Non-contact optical super-resolution imaging study based on height-variable microsphere

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Abstract. Super-resolution images can be achieved by coupling the microscale dielectric microsphere with white-light optical microscopy. This paper presented a method for adjusting the distance between microsphere and sample to study the imaging ability of the microsphere. By this method, the nanofeatures on the Blu-ray disc surface could be observed. The super-resolution images when microspheres at different heights were compared to analyse the changing trend of imaging ability with distance. The optical simulation results illustrated that super-resolution imaging ability was related to the position of the photonic nanojet. As the photonic nanojet was inside the sample, the super-resolution image could be achieved even if the microspheres didn’t touch the sample. This work has great significance for manipulating microsphere to non-contact image.

1. Introduction

The resolution of conventional optical microscopes was about 200 nm, which limited observation of sample with nanostructures [1-2]. Therefore, overcoming the diffraction limit to realize super-resolution imaging is of great significance to life science [3], biotechnology [4], material science [5] etc. Recently, Wang et al. reported that the super-resolution images could be achieved by coupling the microscale dielectric microsphere with white-light optical microscopy [6]. The microsphere was able to collect evanescent waves in the near field of the object and transport super resolution information to the far field, which was considered as one of the reasons for achieving super resolution imaging of microsphere [7-8]. Compared with other technologies and instruments, such as scanning electron microscopy (SEM), near-field scanning optical microscopy (NSOM), fluorescence microscopes, this method based on microspheres appeared unique ability for non-invasive, real-time, low-cost and white-light imaging. The microspheres were spread on the surface of the sample and the structure under the microspheres could be observed. However, the contact between the microspheres and the sample had possibility to pollute and destroy the nanostructure of the sample surface, especially for biological samples. So the method of maintaining a certain distance between the microsphere and the surface was significant for the application of this super-resolution technique.

In this work, we attached the microsphere to the probe by using optical glue. The probe was mounted on the translation stage. When the translation stage was driven, the microsphere would move correspondingly. By this way, the bottom of the microsphere would not touch the surface of the sample and the distance between the microsphere and sample surface could be adjusted by manipulating the stage along Z-axis. The imaging ability of microsphere at different distance from the
surface of the sample was compared. Optical simulations were carried out to analyze experimental results. It was found that the super-resolution imaging abilities of the microsphere at different heights was related to the position of the photonic nanojet. When the photonic nanojet was inside the sample, the microsphere was still able to achieve super-resolution images even if the microsphere didn’t touch the sample.

2. Experiments

2.1. Experimental setup

Figure 1 showed the schematic of the experimental setup. The microsphere was adhered to tip of the probe (ST-20-2, Picoprobe) by optical glue. The optical simulation illustrated that the influence of probe and optical glue on imaging was too slight to be neglected. The probe was mounted on the translation stage which had three linear motion along the X, Y, Z axis and rotation along the X axis. In the translation stage, the stages along X, Y axis were motorized stages (KS102-70R, SURUGA SEIKI), the stage along Z axis was a manual stage (B31-80A, SURUGA SEIKI), and the rotation was manipulated by a rotating mechanism (DCM 210, Cascade Microtech). The sample was placed on a probe station (M150, Cascade Microtech). The super-resolution images were observed by an optical microscope (PS-888 Microscope, SEIWA OPTICAL) which was equipped with a 50X objective lens (M Plan Apo, SEIWA OPTICAL). Peak illumination wavelength of the light source (halogen lamp, LampLink2, OPTEM) was 590 nm. The position of the probe in the vertical plane was achieved by zoom lens (CORRECT TOKYO ZOOM 0.75X-4.5X).

![Figure 1. Optical super-resolution experimental system.](image1)

![Figure 2. Vertical views of the probe. (a) The probe above sample surface. (b) The probe touched the sample. The scale bar was 500 μm.](image2)
Figure 3. The sample images achieved by microscope and SEM. (a) The SEM image of sample surface. (b) The optical microscope image of microsphere in air. (c) Image of nanostructure. The scale bars in (b) and (c) were 10 μm.

2.2. Experiments and results

Figures 2(a)-(b) were the vertical view of the probe. The probe moved towards the sample by manipulating the translation stage along Z-axis until the microsphere started to touch the sample surface. The microsphere was adhered to the tip of the probe. To ensure the microsphere touch the sample firstly during the experiment, the probe was tilted to a certain angle. Once the microsphere touched the sample surface, the probe would deform and move forward slightly, which determined contact state. The reflected irradiating light on the cantilever will slightly change. The sample was Blu-ray disc. As figure 3(a) (SEM image) showed, the nanostructure on the sample surface was the 220 nm wide stripes spaced by 130 nm gaps. As figure 3(b) shows, the stripes were not observed when the microsphere was about to touch the sample surface. The microspheres with different material need different observing ways to get the best imaging quality [9]. The microspheres used in experiments were made of barium titanate glass (BTG, with a refractive index of 2.1), which should be full-immersed in the liquid medium when used for super-resolution imaging. Additional, when the refractive index contrast between the microsphere and air was more than 2, the photonic nanojet unable to be generated [10]. Therefore, the super-resolution image could not be observed in air. As figure 3(c) shows, as the microsphere with a diameter of 16 μm was immersed in liquid (alcohol), the stripes on sample surface were observed. Therefore, the nanofeatures on the Blu-ray disc surface were observed by this method.

Manipulating the translation stage along Z-axis step by step, the distance between the bottom of microsphere and the sample surface would be adjusted. As figures 4-5 showed, when the microsphere gradually moved away from the sample, the super-resolution image changed accordingly. When immersed in different liquid, the clarity and magnification of imaging were different. The diameter of the BTG microsphere showed in figures 4-5 was ~20 μm. In figure 4, the microsphere was immersed in alcohol. The figures 4(a)-(d) were the super-resolution images of stripes, when the distance between microsphere bottom and sample surface were 0 microns, 2 microns, 4 microns and 6 microns, respectively. The stripes were observed clearly in figures 4(a)-(b). In the figure 4(c), image became blurred, but the stripes could still be distinguished barely. The stripes were completely incapable of being seen in figure 4(d). In figure 5, the microsphere was immersed in Cedarwood oil. The figures 5(a)-(d) were the super-resolution images of stripes, when the distance between microsphere bottom and sample surface were 0 microns, 3 microns, 6 microns and 9 microns, respectively. The change process of the super-resolution images in figure 5 was similar to that in figure 4. Therefore, when the microsphere moved far away from the sample, the image became blurred until it can’t be seen. However, when the distance of the microsphere to the sample was within a certain range, the imaging ability of microsphere was almost unaffected.
Figure 4. Super-resolution images and optical simulations of alcohol-immersed microsphere. The distance of the bottom of microsphere and sample surface was 0 μm (a, e), 2 μm (b, f), 4 μm (c, g), 6 μm (d, h). The all scale bars were 5 μm.

Figure 5. Super-resolution images and optical simulations of Cedarwood-oil-immersed microsphere. The distance of the bottom of microsphere and sample surface was 0 μm (a, e), 3 μm (b, f), 6 μm (c, g), 9 μm (d, h). The all scale bars were 5 μm.

2.3. Optical simulations
To analyse the effects of the distance on imaging quality, the optical simulations were performed using COMSOL Multiphysics software. A plane wave with a wavelength $\lambda$ of 590 nm polarized along the X-axis was set as the illuminating light. The diameter and material of the microsphere were 20 μm and BTG (with a refractive index of 2.1), respectively. The material of the sample at the bottom was polycarbonate (PC, with a refractive index of 1.58). For two different types of immersion, the environment was set as alcohol (with a refractive index of 1.36) and Cedarwood oil (with a refractive index of 1.52), respectively.

Figures 4(e)-(h) and figures 5(e)-(h) showed the simulation results of intensity distribution ($|E|^2$) in the vertical plane. The illuminating light was focused by the microsphere when it passed through the microsphere, and a photonic nanojet with high optical intensity was generated [11]. The super-resolution imaging capability of the microsphere was directly related to the focal waist of the photonic nanojet [12]. When the microspheres move upwards, the spot also moves upwards correspondingly. It was found that when the photonic nanojet was inside the sample, the stripes could be observed clearly.
When the photonic nanojet was located on the boundary of the sample surface, the image became blurred. When the photonic nanojet was above the sample surface, the stripes could not be seen. The super-resolution imaging ability was related to the position of the photonic nanojet. Therefore, when the photonic nanojet was inside the sample, the super-resolution image still be achieved even if the microspheres didn’t touch the sample.

3. Conclusions
In this paper, a manipulation method of microsphere for optical super-resolution imaging was presented. The microsphere was adhered to a probe by optical glue. When the microsphere was immersed in liquid medium, the nanostructures on the Blu-ray disc surface were observed. By driving the translation stage where the probe mounted on, the distance between the bottom of microsphere and the sample surface could be adjusted. Comparing super-resolution images achieved by microspheres at different heights, the changing trend of imaging ability with distance was found. The optical simulation results demonstrated that super-resolution imaging ability was related to the position of the photonic nanojet. As long as the photonic nanojet was inside the sample, the super-resolution image still be achieved even if the microspheres didn’t touch the sample. Therefore, the super-resolution images could be observed at no risk of polluting and destroying the nanostructure of the sample surface. This work had practical significance for the development of super-resolution imaging.

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