Optical sectioning structured illumination microscopy with improved lateral resolution

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In this investigation, we propose an approach that combines super-resolution and optical sectioning techniques in structured illumination microscopy to obtain high-resolution 3D images of industrial samples. In the proposed system, we adopt a digital micromirror device instead of using a grating such as a Ronchi ruling to generate multiangle phase shift structured patterns. Also, a high-resolution image of each pixel can be acquired by using the 2D Fourier transformation method, and subsequently the high-resolution 3D image is reconstructed by applying it to the height map corresponding to each axial position. To experimentally verify the system performance, various step height standard specimens were measured, and the results were compared with those by the conventional ways.

NOMENCLATURE

I_1 = image with the 0-phase shifted sinusoidal pattern
I_2 = image with the $2\pi/3$-phase shifted sinusoidal pattern
I_3 = image with the $4\pi/3$-phase shifted sinusoidal pattern
I_S = optical sectioning image

1. Introduction

Recently, semiconductor and display products have been gradually miniaturized, and the circuit patterns become more complicated for multi-functionalities. In the manufacturing process, these products should be inspected to avoid failure, and high-resolution microscopic technologies need to be developed. For the purpose, confocal scanning microscopes and interferometric microscopes are currently applied to meet the demands required by industries. However, the conventional microscopes have fundamental limitations in obtaining high-resolution images due to the lateral resolution limit. One of the candidates for this purpose is the structured illumination microscopy (SIM) because it has the capability to improve the lateral resolution in the 3D imaging.

Typically, SIM has been developed in two ways, a super-resolution SIM (SR-SIM) and a 3D optical sectioning SIM (OS-SIM). By collecting several patterned images, SR-SIM analyzes them in reciprocal space such as in the Fourier domain to enhance lateral resolution [1]. On the other hand, OS-SIM can provide 3D imaging of the sample by detecting the visibility of the illumination pattern [2].

In this investigation, we describe a combined technique of SR-SIM and OS-SIM based on the same optical configuration. After the construction of the SIM with a deformable micromirror device, each measurement algorithm is implemented, and the measurement results are combined to obtain the high-resolution 3D image of the specimen.

2. Structured illumination microscopy

2.1 Super-resolution structured illumination microscopy

Beyond the diffraction limit caused by the numerical aperture of a microscope, SR-SIM can enhance the lateral resolution by involving the illumination pattern to the sample. In this case, the spatial frequencies of the pattern and the specimen are mixed together, and they can be extended beyond the optical transfer function (OTF) determined by the diffraction limit as shown in Fig. 1. Based on the Moiré effect between the sinusoidal illumination pattern and sample's structural distribution, the spatial frequency information of the sample beyond the OTF can be down-shifted and collected through the imaging system. By combining the spatial frequency contents of rotated images, therefore, the whole spatial frequency region is extended twice in linear SR-SIM, which indicates the lateral resolution of the reconstructed image is improved twice compared to that of the original image.

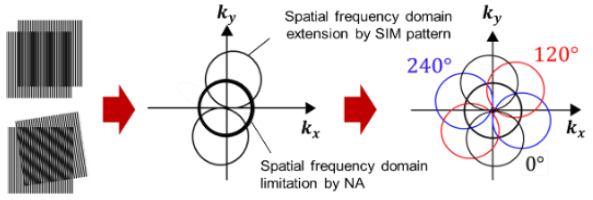

Fig. 1 Extended spatial frequency region by structured illumination in SR-SIM.

2.2 Optical sectioning structured illumination microscopy

In OS-SIM, a specimen is illuminated by a sinusoidal pattern which enables to localize the measurement area, and the 3D optical sectioning images can be obtained according to the axial scanning by eliminating the background intensity. At each axial position, the sinusoidal pattern is phase shifted with an amount of 0, $2\pi/3$, and $4\pi/3$ to get the images of I_1, I_2, and I_3, respectively. From phase shifted images, the optical sectioning image or the contrast of the sinusoidal pattern (I_S) is calculated as a form of [2]

$$I_S = [(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2]^{1/2} \quad (1)$$

During axial scanning, the sectioning image is collected at every axial position, and then the contrast curve at each pixel of images can be drawn with the axial position. In this case, the contrast peak position at each pixel means the best focus position of the surface of the specimen, which leads to reconstructing the 3D surface profile of the specimen.

2.3 Structured illumination microscopy for high-resolution 3D imaging

Figure 2 shows the optical configuration of the structured illumination microscopy combined with SR-SIM and OS-SIM. A digital micromirror device was used for generating the sinusoidal pattern for the illumination, of which the pattern was rotated and phase shifted. A specimen was attached to the moving stage, and the contrast of the pattern was obtained along the axial positions. In SR-SIM, the high-resolution images were obtained by using the 2D Fourier transformation to combine the spatial frequency contents while the height information of the specimen was calculated by the contrast peak detection at every pixel of the image in OS-SIM. In the final stage, the measurement results of the two modes are combined to reconstruct the high-resolution 3D image of the specimen.

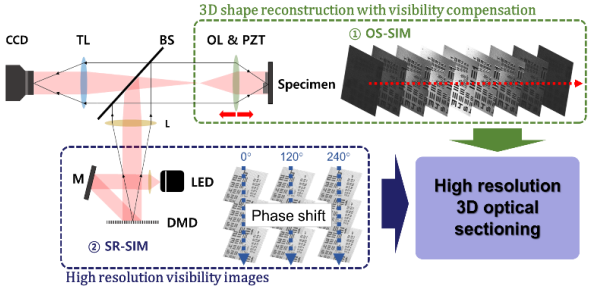

Fig. 2 Optical configuration of the structured illumination microscopy for high-resolution 3D imaging; M, mirror; DMD, digital micromirror device; L, lens; BS, beam splitter; OL, objective lens; TL, tube lens.

3. Experimental results

Figure 3 shows the result of calculating the modulation transfer function (MTF) with a 20x microscope objective by measuring a USAF1951 resolution target. The MTF values of the proposed system were higher than those of the conventional widefield microscope, and it was confirmed that the lateral resolution was enhanced. On the other hand, as shown in Fig. 4, the lattice specimens of standard height specimens with different pitches were measured to verify the longitudinal measurement performance of the proposed system. For comparison, the same specimens were also measured by a white light scanning interferometer (WLSI). As the result, the step heights were very close to that of WLSI within 0.1 μm, and they were similar to 1 μm, provided by the manufacturer.

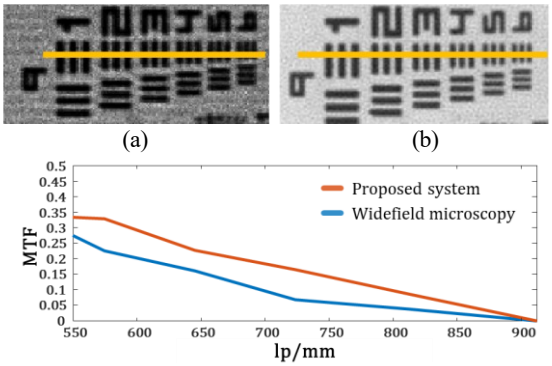

Fig. 3 Images of the resolution target obtained by (a) the widefield microscopy and (b) the proposed system, and (c) MTF results.

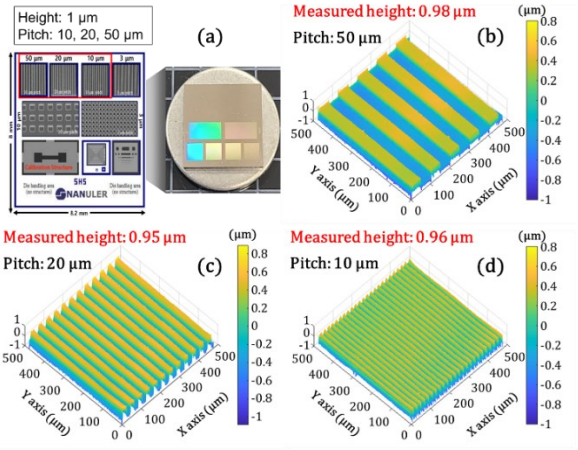

Fig. 4 (a) Standard height specimen (1 μm nominal height), the measurement results of (b) 50 μm, (c) 20 μm, and (d) 10 μm pitches by the proposed system.

4. Conclusions

We demonstrated structured illumination microscopy for high-resolution 3D imaging by combining the operating principles of SR-SIM and OS-SIM. In the experiments, the resolution target and the step height specimens were used to confirm the lateral resolution enhancement and 3D measurement capability, respectively. We believe this combined approach of structured illumination microscopy can be successfully applied in semiconductor and display industries.

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