achieving the highest visibility and spatial resolution of the retrieved microscopic ghost images were derived. This causes a trade-off between resolution and CNR for macroscopic objects, whereas it should consider the saturation of intensity of the detected signal and noise signal for microscopic objects.

4.3 | Reconstruction algorithm

Different methods of data processing of the object and reference signals lead to ghost images with different qualities. The imaging resolution in pseudothermal ghost imaging is limited by the transverse size of the speckles in the object field for the standard reconstruction algorithm. A high reconstruction efficiency and error tolerance algorithm can provide great help in the application of pseudothermal, microscopic ghost imaging. A reconstruction algorithm of a pseudothermal ghost image, relying on the powerful sparse reconstruction theory called compressive sensing has dramatically improved the quality of the ghost images with fewer measurements. Gazit et al[4] successfully applied super-resolution and sub-wavelength imaging in the experiment relied on newly developed compressed sensing techniques. The spatial resolution of the retrieved image is five times higher than the finest resolution defined by a spatial filter. Compared with quantum ghost imaging, this technique shows much higher efficiency in the process of image data extraction, and the recovered ghost image's spatial resolution can overcome the diffraction limit. They believe it can provide a major improvement of 'looking beyond the resolution limit'.

Later on, Han et al[5] combined ghost imaging via sparsity constraint (GISC) with Fourier-transform for the image reconstruction. GISC has successfully applied to LiDAR, spectral camera and Lensless Wiener-Khinchin Telescope, which has been further expanded into the X-ray range. GISC can apply to an optical microscope as a simple computerised image processing tool, delivering results in almost real time with practically no additional hardware. It is a significant step towards realising tabletop high-resolution 3D imaging of complex materials, such as biomolecules and nano-materials.

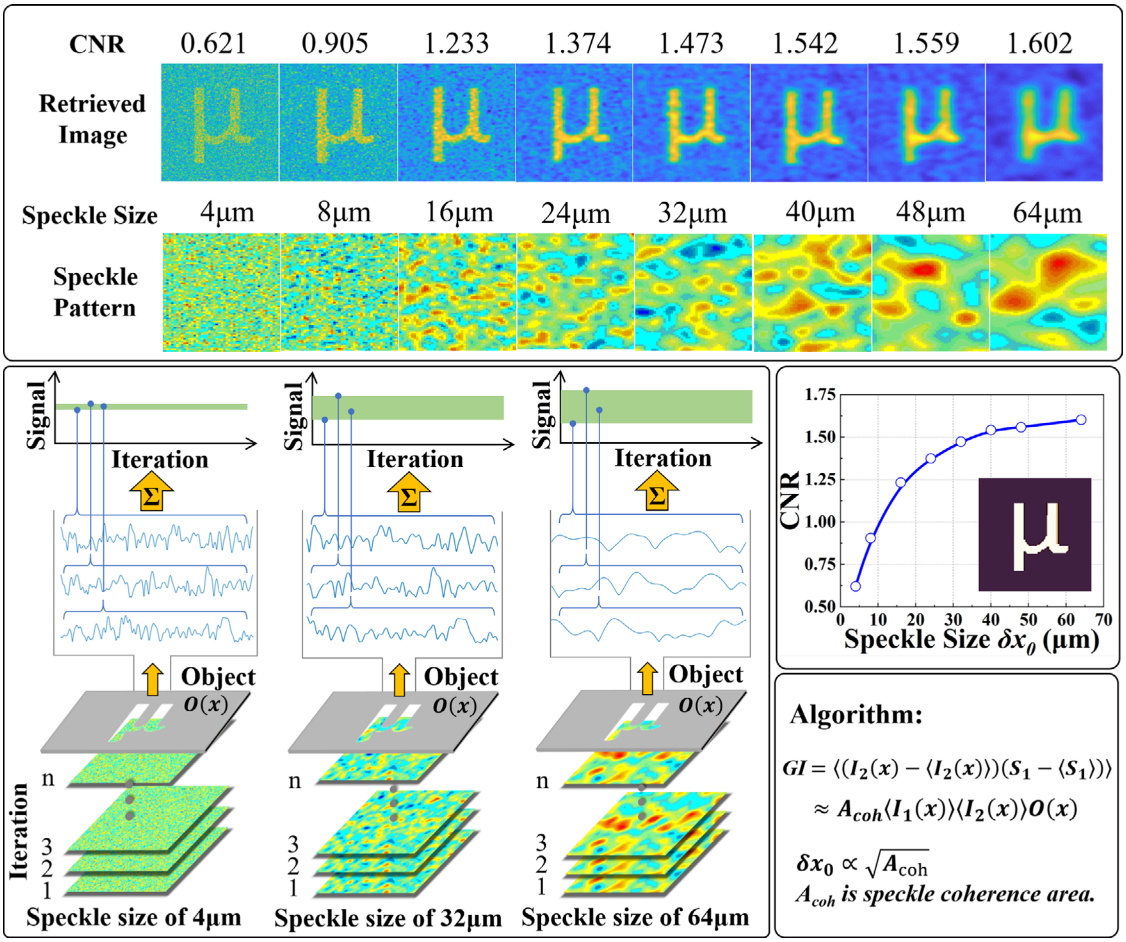

FIGURE 4 Simulated CNR of the retrieved ghost image versus speckle size. The insert curve shows the CNR increases with the speckle size δx_0. The top figures show the retrieved image and corresponding speckle patterns for different speckle sizes

Based on a random-phase modulator and GISC to get speckle patterns, Li et al[6] developed a single-frame, wide-field nanoscopy with fluorescence illumination. Fluorescence is true thermal light and has important similarities. Namely, the speckle size of a pseudothermal light is the same as for a thermal light source and corresponds to the coherent areas. This source can be used for ghost imaging with the same setup and reconstruction algorithm. In the experiments, they demonstrated a resolution of 80 nm at a high SNR in the visible spectral range. This technique paves the way to real-world applications drawing on the ghost imaging protocol, with the possibility of exploiting all the advantages of ghost imaging against standard imaging.

4.4 | XUV and X-ray ghost imaging

Moving beyond the domain of visible-light optics to explore the high-resolution image, ghost imaging has now been realised using hard X-rays and XUV. For analysis of biological samples and in nano-physics, XUV and X-ray radiography is an invaluable tool. These sources can resolve very fine structures and is therefore well suited to record high-resolution images. These high-resolution and chemical composition-sensitive images combined with visible fluorescence images of biological structures can be the key to a more profound understanding of the inner mechanisms of cells. While the idea to get a high-resolution image by ghost imaging in X-ray and XUV experiments has only recently started to receive significant attention, demonstrations at the synchrotron and FEL sources have already been conducted.

XUV radiation can provide high-spatial-resolution imaging and the ability to look inside thick samples that are opaque for visible light. Kim et al[7] demonstrated ghost imaging at an XUV FEL facility. A diffuser was employed to generate a speckle pattern, which is made of silica nano-spheres of approximately 200 nm in diameter. The ghost image of a double-slit structure was obtained by computing the correlations between a reference area and a bucket region. This initial research paves the way for XUV

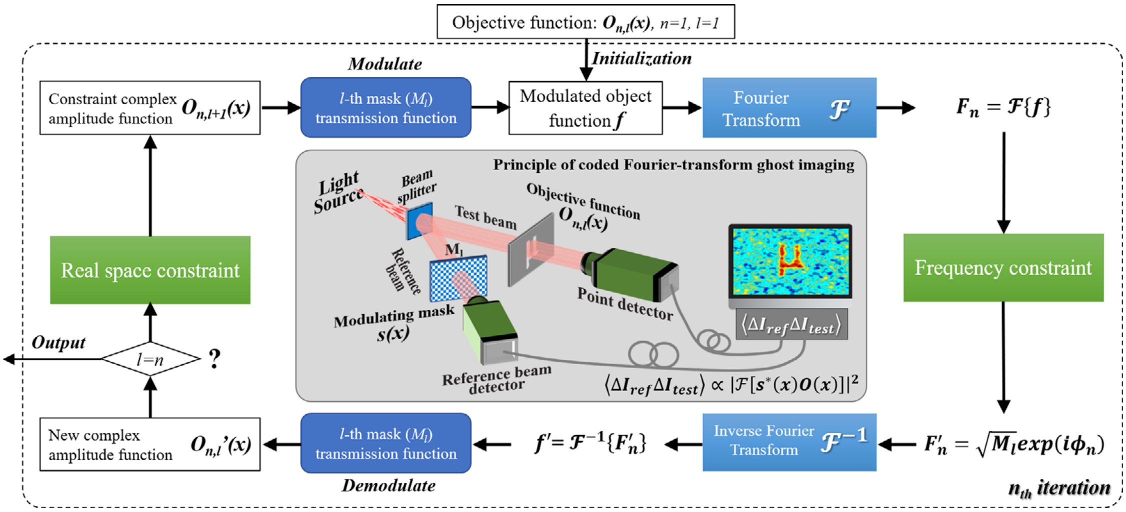

FIGURE 5 Phase retrieval process and principle of coding Fourier transform ghost imaging. $\langle \Delta I_{ref}\langle x_{ref}\rangle \Delta I_{test}\langle x_{test}\rangle\rangle$ is the correlation function between the intensity of the test beam and the reference beam. The mask (M_l) in the reference beam can non-locally modulate the sample in the test beam. By measuring the intensity correlation between the two beams, the Fourier-transform patterns of the object encoded by the mask in real space can be obtained. There are n iterations between real space and frequency space

pseudothermal ghost imaging at FEL facilities. Unfortunately, there is no work done in the field of tabletop XUV ghost imaging so far.

X-ray ghost imaging is also feasible, and two possible schemes have been demonstrated successfully. One relies on a crystal beam splitter to perform X-ray classically ghost imaging. This approach demands high-flux intensity sources, which can be only realised in large-scale facilities such as synchrotrons. Direct real-space X-ray ghost imaging experiments have been performed with synchrotron radiation by Pelliccia et al.[8] The shot noise of the synchrotron emission process is measurable as speckles, leading to a speckle correlation between the two beams. The ghost image was retrieved by using the intensity correlation between the bucket signal and the image of the empty beam.

Another approach is based on intensity modulation. Here the speckles are generated by absorption in a set of modulation masks that transmit a series of X-ray patterns. Han's group[9] experimentally realised X-ray ghost imaging at the same time as Pelliccia et al.[8] They demonstrate a lensless Fourier-transform ghost imaging (FGI) method using a hard X-ray pseudothermal source (see Figure 5), which is feasible to achieve high-resolution microscopy with a tabletop X-ray source. Thanks to the pseudothermal ghost imaging, the diffraction pattern of a sample in the testing path can be non-locally encoded by inserting modulation components in the reference path in FGI via sparsity constraints, which is different from CDI techniques. Multiple encoding of the sample can be easily realised and better image quality may be expected. These researches pave the way for ghost imaging with a low-dose, tabletop pseudothermal light sources to affect applied X-ray.

For future applications of ghost imaging in life science, these large-scale light sources pose severe limitations. Zhang et al[10] realised ultralow-dose X-ray ghost imaging using a tabletop X-ray source. The spatial resolution could be improved with finer speckle patterns or various computational methods by shortening the longitudinal coherence length. Thus, radiation damage to biological specimens could be greatly reduced with this new technique.

Another promising alternative is the compact and highly coherent XUV sources based on laser-driven high harmonic generation fitting on an optical table. These sources are very promising for establishing XUV microscopic ghost imaging as a new tool for high-resolution microscopy. However, unlike in the X-ray range shift from transferring the concepts realised for visible ghost imaging to the XUV is not straightforward. On the one hand, the main obstacle is the preparation of optical elements. It's difficult to produce high-quality optics in the XUV regime for realising ghost imaging setups due to the high surface quality requirements given by the short wavelength. Moreover, unlike X-ray, XUV radiation is absorbed strongly in nearly all materials. One challenge is the beam splitter, which is a widely available standard device for visible light. With the inherent loss of almost all materials in the XUV range together with a surface roughness in the order of the wavelength, the available beam splitters have a lower transmission and often modify the spatial distribution of the transmitted and reflected beam differently. The other is the diffuser. The distribution pattern generation method for tabletop X-ray, for example a movable porous gold film deposited on a Si_3N_4 substrate[9] or sandpaper with silicon carbide grains,[10] is no longer suitable for XUV. We must rely on reflective optics including the diffuser. On the other hand, one of the main drawbacks of pseudothermal ghost imaging is the long acquisition time required for reconstructing the image with a higher CNR in comparison with conventional imaging. This limits its scope of application, especially for imaging a fast-moving object. To solve these obstacles, a grazing incidence, programmable digital micro-mirror devices (DMD) can be employed to realise arbitrary illumination patterns with a known intensity distribution. Together with advanced algorithms, this can increase the speed of speckle field generation and image reconstruction in comparison with the rotating groundglass. In essence, the DMD is a programmable binary transmission mask, which can be used to structure the detected field intensities and become the main tool in the control of amplitude and phase of light fields in a wide spectral region including the XUV.

5 | CONCLUSIONS

We have provided a review of the high-resolution pseudothermal ghost imaging techniques and given a summary of some major developments since the question was proposed by Shih's group.[1] For real-world applications of pseudothermal ghost imaging, reducing the exposure and data processing times and increasing the image quality is desired. We have discussed some important aspects of the corresponding technique, including optimising the algorithm, higher-order correlation imaging method, speckle manipulation method and so on.

We conclude there are three major research directions to establish pseudothermal ghost imaging for high-resolution imaging: The first is improving the image quality by speckle pattern manipulation and advanced algorithms. The second is the transfer to the XUV and X-ray which requires solving several technical issues. The last is the multiplexing-based pseudothermal ghost imaging, which is very flexible and can be easily combined with traditional imaging methods. It can provide a novel idea for breaking the resolution limitation. As a multiplexing imaging technology based on the high-order correlation of pseudothermal light, pseudothermal ghost imaging not only may apply to many applications but also can be used, for example to obtain a first support head for CDI for a faster convergence, which gives a simple and readily implementable route to high-resolution microscopy. Also, it's very promising and open applications of microscopic imaging in biological science and nano-physics.

6 | FUTURE PROSPECTS

High-resolution microscopic ghost imaging with a low-dose pseudothermal light is ambitious, but it promises to yield novel and versatile tools for identifying microbes or molecules in situ and in real time in the microscope whilst radiation damage-free. Inspecting the Abbe criterion reveals a more straightforward approach to resolve nanoscopic objects, shortening the wavelength of the illumination. Using radiation in the sub-keV regime, XUV or X-ray can improve the resolution by several orders of magnitude compared to traditional microscopic imaging. Significant progress has been made recently regarding lensless imaging techniques, like CDI. Because of the requirements for high coherence and brightness, mostly synchrotron radiation and X-ray FEL sources can be used for X-ray CDI applications. Currently, the tabletop, compact, and highly coherent XUV radiation based on laser-driven high harmonic generation is mostly an ideal source for diffraction-based imaging. In CDI, resolving the measurement is limited by the numerical aperture and the wavelength. However, breaking the barrier is not possible from a classical point of view. The techniques are just approaching the barrier, because of the strong coupling between resolution and radiation dose. Besides, the radiation damage prohibits quantitative imaging of a wide range of biological specimens or nano-materials at nanometre-scale resolutions.

Fortunately, multiplexing, the most basic idea of ghost imaging, enables one to trade the resolution of the probe or detection system for the resolution at which the probe can be patterned or measured. This trade-off may make it possible to collect data at a higher resolution. Alternatively, it may be a simpler or cheaper option than increasing the detector resolution. The only possible way multiplexing can be used to mitigate radiation damage is when it is combined with pseudothermal ghost imaging. This idea opens potential options for together with the CDI incorporated into the highly coherent XUV microscopic ghost imaging system to achieve microscopic imaging. With an improved imaging setup and reconstruction algorithm, we can expect to obtain information about the specimen and the enhanced resolution will be sufficient for locating with a precision below Abbe's diffraction limit in real and beyond other techniques.

ACKNOWLEDGEMENTS
This work was supported by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2051 [Project-ID 390713860], 'Balance of the Microverse'; Federal State of

Thuringia and the European Social Fund (ESF) Project [2018 FGR 0080].

Open access funding enabled and organized by Projekt DEAL.

ORCID

Z. Sun https://orcid.org/0000-0002-4224-9811

REFERENCES

1. Angelo, M.D., Valencia, A., Rubin, M.H., & Shih, Y.H. (2005). Resolution of quantum and classical ghost imaging. *Physical Review A*, *72*, 013810.
2. Cao, D.Z., Xiong, J., Zhang, S.H., Lin, L.F., Gao, L., & Wang, K. (2008). Enhancing visibility and resolution in Nth-order intensity correlation of thermal light. *Applied Physics Letters*, *92*, 201102.
3. Sun, Z., Tuitje, F, & Spielmann, C. (2019). Toward high contrast and high-resolution microscopic ghost imaging. *Optics Express*, *27*, 33652–33661.
4. Gazit, S., Szameit, A., Eldar, Y. C., & Segev, M. (2009). Super-resolution and reconstruction of sparse sub-wavelength images. *Optics Express*, *17*, 23920–23946.
5. Han, S., Yu, H., Shen, X., Liu, H., Gong, W., & Liu, Z. (2018). A Review of Ghost Imaging via Sparsity Constraints. *Applied Sciences*, *8*, 1379.
6. Li, W., Tong, Z., Xiao, K., Liu, Z., Gao, Q., Sun, J., Liu, S., Han, S., & Wang, Z. (2019). Single-frame wide-field nanoscopy based on ghost imaging via sparsity constraints. *Optica*, *6*, 1515–1523.
7. Kim, Y. Y., Gelisio, L., Mercurio, G., Dziarzhytski, S., Beye, M., Bocklage, L., Classen, A., David, C., Gorobtsov, O. Yu., Khubbutdinov, R., Lazarev, S., Mukharamova, N., Obukhov, Y. N., Rösner, B., Schlage, K., Zaluzhnyy, I. A., Brenner, G., Röhlsberger, R., von Zanthier, J., Wurth, W., & Vartanyants, I. A. (2020). Ghost imaging at an XUV free-electron laser. *Physical Review A*, *101*, 013820.
8. Pelliccia, D., Rack, A., Scheel, M., Cantelli, V., & Paganin, D. M. (2016). Experimental X-Ray Ghost Imaging. *Physical Review Letters*, *117*, 113902.
9. Yu, H., Lu, R., Han, S., Xie, H., Du, G., Xiao, T., & Zhu, D. (2016). Fourier-Transform Ghost Imaging with Hard X Rays. *Physical Review Letters*, *117*, 113901.
10. Zhang, A.X., He, Y.H., Wu, L.A., Chen, L.M., & Wang, B.B. (2018). Tabletop x-ray ghost imaging with ultra-low radiation. *Optica*, *5*, 374–377.

How to cite this article: Sun, Z., Tuitje, F., & Spielmann, C. (2021). A review of high-resolution microscopic ghost imaging with a low-dose pseudothermal light. *Journal of Microscopy*, *284*:3–11. https://doi.org/10.1111/jmi.13048