Structured illumination imaging without grating rotation based on mirror operation on 1D Fourier spectrum

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Abstract: Structured illumination microscopy (SIM) is a rapidly developing a super-resolution optical microscopy technique. With SIM, the grating is needed in order to rotate several angles for illuminating the sample in different directions. Multiple rotations reduce the imaging speed and grating rotation angle errors damage the image recovery quality. We introduce mirror transformation on one-dimension (1D) Fourier spectrum to SIM for resolving the problems of low imaging speed and severe impact on image reconstruction quality by grating rotation angle errors. When mirror operation and SIM are combined, the grating is placed at an orientation for obtaining three shadow images. The three shadow images are acquired by CCD at three different phase shift for a direction of grating. Thus, the SIM imaging speed is faster and the effect on image reconstruction quality by grating rotation angle errors is greatly reduced.

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1. Introduction

With light as a carrier, humans can observe the normal activities of life in the microcosm in a nearly noninvasive manner. The appearance of optical microscope opens a new world for microcosm’s space. In recent years, how to realize high spatial and temporal resolution of imaging system has been an important subject in the field of optical microscopy [1–3]. However, the spatial resolution of traditional optical microscopy imaging technique is limited by diffraction limit which greatly restricts the application of optical microscopy technology. Super-resolution imaging emerges as the need for microstructure detection [4]. Structured illumination microscopy (SIM) is one of the most popular super-resolution optical microscopy techniques. In 2000, Gustafsson [1] optimized the generation mode of sinusoidal structured light and set up a set of structured light illumination micro system which successfully doubled the horizontal resolution. In SIM, a spatial modulated illumination light is obtained by inserting a diffraction grating into the illumination path. The illumination light is used to image the sample in different directions to obtain a set of images and a super-resolution image is generated through an algorithm based on Fourier space structure [5]. Compared with confocal microscopy [6–9] and stimulated-emission-depletion (STED)
technique [10–12], the measurement process of SIM is simpler. The SIM systems [1,5–12] can be applied in both wide-field techniques and point scanning techniques.

In application, SIM is very suitable for super-resolution imaging of living cells [13–15], due to relatively high imaging speed and low damage rate to samples. The imaging speed of SIM must be fast enough, because living cells are dynamic targets constantly changing in observation. In SIM, however, the grating requires multiple rotations to realize the illumination light imaging the sample in different directions [16–20]. The multiple rotation operations slow down the imaging speed and affect the imaging results of dynamic living cells [21–23]. Moreover, there is an angle error in each grating rotation. The angle errors of grating rotation can greatly affect the quality of sample recovery in SIM.

In theory, the reconstruction of a super-resolution image requires multiple original images with different light phases and carrier frequency directions. Considering the effect of multiple grating rotations on imaging velocity and sample recovery quality, some researchers have thought about reducing the amount of original images in SIM. Proposed by Orieux in 2012 [24], the reconstruction algorithm based on Bayesian estimation is introduced to SIM so that only two structured light images with different phases can be used to reconstruct the super-resolution image in single carrier frequency direction. However, as Bayesian estimation algorithm can only get the approximate solution of the reconstruction spectrum and the amount of computation is large, SIM based on Bayesian estimation has not been paid much attention.

Recently, some advanced and convenient SIM systems [19,21] based on a spatial light modulator (SLM) are proposed to replace those based on physically grating rotation. Although SLM does bring in some advantages, like fast pattern change, physically rotating a grating is still widely used in the practical experiments and commercial applications. In our article, the SIM system is based on the physical grating rotation. Even for SLM based systems, our method can still help reduce the data volume requirement.

In order to increase the imaging speed and reduce the effect on the quality of sample recovery caused by multiple rotations, the mirror transformation on 1D Fourier spectrum is introduced into SIM technique for expanding the sample spectrum with less number of grating rotations. By using the symmetry of the real part of 1D Fourier transform and mirror operation, the analytical signal can be constructed and the sample spectrum can be expanded. Thus, in SIM based on mirror transformation (MTSIM), grating only needs to be used once which can greatly increase the imaging speed and reduce the grating rotation angle errors for dynamic living cells. The corresponding simulation is given to validate the performance of MTSIM. The experimental results are conducted to verify the super-resolution imaging ability of MTSIM. The experimental results show that MTSIM can indeed enhance the resolution of the recovery image as SIM.

2. Method

In SIM, the grating centers on the optical axis and rotates specific angles as shown in Fig. 1(a) [25]. For each angle of the grating rotation, considering the $0, \pm 1$ order diffraction light, the spectrum of the sample obtained from SIM can be regarded as the spectrum combination of three order diffraction light illumination samples. In fact, the $\pm 1$ order diffraction light illuminating sample is equivalent to moving the sample spectrum in two directions in the frequency domain. In order to realize the super-resolution effect based on SIM, it is necessary to calculate the sample spectrum corresponding to $0, \pm 1$ order diffraction light [26–29]. In practice, however, the spatiotemporal modulation of the illumination arm is technically difficult. Therefore, virtually structured detection (VSD) [30] is designed with a model of digital grating, which requires dynamic phase modulation in light detection arm of system. In the VSD, the spatiotemporal modulation is achieved by mathematical processing of digital images.
Figure 1(a) illustrates a schematic diagram of the VSD based imaging system. The reflected light from the sample is adjusted by the 2D (X and Y) scanning system and is relayed to the image plane (CCD). A CCD camera is employed to map intensity distribution of individual sampling points. The stack of 2D light profiles is used to construct super-resolution image by employing the system based on VSD. A digital grating with modulated transmittance is positioned at the image plane as the circle in Fig. 1(a) and CCD is placed behind the digital grating. For each scanning position, CCD sums up all transmitted signal through the digital grating and assigns the integrated intensity to the single pixel corresponding to the current scanning position. After each complete frame is scanned with a digital grating, one CCD-picture is built up. Several such CCD-pictures are generated with a set of digital gratings whose modulated transmittance is phase-shifted in space, in order to reconstruct a super-resolution image of the sample [30–33]. From the schematic of principles of SIM and MTSIM shown in Figs. 1(b) and 1(c), MTSIM does not rotate the grating but only needs to do three-step phase shift for the demodulation calculation, thus reducing the system complexity and data volume.

In VSD, the digital grating with sinusoidal function is expressed as follows

\[ m(x, y) = \cos[2\pi k_0 (x \cos \theta + y \sin \theta) + \phi], \]  

where \( \theta \) is the rotation angle of the digital grating sinusoidal stripes and \( \phi \) represents a constant phase translation. The carrier frequency \( k_0 \) is set here to same as the cutoff frequency \( f_c \). The frequency is from grating in SIM [20] and structured detection [30]. The structured illumination process [20] is expressed as follows

\[
\begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix} \cdot (\vec{k}) =
\begin{bmatrix}
1 & 1 & 1 \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\begin{bmatrix}
H & 0 & 0 \\
0 & H & 0 \\
0 & 0 & H
\end{bmatrix}
\begin{bmatrix}
S(\vec{k}) \\
S(\vec{k} + \vec{k}_0) \\
S(\vec{k} - \vec{k}_0)
\end{bmatrix},
\]

where \( H \) is the rotation angle of the digital grating sinusoidal stripes and \( \phi \) represents a constant phase translation.
where $I_n$ represents the spectrum of image function received by CCD. The functions $S(k)$, $S(k - k_0)$, and $S(k + k_0)$, represent the sample spectrum corresponding to 0 and ±1 orders diffraction light. The symbol $H$ is the optical transfer function (OTF) of the system. OTF is a circular supporting plane in frequency domain and the spectral components above cutoff frequency are suppressed which is equivalent to a low pass filter circular hole in frequency domain. The parameter $k$ represents the spatial frequency and $\phi_i$ represents the phase shift. Selecting different phase shift $\phi_i$, a system of linear equations can be set up in frequency domain to solve the spectrum of sample corresponding to 0 and ±1 order diffraction light. Here phase shift is implemented by moving grating in experimental system. The spectra, $S(k)$, $S(k - k_0)$ and $S(k + k_0)$, can be decoupled and are used for image reconstruction.

![Image](image.png)

Fig. 2. The real part of the 1D arbitrary real-valued signal Fourier transform is even: (a) The blue curve represents an arbitrary 1D time domain real-valued signal while the red curve stands for the real part of its Fourier transform spectrum. (b) The imaginary part of the 1D signal Fourier transform spectrum.

We propose MTSIM for reducing the amount of original images to increase the imaging velocity and reduce the effect of multiple grating rotations on sample recovery quality. Here, MTSIM is considered and applied for VSD model. For arbitrary signal $f(t)$, the real part of its Fourier transform is even symmetric. The blue and red curves in Fig. 2(a) are an arbitrary 1D time domain signal and the real part of its Fourier transform spectrum respectively. The red curve shows that the real part of the arbitrary 1D signal Fourier transform spectrum is indeed symmetric. The green curve in Fig. 2(b) is the imaginary part of the arbitrary 1D signal Fourier transform spectrum. It can be seen clearly that the imaginary component of the arbitrary 1D signal Fourier transform spectrum is centro-symmetric.

In our method, the mirror operation based on the symmetry of the real part of 1D Fourier transform spectrum is used to expand the sample spectrum. In MTSIM, the grating is only used once to get the sample spectrum corresponding to 0 and ±1 orders diffraction light at a certain angle. On this basis, the sample spectrum is mirrored centered on the origin of the coordinates. In Fig. 3, the sample spectrum corresponding to first and third quadrant is mirrored to second and fourth quadrant utilizing the mirror operation based on the symmetry of the real part of 1D Fourier transform spectrum. Thus, it is clearly that the sample spectrum can be expanded by the mirror symmetry of 1D Fourier transform with the grating only used once in MTSIM.

Considering that only the real part rather than the imaginary component of 1D Fourier transform is symmetric, the mirror operation based on the real part of 1D Fourier transform spectrum has certain application limitations. In other words, the MTSIM technique is suitable...
for amplitude-only samples. In our article, the sample in the first experiment is the standard optical target (USAF 1951 1X, Edmond) which can be regarded as an amplitude-only object. The samples in the second and third experiments are thin biological samples (the fresh isolated frog retina and the mouse cortex slice), which can be regarded as amplitude-dominated samples with a little phase information. The experimental results in the later section demonstrate that MTSIM can achieve the image reconstruction with super-resolution ability when the samples are amplitude-only object and amplitude-dominated object with a little phase information.

The mirror operation is defined mathematically as follows

$$S'_{\text{Re}}(x,y) = \begin{cases} S_{\text{Re}}(x,y), & \text{if } x>0 \text{ and } y>0, \\ S_{\text{Re}}(x,-y), & \text{if } x>0 \text{ and } y \leq 0, \\ S_{\text{Re}}(-x,y), & \text{if } x \leq 0 \text{ and } y>0, \\ S_{\text{Re}}(-x,-y), & \text{if } x \leq 0 \text{ and } y \leq 0, \end{cases}$$

where $S'_{\text{Re}}$ and $S_{\text{Re}}$ are Fourier spectrum after and before the operation respectively. The idea of MTSIM is that by using the mirror operation based on the symmetry of real part of 1D Fourier transform spectrum and expanding the sample spectrum, the MTSIM super-resolution imaging can be achieved while the grating only be used once.

![Fig. 3](image)

Fig. 3. The grating rotates at 45°, and the sample spectrum is expanded by using the mirror operation based on the symmetry of the real part of 1D Fourier transform spectrum: (a1) The 1024 × 1024 sample image, (a2) The sample spectrum corresponding to 0 order diffraction light at 45° rotation of grating, (b1) The sample spectrum in the first quadrant corresponding to 1 order diffraction light at 45° rotation of grating, (b2) The sample spectrum in the second quadrant, (b3) The sample spectrum in the third quadrant corresponding to -1 order diffraction light at 45° rotation of grating, (b4) The sample spectrum in the fourth quadrant. The 2D Fourier spectrum in the second and fourth quadrants are expanded by those in the first and third quadrants by applying the mirror operation based on the symmetry of the real part of 1D Fourier transform.

The image in Fig. 3(a1) is regarded as the tested sample. The pattern in Fig. 3(a2) represents the sample spectrum corresponding to 0 order diffraction light at 45° rotation of grating. The two patterns in Figs. 3(b1) and 3(b3) represent the sample spectrum corresponding to ±1 orders diffraction light at 45° rotation of grating. It can be seen from the Figs. 3(b1) and 3(b3) that the spectrum of the sample is shifted in two directions by ±1 orders diffraction light. In SIM, the grating centers on the optical axis rotating at 0°, 45°, 90° and 135°. The sample spectrum corresponding to each rotation angle can be obtained through Eqs.
(1) and (2). By integrating the sample spectrum at different angles, the sample can be recovered by inverse Fourier transform for integrated spectrum in traditional SIM technique.

SIM requires the grating to rotate more than one angles centered on the optical axis. Thus, the operation is complicated and inconvenient, since it reduces imaging speed for observing dynamic samples. Moreover, in practice, there is an angle error in each grating rotation. The more the number of grating rotations, the greater the effect of accumulated errors on the quality of sample recovery.

It is clear that the images in Figs. 3(b1)-3(b4) are 2D Fourier spectrum in the first to fourth quadrants respectively. As mentioned above, the 2D Fourier spectrum in the first and third quadrants corresponds to ± 1 orders diffraction light at 45° rotation of grating. The 2D Fourier spectrum in the second and fourth quadrants are expanded by those in the first and third quadrants by applying the mirror operation based on the symmetry of the real part of 1D Fourier transform.

In order to expand the 2D sample Fourier spectrum in the first and third quadrants to the second and fourth quadrants by applying the mirror operation based on the symmetry of the real part of 1D Fourier transform, the next few steps are taken as Fig. 4 shows.

1. The 2D Fourier spectrum in the first, second, third and fourth quadrant are defined as S1, S2, S3 and S4 respectively. P1X and P1Y are obtained by 1D inverse Fourier transformation of S1 in the direction of X and Y respectively.

2. M1X and M1Y are obtained by applying mirror transformation to P1X and P1Y respectively.

3. F2 is the 2D Fourier spectrum in the second quadrant by multiplying the results of 1D Fourier transformation for M1X and M1Y. Here, F2 and S2 are symmetric along the Y axis.

4. In the same way, the 2D Fourier spectrum in the fourth quadrant can be obtained from S4 by using the mirror symmetry of the real part of 1D Fourier transform.

The core idea is that we decompose the 2D sample Fourier spectrum into 1D Fourier spectrum first, then apply the mirror transformation to 1D Fourier spectrum and synthesize the 1D Fourier spectrum after mirror transformation into 2D sample Fourier spectrum finally.
By using the mirror symmetry of the real part of 1D Fourier transform, Figs. 3(b2) and 3(b4) represent the sample spectrum in the second and fourth quadrants respectively. It can be seen that under the condition of using the mirror symmetry of the real part of 1D Fourier transform, the grating only needs to be used once, rotating 45° with the optical axis. The sample spectrum of four quadrants can be obtained. Thus the number of grating rotations in the experiment is reduced, in which the operation is simpler with the imaging speed increased and is much more suitable for dynamic sample imaging.

![Sample Spectrum](image)

Fig. 5. MTSIM can indeed enhance the retrieval image resolution: (a) the sample spectrum corresponding to 0 order diffraction light at 45° rotation of grating, (b) the sample spectrum of the retrieval image by MTSIM.

The two images in Fig. 5 are the sample spectrum corresponding to 0 order diffraction light at 45° rotation of grating and the retrieval result by MTSIM respectively while the sample image is displayed in Fig. 3(a1). It is clear that compared to Fig. 5(a), the sample spectrum in Fig. 5(b) has a distinct increase. This shows that MTSIM can indeed enhance the retrieved image resolution as SIM.

3. The image reconstruction test

The two results in Fig. 6 represent the image reconstruction output by SIM and MTSIM respectively while Fig. 3(a1) is adopted as the sample image. It can be seen that compared with SIM, the reconstruction effect of MTSIM is basically the same due to the values of normalized correlation coefficient (NCC) [32]. In MTSIM, the grating is only used once in the experiment and the operation is simpler than SIM. The operation of grating in MTSIM is greatly simplified.

![Image Reconstruction](image)

Fig. 6. The image reconstruction result: (a) the result of SIM with NCC = 0.9995; (b) the result of MTSIM with NCC = 0.9991. SIM requires the grating to rotate at 0°, 45°, 90° and 135° with the optical axis as the centre while MTSIM only uses the grating once with the angle between the grating and the optical axis being 45°.

SIM requires the grating to rotate at 0°, 45°, 90° and 135° with the optical axis as the center. In practical operation, the actual rotation angle of grating and the theoretical value will have errors. The more the number of grating rotations, the greater the effect of accumulated errors on the sample recovery quality. In this paper, mean squared error (MSE) is used to evaluate the effect of image reconstruction. The smaller the MSE, the better the effect of image reconstruction. The definition of MSE between object image $f_{obj}$ and reconstructed image $f_{re}$ is shown as following

$$
MSE = \frac{1}{M \times N} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \left[ f_{obj}(m,n) - f_{re}(m,n) \right]^2,
$$

(4)
where $M \times N$ represents the total number of pixels in two images.

Recently, some modern reconstruction algorithms are proposed for estimating the experimental rotation angles in SIM to reduce the grating rotation errors in SIM. In [34], the authors present a fast and efficient way of iteratively determining the pattern positions with high precision.

Although there are modern algorithms estimating the experimental rotation angles, the grating rotation angle errors cannot be completely eliminated in the actual experiment. Despite that the grating rotation angle errors may be small, the angular errors still affect the image reconstruction quality unavoidably. The affect will become weak for the SIM methods with reduced reference images [35–37]. In this case, increasing the robustness to angular errors is very necessary for the practical application of SIM.

Fig. 7. The robustness on angular error and shot noise: (a) MSE curves between sample image and the retrieval result by SIM and MTSIM with the grating rotation angle error varying from $-1.5^\circ$ to $1.5^\circ$. The theoretical values for SIM are $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$. The theoretical values for MSIM is $45^\circ$. (b) Robustness result for shot noise.

The blue and red curves in Fig. 7(a) display the MSE change trends between the sample image and the retrieval result by SIM and MTSIM. For MTSIM, the theoretical value of the grating rotation angle is $45^\circ$ while the grating rotation angle error varies from $-1.5^\circ$ to $1.5^\circ$. For SIM, the theoretical values of grating rotation angles are $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$ while each grating rotation angle error varies from $-1.5^\circ$ to $1.5^\circ$. The sample image is a grey scale image. The horizontal coordinate is the grating rotation angle error between theoretical value and the actual grating rotation angle. Figure 7(a) shows that for the same grating rotation angle error, the MSE between sample image and the retrieval result by MTSIM is obviously less than that by SIM.

The robustness of MTSIM and SIM is tested for shot noise. The definition of SNR of noisy image $f_{noi}$ and true image $f_{true}$ is given as following
The robustness test on shot noise is simulated and shown in Fig. 7(b). The comparison of SNR by SIM and MTSIM demonstrates that MTSIM is more robust to shot noise than SIM.

\[ \text{SNR} = 10 \times \log_{10} \left( \frac{\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f_{nm}^2(m, n)}{\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} [f_{nm}(m, n) - f_{nm}(m, n)]^2} \right). \]  

Fig. 8. The super-resolution ability proof of MTSIM on the resolution test target: (a) Super-resolution recovery image of the test target acquired by VSD; (b) Super-resolution recovery image of the test target acquired by MTSIM; (c) Normalized intensity curves along x axis. The purple curve is normalized intensity along x direction of the area specified by purple line in (a). The green curve is normalized intensity along x direction of the area specified by green line in (b); (d) Normalized intensity curves along y axis. The blue curve is normalized intensity along y direction of the area specified by blue line in (a). The red curve is normalized intensity along y direction of the area specified by red line in (b).

In VSD, when the angle rotation error exists, the digital grating with sinusoidal function can be expressed as follows

\[ m(x, y) = \cos \left\{ 2\pi f_0 \left( x \cos(\theta + \Delta \theta) + y \cos(\theta + \Delta \theta) \right) + \phi \right\}, \]  

where \( \Delta \theta \) represents the angle rotation error between theoretical rotation angle and actual rotation angle.

In SIM, grating is needed to rotate at 0°, 45°, 90° and 135° with the optical axis as the center. Four images in Fig. 7 are the retrieval results by MTSIM and SIM. The image corresponding to red curve is the retrieval result by MTSIM when the actual grating rotation angle is 43.5°. The other one corresponding to blue curve is the retrieval result by SIM when the actual grating rotation angles are −1.5°, 43.5°, 88.5° and 133.5°. The comparison between two recovery images in Fig. 7 clearly shows that MTSIM significantly reduces the effect on image reconstruction quality by grating rotation angle errors. On the contrary, SIM is very sensitive to grating rotation angle errors, which greatly affect the image recovery quality. The result means that MTSIM is more robust for the orientation control of the grating.

4. Experiment

To further validate the super-resolution imaging ability of MTSIM, two experiments are conducted [30]. The experimental data in Figs. 8 and 9 is the same data set as in [30]. The sample image is the standard optical target (USAF 1951 1X, Edmond). Figures 8(a) and 8(b) are the recovered images acquired by VSD and MTSIM respectively. The period of the smallest grating (green and red lines in Fig. 8(b) of this test target is 4.4 µm. Obviously, the smallest bars in colorful rectangles in Figs. 8(a) and 8(b) can be differentiated in both x and y directions.
directions. Figures 8(c) and 8(d) are normalized intensity curves along x and y axis respectively. The purple and green curves are normalized intensity along x direction of the area specified by purple and green lines in Figs. 8(a) and 8(b). The blue and red curves are normalized intensity along y direction of the area specified by blue and red lines in Figs. 8(a) and 8(b). By contrast, it is clear that the super-resolution image recovery abilities of VSD and MSIM are basically the same while MTSIM only needs the grating to be used once.

![Image](image_url)

Fig. 9. The biological sample experiment: (a) Super-resolution recovery image of the freshly isolated frog retina acquired by VSD. (b) Super-resolution recovery image of the retina acquired by MTSIM. (c) Reflectance profiles of the green and red line areas in (a) and (b). The green and red curves are normalized intensity profiles along the green line in (a) and the red line in (b) respectively.

The second step of the experiment is to verify the feasibility of MTSIM on biological specimen. The fresh isolated frog retina is used as the test sample. The diameter of frog rods is ~5-8 µm and cones ~1-3 µm. Figures 9(a) and 9(b) are the super-resolution recovery image of the freshly isolated frog retina acquired by VSD and MTSIM respectively. Evidently, individual photoreceptors can be detected and resolved in Figs. 9(a) and 9(b) proving the super-resolution image recovery ability of MTSIM. The green and red curves in Fig. 9(c) are normalized intensity profiles along the green line in Fig. 9(a) and the red line in Fig. 9(b) respectively. The clear bumps corresponding to photoreceptors are prominent in the red and green curves in Fig. 9(c). The theoretical resolution of conventional SIM which employs a 5X objective with 0.1 NA is 5 µm. The lateral resolution of VSD is 2.5 µm nearly the same as that of MTSIM. The specific resolution value and resolution enhancement fold clearly show the super-resolution ability of VSD and MTSIM. This testifies that the individual photoreceptors of freshly isolated retinas can be clearly differentiated in MTSIM.

To sum up, the experimental results of both standard optical target and biological sample demonstrate that MTSIM can acquire the image reconstruction with approximate super-resolution ability under the condition that the grating is only used once compared with VSD. Thus, the detailed structures in biological sample can be revealed by super-resolution imaging of MTSIM. The conclusion complies with the numerical analysis above for the super-resolution ability and feasibility of MTSIM.
Fig. 10. The biological sample (the mouse cortex slice) experiment by SIM and MTSIM: (a) Super-resolution recovery image of the mouse cortex slice acquired by SIM. (b) Super-resolution recovery image of the mouse cortex slice acquired by MTSIM. The green and red curves are normalized intensity profiles along the green line in (a) and the red line in (b) respectively. By applying the mirror operation based on the symmetry of the real part of 1D Fourier transform, MTSIM is able to achieve the image reconstruction with approximate super-resolution ability under the condition that the grating is only used once compared with SIM.

In addition, to further validate the feasibility of MTSIM, a biological sample (the mouse cortex slice) experiment by SIM and MTSIM is added. Figures 10(a)-10(b) represent the super-resolution recovery images of the mouse cortex slice by SIM and MTSIM respectively. The experimental data in Fig. 10 is from the resources by a biomicroscopy lab in Boston University [38,39]. The green and red curves in Fig. 10(b) are normalized intensity profiles along the green line in Fig. 10(a) and the red line in Fig. 10(b) respectively. The result with the experimental SIM data has demonstrated that introducing the mirror operation based on the symmetry of the real part of 1D Fourier transform to SIM can also achieve image reconstruction with super-resolution ability.

5. Conclusion

We propose MTSIM with grating only needed to be used once to increase the imaging speed and reduce the effect on image recovery quality caused by grating rotation angles. By applying the mirror operation based on the symmetry of the real part of 1D Fourier transform, the sample spectrum can be expanded with the grating only used once in MTSIM. Thus, the imaging speed can be greatly increased with simpler operation and the effect on image reconstruction result caused by grating rotation angle errors can be available reduced. With improved speed and more robust grating control, MTSIM is much more suitable for dynamic samples imaging.

Funding

National Natural Science Foundation of China (Nos. 61575055, 61575053, 11874132); National Institutes of Health (NIH) (Grant ROI EY024628); and Open Fund Project Foundation of Guangdong Provincial Key Laboratory of Modern Geometric and Mechanical Metrology Technology (No. SCMKF201804).

Acknowledgments

The authors express sincere gratitude to Dr. Benquan Wang for his assistance in experimental data.

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