

Extended depth-of-field magneto-optical Kerr microscopy for applications in three-dimensional nanomagnetism

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(Received 15 January 2026; revised 27 April 2026; accepted 15 June 2026; published 21 September 2026)

High-resolution imaging of magnetic nanostructures is essential for understanding fundamental spin phenomena and designing advanced devices. Recent developments in three-dimensional (3D) nanomagnetism have highlighted the growing need for imaging techniques that can capture magnetic structures across curved or tilted surfaces with high sensitivity. Though widely used as a powerful technique for imaging magnetization states, conventional magneto-optical Kerr effect (MOKE) microscopy faces inherent limitations in measuring nonplanar systems due to its shallow depth of field (DOF). Here, we present an extended depth-of-field MOKE imaging approach, combining through-focus scanning with image-stitching-based reconstruction, to obtain sharp and well-resolved magnetic domain images across nonplanar sample geometries. The method is validated on both perpendicularly and in-plane magnetized films tilted on purpose for this study, enabling quantitative analysis of domain morphology and detection sensitivity. This laboratory-accessible technique provides a fast and versatile route for 3D magnetic imaging, complementing large-scale x-ray-based methods and offering a practical tool for investigating nonplanar magnetic samples with tilted or curved 3D geometries.

DOI: [10.1103/jb45-29sy](https://doi.org/10.1103/jb45-29sy)

I. INTRODUCTION

The exploration of three-dimensional (3D) nanomagnetism has attracted growing attention in recent years [1–5], driven not only by the fundamental interests in curved and topologically complex magnetic textures [6–8] but also their potential applications in next-generation spintronic devices [9–11]. Unlike conventional thin-film systems, where magnetization on planar surfaces can be easily probed, emerging 3D nanomagnetic architectures often involve tilted facets, patterned structures, or nonplanar substrates. These structural complexities introduce additional challenges for magnetization imaging, demanding advanced detection techniques that combine height axial (z axis) spatial resolution with sensitivity to arbitrary magnetization components.

Recent advances in electron- or x-ray-based magnetic tomography and laminography have demonstrated their

capability in investigating 3D magnetization over complex geometries [12–18]. However, these approaches typically require large-scale facilities, highlighting the need for complementary, laboratory-accessible techniques that enable three-dimensional magnetization resolution in compact tabletop setups. Magneto-optical Kerr effect (MOKE) microscopy has long served as a powerful and versatile tool for visualizing magnetic domains and dynamics, offering diffraction-limited resolution together with comparatively fast data acquisition and a noninvasive nature [19]. While focused-laser-based dark-field MOKE magnetometry has been utilized to characterize the magnetization vector in 3D magnetic nanostructures [20], direct MOKE microscopy for imaging 3D nanomagnetic samples faces intrinsic limitations. Of note, the shallow depth of field (DOF), imposed by high-numerical-aperture objectives, leads to blurred off-focus regions when imaging nonplanar surfaces. Another challenge originates from the fact that both in-plane (IP) magnetization (longitudinal and transversal Kerr effects) and out-of-plane component (polar Kerr effect) contribute to the overall detected signal [21], making the interpretation of measurements more complicated on complex geometries.

Progress in computational optics and imaging reconstruction has opened promising pathways to address these challenges [22,23]. One simple but effective strategy

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can be through-focus scanning [24], which involves capturing a stack of images by varying the focus distance to cover the region of interest (ROI) of the structure. Subsequently, the sharp and well-resolved regions within the focus range from each image are stitched together [25], effectively extending the depth of field and enabling high-quality imaging across nonplanar surfaces. While proven practicable in various optical microscopy modalities, the applicability of through-focus scanning in MOKE microscopy has yet to be validated. Furthermore, as the effective incident angle of illumination varies with the local surface slope, the Kerr responses associated with in-plane and out-of-plane magnetization components need to be carefully evaluated.

In this work, we introduce an extended depth-of-field (EDOF) MOKE microscopy approach specifically designed for nonplanar or tilted magnetic samples. By systematically integrating through-focus scanning with an image-stitching procedure, we reconstructed domain images that remain sharp and well-resolved across the entire field of view. Moreover, we analyzed the mechanisms that govern Kerr response under different illumination conditions, providing insights into how MOKE microscope can intrinsically probe in-plane magnetization along nonplanar surfaces. This methodology not only extends the applicability of MOKE microscopy beyond flat films but also establishes a versatile platform for

studying complex magnetic systems with nonplanar 3D geometries.

II. EXPERIMENTAL METHODS

A. MOKE microscope setup

A home-built MOKE microscope was employed for the experiments. The illumination source was a high-power LED with four LED units, configured in a Köhler illumination scheme [26] to ensure uniform sample illumination. Two Glan-Taylor polarizers served as the polarizer and analyzer, respectively, and a $\lambda/4$ waveplate was used as the compensator. Imaging was performed using a $20\times/0.5$ objective and a digital complementary metal-oxide semiconductor (CMOS) camera. A piezo stage with z -axis movement was implemented for focusing and adjusting the distance between the sample surface and the objective, as illustrated in Fig. 1(a). A three-dimensional magnetic field was generated by a hexapole electromagnet, with its strength and orientation monitored using an *in situ* 3D magnetic field sensor together with three unidirectional Hall sensors mounted on the pole pieces [27].

B. Workflow for EDOF MOKE imaging

In our EDOF MOKE imaging scenario, a through-focus-scanning-based approach was adopted, with the

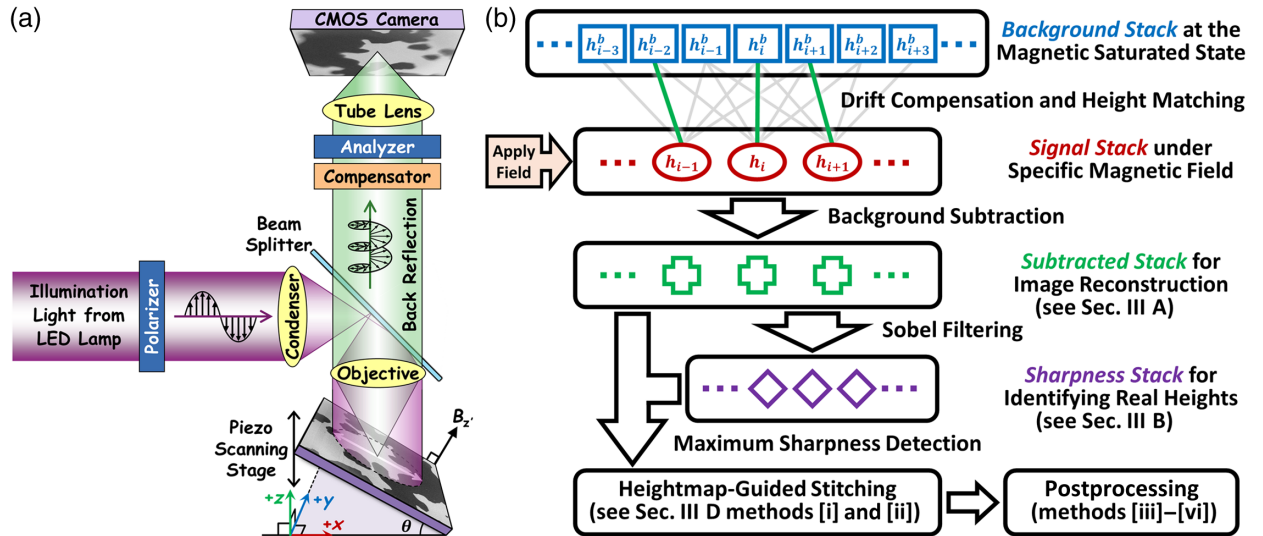


FIG. 1. Experimental setup and workflow for EDOF MOKE microscopy. (a) Optical path of the wide-field MOKE microscopy system. The flat magnetic sample was mounted on a tilted sample holder to imitate a nonplanar surface. (b) Flowcharts illustrating the EDOF MOKE imaging process. Unlike conventional MOKE microscopy, where the sample position remains fixed while the magnetic field is varied, here a series of images at different heights h_i are acquired by moving the sample along z axis for each magnetic field value. This procedure ensures that magnetization variations across the nonplanar surface are fully resolved. The resulting *Signal Stack* is then compared with a preacquired *Background Stack* that captures the sample features at different heights h_i^b . After drift compensation, height matching, and background subtraction, the *Subtracted Stack* used for image reconstruction is prepared (see Sec. III A). Finally, Sobel-filter-based sharpness detection is used to guide the reconstruction of an image that is uniformly sharp and well-resolved across the entire field of view (see Sec. III B). Additional postprocessing is applied to further improve the image quality (see Secs. III C and III D).

overall workflow illustrated in Fig. 1(b) (see also Secs. III A–III C for details). The central idea of through-focus scanning is to capture images at different focal planes, so that features located at various heights of the sample can be clearly resolved and stored in separate frames. A subsequent reconstruction step then stitches together the sharp features from each frame to generate an all-in-focus image. When adapted to MOKE imaging, however, this procedure requires specific modifications with respect to background subtraction. In conventional MOKE microscopy, a uniform background image taken at the saturated state of the sample is typically subtracted from the signal image to ensure a good signal-to-noise ratio. For nonplanar structures, where magnetization information is distributed across different heights, a single background image is thus insufficient for all focal planes. Instead, a series of background images corresponding to different heights must be captured in advance. These images form a *Background Stack* that serves as the reference for image reconstruction. Once the external magnetic field is changed, another series of images within the range of interest is acquired, forming a *Signal Stack* that contains the nonuniform magnetization signals at different heights. After lateral drift compensation and height matching between those two stacks (see Sec. III A), background subtraction is performed between each background-signal image pair to obtain a *Subtracted Stack*. The sharpness of each image in the *Subtracted Stack* is then evaluated using a Sobel filter (which is generally a derivative of the image), and the final image can be reconstructed by stitching together the sharpest regions (see Sec. III B).

As a proof of concept, we first demonstrated the EDOF MOKE imaging method on a sputtered Ta(5)/Co₄₀Fe₄₀B₂₀(0.8)/MgO(1.1)/Ta(2) multilayer (thicknesses are given in nm) exhibiting perpendicular magnetic anisotropy (PMA). The sample was tilted by 10° to mimic a nonplanar structure. The range of through-focus scanning was $\pm 24\ \mu\text{m}$ with a step size of 200 nm. We also performed additional postprocessing to the stitching results for further enhancing the signal-to-noise ratio (see Sec. III C). All those reconstruction products were then evaluated and compared quantitatively in Sec. III D.

III. ALGORITHM DESCRIPTION AND EVALUATION

A. Drift compensation and height matching

Drifts in a MOKE microscope induced by the application of magnetic fields, mechanical instabilities, or thermal fluctuations can compromise the image quality, especially after background subtraction. For a through-focus scanning scenario of three-dimensional structures, drifts along the z direction may also lead to varying degrees of defocusing across the sample, which cannot be easily

corrected only by two-dimensional image alignment. Therefore, matching each signal image to a specific background image taken at the same height, together with the lateral drift compensation, must be achieved before image reconstruction. In order to enable automated processing, we sequentially applied a Sobel filter and a Gaussian filter to the signal images [Figs. 2(a)–2(c)]. Features used for alignment were then selected from a 21×21 -pixel square region centered around each global maximum, as shown in Fig. 2(d). These steps help to guarantee that the selected region is always located within the in-focus area.

Alignment was performed between the selected signal image and a series of background images with the relative nominal height offset defined as Δh [Fig. 2(e)]. An algorithm based on the normalized cross-correlation coefficient in the Fiji software [28,29] was utilized for drift compensation, with the searching window set to five pixels (approximately equal to $1.47\ \mu\text{m}$). Figures 2(f) and 2(g) show the subtracted images before and after drift compensation, respectively, from which it can be observed that nonmagnetic features cannot be eliminated through subtraction if the heights of the signal and background images are not identical. Furthermore, the residual visibility of nonmagnetic features can be utilized to identify the best-matching background image at a specific height. By applying a median filter, which computes the local median of pixel values to the subtracted images and then a Gaussian filter to the resulting changes, the best-matching background image showing the least features can be effectively identified through a brightness analysis, as shown in Figs. 2(h) and 2(i). Figure 2(j) shows the overall sample drift between *Signal Stack* and *Background Stack* during the imaging experiment. It is worth noting that drifts along lateral axes can also be compensated in real time at the hardware level by controlling the movement of the piezo stage along x - and y -directions.

B. Heightmap-guided image stitching

1. Sharpness-based stitching

Following the background subtraction steps described above, a series of subtracted images were generated [Fig. 3(a)]. Applying another Sobel filter allowed the identification of sharp regions in each subtracted image at different heights [Fig. 3(b)]. By comparing the sharpness across regions, a heightmap was generated in which each pixel value corresponds to the height index of the sharpest frame within the *Subtracted Stack* [Fig. 3(c)]. Based on this heightmap, the sharpest regions from the *Subtracted Stack* were stitched together to reconstruct a fused domain image, as shown in Fig. 3(d).

The reconstructed image exhibits sharp domain edges across the entire field of view. However, since spatial information in magnetic systems is primarily concentrated at the domain edges rather than within the domains,

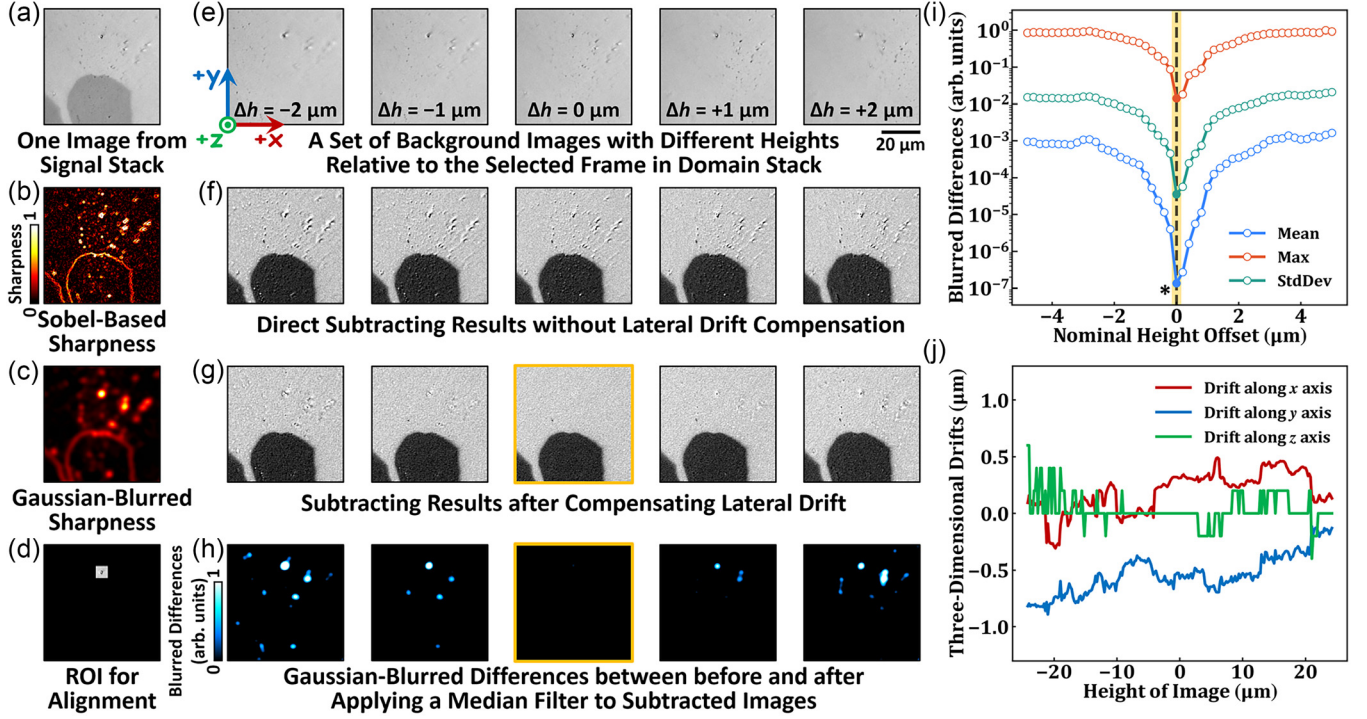


FIG. 2. Drift compensation and height matching procedures, illustrated using a Ta/CoFeB/MgO/Ta sample exhibiting perpendicular magnetic anisotropy. (a)–(d) Identification of ROI for alignment. (a) Selected signal image as an example. (b) Application of a Sobel filter allows identifying structural features. (c) Subsequent application of a Gaussian filter removes random noise. (d) Selected feature region for alignment. (e)–(i) Matching the best background image to the signal image. (e) Background images acquired at different heights relative to the original image height ($\Delta h = h_i - h_j^b$). (f) Background-corrected images without drift compensation. Extra features in the images appear due to small lateral drifts along x - and y -directions, together with the differences in focus distances between the signal image and background images. (g) Subtracted images after drift compensation. Though the lateral drifts are compensated, changes in imaging heights between the signal and background images still result in minor topography-related features. (h) Gaussian-filtered results after calculating the changes induced by a median filter, among which the optimal background image with minimum extra features is picked and marked by the yellow frame. (i) Brightness analysis results for a series of images prepared as in (h), with the optimal height offsets indicated by the minimum of the blurred differences. (j) Computed 3D drifts between the entire *Signal Stack* and *Background Stack* during the experiment. Panels (a)–(h) share the same scale bar, and panels (b)–(c) share the same colormap.

comparing sharpness directly across the entire image may lead to difficulties in identifying the height indices for regions inside the magnetic domains, as indicated by the noise-like features within domain areas shown in Figs. 3(c) and 3(d). One practical way to address this issue consists of applying a Gaussian filter followed by a Sobel filter to Fig. 3(d) in order to identify the domain edges in the fused image. After subsequent binarization, an edge mask, as shown in Fig. 3(e), is generated. This mask allows featureless pixels in Fig. 3(c) to be filtered out, enabling a more reliable heightmap extraction for image stitching.

2. Real-shape-guided stitching

In cases where the three-dimensional topography of the real sample is known in advance or qualitatively accessible, for example, from atomic force microscope, scanning electron microscope [30], or interferometric techniques such as phase-shifting or white-light interferometry [31],

pixel-wise height information can be incorporated as an additional input, enabling heightmap fitting to further improve the reconstruction quality. Assuming that the experimentally measured heightmap and the intended profile are related through a linear transformation arising from imperfect calibration during device fabrication or inaccuracies in stage movement, this fitting procedure can then be achieved by minimizing the loss function:

$$\mathcal{L}_1 \equiv \frac{1}{2} \sum_{\mathbf{k} \in \mathbf{K}} \{O(\mathbf{k}) - [\alpha I(\mathbf{R}(\varphi) \times \beta \mathbf{T}(\mathbf{k})) + h_z]\}^2, \quad (1)$$

where $\mathbf{k} = k(x, y)$ indicates one pixel of the image within the entire field of view, $\mathbf{K}$ denotes the set of image pixels used for fitting, $O(\mathbf{k})$ and $I(\mathbf{k})$ represent the experimentally observed and a priori intended heightmap index at pixel $\mathbf{k}$, respectively. α is the z -direction distortion factor, $\mathbf{R}(\varphi)$ is the rotation matrix, β is the lateral expanding factor,

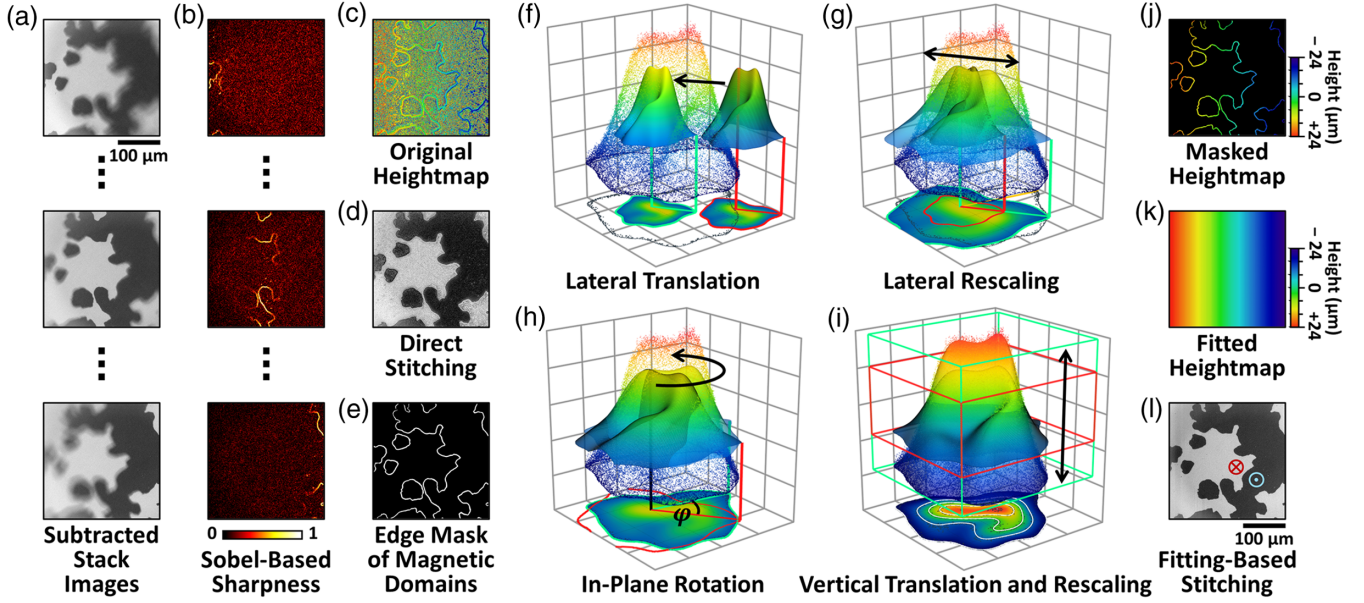


FIG. 3. Heightmap-guided image stitching methods. (a) Representative images from the *Subtracted Stack* at different heights h_i . (b) Sharpness evaluation of each subtracted image using a Sobel filter. (c) Heightmap obtained by assigning, for each region, the height index of the sharpest image within the *Subtracted Stack*. (d) Domain image reconstructed by stitching together the sharpest regions according to the heightmap in (c). (e) Edge mask generated from (d). (f)–(i) General optimization sequence for heightmap fitting. (f) Lateral translation is achieved by aligning the observed and intended reference points, corresponding to the $T(\mathbf{k})$ operation in Eq. (1). (g) Lateral rescaling by calibrating featured lateral sizes, corresponding to the expanding factor β in Eq. (1). (h) In-plane rotation around z axis, corresponding to the rotation matrix $R(\varphi)$ in Eq. (1). (i) Vertical translation and rescaling along z axis, corresponding to the factor h_z and α in Eq. (1), respectively. (j) Masked heightmap obtained by applying the edge mask in (e) to the original heightmap in (c). (k) Fitted two-dimensional heightmap. (l) Final composite image with enhanced clarity. Blue $\odot$ and red $\otimes$ symbols denote magnetic domains with magnetization pointing out of and into the sample surface, respectively. Panels (a)–(e) and (j)–(l) share the same scale bar, and panels (c) and (j)–(k) share the same colormap.

$T(\mathbf{k}) = \mathbf{k} - \mathbf{k}_0$ stands for the lateral translation operation where $\mathbf{k}_0$ is the rotation center, and h_z is the overall offset along the z direction.

The optimization process presented in Eq. (1) is schematically demonstrated in Figs. 3(f)–3(i), where an artificial 3D surface serves as an example to illustrate the algorithm. Here, the solid surfaces denote the (intermediate) fitting results, whereas the dotted surface corresponds to the surface derived directly from the experimentally observed heightmap. First, the lateral translation shown in Fig. 3(f) can be achieved by overlapping the representative reference points between the intended and the observed heightmaps. Next, as shown in Fig. 3(g), the lateral dimensions are calibrated using feature sizes. Subsequently, by performing an in-plane rotation around the z axis, the intended and observed heightmaps are aligned laterally [Fig. 3(h)]. This is then followed by a vertical translation and rescaling along the z axis, after which the observed heightmap can be well fitted, as shown in Fig. 3(i).

In the case of our tilted test sample, however, the required transformations can be simplified and result in a direct 3D fitting of the tilted plane. After applying the edge mask [Fig. 3(e)] to the original heightmap [Fig. 3(c)],

we obtained the masked heightmap shown in Fig. 3(j). The subsequent fitting process can be viewed as an extrapolation of the effective height indices onto the broader two-dimensional plane, as illustrated in Fig. 3(k). Based on the fitted heightmap, regions from subtracted images corresponding to different focal heights were stitched together. This produced a composite image with consistent clarity across the entire field of view, as shown in Fig. 3(l).

C. PSF-based postprocessing

We now turn to a more sophisticated approach beyond the sharpness-based method introduced above, aiming at further improving the reconstruction quality. From this perspective, the overall *Subtracted Stack* is treated as a 3D matrix. The fitting process in Eq. (1), followed by image stitching, thus essentially constitutes a resampling procedure as illustrated in Fig. 4(a). In the case of a tilted surface, the central resampling plane shown in green corresponds directly to the reconstructed image of Fig. 3(l). Furthermore, by manually adjusting the z -direction offset h_z in Eq. (1), the *Resampled Stack* representing the stitched

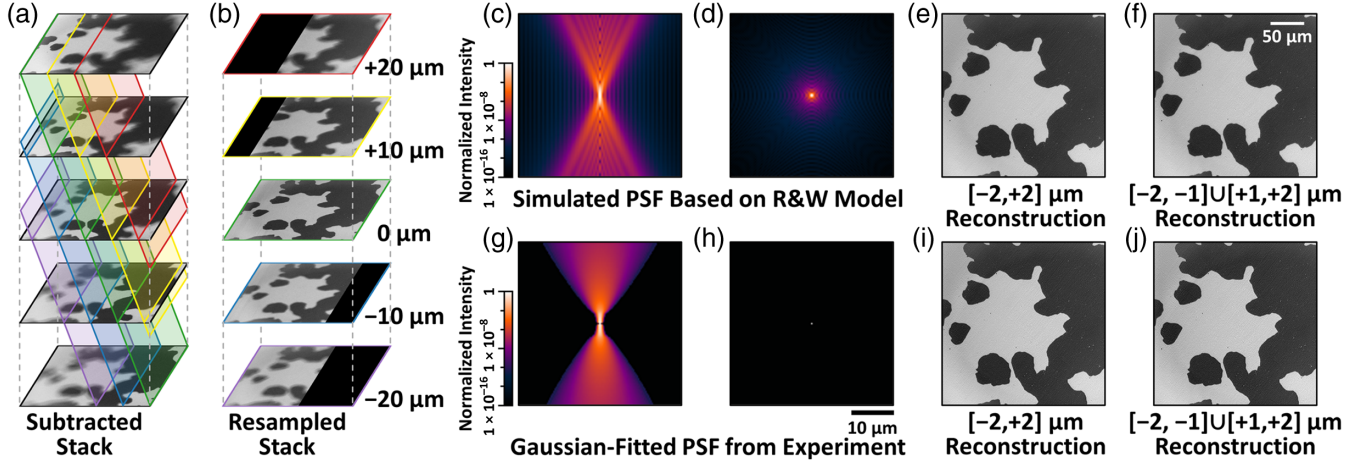


FIG. 4. PSF-based image reconstruction methods. (a) Fitting-based stitching can be regarded as the resampling of the *Subtracted Stack*, in which the intersection lines between the colored fitting plane and the subtracted frames are extracted to generate the resampled frames. (b) Resampled frames exhibiting various degrees of blur. (c) Side view ($y = 0$) and (d) top view ($z = 0$) of the PSF simulated using the Richards & Wolf 3D optical model. (e),(f) Reconstructed images obtained through iterative optimization with the simulated PSF and resampled frames within a range of (e) $\pm 2 \mu\text{m}$ and (f) $\pm 2 \mu\text{m}$, but with the sharpest frames excluded. (g) Side view ($y = 0$) and (h) top view ($z = 0$) of the PSF derived by fitting the resampled frames. (i)–(j) Reconstructed images obtained through iterative optimization with the Gaussian-fitted PSF and resampled frames within a range of (i) $\pm 2 \mu\text{m}$; and (j) $\pm 2 \mu\text{m}$, but with the sharpest frames excluded. Panels (c)–(d) and (g)–(h) share the same scale bar together with the colormap, and panels (e)–(f) and (i)–(j) share the same scale bar.

domain images with different degrees of blur is obtained, as shown in Fig. 4(b). Each blurred image can thus be considered as the convolution of the sharpest resampled frame ($h = 0 \mu\text{m}$) and a point spread function (PSF) that varies with the defocus distance h due to the nature of the objective [32]. Owing to this, not only the sharpest frame but also the blurred frames of the *Resampled Stack* contain information about the magnetic states of the sample, which can be utilized collectively to improve imaging quality.

1. Simulated-PSF-based reconstruction

Using the built-in “Richards & Wolf 3D Optical Model” [33] in the Fiji plugin “PSF Generator” [34,35], where vectorial-based diffraction is considered to evaluate the off-focus pattern, the PSF of our optical system was simulated with realistic optical parameters, as presented in Figs. 4(c) and 4(d). This generated PSF and the corresponding multilevel blurred *Resampled Stack* were utilized jointly for an iterative reconstruction performed by minimizing the loss function defined as

$$\mathcal{L}_2(\mathbf{R}_i) \equiv \frac{1}{N} \sum_{h \in H} \hat{\mathcal{L}}_2(\mathbf{R}_i, h) \equiv \frac{1}{N} \sum_{h \in H} \frac{1}{2} [\mathbf{E}_i(h)]^2 \equiv \frac{1}{N} \sum_{h \in H} \frac{1}{2} [\mathbf{R}_i * \mathbf{PSF}(h) - \mathbf{S}(h)]^2. \quad (2)$$

Here, N is the total number of resampled frames at different heights used for optimization and $\hat{\mathcal{L}}_2(\mathbf{R}_i, h)$ is the loss function component corresponding to each specific defocus distance h . $\mathbf{R}_i$ is a two-dimensional matrix regarding the PSF-based reconstructed image at iteration i , “*” denotes the convolution operator, $\mathbf{PSF}(h)$ is the height-dependent point spread function with each pixel value given by $\mathbf{PSF}(h, x, y)$, and $\mathbf{S}(h)$ represents the image at defocus distance h in the *Resampled Stack*. $\mathbf{E}_i(h) = \mathbf{R}_i * \mathbf{PSF}(h) - \mathbf{S}(h)$ thus defines the error function matrix between the forward-propagated blurred estimate and the specific resampled frame. The height range H limits the number of images used for optimization and was set to $\pm 2 \mu\text{m}$ in this case, corresponding to a total of 21

resampled frames with the through-focus scanning step of 200 nm .

For each iteration, the pixel-wise gradient of the loss function component $\hat{\mathcal{L}}_2(\mathbf{R}_i, h)$ with respect to a specific pixel $[\mathbf{R}_i]_{x,y} = \mathbf{R}_i(x, y)$ can be expressed as

$$\frac{\partial \hat{\mathcal{L}}_2(\mathbf{R}_i, h)}{\partial [\mathbf{R}_i]_{x,y}} = \sum_{p,q} [\mathbf{E}_i(h)]_{p,q} \cdot \frac{\partial [\mathbf{E}_i(h)]_{p,q}}{\partial \mathbf{R}_i(x, y)}. \quad (3)$$

Note that $[\mathbf{E}_i(h)]_{p,q}$ stands for the value of the error function matrix $\mathbf{E}_i(h)$ at pixel (p, q) . Coordinates p and q are introduced here to properly apply the chain rule and are not necessarily equal to x and y , respectively. Following

the definition of convolution, the last term of Eq. (3) can be further expanded as

$$\begin{aligned}\frac{\partial[E_i(h)]_{p,q}}{\partial R_i(x,y)} &= \frac{\sum_{u,v} R_i(u,v) \cdot \text{PSF}(h, p-u, q-v)}{\partial R_i(x,y)} \\ &= \text{PSF}(h, p-x, q-y) \\ &= \widetilde{\text{PSF}}(h, x-p, y-q).\end{aligned}\quad (4)$$

Here, $\widetilde{\text{PSF}}(h)$ denotes the PSF at height h flipped along both the x - and y -directions, which can reduce to $\text{PSF}(h)$ itself under symmetric coordinate selection. Substituting Eq. (4) into Eq. (3) and evaluating the derivative at the pixel level yields

$$\begin{aligned}\frac{\partial \hat{\mathcal{L}}_2(\mathbf{R}_i, h)}{\partial [\mathbf{R}_i]_{x,y}} &= \sum_{p,q} [E_i(h)]_{p,q} \cdot \widetilde{\text{PSF}}(h, x-p, y-q) \\ &= [E_i(h) * \widetilde{\text{PSF}}(h)]_{x,y},\end{aligned}\quad (5)$$

which can be compactly written in matrix form as

$$\frac{\partial \hat{\mathcal{L}}_2(\mathbf{R}_i, h)}{\partial \mathbf{R}_i} = E_i(h) * \widetilde{\text{PSF}}(h). \quad (6)$$

Note that the flipped PSF here essentially reverses the forward convolution operation, thereby enabling efficient error backpropagation without resorting to explicit deconvolution procedures [36]. Taken together, the updated estimate $\mathbf{R}_{i+1}$ for the next iteration can be expressed as

$$\begin{aligned}\mathbf{R}_{i+1} &= \mathbf{R}_i - \frac{\lambda}{N} \sum_{h \in H} \frac{\partial \hat{\mathcal{L}}_2(\mathbf{R}_i, h)}{\partial \mathbf{R}_i} \\ &= \mathbf{R}_i - \frac{\lambda}{N} \sum_{h \in H} E_i(h) * \widetilde{\text{PSF}}(h),\end{aligned}\quad (7)$$

where λ is the nominal learning rate and is set to 1 throughout this work for simplicity. Given the ill-posed nature of this PSF-based reconstruction [37], a Laplacian regularization is additionally incorporated into the iteration, yielding

$$\mathbf{R}_{i+1} = \mathbf{R}_i - \lambda \left[\frac{1}{N} \sum_{h \in H} E_i(h) * \widetilde{\text{PSF}}(h) + \delta \nabla^2 \mathbf{R}_i \right]. \quad (8)$$

This incremental term imposes a spatial smoothness constraint by suppressing high-frequency artifacts, thereby helping to stabilize the reconstruction, where the regularization parameter δ is set to 0.02. The iteration is terminated when the relative change in the averaged absolute error satisfies

$$\gamma \equiv \frac{|\bar{E}_i - \bar{E}_{i-1}|}{\bar{E}_{i-1}} < 10^{-6}, \quad (9)$$

where $\bar{E}_i = \frac{1}{N} \sum_{h \in H} \langle |E_i(h)| \rangle$ denotes the averaged absolute error over both pixel values and defocus distances h and γ represents the iteration efficiency.

Upon convergence, the final reconstructed image shown in Fig. 4(e) was obtained, exhibiting improved image quality relative to the previous fitting result [Fig. 3(l)]. To evaluate the robustness of this algorithm, we repeated the reconstruction after excluding the images within the intrinsic depth of field ($\pm 1 \mu\text{m}$) from the previous image stack ($\pm 2 \mu\text{m}$). The resulting reconstructed image is shown in Fig. 4(f).

2. Gaussian-PSF-based reconstruction

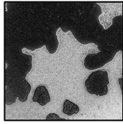
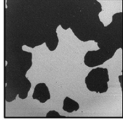
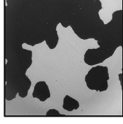
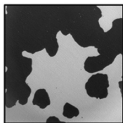
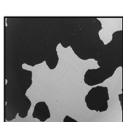
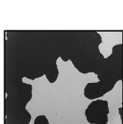
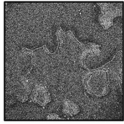
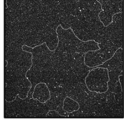
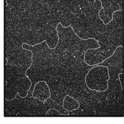
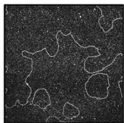
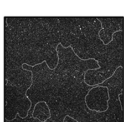
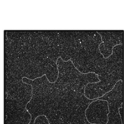
For comparison, a Gaussian-type PSF was estimated by evaluating the degree of blurring in the *Resampled Stack* [Fig. 4(b)] with respect to the sharpest resampled frame, as shown in Figs. 4(g) and 4(h). The resulting PSF exhibits qualitative agreement with the previously simulated one. Unlike the simulated-PSF-based reconstruction, which relies on prior knowledge of the optical parameters of the imaging system, the present fitting-based approach employs a simplified Gaussian model to approximate the effective PSF directly from the *Resampled Stack* itself. As a result, this empirical approach is expected to account for integrated system imperfections such as illumination inhomogeneity and deviations in the effective numerical aperture (NA), offering a practical alternative for image reconstruction. The corresponding reconstructed images based on the fitted Gaussian-type PSF are shown in Figs. 4(i) and 4(j), respectively.

D. Comparison of different reconstruction methods

So far, we have presented the domain image reconstruction using several algorithms or postprocessing methods, including direct sharpness-based stitching, real-shape-guided fitting-based stitching, and the simulated- or fitted-PSF-based reconstruction. Beyond these methods, we further calculated the mean and median values of the resampled frames over a defocus distance range of $\pm 400 \text{ nm}$ as reference values. The performance of all the methods was evaluated by comparing the average signal-to-noise ratio defined as the brightness difference between two opposite magnetization states over noise variation, together with the average edge sharpness calculated at domain wall regions, as listed in Table I. Based on these criteria, the reconstruction strategies can be summarized as follows:

- [i] Sharpness-based stitching (see Sec. III B 1). As the most straightforward method, direct stitching based on sharpness puts together the sharpest segments from the *Subtracted Stack*, which can indeed ensure sharp edges after stitching. However, due to its

TABLE I. Performance comparison of different reconstruction methods introduced in the main text. Rows 4 and 5 list the average intensity and standard deviation measured in the bright and dark domain regions, respectively, together with the corresponding noise ratio in percentage. Row 6 summarizes the average signal-to-noise ratio (S/N), serving as one quantitative metric for reconstruction quality. Here, the signal is defined as the average brightness difference between the bright and dark domain regions, while the noise is systematically evaluated over the entire image based on the deviations. The last two rows present the absolute Laplacian-filtered domain image, highlighting the domain boundaries, as well as the corresponding average edge sharpness $\bar{\eta}$ calculated by averaging pixel values within the edge mask shown in Fig. 3(e). For both quality indicators, S/N and $\bar{\eta}$, higher values indicate better performance. As inspired by method [v], averaging only five images yields a high S/N , but at the expense of substantially reduced edge sharpness. In contrast, method [iii] achieves the highest edge sharpness using 21 input images while maintaining a reasonable S/N , demonstrating the effectiveness of the PSF-based reconstruction approach. The weak asymmetric intensity features visible at the corner of some reconstructed images originate from residual illumination inhomogeneity caused by the tilted sample surface and slight lateral drift between signal and background images during postprocessing. This effect is not related to the magnetic signal and can be further minimized by applying a real-time drift correction during the measurement.

Algorithms and postprocessing methods	[i] Sharpness-based stitching	[ii] Real-shape-guided stitching	[iii] Simulated-PSF-based reconstruction	[iv] Gaussian-PSF-based reconstruction	[v] Mean-value projection	[vi] Median-value projection
Range of used resampled frames (μm)	Not applicable	$h = 0$ (1 frame)	$ h \in [0, 2]$ (21 frames)	$ h \in [0, 2]$ (21 frames)	$ h \in [1, 2]$ (12 frames)	$ h \in [0, 0.4]$ (5 frames)
Reconstructed domain image						
Bright-region intensity	$40,029 \pm 1663$ ($\pm 4.2\%$)	$40,188 \pm 1085$ ($\pm 2.7\%$)	$40,208 \pm 1074$ ($\pm 2.7\%$)	$40,191 \pm 975$ ($\pm 2.4\%$)	$40,192 \pm 912$ ($\pm 2.3\%$)	$40,188 \pm 945$ ($\pm 2.4\%$)
Dark-region intensity	$32,962 \pm 1732$ ($\pm 5.3\%$)	$33,335 \pm 947$ ($\pm 2.8\%$)	$33,318 \pm 967$ ($\pm 2.9\%$)	$33,336 \pm 846$ ($\pm 2.5\%$)	$33,337 \pm 772$ ($\pm 2.3\%$)	$33,336 \pm 785$ ($\pm 2.4\%$)
Average signal-to-noise ratio (S/N)	4.158	6.777	6.773	7.563	8.191	7.969
Absolute Laplacian-filtered domain image						
Average edge sharpness ($\bar{\eta}$)	0.753	0.625	0.799	0.787	0.602	0.587
				0.630		0.592

limited capability to distinguish homogeneous in-domain regions, randomly distributed noise might be prominent and wrongly identified as target features. This can degrade the overall image quality, characterized by a small signal-to-noise ratio in the second column. Nevertheless, this reconstructed image and its corresponding heightmap serve as the foundation for all the other reconstruction processes presented here.

- [ii] Real-shape-guided stitching (see Sec. III B 2). With the help of prior height information from the real shape and the masked heightmap shown in Fig. 3(j), only the heights of reliable pixels are used for image reconstruction, while the heights of remaining pixels are extrapolated through fitting. This approach not only ensures a continuous and more realistic heightmap but also yields a reconstructed image with enhanced quality, including well-resolved in-domain regions. The smaller average edge sharpness $\bar{\eta}$ compared with the sharpness-based stitching method can be attributed to noise and defects located next to domain edges during image acquisition.
- [iii] Simulated-PSF-based reconstruction (see Sec. III C 1). Regarding the PSF-based reconstruction methods, as multiple frames from the *Resampled Stack* are collectively exploited, the average edge sharpness is significantly improved without sacrificing much signal-to-noise ratio compared with the real-shape-guided stitching. Notably, when frames within the intrinsic depth of field are excluded for the reconstruction (fifth column), the average signal-to-noise ratio increases further. This behavior can be attributed to the exclusion of incompletely compensated morphological defects and random noise, which manifest as high-frequency features and are more pronounced in sharper resampled frames. Meanwhile, the absence of the sharpest frames can also lead to a decrease in the average edge sharpness owing to the loss of high-frequency details.
- [iv] Gaussian-PSF-based reconstruction (see Sec. III C 2). As the Gaussian model is rooted in geometric optics rather than wave optics, it cannot capture the diffraction-limited features of a realistic point spread function. This results in the suppression of high-frequency information, leading to smoother reconstructions with an increased signal-to-noise ratio but a reduced average edge sharpness compared with the previous method, where a physically accurate, diffraction-based PSF is employed.

Apart from the methods discussed above, two additional postprocessing approaches, namely, [v] mean-value projection and [vi] median-value projection, are included for reference. Five central frames selected from the *Resampled Stack* within the range of the intrinsic depth

of field are considered, and the mean or median values at each pixel across these frames are computed to generate the final image. Using this approach, the averaging of resampled frames can improve the signal-to-noise ratio by 22%, compared with the real-shape-guided stitching. However, as the effective focus distance of these involved frames varies, this inevitably leads to a degradation of edge sharpness. In comparison, the median projection results in a moderate reduction in edge sharpness, while still enhancing the signal-to-noise ratio to some extent by suppressing outlier pixels.

To further examine the dependence of reconstruction performance on the number of used resampled frames, we also present in Fig. 5 the evolution of the average signal-to-noise ratio (S/N) and edge sharpness ($\bar{\eta}$) for different reconstruction methods. As the number of used resampled frames increases, the signal-to-noise ratio improves for all reconstruction methods. This enhancement arises not only from the incorporation of additional signal information but also from the inclusion of defocused frames with inherently suppressed high-frequency noise. In contrast, the evolution of edge sharpness differs significantly among the methods. For the simulated-PSF-based reconstruction (method [iii], as shown in Fig. 5(a), a high sharpness is obtained when only the single central frame is used, which is accompanied by a relatively low S/N. This indicates that random noise is amplified together with the real magnetic contrast. As more frames are taken into account, the suppression of noise leads to a continuous increase in S/N, while the sharpness initially decreases and then gradually recovers, reaching a maximum at approximately 21 frames ($|h| \in [0, 2] \mu\text{m}$). For the Gaussian-PSF-based reconstruction (method [iv]), as shown in Fig. 5(b), the maximum sharpness is achieved when 9 frames ($|h| \in [0, 0.8] \mu\text{m}$) are used. For both mean-value projection [method [v], Fig. 5(c)] and median-value projection [method [vi], Fig. 5(d)], however, the sharpness decreases monotonically while increasing the frame number, as defocused images are directly incorporated into the averaging process.

Moreover, when progressively removing frames from the central set of 21 frames, more pronounced differences can be observed. For the PSF-based reconstruction methods [Figs. 5(a) and 5(b)], reducing the number of central frames leads to a further increase in S/N, which can be attributed to the removal of high-frequency noise components contained in the well-focused images. In comparison, for the projection-based methods [Figs. 5(c) and 5(d)], reducing the number of frames naturally results in a decrease in S/N due to the reduced signal averaging. As for edge sharpness, the PSF-based methods remain nearly unchanged at the initial stage of frame removal, whereas the projection-based methods exhibit a consistent decrease. These observations further highlight the advantages of PSF-based approaches in preserving reconstruction quality.

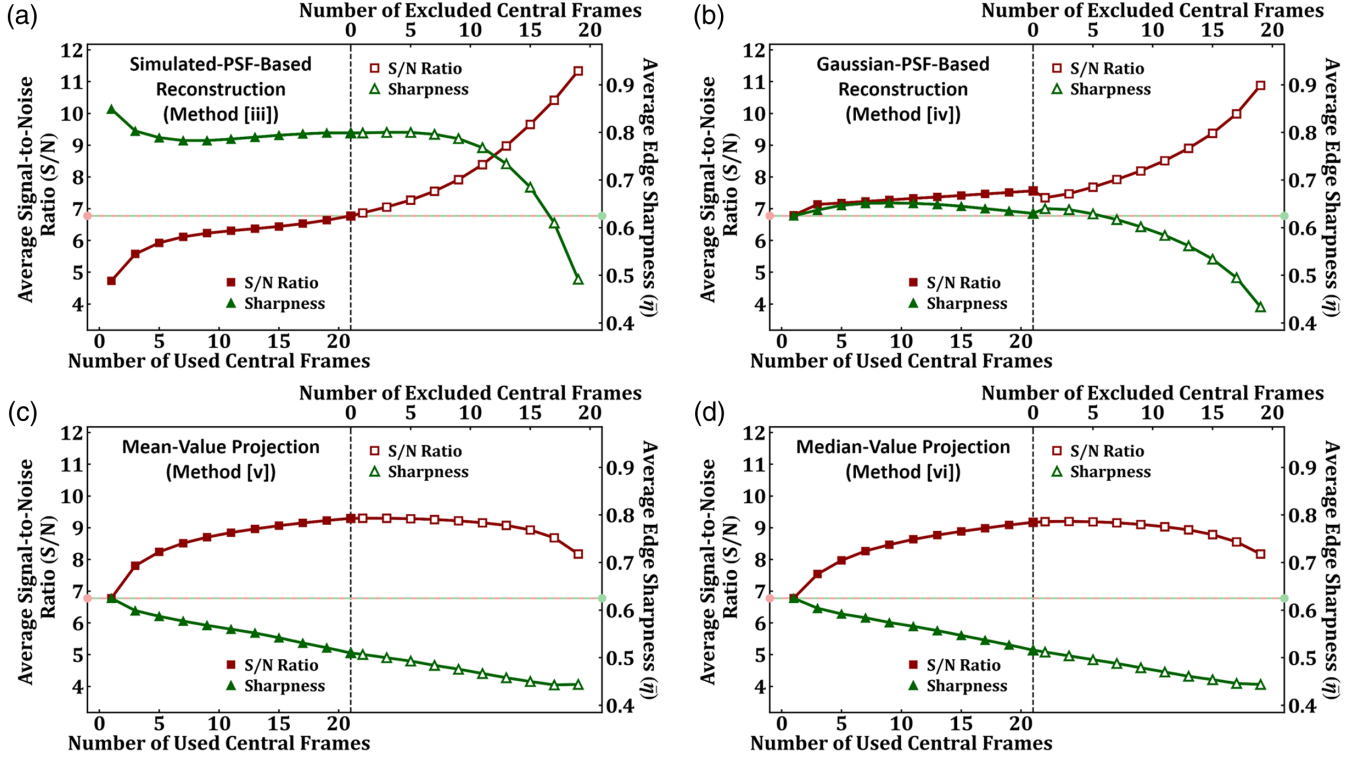


FIG. 5. Reconstruction performance as a function of the number of used resampled frames. (a) Average signal-to-noise ratio (S/N, left axis) and edge sharpness ($\bar{\eta}$, right axis) as functions of the number of used central resampled frames (bottom axis, filled symbols) for the Simulated-PSF-based reconstruction (method [iii]). Open symbols, referenced to the top axis, show the corresponding variation in reconstruction performance when central resampled frames are progressively excluded from an initial set of 21 frames. (b) Same as (a), but for the Gaussian-PSF-based reconstruction (method [iv]). (c) Same as (a), but for the mean-value projection (method [v]). (d) Same as (a), but for the median-value projection (method [vi]). The horizontal dashed line in all panels indicates the reference value obtained using the real-shape-guided stitching (method [ii]).

Based on the analysis above, it can be concluded that for the sample under investigation, the simulated-PSF-based reconstruction method provides the best edge sharpness among all the methods evaluated, while maintaining a decent signal-to-noise ratio. However, the PSF-based methods require dense vertical oversampling, with scanning steps much smaller than the intrinsic depth of field, as well as additional postprocessing. By contrast, the real-shape-guided stitching yields reasonably good results with limited input data and modest computational cost and is therefore primarily employed for subsequent sections of this work.

IV. RESULTS AND DISCUSSION

A. Labyrinthine domain pattern reconstruction

To validate the reliability and applicability of the EDOF MOKE imaging approach presented here, we conducted experiments on another sample composed of $\text{Ta(5)}/[\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}(0.8)/\text{MgO}(1.1)/\text{Ta}(1)]_3/\text{Ta}(1)$ as a representative case. This sample was prepared near the spin reorientation transition at room temperature, exhibiting a perpendicularly magnetized labyrinthine domain

pattern in the demagnetized state with the characteristic domain size determined solely by its intrinsic magnetic parameters [38]. Such a property makes it suitable as a standard specimen for assessing imaging performance under various tilt angles.

Using the previously described stitching method (see Sec. III B 2), the magnetic domain morphologies at different sample tilt angles were reconstructed from those captured raw images, as shown in Fig. 6(a). As the magnetic domain features are closely spaced in this case with the widths on the order of $1\ \mu\text{m}$ (corresponding to approximately 3–4 pixels), the additional edge mask shown in Fig. 3(e) is not strictly required. It should also be noted that the illumination cannot be maintained uniformly across the field of view due to the tilted reflective surface, which leads to the inhomogeneity of brightness in these reconstructed images. To eliminate the influence of this effect on domain pattern characterization, the reconstructed images were then binarized for further analysis [Fig. 6(b)].

The domain pattern acquired from a tilted surface represents the projection of the actual domain structure along the tilted surface onto the horizontal plane. In other words, for the inherently isotropic labyrinthine domains,

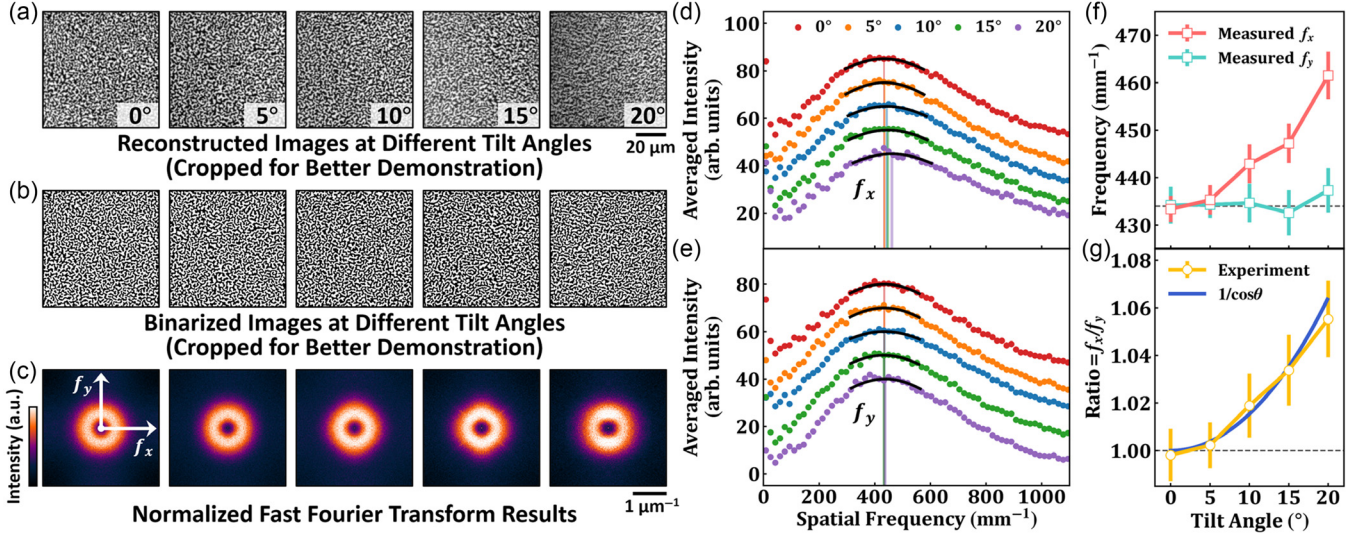


FIG. 6. Out-of-plane labyrinthine domain pattern reconstruction, demonstrated using a magnetic Ta/[CoFeB/MgO/Ta]₃ multilayer with PMA and close to the spin reorientation transition. (a) Reconstructed labyrinthine domain images acquired at different tilt angles. (b) Binarization results of (a). (c) 2D FFT results of the binarized domain images. (d)–(e) Profiles along the x - (d) and y -directions (e) directions of the 2D FFT results. To reduce fitting errors, pixels within $\pm 15^\circ$ angular ranges along either the x - or y -directions were averaged. Vertical lines in the figures indicate the peak positions and uncertainties obtained from Gaussian fitting. (f) Summary of the spatial frequencies of labyrinthine domains along the x - and y -directions as a function of tilt angle. (g) Spatial frequency ratio f_x/f_y as a function of tilt angle, together with the theoretical $1/\cos\theta$ relation based on the projected geometry. Panels (a)–(b) share the same scale bar.

tilting the sample results in the compression of the pattern along the tilt direction by a factor of $\cos\theta$. This geometric effect can be quantitatively verified by comparing the domain periodicities along the x - and y -directions. By performing a two-dimensional fast Fourier transform (2D FFT) on the binarized images, the intensity distributions in the frequency domain were obtained, as shown in Fig. 6(c). Radial profiles along x - and y -directions within a $\pm 15^\circ$ angular range were extracted and averaged, yielding the directional intensity distributions as a function of spatial frequency, as illustrated in Figs. 6(d) and 6(e), respectively. Gaussian fitting was then applied to determine the peak positions, based on which the spatial frequencies at each tilt angle were obtained [see Fig. 6(f)]. The horizontal spatial frequency f_x increases with the tilt angle, whereas the vertical frequency f_y remains mostly unchanged. The resulting frequency ratio f_x/f_y was subsequently calculated and presented in Fig. 6(g), alongside the theoretical expectation of $1/\cos\theta$. Within the experimental uncertainty, the measured frequency ratio agrees well with the theoretical prediction, further confirming the validity of the image-stitching procedure and demonstrating its applicability to magnetic imaging on nonplanar surfaces.

B. Kerr response to in-plane magnetization

In addition to the domain image reconstruction of PMA samples, the capability of imaging IP magnetization, as well as investigating quantitatively the response to non-planar IP components, constitutes another significant

aspect for 3D magnetic imaging [39]. For this purpose, we employed a 40-nm-thick CoFeB film as a representative IP sample. In conventional MOKE microscopy, illumination and collection optical paths are usually perpendicular to the sample surface, and the detection of in-plane magnetization signals is made possible by selecting specific wave vectors of the incident light. However, for a tilted sample surface, the effective incident angle differs from that in the untilted configuration, giving rise to additional contributions to the detection sensitivity of in-plane magnetization [40,41] and leading to more complex signal responses and underlying mechanisms.

In our measurement system, the wave vector selection was implemented by inserting a rotatable aperture with one off-axis hole at the conjugate position of the objective's back focal plane. This configuration allows only the light passing through the hole to reach the sample surface, while blocking all the other components. The first column of Fig. 7(a) shows the images at the back focal plane of the objective during the measurement of a planar sample, after inserting an auxiliary Bertrand lens in the optical path before the tube lens and camera. Since those images are reflected once from the sample surface before being collected by the camera, they appear horizontally flipped. Here the image edges are defined by the size of the objective's back pupil, as indicated by the yellow circles. As the sample's tilt angle increases, the LED images can be seen moving progressively to the right with respect to the front pupil indicated by the white circles, eventually moving beyond its boundary.

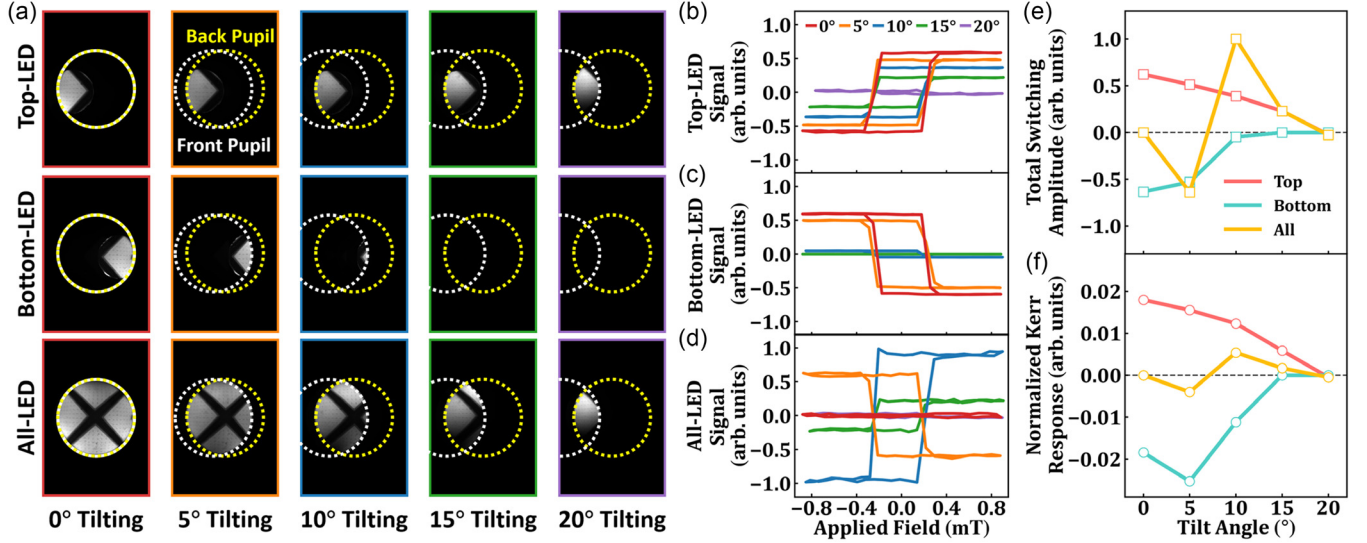


FIG. 7. Measurement results of a tilted in-plane magnetized film at different tilt angles, demonstrated using a thick CoFeB layer exhibiting in-plane magnetic anisotropy. (a) Conoscopic images at the back focal plane of the objective lens captured with different tilt angles of the sample after the insertion of a Bertrand lens. Here, yellow and white dashed circles indicate the edge of the back and front pupils of the objective, respectively. (b)–(d) Measured hysteresis loops at different tilt angles using (b) top-, (c) bottom-, and (d) all-LED units. (e) Summary of the total switching amplitudes at different tilt angles obtained from the corresponding hysteresis loops. (f) Calculated normalized Kerr response at different tilt angles.

The corresponding hysteresis loops under each illumination and tilting condition are presented in Figs. 7(b)–7(d), respectively. Note that the applied magnetic field was always aligned with the tilted sample plane by means of the hexapole electromagnet available in our setup [27]. Under the top-LED illumination, the absolute switching amplitude of the hysteresis loop exhibits a monotonic decrease with the increasing tilt angle, whereas under the bottom-LED illumination, it initially decreases slightly from 0° to 5° before dropping sharply to almost zero. Under all-LED illumination, the switching amplitude is nearly zero at the tilt angle of 0°, owing to the full compensation among the LED units. As the tilt angle increases from 0° to 5°, the equalization gets disrupted, resulting in the switching behavior similar to that observed under bottom-LED illumination. When the tilt angle increases further from 5° to 10°, the switching reverses its sign and begins to resemble that under top-LED illumination. These changes in switching amplitudes as a function of tilt angle are summarized in Fig. 7(e), where the y axis represents the total switching amplitude under identical LED output. After dividing the switching amplitude of each hysteresis loop by the corresponding mean light intensity under the given illumination conditions, the normalized Kerr response for each measurement configuration was calculated, as presented in Fig. 7(f). Interestingly, although the absolute switching amplitude under all-LED illumination appears larger than that under top- and bottom-LED illumination at tilt angles of 5° and 10°, the corresponding Kerr response is in fact smaller.

Furthermore, the Kerr response for all illumination conditions shifts toward the negative direction when the tilt angle increases from 0° to 5°. These observations indicate that the Kerr sensitivity is strongly influenced by the illumination geometry and evolves nonlinearly with sample tilt.

To understand the trends described above, we schematically show in Figs. 8(a)–8(d) the representative light paths for illumination during the measurement, incorporating the sample surface, objective lens, and the LED image at the back focal plane. Note that only geometric optics arguments are considered here. For a planar sample [Fig. 8(a)], the incident angles of light originating from the top-LED unit θ_T and bottom-LED unit θ_B are identical and approximately equal to $\arcsin(\text{NA})$, with NA being the numerical aperture of the objective. As the tilt angle increases, the clockwise rotation of the sample surface leads to a decreasing $\theta_T < \theta_T$ [Fig. 8(b)] and increasing $\theta_B' > \theta_B$ [Fig. 8(c)] for the top- and bottom-LED units, respectively. In other words, incident light from the top-LED unit becomes less effective in detecting in-plane magnetization, whereas that from the bottom-LED unit becomes more effective. This mechanism helps to explain the negative shift in the Kerr response observed at the tilt angle of 5° in Fig. 7(f).

Another significant factor governing the observed hysteresis loops is the fraction of reflected light collected by the objective lens. As indicated in Fig. 7(a), tilting of the sample can cause the reflected image to fall partially outside the objective's front pupil, and thus it cannot be

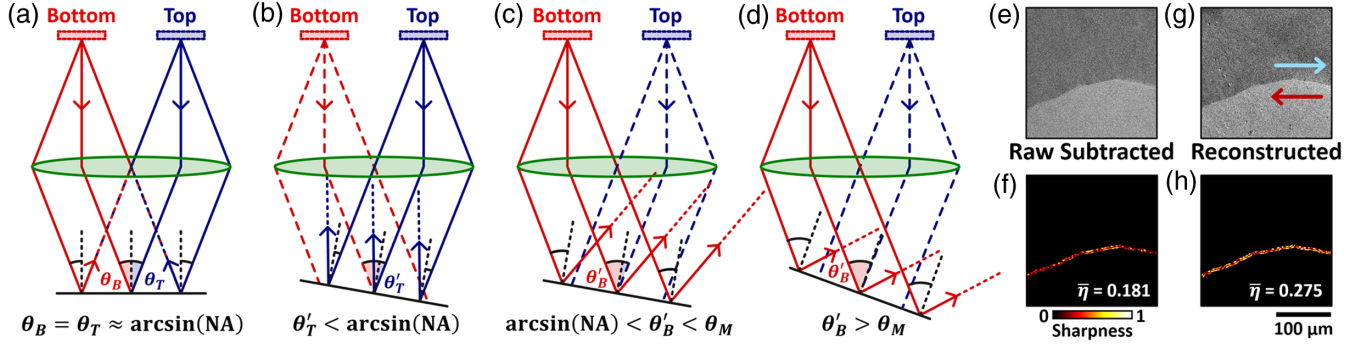


FIG. 8. Light-path sketches and in-plane domain image reconstruction. (a) For a planar sample surface, the effective incident angles for the top- and bottom-LED units are identical. (b)–(c) When the sample surface is tilted clockwise, the effective incident angle for the top-LED unit decreases (b), while that for the bottom-LED unit increases (c). (d) If the tilt angle becomes sufficiently large, no reflected light under bottom-LED illumination can eventually be collected by the objective due to its finite numerical aperture. (e) Directly imaged in-plane magnetic domains on a tilted film under all-LED illumination. (f) Calculated edge sharpness of image (e). (g) Reconstructed in-plane domain image with clear details across the entire field of view. Blue and red arrows denote the in-plane magnetization of magnetic domains. (h) Calculated edge sharpness of image (g). Panels (e)–(h) share the same scale bar, and panels (f),(h) share the same colormap.

fully captured by the camera. Considering that the bottom-LED image is located on the left side of the figure and the reflected light propagates toward the right, this mechanism has a stronger impact on the bottom-LED illumination compared with the top-LED scheme. Under the top-LED illumination [Fig. 8(b)], as long as the tilt angle remains below $\theta_T \approx \arcsin(\text{NA})$, the reflected light is still largely collected by the objective, yet the variations in switching amplitude of hysteresis loops are primarily determined by the effective incident angle. Under the bottom-LED illumination [Fig. 8(c)], however, even a small tilt leads to a significant loss of the reflected light. This accounts for the observation that, although the normalized Kerr response increases with the tilt angle from 0° to 5° under bottom-LED illumination [Fig. 7(f)], the absolute switching amplitude still decreases [Fig. 7(e)], as there is an approximately 40% reduction in the illumination intensity. Moreover, for a sufficiently large tilt angle (θ_M) determined by the numerical aperture and specific focus distance [Fig. 8(d)], none of the reflected light from the bottom-LED unit can be eventually collected by the objective. As a result, both the switching amplitude and the experimentally measured Kerr response approach zero at larger tilt angles of 15° and 20° .

Returning to the response under all-LED illumination, since the overall illumination changes moderately from 0° to 5° , the Kerr response at a tilt angle of 5° is primarily governed by the changes in the effective incident angle, which has the same sign as that of the bottom-LED illumination. For tilt angles larger than 10° , the absence of reflected light from the bottom-LED unit induces the dominance of the top-LED unit, thereby reversing the overall measured switching direction. Owing to the competing contributions from the top- and bottom-LED illuminations, the Kerr response under all-LED illumination

always lies between those obtained under the two individual illumination conditions, as revealed in Fig. 7(f). It is worth noting that although only the Köhler illumination path is depicted here, these arguments can be generalized to other configurations as the effective collecting angle of the objective remains unchanged.

The analysis above reveals the capability of detecting in-plane magnetized signals from a nonplanar sample surface. Even under all-LED illumination without additional wave vector selection, the MOKE microscope retains an intrinsic sensitivity to the in-plane magnetization along the tilting direction, as long as the tilting angle is smaller than $\arcsin(\text{NA})$ defined by the objective. Building on this intrinsic sensitivity, we performed imaging of the in-plane magnetized domains under all-LED illumination, with the tilt angle set at 10° to maximize the magneto-optical Kerr response. The directly imaged domain pattern is shown in Fig. 8(e). Sharpness analysis [Fig. 8(f)] indicates that the domain boundaries are well defined near the center but blurred toward the edges. After employing the previously described through-focus scanning followed by image-stitching procedures (see Sec. III B 2), we obtained the reconstructed image shown in Fig. 8(g), which is well resolved and clear across the entire field of view, with a 52% improvement in edge sharpness indicated in Fig. 8(h).

V. CONCLUSIONS

In summary, we have presented an extended depth-of-field MOKE microscopy approach capable of capturing high-quality magnetic domain images on nonplanar sample surfaces. By performing through-focus scanning followed by image stitching based on sharpness analysis, we obtain magnetic domain images that are both sharp and well-resolved across the entire field of view. Overall, the

performance of the reconstruction method depends on the interplay between domain size, image resolution, and signal-to-noise ratio, and the optimal parameters may therefore vary. In our representative case, while the real-shape-guided stitching method proves effective in preserving edge sharpness and suppressing random noise, PSF-based reconstruction methods can further enhance both the signal-to-noise ratio and edge definition, particularly in regions affected by high-frequency noise or imaging defects. The reliability of such a reconstruction strategy is quantitatively assessed by measuring and stitching domain images of a perpendicularly magnetized sample exhibiting isotropic periodic magnetic domains in the demagnetized state at different tilt angles. The observed spatial frequency of domains extracted from FFT analysis follows the expected $1/\cos\theta$ dependence on the tilt angle. The Kerr response from an in-plane magnetized sample is also systematically investigated by varying the tilt angle under different illumination schemes. After analyzing the contributions of individual wave vectors from each LED unit, we have quantified how the effective incident angles influence the MOKE signal for in-plane magnetization, demonstrating quantitatively the intrinsic capability of MOKE microscopy to resolve in-plane magnetic signals on nonplanar surfaces.

Although demonstrated here as proof-of-concept cases with intentionally tilted flat samples, the presented methods and findings show promising potential for extension to more complicated 3D geometries. In particular, the approach is well suited for structures with surface-accessible magnetization, such as twisted or bent nanowires [11,42] or spiral architectures [9], where magnetic domains remain optically addressable. The simplicity and flexibility of this laboratory-accessible method make it compatible with standard MOKE microscopy setups with only moderate modifications, thereby extending its accessibility to a broad research community. Compared with x-ray-based magnetic domain reconstruction techniques, the present approach does not require large-scale facilities and enables significantly more straightforward experimental deployment. Its relatively fast imaging speeds further facilitate the observation of magnetic domain evolution in near real time.

However, its applicability becomes limited in highly complex 3D systems, such as 3D artificial spin ice [43] or nanowire networks [44], where strong structural occlusion can severely hinder both illumination and detection in a coaxial optical configuration. In addition, the effective signal collection is fundamentally constrained by NA of the objective, as surfaces with local tilting angles exceeding $\arcsin(\text{NA})$ do not produce detectable reflected signals. One possible route to mitigate these limitations is to introduce controlled 3D sample rotation, enabling systematic angular scanning over a range of spatial orientations. At each orientation, multifocus image stacks could be

acquired, followed by appropriate quantitative normalization of the detected signals to account for angle-dependent variations, and a subsequent image reconstruction process to recover otherwise inaccessible regions.

Additionally, it is worth noting that light reflected from off-focus surface regions may interfere with the reconstruction process. An effective solution in that case, inspired by the widely used confocal microscopy technique in biological research [45], could comprise inserting a pinhole together with auxiliary lenses into the imaging path before the camera [46]. This configuration selectively collects signals originating only from the focal plane, which are subsequently used for image reconstruction. There are also additional algorithms for reconstruction involving neural networks and deep learning [47], but these are beyond the scope of the present manuscript. Future improvements could also involve synchronization with pulsed magnetic fields or the implementation of real-time image processing, to enable the time-resolved measurement of magnetization dynamics. We believe that the continued development of such integrated imaging strategies promises to provide a powerful tool for investigating surface magnetization states in 3D geometries, thereby opening new avenues for tabletop studies of nonplanar magnetic nanostructures and spintronic devices.

ACKNOWLEDGMENTS

This work was supported by the European Community under the Horizon 2020 Program, Contract No. 101001290 (3DNANOMAG). This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/PIN1629824], through the TOMOCHIRAL project. For open access purposes, the author has applied a CC BY public copyright license to any author-accepted manuscript version arising from this submission. The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Program. Funding from TU Wien's Blue Sky "Phoenix" program is acknowledged. We also thank Dr. Jakub Mateusz Jurczyk for his support during the measurements.

DATA AVAILABILITY

The data that support the findings of this article are openly available in TU Wien Research Data [48].

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