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Engineering near-field focusing of a microsphere lens with pupil masks

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ABSTRACT

Recent researches have shown small dielectric microspheres can perform as super-resolution lens to break optical diffraction limit for super-resolution applications. In this paper, we show for the first time that by combining a microsphere lens with a pupil mask, it is possible to precisely control the focusing properties of the lens, including the focusing spot size and focal length. Generally, the pupil mask can significantly reduce the spot size which means an improved resolution. The work is important for advancing microsphere-based super-resolution technologies, including fabrication and imaging.

1. Introduction

The diffraction limit of light focusing was discovered by Ernst Abbe [1]. This fundamental rule restrained the performance of conventional optical instruments to a resolution of roughly $\lambda/2$ in far-field in free space, where λ is the wavelength of incident light. Breaking diffraction limit and developing super-resolution technologies are constant themes in optical researches. One solution is near-field optics, which explores the optical phenomena occurring at subwavelength distance from scattering objects and often collecting information in evanescent wave at the boundary of two different media. Near-field scanning optical microscopy (NSOM), for example, has been developed to enhance the resolution by replacing lens with a tiny tip [2]. Nevertheless, the slow processing speed and the surface dependence limit its utility. Superlens and hyperlens, which were developed under the umbrella of Pendry's perfect lens concept, use metal and artificially engineered metamaterials to gain super-resolution at given optical wavelength. Their resolution is fundamentally limited by the material loss in metals [3–7]. Recently, it was discovered that microsphere can generate super-resolution focusing beyond diffraction limit, a phenomena known as 'photonic nanojet' [8–12]. This has led to the development of an exciting super-resolution imaging technique 'microsphere nanoscopy' by the present authors [13,14]. Different samples have been directly imaged in sub-wavelength resolution and real time without labeling, including both non-biological (nano devices, structures and materials) and biological (subcellular details, viruses) samples [15–17]. Besides our work, a notable advancement on the 'microsphere nanoscopy' technique is obtained by Darafsheh et al. who studied confocal mode imaging with microsphere superlens. Higher contrast super-resolution images have been achieved in their study due to the ability of confocal microscopy to reject out-of-focus lights [18]. Besides imaging, the microsphere lens has also been widely used for other applications, including for example nanofabrication and ultrahigh density data storage [19–22].

Ability to precisely control of focusing properties is highly desired for microsphere-based technologies. Despite in theory the best focusing can be obtained via controlling particle size, its refractive index with respect to surrounding medium and incident wavelength, in reality these conditions could be difficult to meet since desired microspheres may not be commercially available. It is therefore highly desirable to develop a new technique that can control the near-field focusing of a microsphere lens in a flexible and easy-to-implement way. In this paper, we propose to use pupil mask to achieve such controllability. It shall be noted we are dealing with near-field problems here, in which the focus is located very close to particle surface and evanescent wave components could be involved. This demands a full wave numerical simulation to include both propagating and evanescent wave modes. In contrast to this, previous researches on pupil mask assisted optical super-resolution were often focusing on far-field problems where no evanescent waves will be involved and simplified formulations can be used. Paeder et al. studied the effect of annular amplitude and phase masks on far-field microlenses [23]. Plenty of similar literature can be found in this regards, with applications in photolithography [24], data storage and confocal scanning microscopy [25,26] etc.

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2. Simulation method

To describe the optical properties of small sphere, Mie theory plays a significant role over a century [27]. Many of the basic phenomena of microsphere focusing can be interpreted by this theory. However, focusing properties of small particle with pupil mask cannot be tackled by Mie theory and we seek to solve the problem with full wave simulation approaches. Several numerical calculation methods may be suitable for such propose, which includes for example the multiple multi-pole (MMP) [28] technique, discrete dipole approximation (DDA) [29] and pure numerical methods such as finite element method (FEM) [30], finite difference time domain (FDTD) technique [31], and Finite Integral Technique (FIT) [32]. The FIT technique, proposed by Weiland, provides a universal spatial discretization scheme, applicable to various electromagnetic problems, ranging from static field calculations to high frequency applications in time or frequency domain. Unlike most numerical methods, FIT discretizes Maxwell's equation in an integral form rather than the differential ones. In the case of Cartesian grids, the FIT formulation can be rewritten in time domain to yield standard FDTD methods. While in the case of triangular grids, the FIT has tight links with FEM methods formulated in Whitney forms [30]. In this paper, a commercial FIT software package (CST MICROWAVE STIDIO) was used. For better accuracy on simulation results, we have chosen to use triangular grids thus a FEM-like method in simulation, which are naturally conformal to the circular boundary of a sphere. The particle was discretized by tetrahedral meshes at a mesh density of $\lambda/4$, where λ is incident wavelength. The incident wave is a linearly polarized plane wave with electric vector polarized along the x-axis. The desired linear equation system solver accuracy in terms of the relative residual norm was set as 10^{-6}, which enforce a termination criterion for the solver. The retardation effect and contributions from all necessary orders of partial waves dipole, quadruple, etc. are inheritably considered in our modeling. Due to limitation of computation resources, the studied particle diameter was limited to 3 μm and below.

3. Results and discussions

Fig. 1 shows the schematics and corresponding electric intensity field distribution for (a, b) no-mask and (c, d) with mask

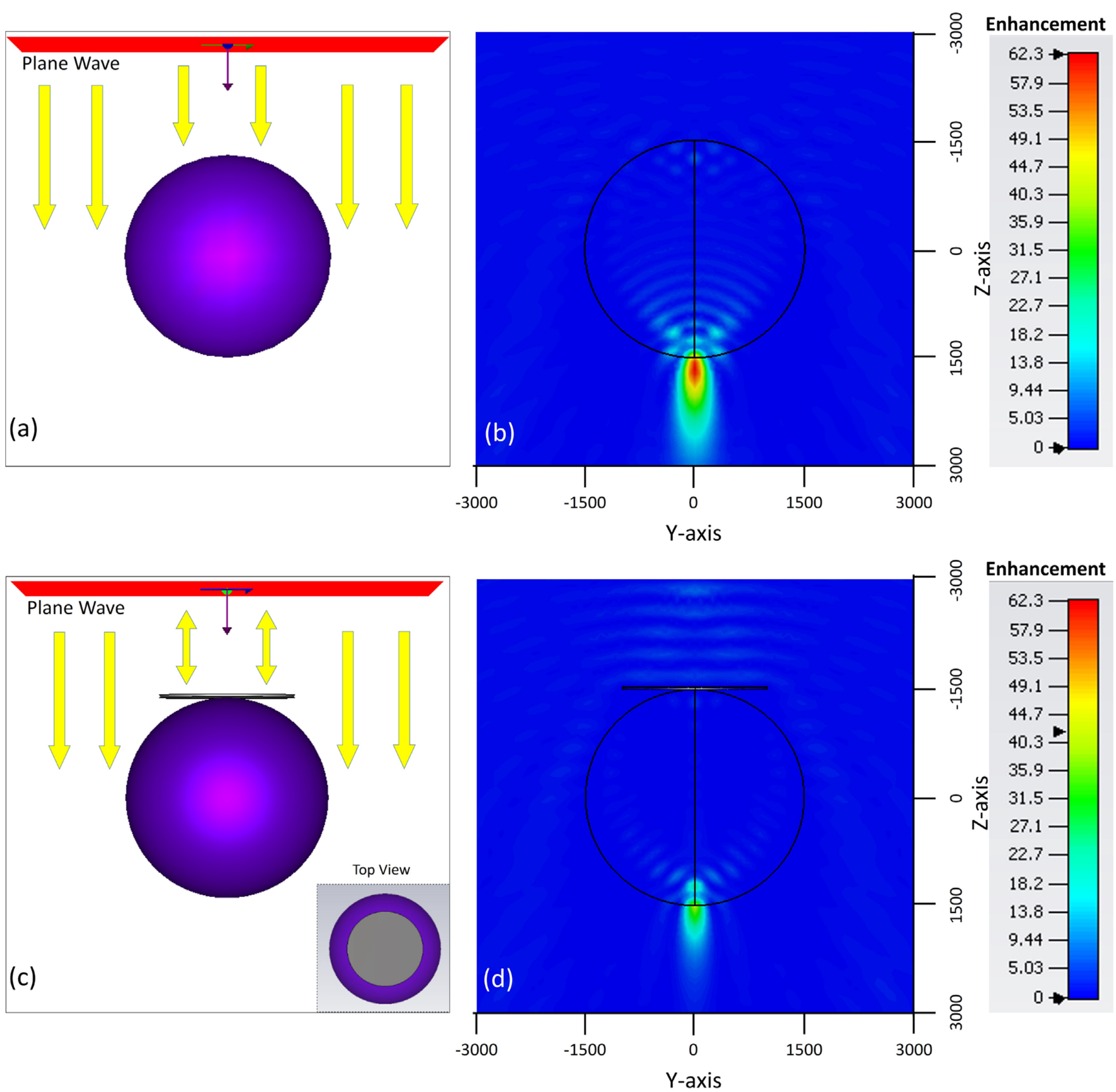

Fig. 1. Schematic diagrams and $|E|^2$ intensity field distributions for two microsphere systems. (a,b) single microsphere, (c,d) proposed microsphere with pupil mask system. Parameters: wavelength 600 nm, microsphere diameter 3 μm, and (c) with mask diameter 2 μm, refractive index (RI) of microsphere is 1.46 and mask material PEC).