Large field-of-view super-resolution image obtained by manipulating submerged microsphere

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Abstract. Images with super-resolution can be obtained by dielectric microspheres with appropriate refractive index. However, in practical applications, the microsphere must be moved to the desired position and can scan the large specific area. Here we present a simple method of positioning a microsphere by using a four-dimensional precision translation stage. The simulations have been performed to confirm that 16 µmΦ barium titanate glass (BTG) microsphere submerged in alcohol can obtain high quality images and the influence of the probe and the flowing liquid on imaging can be ignored. Therefore, by driving the translation stage, the submerged microsphere can scan the sample surface along the X and Y axis at the speed of 10 µm/s and the large field-of-view image can be achieved by stitching the pictures of different positions. This work has provided a new technique in super-resolution imaging and can be widely applied in field of scientific research.

1. Introduction
Conventional optical microscopes have played a significant role in promoting the development of scientific research, especially in life science [1], material [2] and biotechnology [3]. Progress in these fields has put forward higher requirements on the resolution of imaging technology. However, the optical microscope, the resolution of which is limited by the diffractive nature of light, can only resolve features of half of the wavelength of illumination [4]. As a result, several optical imaging techniques with super-resolution have been successfully actualized. Though these devices, such as near-field scanning optical microscopy (NSOM) [5], scanning electron microscopy (SEM) [6], fluorescence microscopes [7], etc, can overcome the classical optical diffractive limit to obtain the super-resolution images, they suffer from cost, efficiency and rather complicated operations. Therefore, a low-cost and easily operated scheme for super-resolution imaging is highly desirable.

It has been demonstrated that fused silica microsphere with refractive index n~1.46 and diameter from 2 to 9 µm on top of the object can achieve a super-resolution image in air with a white light source [8]. The microsphere on top of the sample surface converted the near-field evanescent waves including fine feature information into far-field propagating waves [9], creating a magnified image in the far-field, which is collected by a conventional optical microscope. Later on, it was reported that high refractive index microsphere, completely immersed in liquid, actually increased the resolution of image [10]. Moreover, photonic nanojet generated by microspheres is essential to the resolution imaging capability [11]. Microscopes are often used to observe specific positions, but the spheres are on the sample surface at arbitrary. In addition, the field-of-view of the imaging system is confined to...
the place under the microsphere, but the field-of-view of a microsphere mostly cannot contain the whole sample. To image the large samples, the microsphere must be moved to the desired position and scan the area successively.

In this work, we present a simple and practical method of super-resolution optical microscopy based on scannable probe-combined microsphere. A numerical study of the light propagation through BTG microspheres of different sizes in different media using the finite element method (FEM) is performed. This allowed choosing the appropriate size of spheres in suitable liquid to form a super-resolution image with high definition and contrast. The selected microsphere was stuck to the tip of the probe with optical glue and the influence of the probe on imaging has been analysed by the FEM. The probe was fixed on a four-dimensional precision translation stage and thus the microsphere attached it can be moved to any desired area in three dimensional space. A large field-of-view super-resolution image was obtained by scanning the sample surface. In addition, the effect of the movement of spheres in liquid on imaging must be considered. This method of combining optical microscope with microsphere is ingenious and will allow affordable super-resolution imaging of large continuous area.

2. Experiments

2.1. Simulations

The images obtained by microspheres of various sizes in diverse liquids have different qualities. Therefore, selecting the microsphere and the liquid is the vital step of the experiment. The numerical simulations on illuminating light propagation through a 12 μm, 16 μm and 20 μm φ BTG microsphere submerged in alcohol and Cedarwood oil medium respectively have performed by FEM in COMSOL multiphysics software. The refractive indices of the BTG microsphere, the alcohol and the Cedarwood oil are 2.1, 1.36 and 1.52, respectively. Since the peak of the halogen lamp that was used in the experiments is 600 nm, the incident light for simulations was set as a plane wave with a wavelength of 600 nm.

Figure 1 shows the simulated results of electric field distribute (|E|) in the vertical plane. As illustrated in the figure 1, a photonic nanojet that locates in the vicinity of the rear-surface of the sphere is a narrow light beam with high optical intensity. It has been demonstrated that the super-resolution imaging capability of a microsphere is dependent on the waist of its photonic nanojet. The waist is the full width at half maximum (FWHM) of the nanojet along the X axis at the peak intensity of the Y axis. The microsphere that generated the minimum waist can obtain the best resolution. The waists of the nanojet in the (a)-(f) are 258.5 nm, 260.2 nm, 324.9 nm, 278.7 nm, 317.0 nm and 338.4 nm. The waists of the 12 μm and 16 μm φ microsphereimmerged in alcohol were almost equal, but the 16 μm φ microsphere can provide a bigger field-of view. Figures 1(g-l) were the images that achieved in the experiments with the materials corresponding to the simulations in figures 1(a-f). By contrast, the figure 1(i) image had the higher contrast and better clarity, which proved that the 16 μm φ microsphere submerged in the alcohol was the best choice for imaging.

Because the microsphere was attached to the probe, the effect of the probe on imaging must be considered. The diameter of the probe tip was 1 μm and the contact area between microsphere and probe was estimated to be about 5 μm. The waist of the nanojet in figure 1(c) is 260.2 nm and that in figure 2(a) is 263.1 nm, which revealed that the probe has almost a negligible influence on the near-field focusing. In addition, the effect of alcohol flow caused by microsphere scanning in the liquid on imaging should also be taken into account. The waist of the figure 2(c), that is 258.7, is similar to the microsphere motionless. Therefore, the influence of the probe and the flowing liquid on imaging can be ignored.
Figure 1. COMSOL simulated results of electric field distribute (|E|) in the vertical plane and the images on Blu-ray disc by the microsphere. (a-f) FEM simulations of the light propagation through a 12 μm (a,b), 16 μm (c,d) and 20 μm (e,f) φ BTG microsphere in alcohol (a,c,e) and Cedarwood oil (b,d,f) media respectively. (g-l) Images obtained by using the optical microscope combined with the 12 μm (g,h), 16 μm (i,j) and 20 μm (k,l) φ BTG microsphere immerged in alcohol (g,i,k) and Cedarwood oil (h,j,l) media respectively.

Figure 2. COMSOL simulated results of electric field distribute (|E|) in the vertical plane for (a) probe-combined microsphere and (c) microsphere scanning in the alcohol. (b) The Velocity distribution of the alcohol.
2.2. Optical setup
Figure 3 illustrates the configuration for obtaining large field-of-view super-resolution images. The sample to be observed was put on the professional probe station (M150, Cascade Microtech), which was equipped with an optical microscope (PS-888 Microscope, SEIWA OPTICAL). The microscope included a white light source (halogen lamp, LampLink2, OPTEM) and a 50X objective lens (0.42 NA, M Plan Apo, SEIWA OPTICAL) with 20.5 mm working distance. Virtual images through microsphere in the far-field were recorded by a colour charge-coupled device (CCD) camera (FL3-U3-13S2C-CS, point grey). The microsphere was attached to a probe (ST-20-2, Picoprobe) and the probe was fixed on a four-dimensional precision translation stage. The microsphere can be driven automatically by the stepper motor along the X and Y axes with the resolution of 5 µm (KS102-70R, SURUGA SEIKI). The Z axis (B31-80A, SURUGA SEIKI) and rotation around the X axis (DCM 210, Cascade Microtech) that are manual operation were used to change the distance between the sample surface and the sphere and adjust the probe angle respectively.

![Figure 3. Setup for optical super-resolution experiment.](image)

Figure 3. Setup for optical super-resolution experiment.

3. Results and discussions
The Blu-ray disc with the nano-feature of 220 nm wide stripes spaced by 130 nm groves was an ideal sample for super-resolution imaging. The SEM image of the sample surface was shown in figure 4 (a). According to the above analyse, the 16 µm φ microsphere submerged in alcohol can achieve images with high definition and contrast. The microsphere imaging technique required the sphere touched the sample surface. Thus the probe should adhere to the upper part of microsphere with optical glue and the angle between the probe and the sample surface was set to be 20°. The translation stage was operated along the Z axis manually until the sphere started to touch the sample surface. However, as shown in figure 4(b), the super-resolution image was not achieved by the BTG microsphere in air. In contrast, when the microsphere was immerged in alcohol, approximate 13 periods of stripes of Blu-ray disc were observed in figure 4(d), that is, the features are magnified for 3.52 times (16 µm /0.35 µm /13).

Figure 5 indicated the image of the 9 different positions on the Blu-ray disc surface, which was obtained by motorizing the translation stage to scan the microsphere along the X and Y axis at the speed of 10 µm/s. The zoomed images of the microspheres are respectively shown in the figure 5(a-i). As shown in figure 5(g), the large field-of-view image was obtained by stitching the zoomed image.
The experimental results revealed that the optical microscope in combination with microsphere can resolve the feature of 130 nm gap, which not only demonstrated the 16 µm BTG microsphere submerged in alcohol can provide high quality images, but also catered to the simulation results that the probe and the flowing liquid have almost no effect on imaging. The figure 5(a) indicated that the field-of-view of a microsphere only account for a little of optical microscope. As a result, the view of a microsphere cannot contain the whole area when the target object to be observed was slightly big. However, this method of operating the translation stage and stitching the local images extended the field-of-view of the imaging system. As show in figure 5(g), the image which consisted of nine local images can observe about four views of microsphere.

![Figure 5](image.png)

Figure 5. Scanning image of the sample surface. By scanning the probe along the X and Y axis, super-resolution image of large continuous area on sample surface could be achieved. (a)-(i) Images of microsphere at 9 different positions during scanning process. (g) The large field-of-view super-resolution image.

4. Conclusions
We have displayed a technique that the super-resolution image over a large area can be achieved by using a conventional optical microscope in combination with a 16 µm BTG microsphere submerged in alcohol. The microsphere was stuck to the probe and the probe was mounted to the translation stage. The translation stage was operated automatically along the X and Y axis so that the microsphere can scan the desired sample surface. Meanwhile, the CCD camera can record the image of the local nano-feature of sample. Large field-of-view super-resolution image can be obtained by stitching the recorded part image together. Therefore, this simple and efficient method provided a new alternative for super-resolution imaging technology over large-area.

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