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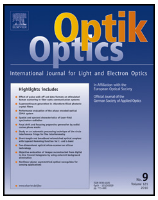

Original research article

Super-narrow focusing and ultra-long working distance by different shapes of dielectric microlenses

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ABSTRACT

The dielectric microlens, surmounts the diffraction limit, consider as a super-focusing and super-resolution imaging microlens. In this paper, the super-focusing and working distance between microlens and test sample are investigated through different shapes of dielectric microlenses. The result shows that the hollow sphere microlens, an innovative design of nanoparticle with a solid sphere including a hollow core region, is an optimal spherical microlens with super-resolution. After optimization, a hollow sphere microlens with the ratio of inner and outer radius r/R of 1:2 and the refractive index of 1.6 is designed and a super-narrow photonic nanojet with the full width at half maximum of 164 nm has been achieved under the incident wavelength of 500 nm. When the hollow sphere microlens is immersed in water or oil, it can focus the 500 nm incident light 3 μm away from the hollow sphere lower surface. Increasing the refractive index of hollow spheres, the resolution reaches 0.22 λ. With the super-focusing and ultra-long working distance, the hollow sphere microlens could be applied for detecting a test sample to acheive a super-resolution imaging and a test sample can be distinguished clearly when combined with a conventional optical microscope, which is particularly available for the test samples with the extreme matte surfaces.

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1. Introduction

Over the past several decades, conventional optical microscope have been proverbially applied in the biology, chemistry, physics, astronomy and many fields, which have brought about innumerable progresses in application research. However, the optical diffraction limit to 0.5 λ restricts the resolution and application of optical microscope because of the loss of the evanescent waves [1–3], where λ is the wavelength of the imaging illumination of optical microscope. Therefore how to solve and surmount optical diffraction limit has been payed attention [4–6]. The resolution of conventional optical microscope has been remarkably improved by the fluorescence microscopes during the last decade, such as stochastic optical reconstruction microscopy (STORM) [7], structured illumination microscopy (SIM) [8], photo-activated localization microscopy (PALM) [9] and stimulated emission depletion (STED) microscopy [10]. However, above fluorescence microscopes can only distinguish some specific unit of materials and lose structural information, which restricts their further applications in the research of many metamaterials with nanostructures [11,12]. Near-field scanning optical microscopy (NSOM) [13], developed by a probe with aperture far less than wavelength instead of an optical lens, has been proved to obtain super-resolution through point scanning. Because the export of data via NSOM is still determined by probe scanning, the inferiority of time-inefficiency

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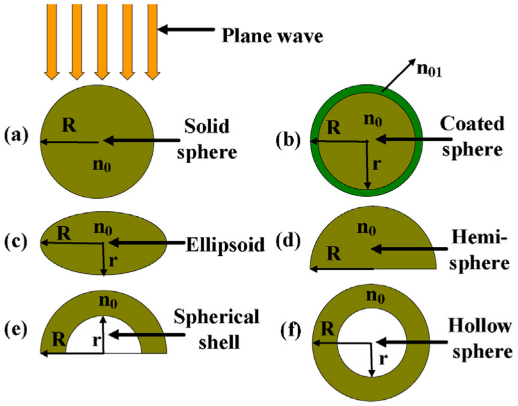

Fig. 1. different shapes of microlenses are illuminated by plane wave.(a) solid sphere, radius R = 2 μm, (b) coated sphere, radius R = 2 μm, r = 1.8 μm, (c) ellipsoid, radius R = 2 μm, r = 1 μm, (d) hemisphere R = 2 μm, (e) spherical shell, radius R = 2 μm, r = 1 μm, (f) hollow sphere, radius R = 2 μm, r = 1 μm.Other parameters: wavelength 500 nm, refractive index $n_0 = 1.6$, $n_{01} = 1.8$.

Table 1
The accurate value of FWHM and working distance of microlens.

Shape of microlens	Maximum intensity	FWHM (nm)	Working distance (μm)
Solid sphere	171.5	218	0.072
Coated sphere	11.05	283	0.25
Ellipsoid	45.76	348	0.45
Hemisphere	98.24	287	0.15
Spherical shell	29.89	202	0.2
Hollow sphere	34.7	164	0.072

is existed in NSOM microscopy. Superlens and hyperlens with a negative refractive index can gain super-resolution based on the Pendry's perfect lens theory [14–18], however their application is limited by the light loss in meta-materials and fabrication of superlens and hyperlens. Recently, various metalenses based on the metal and dielectric metasurface have been investigated [19–26], but the resolution is about 0.75 λ [27], which do not realize the super-resolution imaging with conventional optical microscope.

Dielectric microlenses have been discovered as an effective method to achieve super-resolution imaging. Enhanced resolution of optical microscope has also been discussed by microsphere beyond the Abbe diffraction limit [28–35]. However, the resolution does not satisfy our requirement. The focal position of the microscale spherical lens have been discussed by Cao et al. [36], it only refers to the focal position is inside or outside the microsphere, which only relates the imaging of microscale spherical lens. Gang Chen et al. investigated the ultra-long focal length of planar lens by muti-sphere, which can enlarge the working distance, but the resolution is only 0.44 λ [37]. Alginate microsphere has been fabricated by bipolar wave-based drop-on-demand jetting [38]. Among these studies, ability to control of focusing characteristics is urgently demanded for microlens based technologies. Imaging resolution enhancement of microlens has been verified by simulation and experiment, and silica (SS) microspheres, polystyrene (PS) microspheres and barium titanate glass (BTG) [3] microspheres have been processed and applied in many laboratories [3,39,40]. However, properties of the present dielectric microlens are unable to satisfy requirement in biology and nanoscale materials fields, and working distance (WD), defined as the distance between the test sample and the lower surface of microlens, is rarely reported. Therefore, it is highly desirable to achieve both the super-resolution and ultra-long working distance though the design of novel structure of microlens. Through optimization shape of dielectric microlenses, its refractive index and the medium of immersion, the super-focusing can be achieved.

In this paper, the super-focusing and working distance are discussed by different shapes of dielectric microlens. The hollow sphere microlens, is testified to generate an super-focusing photonic nanojet that can perform as super-resolution microlens coupling with the conventional optical microscope and amplify the evanescent waves that carries the high spatial frequency information of incident light. The hollow sphere microlens is immersed in surrounding medium, the best resolution is 0.22 λ and the ultra-long working distance is 3 μm, which can be used to obtain the super-resolution imaging for the samples with the extreme matte surfaces.

2. Simulation method

In evaluating the optical characteristics of dielectric microlens, Mie theory that can expound many focusing phenomena of microlens plays an important role over a century [41]. However, the calculation of Mie theory is very painful as contain complex Bessel infinite series, we need to search other approaches to solving the problem. Several methods may be appropriate for solving the problem, such as multiple multi-pole (MMP) technique, discrete dipole approximation (DDA)

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