Super-resolution optical microscopy using a glass microsphere nanoscope

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Due to the diffraction of light, a conventional optical microscope has a strict limitation in spatial resolution: the minimum size that can be clearly resolved by the objective with numerical aperture (NA) of 1.4 is around one half of the illumination wavelength, which is a few hundred nanometer in the visible light region [1]. How to break the diffraction barrier has become a vital concern for achieving super-resolution. It is well known that microspheres that are significantly larger than the illumination wavelength can be treated as focusing lenses [2], as the illumination light can be highly focused by the microsphere into a so-called 'photonic nanojet', which has sub-wavelength transverse dimension. On a fundamental level, the focus spot size of an objective, i.e. the transverse dimension of a photonic nanojet for a microsphere lens, is at the basis of the super-resolution imaging capability of microsphere-based optical microscopy [3]. Here, we propose the use of barium titanate glass microspheres for facile and affordable super-resolution imaging of nanometer size objects and provide finite element method (FEM) modeling of the photonic nanojet phenomenon.

The microspheres with diameter of 60 µm are simply put on a sample that is immersed in oil, the former projecting the sample's near-field nano-features into the far-field, generating a magnified virtual image that is recorded through a conventional oil immersion objective with NA of 1.4, as schematically shown in Fig. 1. A halogen lamp with a peak wavelength of 600 nm is used as the white-light illumination source. Figs. 2 and 3 show SEM graphs and optical images of silicon nanostructures, including 200 nm-wide lines with 200 nm interspacing and 120 nm-wide lines with 100 nm interspacing. For the oil immersion objective, the Rayleigh resolution ($0.61\lambda/NA$, λ the illumination wavelength) is estimated to be 260 nm for the main peak of the used white-light source. When no microsphere is used, the oil immersion objective alone cannot resolve line structures indeed. On the other hand, when the microsphere is placed on top of the sample, the individual lines are clearly resolved, demonstrating an experimental resolution between $\lambda/4$ (λ = 400 nm) and $\lambda/7$ (λ = 750 nm) in the visible spectrum range. The virtual image is magnified by a factor of 2.8. We further study the imaging of gold nanorods with axial diameter of 50 nm and length of 100 nm (shown in Figure 4). The nanorods are clearly observable through the microsphere, however, their orientation cannot be distinguished, meaning that the axial diameter of 50 nm is below the super-resolution capability of the microsphere nanoscope. The virtual imaging is implemented in immersion oil with refractive index of 1.52. When the difference of the refractive index between the surrounding media and the microsphere gets bigger, theory predicts even better super-resolution potential. This makes this technique very promising to be used in water-based media for super-resolution imaging of biological samples. A numerical study using FEM of the electromagnetic wave propagation through the microsphere and its surrounding medium is performed to verify the light focusing capability of the microsphere. The simulations indicate that a microsphere with diameter as big as 75 µm shows super-resolution capability in oil and that he big size of the microsphere is also increasing the useful field-of-view.

In conclusion, we achieve super-resolution imaging of nanostructures with sub-diffraction feature sizes by using a microsphere nanoscope in combination with a conventional immersion objective. This in turn provides new pathways for super-resolution optical imaging in real time, which is useful for life science applications and optical nano-sensing.

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[3] H. Yang, N. Moullan, J. Auwerx and M. A. M. Gijs, Small 10 (2014) 1712-1718.

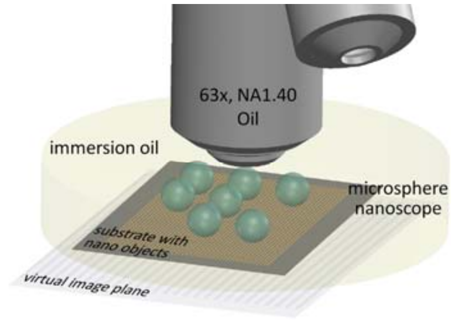

Figure 1. Schematic of the super-resolution imaging setup.

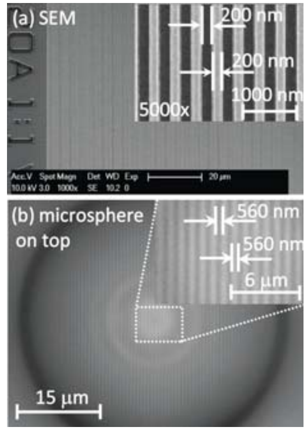

Figure 2. Measurement of nanolines with a width of 200 nm and inter-space of 200 nm, by both SEM and by optical microscopy using a microsphere in combination with an oil immersion objective.

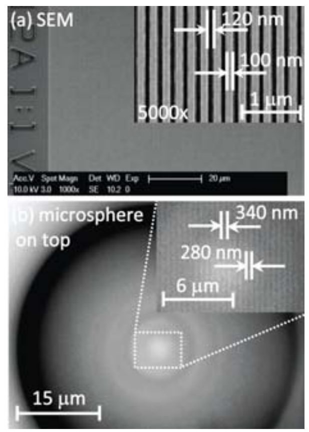

Figure 3. Measurement of nanolines with a width of 120 nm and inter-space of 100 nm, by SEM and optical microscopy with a microsphere.

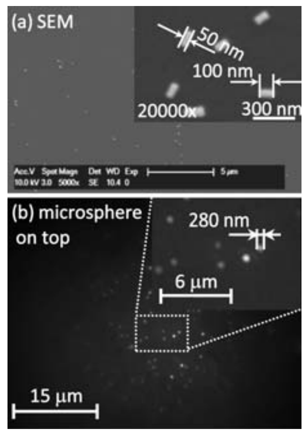

Figure 4. Measurement of gold nanorods with axial diameter of 50 nm and length of 100 nm, by both SEM and optical microscopy with a microsphere.

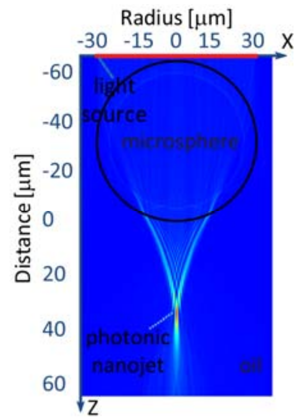

Figure 5. FEM simulation on the light propagation through a microsphere and immersion oil, showing that the light is highly focused into a photonic nanojet.