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Micromotor based on single fiber optical vortex tweezer

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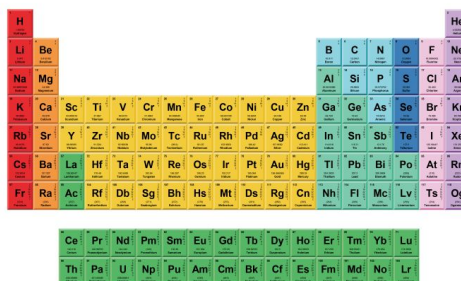
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ABSTRACT

Optical micromotors are powerful tools for trapping and rotating microparticles in various fields of bio-photonics. Conventionally, optical micromotors are built using bulk optics, such as microscope objectives and SLMs. However, optical fibers provide an attractive alternative, offering a flexible photon platform for optical micromotor applications. In this paper, we present an optical micromotor designed for 3D manipulation and rotation based on a single fiber optical vortex tweezer. A tightly focused vortex beam is excited by preparing a spiral zone plate with an ultrahigh numerical aperture of up to 0.9 at the end facet of a functionalized fiber. The focused vortex beam can optically manipulate and rotate a red blood cell in 3D space far from the fiber end facet. The trapping stiffness in parallel and perpendicular orientations to the fiber axis are measured by stably trapping a standard 3- μm silica bead. The rotational performance is analyzed by rotating a trimer composed of silica beads on a glass slide, demonstrating that the rotational frequency increases with rising optical power and the rotational direction is opposite to the topological charge of the spiral zone plate. The proposed fiber micromotor with its flexible manipulation of microparticle rotation circumvents the need for the precise relative position control of multiple fiber combinations and the use of specialized fibers. The innovations hold promising potential for applications in microfluidic pumping, biopsy, micromanipulation, and other fields.

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I. INTRODUCTION

Optical tweezers,¹ which allow stable trapping and precise manipulation of microparticles using two counterpropagating or tightly focused laser beams, were first proposed in 1970 by Ashkin.^{2,3} Over the past decades, optical tweezers have resulted in exciting applications in bio-photonics,^{4–7} micro-rheology,^{8,9} and quantum technology.¹⁰ Multifunctional manipulation of particles has become

a prominent feature of optical tweezers,^{11–13} particularly due to their capability to rotate and trap particles to form a micromotor.^{14–18} The non-contact manipulation of microparticle rotation has significantly contributed to the study of optical micromotors, finding applications in various scientific fields, such as tomography,^{19–21} material transport,^{22,23} nerve fiber growth,²⁴ and others.^{25,26} Light waves can exert torques on the trapped particle through angular momentum transfer, which can be achieved via two methods. One

method involves light scattering on the particle, which generates asymmetric optical forces. This leads to a change in momentum during deflection, exerting torques on the trapped particle and causing it to rotate.²⁷ Asymmetric optical forces can be obtained by a single beam scattering onto precisely prepared asymmetric structures, such as a micro-turbine¹⁴ or a micro-propeller.¹⁸ Alternatively, a series of closely separated optical traps can be created using a spatial light modulator to hold different parts of the same particle.^{28,29} The series of traps can move relative to each other in any plane, exerting asymmetric optical forces on the trapped particle and causing it to rotate. The other method involves the transfer of angular momentum carried by the light wave itself to the trapped particle, exerting a torque. Light waves can be considered to carry spin angular momentum associated with the polarization state of the electric field and orbital angular momentum related to the transverse phase structure of the complex amplitude.^{30,31} A straightforward way to transfer spin angular momentum to a trapped particle is through absorption. However, absorption forces inherently limit the maximum size of the particle that can be trapped by optical tweezers, as absorption also transfers linear momentum, acting to push the particle out of the trap.³² Consequently, the direct transfer of spin angular momentum in optical tweezers is currently restricted to nanoparticles^{33,34} and birefringent particles.^{35,36} By shaping the wavefront of optical components, the light waves can carry orbital angular momentum that can be transmitted to the trapped particle.^{37–40} This method shares numerous similarities with the traditional microscopic trapping methods, including instrumentation—particularly the reliance on high-numerical-aperture (NA) objective lenses. However, the complicated implementations, penetration depths of only a few dozen micrometers, and expensive optical components limit its accessibility.

Optical fibers are increasingly recognized as all-optical platforms for creating miniature and integrated sensors due to their ultra-compact size, low cost, and minimal transmission losses.^{41–44} Leveraging the flexible light-wave guiding and excellent biocompatibility of fibers, optical fiber tweezers have been proposed, enabling precise and localized optical forces to be applied deep within biological tissues.^{45–47} To rotate the trapped particle based on the fiber optical tweezers, there are a variety of approaches. Through the

dislocation of dual fiber optical tweezers^{48–50} or the independent light intensity adjustment of the multiple fiber optical tweezers,⁵¹ the asymmetric optical forces can be exerted on the trapped particle, resulting in rotation. In addition, single fiber optical tweezers can rotate the trapped particle by combining them with external forces, such as temperature gradient forces⁵² and thermophoretic forces.⁵³

However, while these methods can trap and rotate the particle, the combination of multiple forces and specific working environmental requirements limits their applicability in living organisms. Wavefront shaping technology can control light propagation through specialized optical fibers, allowing the direct emission of a tightly focused beam that carries angular momentum. An advanced trapping method has been proposed that replaces part of the optical path in a holographic optical tweezer system with a single special fiber, facilitating intrusive trapping and rotation of particles.^{21,46,54} However, this configuration is not a fully all-fiber holographic optical tweezer, as it still requires spatial optical path devices to construct special optical fields. Moreover, the method is hindered by the length of the specialized optical fibers and associated mode losses and it necessitates a meticulous feedback system for optical phase compensation. Hence, there is a demand for the direct implementation of micromotors through a single optical fiber to achieve multifunctional optical manipulation systems with enhanced flexibility and efficiency.

In this paper, we report an optical micromotor designed for 3D manipulation and rotation of particles using a single fiber optical vortex tweezer. The fiber micromotor consists of a spiral zone plate (SZP) fabricated on the end facet of a functionalized fiber, as shown in Fig. 1(a). A coreless fiber (CF) is employed to expand and collimate light from a single-mode fiber (SMF). We prepare the SZP on the end facet of the CF by focused ion beam (FIB) milling. The tightly focused vortex beam (FVB) is excited using the SZP with an ultra-high numerical aperture (NA) of up to ≈ 0.9 as depicted in Fig. 1(b). We reveal the capabilities of the fiber micromotor by optically trapping microparticles and rotating biological cells. As shown in Figs. 1(c)–1(e), the flexible remote optical trapping of (c) a silica microbead (see the [supplementary material](#), movie 1) and (d) an *Escherichia coli* bacterium (see the [supplementary material](#), movie 2) and (e) the rotation of a red blood cell (RBC) (see the

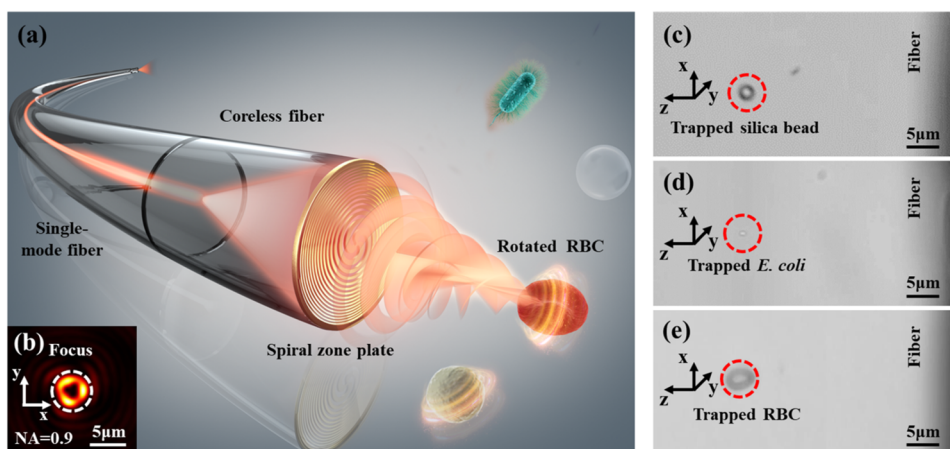


FIG. 1. Principle of the fiber micromotor for rotation and manipulation of a microparticle. (a) Illustration of the fiber micromotor, including a SZP, on the end facet of a functionalized fiber to rotate a red blood cell; (b) an example of radial focal plane simulation in an aqueous solution (the light wavelength is 980 nm; the topological charge of the SZP is 3; the dashed line indicates the width of the outer ring fitted Airy function); micrographs of (c) a 3 μm silica bead, (d) an *Escherichia coli* (*E. coli*) bacterium, and (e) a red blood cell (RBC) that were optically trapped.

supplementary material, movie 3) are experimentally demonstrated, confirming the performance for long distance and rotational optical manipulation.

II. RESULT AND DISCUSSION

A. Design and Fabrication

To implement the optical fiber micromotor, we designed and fabricated a SZP formed by an opaque Au film on the end facet of a functionalized fiber. The SZP is a diffractive optical element used to directly generate a FVB, which can be regarded as a hybrid optical element combining a Fresnel zone plate (FZP) and a spiral phase plate (SPP) (details are described in the supplementary material, S1). Consequently, the implementation of the SZP requires binarization of a superimposed phase, $\phi_{szp}(r, \theta) = \phi_{fzp}(r, \theta) + \phi_{spp}(r, \theta) + n\phi_0$, such that $\phi_{fzp}(r, \theta) = -n\pi r^2/(\lambda f)$ and $\phi_{spp}(r, \theta) = nl\theta$ (n : the refractive index of the aqueous solution, λ : the wavelength of input light in free space, f : the designed focal length, l : the topological charge, r : the radial coordinate, θ : the angular coordinate, and ϕ_0 : the initial phase), leading to a transmittance function of the SZP. Figure S1 presents the simulated results for the designed SZPs with $l = 0$ and 3 according to the diffraction theory. Based on the coherent superposition of diffracted waves from the FZP and the phase accumulation from the azimuth angle along the SPP to the optical axis, the Gaussian beam that passes through the SZP can be coupled to a FVB.

The ultra-high NA of the SZP is essential for trapping a particle, which can be expressed as $n \times \sin(\arctan((D/2)/f))$, where D is the diameter of the SZP, which can be designed to be $120 \mu\text{m}$ to accommodate the fiber. Figure 2 illustrates the calculated optical forces of the FVB excited by SZPs with different f values along the optical axis, ranging from -10 to $10 \mu\text{m}$ in water, where $0 \mu\text{m}$ signifies the focal position. The value of f for the SZP is increased from 50 to $100 \mu\text{m}$ in increments of $10 \mu\text{m}$, resulting in a corresponding reduction in the NA from 1.05 to 0.7 , as shown in the illustration of Fig. 2. Positive values of the optical force indicate that the particle is pushed away from the fiber tip, while the negative values suggest that the

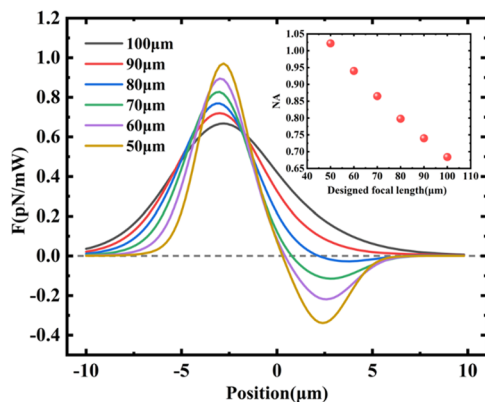


FIG. 2. Calculated optical forces of the FVB excited using the SZP with different designed f values along the optical axis from -10 to $10 \mu\text{m}$, where $0 \mu\text{m}$ is the focal position; the inset illustrates the NA of the SZP corresponding to different f values.

bead is pulled back toward the focal spot. When the pushing and pulling forces are balanced, the particle can be stably trapped. Note that the equilibrium of the optical force occurs only when the values of f are below $80 \mu\text{m}$, close to the focal position, where the corresponding NA exceeds 0.8 , consistent with the existing reports.^{3,45} For the SZP, the width of the narrowest zone can be expressed as $\Delta r = 2\lambda f/D$, which is positively correlated with the f . Hence, the f is chosen to be $60 \mu\text{m}$ to ensure that the SZP achieves the ultra-high NA, providing a sufficiently strong trapping potential and feasibility of preparation at $\lambda = 980 \text{ nm}$. According to the above scheme, SZPs with various values of l are designed on a single fiber. A CF section across a length $L \sim 800 \mu\text{m}$ was utilized to expand the cross section of the output beam of the SMF, adapting it to the full aperture of the SZP, which would otherwise be too small to enable sufficient wavefront manipulation.^{45,53}

The SZPs were fabricated using FIB milling on a functionalized fiber facet, which can be divided into three steps. First, a piece of CLF (THORLABS FG125LA) was fusion spliced to an SMF (CORNING HI1060XP, mode diameter: $5.9 \mu\text{m}$, single-mode at 980 nm). The CF was then cleaved to a length of $\sim 800 \mu\text{m}$ using a fiber precision cleaving system. Next, the end facet of the CF was coated with a 100-nm thick opaque Au-film using a magnetron sputtering coating system. Finally, the SZP was formed by FIB milling (accelerating voltage: 30 kV ; beam current: 3 nA) according to the designed binary mask template, and the entire process took about 10 min . Figures 3(a) and 3(b) show the SEM images of the fabricated SZP for $l = 3$ and -3 , respectively. The SZPs ($D = 120 \mu\text{m}$, $f = 60 \mu\text{m}$) were located at the center of the end facet of the CFs. The dark area represents the exposed quartz after milling, while the light area corresponds to the opaque Au film.

The focusing and mode characteristics of the emitted light from the SZP are crucial for the manipulation and rotation of particles. The vortex focusing behaviors of the SZPs were characterized using a dual beam interference microscopic imaging system.⁵⁵ The focusing performance of the SZP was evaluated by measuring the intensity distribution in the x - z plane as shown in Figs. 3(c) and 3(d) for $l = 3$ and -3 , respectively, where the SZPs were positioned in the x - y plane. The beams were focused at $z = 62 \mu\text{m}$ for $l = 3$ and $z = 65 \mu\text{m}$ for $l = -3$, with the corresponding NAs of the SZPs being ~ 0.9 , according to the NA expression. The measured focal length was larger than the designed focal length due to several factors: the tolerance during the cleaving of CF, which caused the emitted beam of the functionalized fiber to have a divergent angle; misalignment during FIB milling, leading to dislocation; and the measurement errors. As a next step, the vortex properties of the SZP were characterized as shown in Figs. 3(e)–3(j). The intensity distributions in the focal plane were measured as shown in Figs. 3(e) and 3(g) for $l = 3$ and -3 , respectively, both presenting a donut-shaped beam profile. The normalized intensity distributions along the horizontal axis of the focus are shown in Figs. 3(i) and 3(j), featuring dark spots in the center, with the measured results agreeing with the simulation results. In addition, the fiber device can achieve a maximum focusing efficiency of 51% (details are described in the supplementary material, S2).

The topological charge of the beam was experimentally determined from non-coaxial interferences between the beam and a fiber fundamental mode at the focal plane. As seen in Fig. 3(f) for the SZP with $l = 3$, the interferogram clearly exhibits a three-prong fork

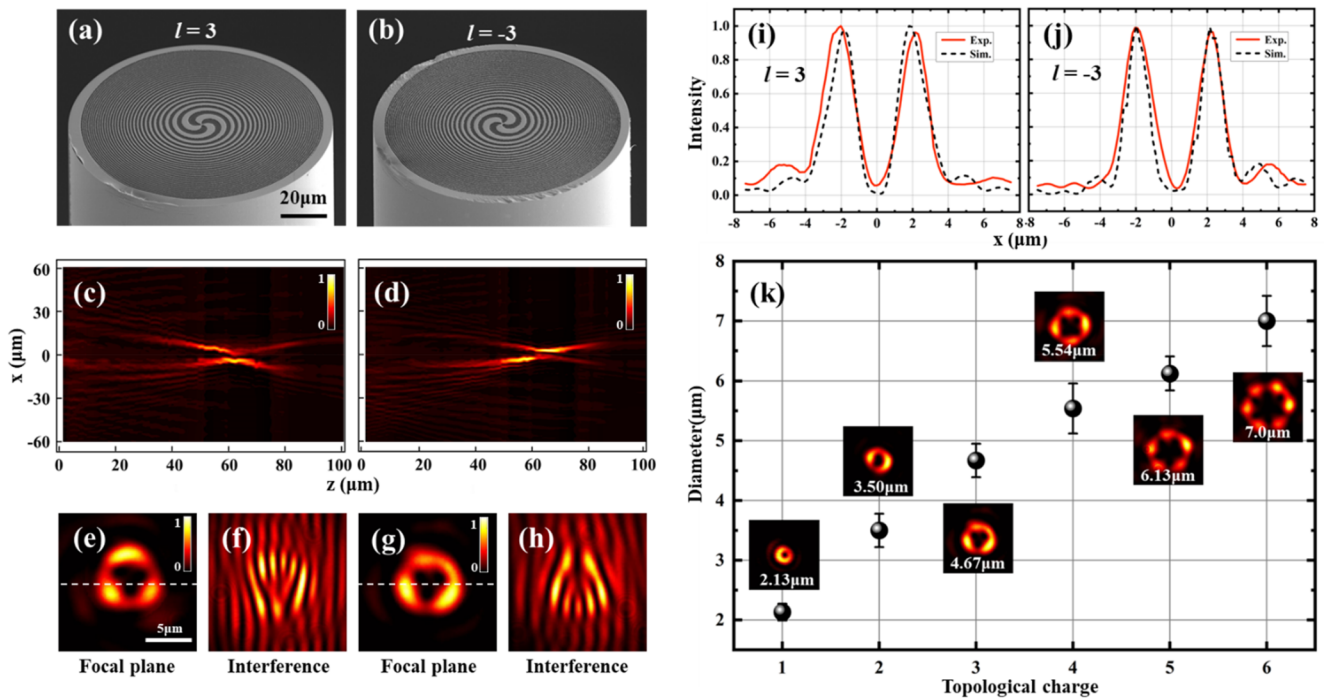


FIG. 3. Measured focusing and mode characteristics of the emitted light from the SZP fabricated on the fiber end facet. (a) and (b) Scanning electron micrographs of the SZPs for $l = 3$ and -3 , respectively, taken from a 45° northeast direction; the measured intensity distribution in the x - z plane for (c) $l = 3$ and (d) $l = -3$; the measured intensity distribution in the focal plane for (e) $l = 3$ and (g) $l = -3$; the interferogram between the beam taken at the focal plane and a fiber fundamental mode for (f) $l = 3$ and (h) $l = -3$; (i) and (j) normalized intensity distribution of simulation (black dashed line) and experiment (red solid line) at the position of white dashed line in panels (e) and (g), respectively. (k) The diameters of the donut-shaped beam profile in the focus plane for the SZPs with different topological charges.

shape with the forks facing upward, confirming that the emitted beam from the SZP carries orbital angular momentum with topological charges of 3. Meanwhile, the optical properties of the SZP for $l = -3$ were characterized using the same method. The interferogram shows a three-prong fork shape with the forks facing downward, as shown in Fig. 3(h), confirming that it produces a vortex beam with topological charges of -3 .

SZPs have been prepared for various l values on the functionalized fibers to fabricate the fiber micromotors. The SZPs have a diameter of $D = 120 \mu\text{m}$ and a designed focal length of $f = 60 \mu\text{m}$, corresponding to $\text{NA} \approx 0.9$. The diameters of the donut-shaped beam profiles with different topological charges in the focal plane were measured as shown in Fig. 3(k). The outer diameters corresponding to $l = 1, 2, 3, 4, 5$, and 6 are $2.13, 3.50, 4.67, 5.54, 6.13$, and $7.0 \mu\text{m}$, respectively (details are described in the [supplementary material](#), S2).

B. Optical trapping and rotation

Next, the performance of the optical fiber micromotor was characterized by trapping freely diffusing standard $3\text{-}\mu\text{m}$ silica beads in water. Figure S4(a) of the [supplementary material](#) shows the schematic diagram of the trapping setup. With a working wavelength of 980 nm , a strong continuous laser was employed for optical manipulation. 99% of the laser energy was coupled into the fiber

micromotor through a 99:1 fiber coupler, while the remaining 1% of the energy was directed to a power meter for real-time monitoring of the input power. The fiber was fixed to a 3D manipulator with an accuracy of $1 \mu\text{m}$. The end of the fiber micromotor was immersed in a homemade windowed liquid chamber where the $3\text{-}\mu\text{m}$ silica beads were suspended. The motion of the trapped particle was recorded from below using an inverted microscope equipped with a high-speed camera, after filtering the scattered light at 980 nm with a short-wave pass filter. The trajectories of the trapped bead were extracted from 10-s long videos acquired at 1000 fps, yielding the dynamic displacements perpendicular (x -axis) and parallel (z -axis) to the fiber axis, as shown in Fig. 4(a). Meanwhile, a spectrograph was connected to the input end of the coupler to record changes in the backscattered signal, which indicated whether the bead was trapped. A noticeable fluctuation in the scattering signal occurred when the fiber micromotor switched from the no-trapping state to the trapping state, as shown in Fig. S4(b).

For the fiber micromotor with $l = 3$, the bead was successfully trapped in the optical potential well and could be manipulated in a three-dimensional space ([supplementary material](#), movie 1). The bead was moved uniformly along the x - and z -axes from 0 to 12 s, then along the $-x$ - and $-z$ -axes from 12 to 24 s, and finally, along the y -axis from 24 to 38 s. These movements can be observed through changes in the position of the bead captured using the camera, demonstrating the capabilities of the fiber micromotor for 3D

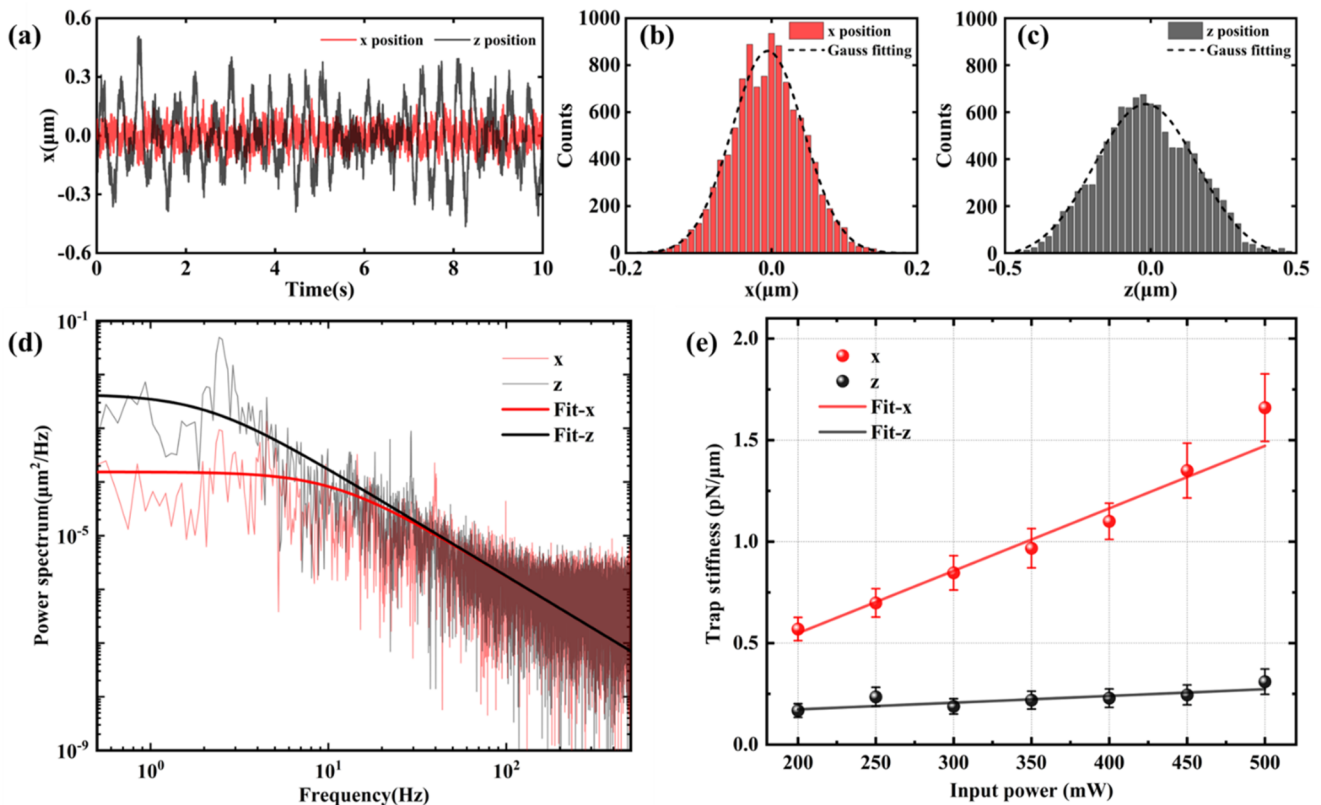


FIG. 4. Analysis of the result from trapping silica beads using the fiber micromotor. (a) Examples of spatial dynamic displacements for a trapped silica bead along with the perpendicular (red, x-axis) and parallel (black, z-axis) directions to the fiber axis for a trapping time of 10 s; histograms of the trapped beads along the (b) x- and (c) z-axes, respectively; Gaussian fits have been used to estimate the stiffness of the optical trapping; (d) power-spectral-density (PSD) analysis of a representative dataset [shown in (a)], including the corresponding fits (thick lines) for the perpendicular (red) and parallel (blue) directions; (e) resulting trap stiffness at different power levels determined using the PSD evaluation.

optical manipulation. It is worth noting that stable optical trapping was consistently achieved with all micromotors over the desired time, and the micromotors were continuously reused for months without any signs of device degradation. This indicates that the fabrication of SZPs on the fiber end facet using the FIB approach is a highly reproducible and reliable method.

In aqueous media, the trapped bead is subject to Brownian motion, which can be determined using the Gaussian distribution histograms of the trapped beads along the x- and z-axes as shown in Figs. 4(b) and 4(c). Consequently, recording its trajectory can be used to analyze the stiffness of the optical trapping.⁵⁶ To quantitatively assess the trapping performance of the optical fiber micromotors, the stiffness of the optical potential well for different powers of the input light was determined by analyzing the dynamic characteristics of the trapped bead. In particular, the Power Spectral Density (PSD) evaluation and the equipartition method were employed to determine the details of the spectral and temporal bead motion characteristics as well as for filtering out potentials (described in the [supplementary material](#), S4). For the PSD evaluation, the key benchmark performance parameter for assessing the trapping capability of the optical well is the optical trapping stiffness

$\kappa = 2\pi\beta f_c$, where f_c is the corner frequency and β is hydrodynamic drag coefficient of the particle.

The PSDs for the measured trajectory as shown in Fig. 4(a) are presented in Fig. 4(d) and indicate two essential features: the platform on the low-frequency side results from confinement within the optical trap, while the slope at the high frequency was related to the free diffusion of the particle. The corner frequency was obtained by best fitting the Lorentz function to the PSD and was subsequently incorporated into the expression used to calculate the stiffness of the optical trap. The stiffness of the implemented micromotor was determined at different input light power levels, both perpendicular and parallel to the fiber axis (κ_x and κ_z), as shown in Fig. 4(e). The stiffness increased linearly with increasing input light power. The measured stiffness from line fitting is 3.08 pN/($\mu\text{m}\cdot\text{W}$) for the x-axis and 0.33 pN/($\mu\text{m}\cdot\text{W}$) for the z-axis. It is noteworthy that the stiffness κ_x is far greater than the stiffness κ_z due to the elongated shape of the FVB, which directly impacts the distribution of particle displacement. Since the intensity distributions of the FVBs in the perpendicular direction are consistent at any angle, the results remain valid across orientations ($\kappa_x = \kappa_y$). The stiffness is determined by the equipartition method, as shown in Fig. S5. Overall,

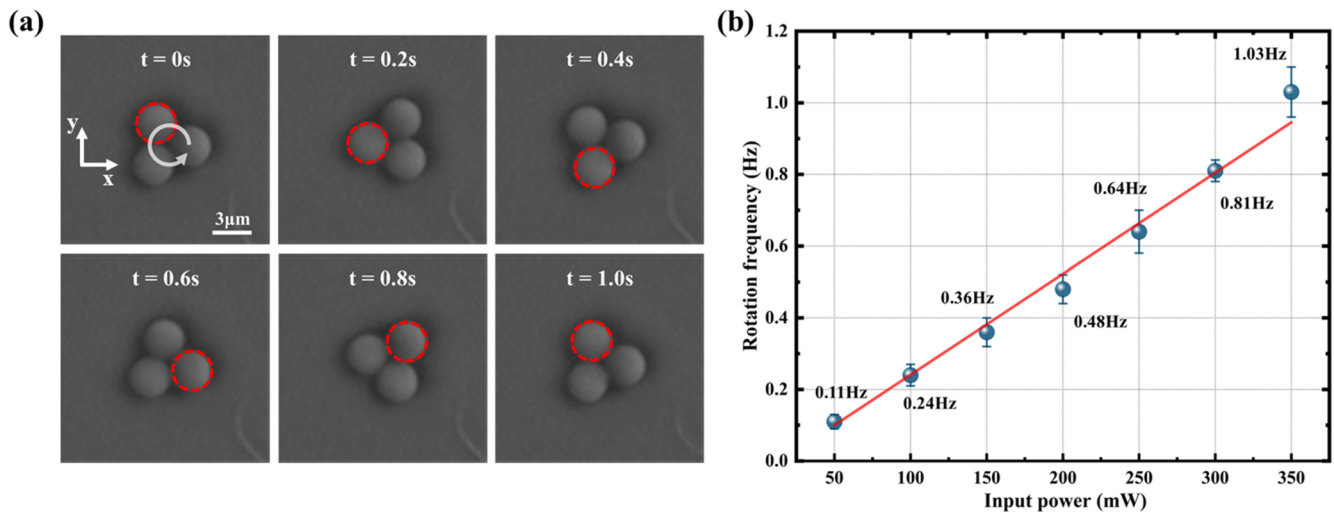


FIG. 5. Analysis of the fiber micromotor rotation trapping. (a) The images recorded during the experiment of the trimer was rotated using the fiber device (the input power is 350 mW; the red dashed circle marks the same silica bead); (b) the rotational frequency of the trimer linearly grows from 0.11 to 1.03 Hz as the input light power increases from 50 to 350 mW at an interval of 50 mW.

a good agreement between the power spectrum analysis and the equipartition method for the stiffness was achieved.

To confirm the rotational ability of the FVB excited by the SZPs, the rotational motion of the trapped beads was induced by vertically inserting the fiber micromotor into the chamber. A trimer composed of three 3- μm standard silica beads was successfully trapped using the micromotor for $l = 3$ and was continuously rotated at a frequency of 1.03 Hz in the counterclockwise direction as shown in Fig. 5(a). The rotation direction corresponds to the micromotor for $l = -3$ (see the [supplementary material](#), movie 4). The rotational frequency per unit power of the trimer is 2.62 Hz/W, as derived from the experimental results shown in Fig. 5(b) (described in the [supplementary material](#), S5). Furthermore, fiber micromotors with different l values can trap and rotate structures composed of different numbers of silica beads (see the [supplementary material](#), movie 5). The number of trapped silica beads increases as l increases, which corresponds to the variation of the diameter in the focal spot with topological charges, as shown in Fig. 3(k).

To sum up, the demonstrated fiber micromotor achieved static trapping and 3D manipulation of a single 3- μm standard silica bead in an aqueous solution, thereby characterizing its performance for trapping microparticles. The bead remained unrotated because its diameter was smaller than that of the focusing spot. Subsequently, the fiber micromotor trapped a trimer composed of silica beads, which had a lateral width larger than the diameter of the focusing spot. The trimer was subjected to torque from excited FVB, confirming that the demonstrated fiber micromotor possesses the ability to rotate micro-objects.

C. Cell trapping and rotation

To demonstrate the capabilities of the fiber micromotor concept for life science applications, biologically relevant objects (*Escherichia coli* bacteria and RBC; the RBC was extracted from the

venous blood of a healthy adult male) were successfully trapped under an appropriate input light power. Notably, when the RBC was trapped, its cell membrane was disrupted when the input light power exceeded 300 mW, while it remained intact when the input light power was below 260 mW.

Figure 6(a) illustrates the process of the RBC being pushed, pulled, and laterally moved at a speed of 10 $\mu\text{m/s}$ with an input light power of 300 mW. The RBC was stably 3D trapped near the focal spot as shown in Fig. 6(a1). Figures 6(a2) and 6(a3) indicate that the trapped RBC was pushed and pulled along the z-axis, respectively. The RBC was then laterally moved along the x-axis as shown in Figs. 6(a4) and 6(a5). Finally, the RBC was moved along the y-axis, which can be discerned from the clarity of the RBC in Figs. 6(a6) and 6(a7). In humans, mature and healthy RBCs are biconcave disks with a diameter of 6–8 μm ,⁵⁷ which is larger than the focal spot of the excited FVB for $l = 3$. Figure 6(b) presents microscopic image frames in the x-z plane recorded during the experiment in which the RBC was rotated by the fiber micromotor for $l = 3$ (see the [supplementary material](#), movie 3). The rotational frequency was calculated based on the unique features of the images. No degradation of the RBC was observed during the trapping experiments at the input light powers of 260, 280, and 300 mW, with the corresponding rotational frequencies of 0.69, 1.07, and 1.2 Hz, respectively, as shown in Fig. 6(c).

D. Discussion

In this work, we demonstrate a single fiber micromotor based on diffractive optical elements (SZP) for the first time, to the best of our knowledge. The SZP is fabricated on the end face of the functional fiber to directly modulate the wavefront of the output beam of the fiber to excite a focused vortex beam. Although the energy utilization of the proposed fiber micromotors is modest compared to that of fiber optic tweezers based on refractive optics, we nonetheless

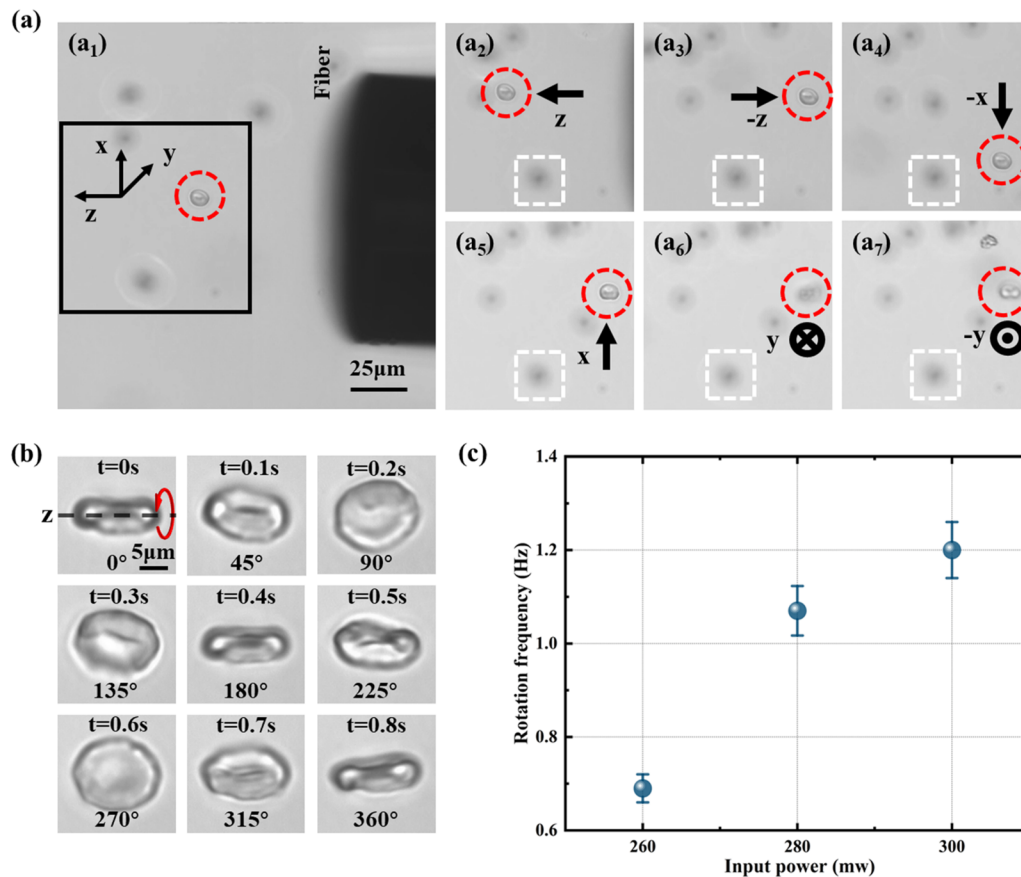


FIG. 6. Analysis of the fiber micromotor rotation trapping of a single RBC. (a) Demonstration of the 3D optical manipulation of the RBC: (a1) the image recorded shows that the RBC was trapped, surrounded by a red dashed line circle, and the black frame marks an enlarged field of observation; panels (a2)–(a7) demonstrate the positions of the RBC after being moved in the (a2) z , (a3) $-z$, (a4) $-x$, (a5) x , (a6) y , and (a7) $-y$ directions, respectively (the reference object was located in a white dashed frame, and the arrow indicates the moving direction); (b) images recorded during the trapping of the RBC was rotated using the fiber micromotor for $l = 3$ (the arrow indicates the rotational direction); (c) the rotational frequencies of the RBC under the input light powers of 260, 280, and 300 mW, respectively.

demonstrate that they can simultaneously trap and rotate particles in a 3D space several tens of micrometers away from the fiber end facet, providing more degrees of freedom for optical tweezers. Compared with holographic fiber optic tweezers, which require special optical fibers and the SLM,^{21,46,54} the proposed fiber micromotor can achieve all fiber manipulation of a single cell, providing a more convenient implementation and cost savings for optical manipulation. Meanwhile, the excited FVB directly exerts torque on the trapped particle, distinguishing it from fiber micromotors that rely on the photothermal forces and optical tweezers, thus reducing the photothermal damage to biologically relevant objects.

The fiber micromotors can be positioned anywhere and allows easy adjustment of the trap potential. Using an inverted microscope, we conduct tracking experiments on standard silica beads that are trapped using the fiber micromotor, examining both position distribution and reflected signals. We perform a quantitative analysis of the dynamics of the trapped bead, confirming that the trapping and rotation forces of the fiber optic motor can be controlled by adjusting the incident light power. In addition, fiber micromotors

with different topological charges can rotate the beads both clockwise and counterclockwise. The flexible and controllable nature of fiber micromotors opens new opportunities for studying physics and applied sciences, including the spin–orbit interaction of angular momentum.³¹ Furthermore, single fiber micromotors can be integrated with on-chip optics⁵⁸ by measuring dynamic changes in backscattered light intensity, providing real-time information on the motion of the trapped particle.

III. CONCLUSION

In summary, we have presented the design, fabrication, and characterization of a single fiber optical micromotor for 3D manipulation and rotation simultaneously. The versatility of the fiber micromotor was demonstrated by trapping and rotating an RBC in a 3D space to provide a single cell multi-functional manipulation. We have validated and analyzed the trapping capability by trapping a standard silica bead and analyzed the rotational performance by rotating a trimer. The demonstrated fiber micromotor can trap

and rotate biologically relevant objects remotely, establishing a new flexible tool for biomedical research.

SUPPLEMENTARY MATERIAL

The [supplementary material](#) encompasses the design of the spiral zone plates, measurement of the SZP on a fiber with various l values, fiber optical trapping setup, methods of estimation of the optical trap stiffness, method of estimation of the rotation (PDF), a video of 3D manipulation of a single bead (movie 1), a video of trapping of the *Escherichia coli* bacteria (movie 2), a video of rotation of a RBC (movie 3), a video of rotation of a trimer with different l values (movie 4), a video of rotation of a trimer with different input light powers (movie 5).

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Luping Wu: Investigation (lead); Methodology (lead); Software (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Zhiyong Bai:** Conceptualization (equal); Data curation (equal); Funding acquisition (lead); Project administration (lead); Resources (lead); Supervision (lead); Validation (lead); Writing – original draft (equal); Writing – review & editing (equal). **Yuji Wang:** Data curation (equal); Methodology (equal); Resources (equal); Software (equal); Visualization (equal). **Rui Liu:** Methodology (equal); Software (equal); Visualization (equal). **Jian Yu:** Funding acquisition (equal); Project administration (equal); Supervision (equal); Validation (equal). **Jianjun Ran:** Funding acquisition (equal); Methodology (equal); Project administration (equal); Supervision (equal); Validation (equal); Visualization (equal). **Zilun Luo:** Methodology (equal); Software (equal); Visualization (equal). **Shen Liu:** Funding acquisition (equal); Methodology (equal); Software (equal); Visualization (equal). **Ying Wang:** Funding acquisition (equal); Methodology (equal). **George Y. Chen:** Conceptualization (equal); Funding acquisition (equal); Methodology (equal). **Jun He:** Conceptualization (equal); Funding acquisition (equal). **Changrui Liao:** Conceptualization (equal); Funding acquisition (equal); Supervision (equal). **Yiping Wang:** Conceptualization (equal); Data curation (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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