A novel fiber optical tweezers with FZP structures on fiber end-face

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ABSTRACT

A novel fiber optical tweezers is proposed to trap subwavelength particles in 3-dimension, the Fresnel Zone Plate (FZP) structure is designed with a high numerical aperture (N.A.) and prepared on the flat fiber end face. According to the core area of 633nm single mode polarization-maintaining fibers, a FZP structure with three zones is designed. The transmitted field distribution is simulated by Finite-difference time-domain (FDTD) method, and the optical force on a 500 nm diameter polystyrene particle in water is calculated from Maxwell Stress Tensor (MST). The results indicate that the FZP structure can generate a subwavelength focal spot and the optical force can trap subwavelength particle in 3D. With focused ion beam (FIB) etching and depositing system, a fiber optical tweezers with the designed FZP structure is fabricated, which could be used widely due to its easy-operating and capability to manipulate subwavelength particles in 3D.

Keywords: optical trapping, optical manipulation, fiber tweezers, Fresnel zone plate, subwavelength structure

1. INTRODUCTION

Since Ashkin et al first used the optical force to trap dielectric particles generated by a high numerical aperture (N.A.) microscopy objective[1]; the optical tweezers has been widely used in many fields, especially in biology as an important tool to manipulate micro biological specimens. The conventional optical tweezers is composed of a high N.A. microscopy objective focusing laser beam to trap micro particles, so it is not convenient to move or rotate micro particles and the complexity of the system limits its application. In 1993 the fiber tweezers was first demonstrated by Constable et al[2] and then had a rapid development due to its facility and easy operating. But it is difficult for a single fiber tweezers to generate a strong gradient force to trap a micro particle stably in 3-dimension, owning to lack of a high N.A. objective. In recent years many kinds of modified single fiber tweezers have been demonstrated to trap micro particles in 3D, such as four-fiber-bundle optical tweezers[3], highly tapered fiber optical tweezers[4], twin-core optical tweezers[5] and hollow tipped metalized fiber probe[6]. However, the modified optical tweezers mentioned above can not behave a high N.A. objective to form a focal spot in subwavelength size and strong gradient force, so the size of particles trapped is usually in micrometers scale. Fresnel zone plate (FZP) generates lens-like focusing and can be able to form a smaller focal spot than the microscopy objective with the same N.A. So the FZP can be used for optical tweezers[7], and lately there are the reports on the optical trapping based on FZP structure[8, 9].

In this letter, a novel fiber optical tweezers is proposed; on the flat end face of the fiber is prepared a plane device of a metal FZP structure. According to the core area of the 633 nm single-mode polarization-maintaining fiber considered as the light emitting area, the metal FZP structure is designed with a high N.A. The intensity distribution of transmitted field is simulated with Finite-difference time-domain (FDTD); the trapping force on a polystyrene particle with the diameter of 500 nm in the water is calculated and analyzed from Maxwell Stress Tensor (MST). With focused ion beam lithography, the fiber optical tweezers with the FZP structure is fabricated.

2. FZP DESIGN

The 633 nm single mode polarization-maintaining fiber has a core diameter of about 4 μm considered as the light emitting area, so the focal length should be designed in several wavelength of incident light to obtain a high N.A. Some researches on the focusing properties of the metal FZP with a focal length of several wavelengths have been reported

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recently.[10, 11] The radius of the m-th zone r_m can be obtained from the design formula of the conventional FZP in the following[12]:

$$r_m = \sqrt{m\lambda f + \frac{m^2\lambda^2}{4}}$$

Where f is the focal length, λ is the wavelength of light in the operating space.

In this letter a positive type FZP is designed with a focal length of 1μm, and only the zones in the light emitting area are involved in simulation, so the zone number is 3.

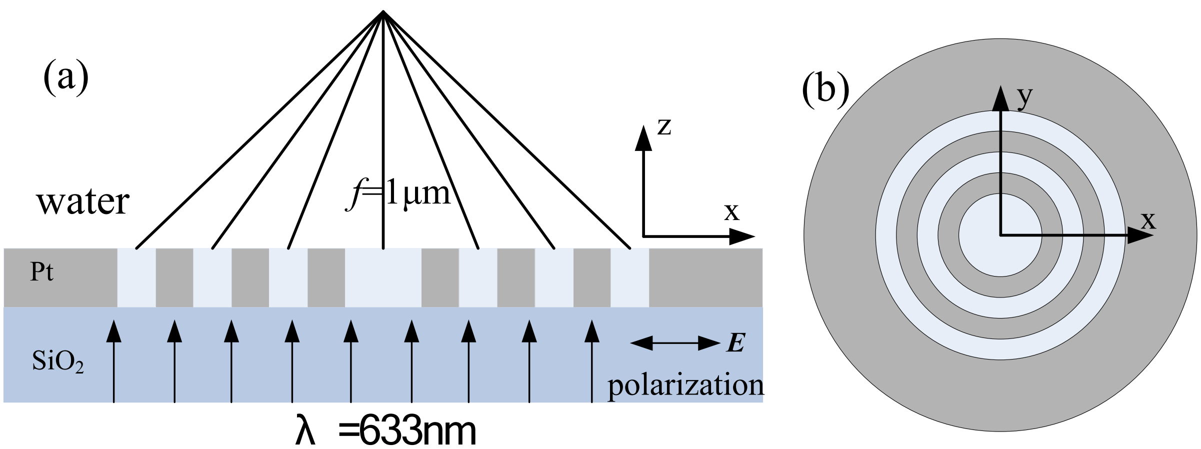

Fig.1 FZP structure diagram. (a) cross section views in xz plane, (b) top-down views

The structure diagram of the designed FZP is shown in Fig.1. A 150 nm Pt film as an opaque mask with the designed FZP structure is prepared on the SiO_2 substrate; the FZP is incident normally by the linearly polarized light with a wavelength of 633 nm and focuses the transmitted light in the water. The incident light polarization and propagation direction is along x and z axis respectively as shown in the Fig.1.

The transmitted field through the FZP is simulated by FDTD method, and the distribution of the transverse field component in XY and YZ plane are shown in Fig.2. The simulation results indicate that the FZP structure only composed of three zones can also focus the transmitted light, and the focal length simulated is 0.97 μm with a little deviation from the designed value. The FWHM of focal spot in XZ plane and YZ plane are 303 nm and 248 nm respectively. The subwavelength focal spot generated by the FZP structure can be used to trap subwavelength particle.

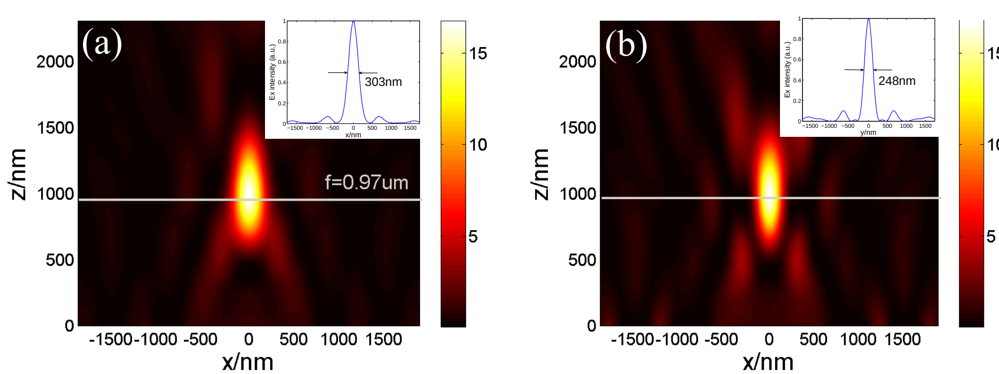

Fig.2 the transverse electric field distribution in (a) XZ plane and (b) YZ plane, the insets are the field distribution along the line in the corresponding plane.

3. TRAPPING FORCE CALCULATION

The optical force exerted on a particle can be calculated by integrating the dot product of MST and normal unit vector outwardly directed over the arbitrary external surface enclosing the particle[13]. In FDTD simulation, the simulation space is divided into the Yee lattice[14], so the MST over the cubic surface enclosing the particle can be obtained easily by FDTD method. Here, the trapping force exerted on a polystyrene sphere of diameter 500 nm in the water generated by the designed FZP structure is simulated. The dielectric constants of water and polystyrene are 1.59 and 1.33 respectively. The incident light has a size of 4 μm×4 μm which covers the designed three zones completely. The optical force is normalized by the incident power, and the dependence of optical force Fz on the sphere position varying along the symmetric axis z with the height increase from the FZP surface is shown in Fig.3 (a). It can be seen that there is a force equilibrium point at z=1.1 μm, when the particle position z is smaller than 1.1μm, the repulsive force push the particle away from the tweezers; when the particle position z is larger than 1.1μm, the attractive force pull the particle back to the equilibrium point. The maximum of repulsive force and attractive force are 62.6 pN/W and 26.9 pN/W respectively. Fig.3 (b), (c) demonstrate the axial force Fx and Fy on the particle positioned along x axis and y axis in the horizontal plane though z axial equilibrium point respectively. The Fx and Fy as the resilience make the particle stay around the equilibrium point, the maximum of the attractive force Fx and Fy are 78.9p N/W and 84.9 pN/W respectively. The optical force generated by the designed FZP can trap the 500 nm diameter polystyrene sphere in 3D nearby the equilibrium point.

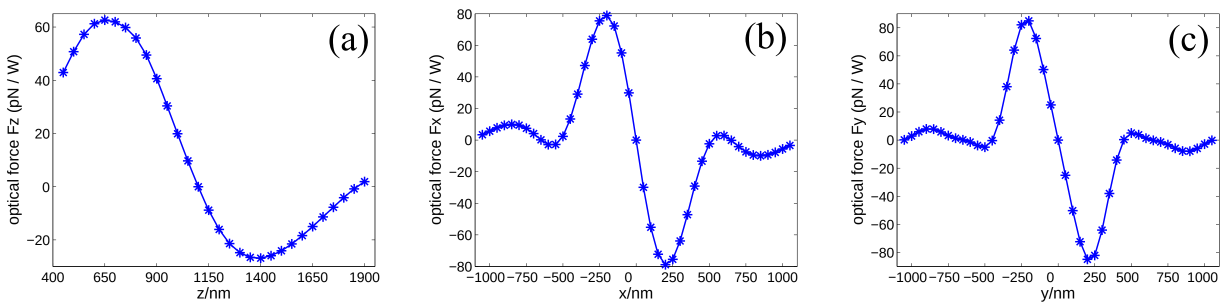

Fig.3. calculation results of the optical force exerted on a 500 nm diameter sphere in the water (a) Fz along the symmetric axis in different height, (b) Fx along the x axis, (c) Fy along the y axis in the horizontal plane through z axial equilibrium point shown in (a)

4. FABRICATION

A 633 nm polarization-holding single mode fiber is used for optical tweezers fabrication. The light incident on the fiber end face has a linear polarization with a wavelength of 633 nm, so the field maintains the incident polarization direction and the field distribution is uniform in the fiber. To fabricate FZP structure on the fiber end face, the fibers are cleaved, cleaned and selected without obvious defects and fluctuations. To improve the conductivity of the fiber, the silver colloid is adhered on the cladding of fiber near the end face and a 10 nm-thick Pt film is deposited on the end face by thermal evaporation. The image of structure on the fiber end face with high resolution can be obtained by the scanning electronic microscopy (SEM), which is helpful to ensure the fabrication accuracy of focused ion beam (FIB). A circular Pt film with thickness of 150 nm and radius of 5 μm as opaque mask is deposited in the central area of fiber end face by the FIB-depositing system. Considering the actual larger light emitting area, the FZP structure with more zones is needed. So the FZP structure consisting of five annular apertures concentric with the circular film is fabricated by FIB, which is large enough to cover the light emitting area completely. The SEM images of the FZP structure on the fiber end face are shown in Fig.4, which is designed with focal length 1μm in the water.

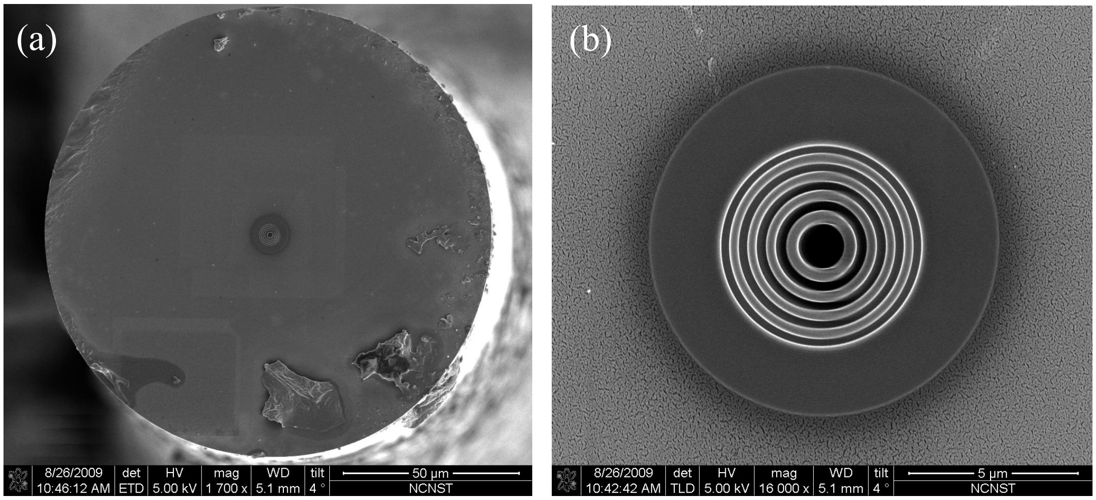

Fig.4 SEM image of the optical fiber tweezers with FZP on the fiber end face. (a) full view of fiber end face with FZP structure, (b) enlarged view of the FZP structure.

5. CONCLUSION

In this letter, a novel optical fiber tweezers used to trap subwavelength particles in 3D is proposed, which is composed of FZP structure designed with a high N.A. on the fiber end face. The transmitted focusing field through the FZP structure with only three zones is obtained by FDTD simulation. The trapping force exerted on a 500nm diameter polystyrene sphere in the water is calculated from MST, the calculation results indicate that the FZP can generate optical force to trap the polystyrene particle in 3D. Considering the actual light emitting area of the fiber, a fiber tweezers with five zones is fabricated by the FIB etching and depositing system. This fiber tweezers are of wide potential applications due to its capacity of trapping sub-wavelength particles in 3D and facility.

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