Deep ultraviolet digital holography for nanoscopic applications

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A deep ultraviolet off-axis digital holographic microscope (DHM) is presented. A high resolution approach has been implemented in the setup using oblique illumination to overcome the limitation introduced by the optical system and the theoretical resolution limit of 250 nm (according to Abbe criterion) has been verified, experimentally.

1 Introduction

Digital holographic microscopy (DHM) is a promising method for 3D microscopy because of its ability to extract the 3D information of the object by taking only one image and deriving the phase and amplitude information of the object wave-front in any plane [1-3]. By improving nanotechnology, the size of structures and functional devices is decreasing down to the nano-scale which is smaller than the wavelength of the light. The diffraction-limited lateral resolution, introduced by Abbe's criterion ($k\lambda / NA$), is a barrier that makes an obstacle for DHM methods to go that deep. To improve the resolution one should increase NA and/or use a shorter wavelength. One approach, to increase NA, is to guide light beams with higher angles to the detector using synthetic aperture techniques, by means of gratings [4] or oblique illumination [5,6]. In this paper we arranged a setup implementing a short wavelength (193 nm) and an objective with high numerical aperture ($NA = 0.75$) and using oblique illumination technique.

2 Experiment

An ArF Excimer Laser, (ExiStar 200 TUI), operating at deep UV (193 nm), was used as a light source. Some advantages of using this light source are as follows: 1) the laser has a short coherence length,($\pm$ 100 µm), which reduces the noise coming from the back reflections, 2) the setup does not need to operate in vacuum, 3) The optical elements made of fused silica can be used in the setup, and 4) a digital camera is commercially available for this wavelength with high UV sensitivity, which can perform direct imaging with no fluorescent plate in front (PCO Sensicam).

To achieve high resolution, oblique illumination is implemented in the setup. The zero order of the diffracted light from the object is shifted to one of the peripheral sides of the objective, instead of passing through the center of the aperture. This shifting enables more additional spatial frequencies to enter the imaging pupil. Guiding higher spatial frequencies to the imaging system is somehow equivalent to increasing the NA of the imaging system. In addition, the poor visibility in conventional bright field imaging, caused by the symmetrical presence of lower frequencies is suppressed and consequently makes it possible to resolve very fine structures in the specimen.

A custom objective was designed to meet the demands of the off-axis setup while having a low price for imaging with a deep UV light. Light coming from the object plane is collimated, respectively focussed towards infinity. This is done by using a half-ball-lens and a custom-design asphere. The half-ball-lens allows the numerical aperture to reach 0.75 as the asphere is used to mainly correct the spherical aberration introduced by the half-ball-lens. The focal length of the objective was set to 1 mm and it can image a field with the radius of 10 µm.

3 Results

To test the resolution of the setup we have used our designed template (the SEM image shown in Fig. 1.a.). The image taken by an optical microscope (Zeiss Axiovert 200, with 100x objective, NA=0.7) is also shown in Fig. 1.b. for comparison. Figure 1.c. and 1.d. show a typical recorded hologram and its Fourier transform, respectively. One of the lobes which is highlighted with a white square is used for image reconstruction. First, the experiment has been done using on-axis illumination. For this case, the reconstructed amplitude and phase of the object are shown in Figs. 1.e. and 1.f., respectively. The line structures with the size of 350 nm can be resolved in the reconstructed image, but the "ito" logo is unclear and the square structures smaller than 400 nm are not recognized. To increase the resolution, the oblique illumination was performed though an incident angle of ~10° (relative to the normal axis of the object plane), from four symmetric directions along the *x* and *y* axis of the object (indicated in Fig.

1.a.). The reconstructed amplitude and phase for two selected directions are shown in Fig. 1.g-j.

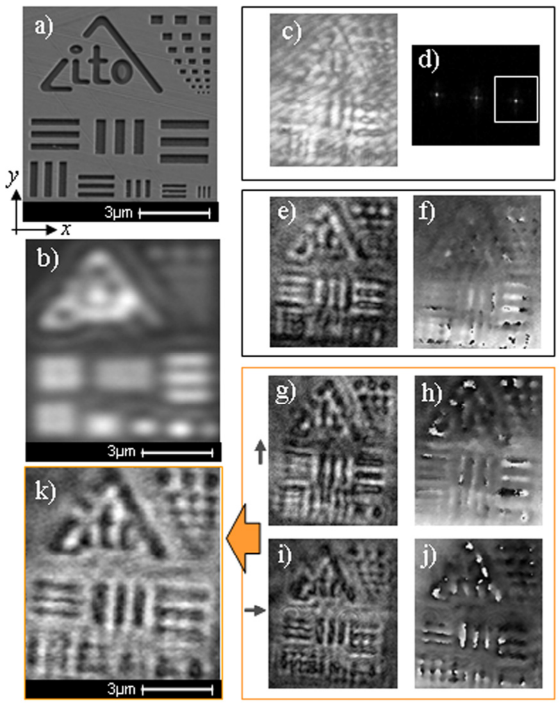

Fig. 1 *(a) The Scanning Electron Microscope (SEM) image of the nano-structured template, (b) the image taken by a Zeiss optical microscope with NA=0.75, 100x objective with no immersion, (c) a typical recorded digital hologram and (d) its Fourier transform, (e) the reconstructed amplitude and (f) phase of the object illuminated with on-axis illumination, (g) the reconstructed amplitude and (h) phase of the object illuminated with oblique illumination along "y" axis, (i) the reconstructed amplitude and (j) phase of the object illuminated with oblique illumination along "x" axis, (k) the final image obtained by combining the reconstructed images taken using oblique illumination form four symmetric directions, in the spatial domain. The scale bar is 3 μm in (a), (b), and (k).*

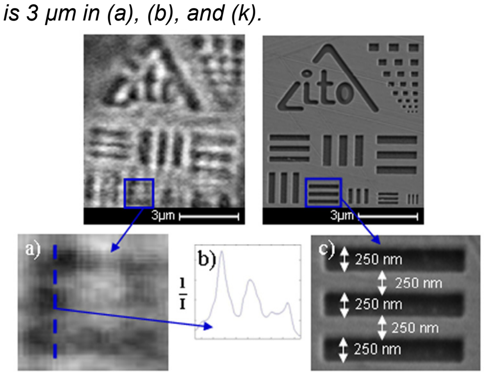

Fig. 2 *A fine comparison of the SEM image of the template (right-center) and the image obtained using our DHM setup (left-center). (a) The magnified DHM image of the 250 nm sized structures, (b) the inversed intensity profile along the dashed line in Fig. 2.a., (c) the magnified SEM image showing the 250 nm sized structures.*

The illumination direction is indicated by an arrow in each image. Artifacts are involved in each image which even makes the larger structures unresolved. To remove the artifacts caused by tilted illumination, we have combined the images taken from four directions in the spatial domain, by adding the complex amplitude of the images. The combined image is shown in Fig. 1.k. In this image the "ito" logo (which has elements with ~300 nm in width) is clear and even the line structures with the width of 250 nm are well-resolved. To better compare the final combined image (Fig. 1.k.) with the SEM image (Fig.1.a.) the small structures are magnified in Figure 2. An inversed intensity profile is plotted for each structure size to better show the visibility of the structures. Figure 2.b. shows a clear profile of the 250 nm sized structures.

4 Conclusion

In this work we have developed an off-axis digital holographic microscope in deep UV, capable of recording 3D images from nanostructures. The setup has been designed with the least possible optical elements in the imaging path to avoid aberration due to the non-perfect optical elements. By implementing the oblique illumination method we are able to detect structures even down to 250 nm and achieved the diffraction limited resolution of the presented imaging system. The setup can be implemented in a way to be able to image in the reflection mode.

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