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Dependence of focal position on the microscale spherical lens imaging

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ABSTRACT

In this paper, hexagonal close-packed colloidal crystal samples are prepared by a self-assembly method. The image properties of three kinds of microspheres (silica, polystyrene and barium titanate glass) on the colloidal samples are studied. These microspheres are placed in air, semi-immersed and full-immersed in ethanol respectively. We find that all these microspheres can magnify the colloidal crystal samples and have the super-resolution imaging ability. Our experimental results indicate that the position of the focal point of the microsphere can affect the super-resolution imaging property, therefore microspheres with different material need different observing ways to get the best imaging quality. The silica microspheres and the polystyrene microspheres need semi-immersion, while the barium titanate glass microspheres need full-immersion to make the focal point close to the microsphere, so that the best imaging quality can be obtained. The mechanisms are also discussed with numerical simulations.

1. Introduction

It is well known that the resolution of a conventional optical microscope is about 200 nm in theory, but in fact a 300 nm object is difficult to be observed. Therefore how to beat Abbe's diffraction limit has become a hot topic in photonics[1–10]. Nowadays, Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM) and Scanning Near-field Optical Microscope (SNOM) have been used to resolve features beyond the diffraction limit. However, SEM and TEM are often used to observe objects in vacuum, so they are unsuitable for the study of live viruses. SNOM which is based on point-by-point scanning of a nano-scale optical tip very close (within a few nanometers) to the target surface to illuminate the targets using the evanescent effect of the optical near-field, takes a long time to acquire the full images. Recently, microscale dielectric spherical lenses have appeared as a simple, real-time, direct and effective approach to obtain super-resolution imaging. Fletcher et al. have observed near field imaging with solid immersion microsphere lens [11]. Lee et al. have reported near-field high resolution by nanoscale spherical lenses [12]. Kim et. al have found that the microsphere lenses have super-resolution ability and their simulation results indicate that the distance between the objective lens and the microsphere lens has an effect on the super-resolution of the microsphere lens [13]. Super-resolution imaging has been observed by microspheres, but the reported observing methods are different. Wang et al. have demonstrated that microspheres in air can collect evanescent waves and transport super resolution information to the far field [14]. Hao et al. have demonstrated a sharper imaging contrast and a comparatively smaller magnification factor by semi-immersing the microspheres in ethanol [15,16]. Darafseh et al. have been experimentally shown optical super-resolution imaging by high-index liquid-immersed microspheres [17]. Li et al. have reported direct white-light optical imaging of 75-nm adenoviruses by submerged microsphere optical nanoscope [18]. Lee et al. have shown immersed transparent microsphere magnifying sub-diffraction-limited objects [19]. Among these studies, the microsphere lenses are full-immersed or semi-immersed in a medium in many cases. The questions about why the reported observing ways are different, and which is the best way to obtain the best imaging quality are less studied. In this paper, the imaging properties of three different kinds of microspheres with different materials are studied. Our experimental results indicate that these microspheres can obtain super-resolution imaging, but microspheres with different material need different observing ways to get the best imaging quality. The low refractive index microspheres need semi-immersion, while the high refractive index microspheres need full-immersion. We find that the position of the focal point of the microsphere can affect super-resolution imaging, and the best imaging quality can be obtained when the focal point of the microsphere is close to the microsphere. With different ways of immersion, the focal point of the different microspheres can be adjusted. Moreover, different kinds of microspheres need different observing ways to get the best imaging property, therefore their imaging results are different. When observing objects well beyond the diffraction limit, two images are formed with low refractive index microspheres semi-

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immersed in a medium, and only one image is formed with high refractive index microspheres full-immersed in a medium. But when observing objects close to the diffraction limit, one super-resolution image is formed for both the low refractive index microsphere semi-immersed and the high refractive index microsphere full-immersed in a medium.

2. Experimental section

Fig.1 illustrates the schematic of the experimental setup. In our experiment, a Leica microscope (DM2500 M) was used. Samples were observed by a 100 × (NA=0.9) microscope objective. The microscope was used in reflection illumination mode and equipped with a CCD camera to record results. Four steps were involved in the experiment. The first step was to fabricate colloidal crystals from polystyrene microspheres. The colloidal crystals were deposited onto clean glass substrate by a vertical convective self-assembly method [20]. By this method, two kinds of PS microspheres, with a diameter of 280 or 710 nm are prepared. The Rayleigh resolution limit for point objects is 366 nm ($r=0.61\lambda/n$ NA), here $\lambda=540$ nm, $n=1$, and NA=0.9 [21]. Therefore, the large objects (fabricated by the 710 nm microspheres) are well beyond the resolution limit, while the small objects (fabricated by the 280 nm microspheres) are close to the resolution limit. In the second step, a silver film was deposited onto the surface of the samples by evaporation. The thickness of the silver layer is 20 nm. Then, three types of microspheres were dropped on the samples. The three microspheres are silica (SS) microspheres, polystyrene (PS) microspheres, barium titanate glass (BTG) microspheres, and their refractive indexes are 1.46, 1.6 and 1.9, respectively. Finally, the fabricated samples were put under the microscope for observation. The colloidal crystals made from PS microspheres are characterized by a scanning electron microscope (FESEM, Hitachi JSM-7600F). The result is shown in the inset of Fig.1.

3. Results and discussion

Figs. 2–4 show the optical microscope images of a large object (fabricated with the 710 nm microspheres) observed with the three different kinds of microspheres. In our experiments, if we find that the depth of focusing in the images is below the focal plane of the microspheres, we define that the images are virtual images, otherwise the images are real images. As shown in Fig.2a, a blurred virtual image is formed when observing with a 4.87-μm-diameter SS microsphere in air, and the magnification factor M is about $-3.2\times$ for the virtual image. No image is formed when the

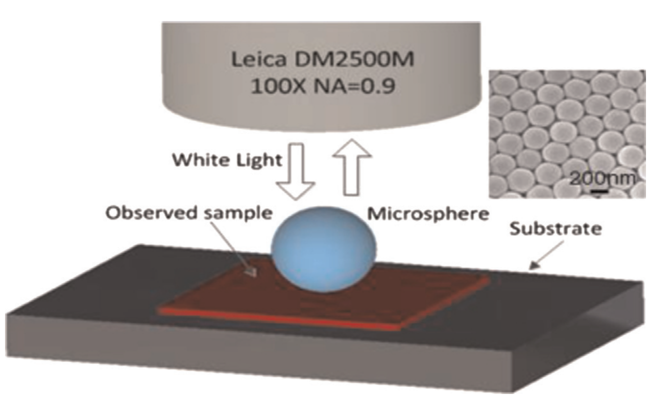

Fig. 1. Schematic illustration of the experimental setup. The inset is the SEM image of a self-assembled PS microsphere array. The diameter of the PS microsphere is 710 nm in this sample.

SS microsphere is full-immersed in ethanol. As the ethanol evaporates, when the silica microsphere is semi-immersed, two virtual images are formed, as shown in Fig. 2b. In Figs. 2b-1, the image is clear and sharp, with a M of $-1.9\times$. In Figs.2b-2, the image is blurring, with a M of $-2.4\times$. With a 4.94-μm-diameter PS microsphere in air, a virtual image is formed in Fig.3a, with a M of -3.1 ×. Similar to the silica microsphere, when the PS microsphere is semi-immersed, two virtual images are formed as shown in Fig.3b, and the M is about $-2.0\times$ and $-2.3\times$ for the clear image and the blurred image, respectively. As indicated in Fig.4a, a real image is formed when observing with a 5-μm-diameter BTG microsphere in air, and the M is 4.1 ×. When the BTG microsphere is full-immersed in ethanol, a virtual image is formed (Fig.4b), with a M of $-3.3\times$. As the ethanol evaporates, the virtual image will become blurred and then disappear.

To explore the imaging behaviors of the three microspheres, the imaging properties of the microspheres on a small object are also studied. Fig. 5a–c are the optical microscope images of a small object (fabricated from the 280 nm PS microspheres) with the three kinds of microspheres. As illustrated in Fig. 5a, a virtual image is formed when a 4.87-μm- diameter SS microsphere is semi-immersed in ethanol, and the M is $-1.82\times$. With a 4.94-μm-diamter PS microsphere semi-immersed in ethanol, a virtual image is formed (Fig. 5b), with a M of $-2.14\times$. No images can be formed with the SS or PS microspheres full-immersed in ethanol. Fig. 5c shows the virtual images formed with the 5-μm-diameter BTG microspheres full-immersed in ethanol, and the M is $-3.2\times$. As the ethanol evaporates, the virtual image will become blurred and then disappear. Fig. 5 demonstrates that all the three kinds of microspheres can obtain super-resolution imaging.

To further analyze the super-resolution imaging behaviors of the three microspheres, the optical microscope images of the small object sample at $d=2.9$ μm (d is the distance between the object and the microsphere lens) with the three microspheres are studied. Fig. 6a displays a virtual image formed with a 4.87-μm-diameter SS microsphere semi-immersed in ethanol, and the M is $-1.8\times$. A virtual image is formed (Fig. 6b) with a 4.94-μm-diameter PS microsphere semi-immersed in ethanol, and the M is $-1.7\times$. No images can be formed with the silica or PS microspheres full-immersed in ethanol. In Fig. 6c, no image is formed with the BTG microsphere full-immersed or semi-immersed in ethanol.

In previous study in ref. [13], their FDTD simulation results indicate that the super-resolution of the microscale hemispherical lens can be affected by the the distance between the objective lens and the microsphere lens. In this paper, to find out the dependence of focal position on the microsphere lens imaging, finite-difference time-domain (FDTD) simulations were carried out using CST program. CST is a commercial FDTD program by calculating the exact solution of Maxwell's equation. Fig. 7 is the simulated focal plane of the object space from the center of the microsphere (F) of the three different kinds of microspheres with different immersion ways. The microsphere are immersed in air in Fig. 7a, semi-immersed in ethanol in Fig. 7b and full-immersed in ethanol in Fig. 7c. For 4.87-μm-diameter SS microsphere, F is 2.80 (Fig. 7a-1). As shown in Fig. 7a-2, F is 2.51 for 4.94-μm-diameter PS microsphere. In Fig. 7a-3, F is 2.01 for 5-μm-diameter BTG microsphere. For the SS or PS microsphere, the focal point is inside the microsphere, while it is outside the microsphere for the BTG microsphere. So a virtual image is formed with the SS or PS microsphere, and a real image is formed with the BTG microsphere, as shown in Fig. 2a, 3a, and 4a, which matches with the geometrical optics prediction. Li et al. have studied the super-resolution imaging performance of microspheres immersed in three liquid types and simulated the focusing properties of microspheres embedded in air and water media. They find out that the position of the focal