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Spectrum analysis of liquid immersion to transparent microsphere based optical nanoscopy

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ABSTRACT

Recently, it was experimentally shown that barium titanate ($BaTiO_3$) glass microsphere immersed in the liquid can be used for super-resolution imaging. However the inherent physical mechanism is still not clear. In this paper, spectrum analysis method is adopted to investigate the effect of liquid immersion to microsphere based optical super-resolution imaging. By tracking the propagation of part of the evanescent wave of the object's spectrum, the range of immersed-liquid's refractive index to achieve super resolution can be derived. To verify this analysis, we theoretically model the imaging process with finite-difference time-domain (FDTD) and angular spectrum propagation method. The result shows that only the $BaTiO_3$ microsphere immersed in the liquid with moderate refractive index, the super-resolution can be achieved. And the lower refractive index of liquid corresponds to larger magnification.

1. Introduction

Due to the presence of diffraction, the resolution of conventional optical microscopy is limited to about half of the illuminating wavelength, which greatly hinders the real-time observation of sub-diffraction-limited objects. The essence of this limit lies in the loss of evanescent wave in the far field. Till now, there have been a lot of methods to beat this diffraction limit, such as fluorescence optical microscopy [1], structured illumination microscopy [2,3], synthetic aperture microscopy [4], Far-field superlens [5], and hyperlens [6,7]. However, their complicated structure or engineering design or technical limitations impede the application to some extent.

In this context, Wang presented a relative simple method [8]. By setting a transparent microsphere with a proper size on the surface of object and then look it through a microscopy, resolution between $\lambda/8$ and $\lambda/14$ can be achieved. Though it can acquire 50 nm resolution, the image is blurred and the contrast is poor. Further studies by Hao et al. [9,10] showed that the quality of image, especially the contrast, can be significantly enhanced if the microsphere was semi-immersed in the liquid. But semi-immersed microsphere is technically complicated due to the dynamical droplet's evaporation process which leads to gradually varying resolution and magnification. Then Arash et al. [11] experimentally demonstrated that $BaTiO_3$ microsphere with refractive index about 1.9 totally immersed in the liquid can image sub-diffraction-limit objects. And the influences of the refractive index of liquid to the magnification of imaging were also experimentally studied [12–17]. In these studies, they all attribute this high resolution to the photonic nanojet focusing phenomenon [18,19]. But the imaging and focusing are two distinctive physical phenomena that do not always have necessary connection in resolution, especially the evanescent wave are included.

In this paper, the influence of liquid immersion to microsphere based optical super-resolution imaging is theoretically investigated. Through tracking part of the evanescent wave of the object's spectrum, the refractive index range of the immersed liquid which can achieve super-resolution can be derived. The direct imaging calculation with FDTD and angular spectrum propagation method are also taken.

2. Spectrum analysis of microsphere imaging

To investigate the super-resolution imaging properties of microsphere immersed in the different liquid, we choose the two slits with width of 100 nm and spacing 300 nm (center to center) as the object to be imaged. This object cannot be resolved by the conventional microscope. First, the spectrum of the object is calculated.

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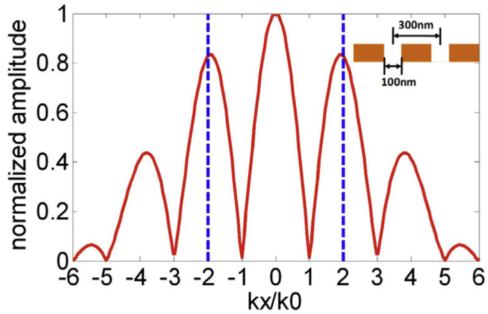

Fig. 1. The spectrum of the two slits with width of 100 nm and spacing of 200 nm.

According to the theory of Fourier optics, the transmission of the two slits can be written as

$$u(x) = rect\left(\frac{x-b}{a}\right) + rect\left(\frac{x+b}{a}\right). \quad (1)$$

Then its spectrum equals the Fourier transformation of u which yields

$$U(\xi) = F\left\{rect\left(\frac{x-b}{a}\right) + rect\left(\frac{x+b}{a}\right)\right\} = 2a \sin c(a\xi) \times \cos 2\pi b\xi. \quad (2)$$

where a represents the width of slit, b is the half of the spacing of the two slits,ξ is the spatial frequency which holds

$$\xi = \frac{\cos\beta}{\lambda} = \frac{k0\cos\beta}{2\pi} = \frac{kx}{2\pi}. \quad (3)$$

Hereβ represents the angle between x axis and propagation direction of plane wave with spatial frequencyξ in the x direction, λ is the wavelength of illuminating light, $k0$ and kx are the wave number in free space and x direction, respectively. Then the spectrum of the two slits is calculated with Eq. (2) and presented in Fig. 1. In the cases $kx/k0 < 1$, the plane wave represented by kx is propagating wave and can propagate to the far field. In the cases $kx/k0 > 1$, the plane wave represented by kx is evanescent wave and attenuates exponentially as propagating toward far field. It shows that the spectrum consists of propagating wave and evanescent wave and extends infinitely. So one important question is that how much spectrum component are needed to be captured in the far-field to resolve the two slits.

Abbe ever stated that for the object with feature size d in the x direction, the wave number component kx lies between $\pm(\lambda/d)k0$ are required to faithfully reconstruct the object. In fact, this condition can be relaxed to a certain extent at the sacrifice of the imaging contrast. For the spectrum in Fig. 1, when we extract the wave number component kx lies between $\pm(\lambda/d)k0 = \pm 2k0$, the object can be faithfully restored, as can be seen in Fig. 2(b). When we extract kx between $\pm 0.75(\lambda/d)k0 = \pm 1.5k0$, the reconstructed intensity distribution is given in Fig. 2(d), which shows that the two slits can just be distinguished. However, when the kx between $\pm 0.7(\lambda/d)k0 = \pm 1.4k0$ is extracted, the object can never be resolved, as can be seen in Fig. 2(f). Other calculations of different objects with the software Matlab 7.0 also show the same result that to resolve the object with feature size d in the x direction, the wave number component kx lies between $\pm 0.75(\lambda/d)k0$ are required at least. So in order to investigate the influences of liquid-immersion to the microsphere based super-resolution imaging, we can check whether these special spectrum components $\pm 0.75(\lambda/d)k0$ can propagate through the microsphere to the far-field. The feature of the object can be resolved only spectrum components larger than $0.75(\lambda/d)k0$ can be captured in the far-filed.

The schematic diagram of the structure under study is shown in Fig. 3. A TM-polarized plane wave with wavelength 600 nm is

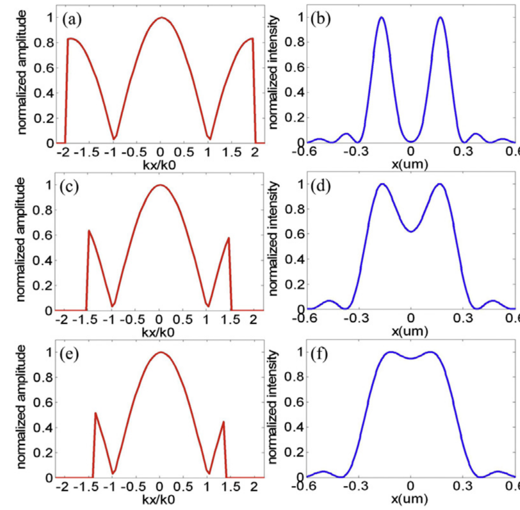

Fig. 2. Part of the object's spectrum and its corresponding restored object. (a) kx lies between $\pm 2k0$ and its reconstructed intensity distribution in (b); (c) kx lies between $\pm 1.5k0$ and its reconstructed intensity distribution in (d); (e) kx lies between $\pm 1.4k0$ and its reconstructed intensity distribution in (f).

utilized as incident light. Two air slits perforated in the Perfect electric conductor (PEC) substrate are used as object, which is also the minimal cell of the Blu-ray disk. The PEC is used to block the background light. A 5 μm-diameter $BaTiO_3$ glass microsphere with refractive index of 1.9 immersed in the liquid with refractive index of n_L is used as imaging lens.

When a microsphere is placed on its surface, the slits near to the contact point can be considered as immersed in the medium with refractive index of 1.9. Hence, the original evanescent wave component $k0$–$1.9k0$ are converted to propagating wave in the microsphere with propagating angleβ of 0–58.2°, according to the Eq. (3). And the incident angleαlies in the range of 31.8–90°. When the microsphere is placed in the air, the critical angle of total reflection is 31.8° at the microsphere/air interface. Consequently, the spectrum component $k0$–$1.9k0$ are trapped in the microsphere, for the incident angle is larger than the critical angle. When the microsphere is immersed in the liquid with refractive index of 1.33, then the critical angle is 44.4°. So part of the evanescent wave of object's spectrum can transmit through the microsphere. It shows that the larger the refractive index of the liquid, more evanescent wave can escape from the microsphere. So the imaging contrast can be improved. Meanwhile, the refractive index of the liquid should not be too high, for the total reflection at the liquid/air interface may be occurred, such as the light path o–b–d in Fig. 3. One thing should be noted that if the object lens of the microscope is also immersed in the liquid, the super-resolution imaging can also be achieved with

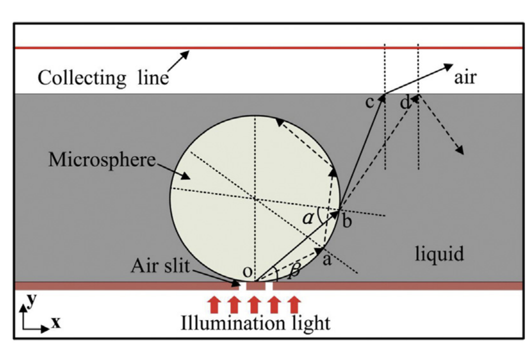

Fig. 3. Schematic of the structure under study.