Optical manipulation and binding of microrods with multiple traps enabled in an inclined dual-fiber system

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We present experimental demonstrations of optical manipulation and optical binding of microscopic glass rods using the multiple traps created by a dual-fiber optical trapping system. Trapping, alignment, rotation, and stacking of glass rods were realized. To the best of our knowledge, this is the first time that cylindrical particles are optically trapped and bound by an optical fiber-based system. The optical manipulation of rods is also investigated through numerical simulations, which are used to quantitatively explain the experimental results. The ability of manipulating multiple particles of different shapes, as well as the integrable nature of the fiber-based setup, bestows the system the potential to be used in microfluidic systems for versatile particle manipulations. © 2010 American Institute of Physics. [doi:10.1063/1.3504716]

I. INTRODUCTION

Optical tweezers (OTs), also known as optical trapping, have been used for a large variety of research in physics and biology owing to their abilities of manipulating microscale and nanoscale particles and simultaneously measuring forces and positions.¹ Compared with traditional objective-based OTs, which are bulky, expensive, and hard to integrate, optical traps built with optical fibers provide a more flexible solution toward compact, low-cost, and integrable trapping systems, which are desirable in microfluidic systems.^{2–8} While most fiber OTs have only been demonstrated for single particle manipulation, in order to manipulate particles in parallel, multiple traps become more attractive in many applications. Multiple traps have been created with various fiber OTs.^{9–12} In our previous work, an inclined dual-fiber optical tweezer (DFOT) system has been systematically studied,⁸ which has been found, for the first time, to enable multiple traps and multiple functionalities.¹²

In this paper, we report, to the best of our knowledge, the first experimental demonstration of optical trapping and optical binding of cylindrical particles by using the multiple traps created with the inclined DFOTs. Manipulation of cylindrical particles in an optical trap is of particular interest due to its importance in various fronts, which have been realized by using objective-based OTs. For example, in biology, a large variety of cells, which can be optically trapped,¹³ are rod-shaped by nature.¹⁴ Optical traps have been reported to fold red blood cells into rodlike shapes¹⁵ and control the positions and orientations of *Bacillariophyceae*, a type of algae with long cylindrical shapes.¹⁶ In a photonic force microscope,¹⁷ an optically trapped cylindrical particle, instead of a regular spherical particle, has been used as a probe to achieve more accurate position detection with a better linearity.¹⁸ Moreover, semiconductor nanowires have been manipulated and assembled into simple structures in an optical trap.¹⁹ However, in literature, trapping of cylindrical particles has not been demonstrated with optical fiber-based optical tweezers.

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FIG. 1. Diagram of multiple traps obtained from the inclined DFOTs. The inset is the top view of the rod trapped at location 3.

On the other hand, optical binding refers to the phenomenon that multiple particles trapped in optical tweezers can be distributed in a self-organized way.^{20–23} The optical binding effects can be explained as the result of the interaction between the particles and the optical field to minimize the energy of the whole particle-light system.²¹ In literature, optical binding has been realized with fiber-based systems, such as the single optical fiber tweezers with an axicon-shaped fiber tip²² and counterpropagating dual-fiber traps.^{10,21} However, the fiber-based optical binding introduced above can only confine particles in a chainlike one-dimensional structure with fixed particle separations, and the observation of optical binding effects was limited to spherical particles. By contrast, we report here that two-dimensional (2D) structures can be achieved by optically binding spherical and cylindrical particles.

The rest of this paper is organized as follows. The principles of multiple traps created with the inclined DFOTs are briefly introduced, followed by a description of the experimental methods. The experimental results of rod manipulation and optical binding are then depicted and qualitatively interpreted. Through simulations of the optical forces and torques, the experimental results are further explained quantitatively. The discussion of the results is also provided, followed by the conclusions.

II. PRINCIPLES OF ROD MANIPULATION

The manipulation of glass rods is enabled by the multiple traps created by the inclined DFOTs, which were discovered by our group previously.¹² As indicated in Fig. 1, there is a three-dimensional (3D) trap located below the intersection of the two beams. This 3D trap (location 1 in Fig. 1) is achieved by balancing the scattering and gradient optical forces induced by the two beams, although neither beam is as strongly focused as those emitted from a high numerical aperture objective.⁸ Micrometer-sized beads can be trapped in the medium without contacting with the substrate. There exist two other 2D traps (locations 2 and 3 in Fig. 1) at the intersections of the two beams and the substrate, respectively. At these two 2D traps, the beam from one of the fibers is dominant, and the scattering force is larger than the gradient force due to the weak focusing effect, resulting in the trapping of particles on the substrate.

Compared to spherical particles that can be controlled in three degrees of freedom (positions), nonspherical particles including rods can be controlled in more degrees of freedom (orientations), and thus better controllability and more functionalities can be realized. To control these many degrees of freedom, an anisotropic optical intensity field is required to orient as well as trap the rods, which is enabled by the inclined DFOTs. First, at the two 2D traps of the inclined DFOTs, the beam shapes on the xy plane are elliptical due to the tilt of the incidence. As a result, the elliptical shape of the spots enables the alignment of the rods along the long axis, which is the y axis in Fig. 1. Second, the intensity distribution is not uniform in the elliptical spot: the intensity at the inner end (i.e., the left end at location 3) of the spot is stronger than that at the outer end

FIG. 2. Experimental arrangement of the inclined DFOTs for creating multiple traps.

(i.e., the right end at location 3) because of being closer to the beam waist. The nonuniform intensity distribution enables the rotation of the rods when they are off axis. Moreover, when the two 2D traps are close to each other, the strong intensity on the yz (vertical) plane tries to pull outside particles onto the plane, which enables the stacking of multiple rods. These functionalities have been demonstrated in experiments and investigated in simulations, as to be discussed in later parts of this paper.

III. EXPERIMENTAL METHODS

The inclined DFOT system was built on the platform of an inverted microscope (CKX41, Olympus Inc.), as shown in Fig. 2. Light from an 808 nm fiber-coupled laser diode (FMXL808-080SA0B, Bluesky Research) was equally split into two lensed fibers (OZ Optics). The optical beams exiting from the lensed fibers were used to form optical traps in water. Each lensed fiber was attached to a miniature 3D translation stage (07TMC521, CVI Melles Griot) to facilitate fiber alignment. The fibers were aligned before experiment once and for all. Both stages were fixed on a board so that they can be moved together as a block by a third 3D stage. The fibers were arranged to form an inclination angle α (see Fig. 1) of 50° with respect to the vertical axis z . The separation between the fiber tips was $45\ \mu\text{m}$ along the y direction. The optical beam emitted from each lensed fiber had a beam waist of $1.35\ \mu\text{m}$, which was located $12\ \mu\text{m}$ from the fiber end face. The total optical power emitted from both fibers was 15.3 mW. A coverglass with a water drop containing silica beads (Bangs Laboratories, Inc.) and glass rods (kindly donated by Professor Wolfgang Losert at the University of Maryland) was placed on a two-dimensional stage. The rods are $3.5\ \mu\text{m}$ in diameter and $8\text{--}15\ \mu\text{m}$ in length. The silica beads have a diameter of $4.74\ \mu\text{m}$ and a density of $2.0\ \text{g/cm}^3$. Both the rods and the beads have a refractive index of 1.45. The experiment was monitored with an oil-immersion objective (PlanC N 100×1.25 , Olympus Inc.) and recorded with a charge-coupled device (CCD) camera (Moticam 1000, Motic).

IV. EXPERIMENTAL RESULTS AND INTERPRETATION

A. Trapping and alignment of glass rods

The multiple traps can be used to manipulate particles with other shapes in addition to the spherical shaped particles. By taking the advantage of the oval shaped spots produced by the inclined DFOTs, nonaxisymmetrical particles can be manipulated to change not only their positions but also their orientations. As an example, micrometer-sized glass rods were successfully trapped and aligned. In the experiment, two free glass rods were brought into the trapping area by moving the coverglass, as shown in Fig. 3(a). Once they were moved close to the two 2D traps, the rods were trapped and aligned along the x axis, as shown in Fig. 3(b). When the water was moved

FIG. 3. Experimental demonstration of trapping and alignment of glass rods. (a) Two free rods were initially lying on the substrate. (b) The two rods were trapped and aligned along the y axis. A third free rod (on the top left side) was moved into the view field serving as a reference. (c) The coverglass was moved along the $+y$ direction. The scale bar is $10\ \mu\text{m}$ in length. The rods are $\sim 3.5\ \mu\text{m}$ in diameter and $8\text{--}15\ \mu\text{m}$ in length.

along the $+y$ axis, the trapped rods stayed stable in the 2D traps, while maintaining the same orientation, as shown in Fig. 3(c). It is noted that the glass rods could not be trapped in three dimensions.

Since the elliptical optical fields on the substrate exhibit directionality (with the long axis along the y axis), as can be seen from Fig. 3, this directionality of the optical field enables control of the orientations of glass rods. When a rod is trapped, both its ends will be trapped by the strongest intensity, resulting in its axis aligned long the long axis of the optical field (the y axis). This explains the results of rod alignment shown in Fig. 3. The reason that glass rods cannot be trapped in three dimensions can be explained as follows. When the coverglass is lifted up so that a rod is moved close to the beam intersection, where the 3D trap for beads is located,⁸ considering the mirror symmetry of the system, the rod will be trapped along the y axis and centered at the 3D trap position. Due to the long length of the rod, each end of the rod will reach one optical axis of the two beams, where only one beam is dominant. Because the scattering force on the beam axis is always larger than the gradient force due to the weak focusing of the optical beams, the ends of the rod are pushed along the $-z$ direction, while the center of the rod is pulled along the $+z$ direction (by the 3D trap). The 3D trap is not strong enough to balance the optical forces at the rod ends as well as the gravity of the rod, and hence no stable 3D trap of the rod can be achieved.

B. Rotation of glass rods

If the motion of the water is controlled to have a relatively fast speed, the trapped rods will escape from the traps. This phenomenon was found to be useful for rotating a rod in a controllable manner (clockwise or counterclockwise). When the water was moved in the $-x$ direction, the outer end of the rod escaped earlier than the inner end, resulting in a clockwise rotation of about 70° , as shown in Figs. 4(a) and 4(b). When the rod was moved back to the trapping area by moving the coverglass in the $+x$ direction, the end that first came into the trap was pushed outside (along the $-y$ direction), as shown in Figs. 4(c)–4(e). The rod was thus rotated clockwise by 180° in the entire process. If the process shown in Figs. 4(a)–4(e) is repeated, the rod can be continuously rotated. When the water was moved in the opposite direction (first $+x$ and then $-x$), the rod was rotated counterclockwise by 180° , as shown in Figs. 4(e)–4(h).

The principle that can be used to explain the rods rotation is illustrated in Fig. 5. Since the beams are inclined, the inner ends of the spots have stronger intensity than the outer ends. The outer end [end 1 in Fig. 5(a)] of the trapped rod will escape earlier than the inner end (end 2) if the drag force from the water is large. After the rod escapes from the 2D trap, it is rotated clockwise, as shown in Figs. 4(b) and 5(b). If the water is moved backward to bring the rod into the trapping area, end 2 will get trapped first, as shown in Figs. 4(c) and 5(c). However, since the scattering force is dominant due to the weakly focused beams, end 2 is pushed outward so that end 1 will be brought into the trapping area. When the rod is finally settled down, it will be aligned along the y axis [Fig. 5(d)] with an orientation opposite to that formed at the beginning of the process [Fig. 5(a)]. Therefore, during the entire process shown in Fig. 5, the rod is rotated clockwise by 180° , which was observed in the experiment. If the water is moved in the opposite direction in each step illustrated in Fig. 5, the rod will then be rotated counterclockwise by 180° during each cycle.

FIG. 4. Experimental demonstration of rotating glass rods. The arrows at the lower right corner indicate the next movement of the coverglass, and the small arrow beside the rod shows the rod orientation. [(a) and (b)] The rod escaped from the trap when the water was moved fast in the $-x$ direction. [(b)–(e)] The rod was retrapped and eventually aligned along the x axis, when the water was moved in the $+x$ direction. The rod was rotated clockwise by 180° in the above process. [(e)–(h)] The process of (a)–(e) was repeated with the opposite direction of water movement. The rod was rotated counterclockwise by 180° . The scale bar is $10\ \mu\text{m}$ in length. The rods are $\sim 3.5\ \mu\text{m}$ in diameter and $8\text{--}15\ \mu\text{m}$ in length.

C. Stacking of glass rods

Glass rods can also be stacked using the multiple traps. As shown in Fig. 6, three glass rods can be stacked in three different ways: (i) the two bottom rods aligned side by side and the third rod on top of the two bottom ones, as shown in Fig. 6(a); (ii) the two bottom rods aligned end to end and the third rod on top of the two bottom ones, as shown in Fig. 6(b); and (iii) the center rod sandwiched by the two outside rods and oriented vertically, as shown in Fig. 6(c). Such stacking can potentially be used to synthesize micro- or nanostructures.

The principle of rod stacking can be explained as follows. If the separation between the two 2D traps is small and two rods are trapped, the rods will contact each other. Since both rods try to align their axes along the y axis, their ultimate positions in the traps will depend on their initial states. If two rods are brought into the traps along the x axis, they will be trapped side by side, as shown in Fig. 6(a). On the other hand, if they are brought into the traps along the y direction, they will push each other end to end, as shown in Figs. 6(b) and 6(c). If there is a third rod in between, it will be squeezed by the two rods from both sides or from both ends, resulting in the stacking of the third rod. In most experiments, the third rods stayed parallel to and on top of the other two rods, as shown in Figs. 6(a) and 6(b). However, in rare cases, when the third rod is squeezed, its one end will be trapped by the 3D trap, which is located above the substrate, resulting in the rods being trapped in a vertical orientation, as shown in Fig. 6(c).

D. Optical binding of silica beads and glass rods

The optical binding arises from the light redistribution induced by the trapped particles.²³ When multiple particles are trapped in an optical field, the interactions between the particles are

FIG. 5. The working principle of rod rotation. The arrows at the top left corner indicate the next movement of the water. The two ovals illustrate the spots of the two beams.

FIG. 6. Experimental demonstration of glass rod stacking. [(a)–(c)] Images of glass rods stacked in different ways. The scale bar is $10\ \mu\text{m}$ in length. [(d)–(f)] Sketches of the stacked rods corresponding to (a)–(c), respectively. The rods are $3.5\ \mu\text{m}$ in diameter and $8\text{--}15\ \mu\text{m}$ in length.

induced by the optical field. The particles trapped upstream can modify the optical fields and influence the behavior of the particles downstream. In this work, optical binding of both spherical beads and microrods can be realized with the inclined DFOTs. As shown in Fig. 7, when bead 1 was trapped in 3D, bead 2 can be optically bound so that it can be manipulated in 3D. Compared to the free beads (beads 3 and 4), bead 2 was lifted up from the coverglass and it remained at the bound position when the water was moved around. If no beads were trapped in the 3D trap, bead 2 could only be trapped on the coverglass by the 2D trap. Similar optical binding effects can also be used to tilt glass rods. As shown in Fig. 8, two glass rods (rods 1 and 3) were tilted up due to the optical binding. The optically bound rods stayed stationary when the water was moved around. The up-tilting of the glass rods cannot be achieved without the bead in the 3D trap. It is noted that the optical binding effects described here created a 2D structure, which is different from one-dimensional chainlike structure created by the previously published work.

In the experimental results of optical binding, the bead in the 3D trap served as a lens, which can be used to refocus both the light beams. This focusing effect can be seen by comparing the spot sizes with [Fig. 8(b)] and without [Fig. 8(a)] the bead being trapped. A similar refocusing effect was studied and verified in an earlier work.²³ The refocusing increases the intensity gradient downstream, and hence the gradient force that is needed to overcome the scattering force is increased. The increase in the gradient force is necessary to keep the bead from being trapped in 3D after the first trapped bead. It seems that the particles downstream are bound to the bead upstream, which explains why it is called optical binding. Owing to the optical binding effect, the downstream beads and rods can be lifted up, as shown in Figs. 7 and 8. Without the 3D trapped bead, only 2D trapping can be realized, which does not have the ability to lift up beads or glass rods.

FIG. 7. Experimental demonstration of optical binding of silica beads. The arrows at the lower right corner indicate the next movement of the coverglass. Bead 1 was trapped in 3D. Bead 2 was optically bound to bead 1, so it was out of focus and not contacting the substrate. Beads 1 and 2 remained in the trapped and bound positions, respectively, when the water was moved in the $+y$ [(a) and (b)] and $+x$ [(b) and (c)] directions. The scale bar is $10\ \mu\text{m}$ in length. (d) A sketch of the three beads on the yz plane. The beads are $4.74\ \mu\text{m}$ in diameter.

FIG. 8. Experimental demonstration of optical binding of glass rods. (a) The three free rods lie on the coverglass, and the silica bead was trapped by the right 2D trap. (b) The bead was trapped by the 3D trap. It can be seen that the light beams were refocused by the bead. (c) Rods 1 and 3 were tilted up by the optical binding, while rod 2 remained free. The optical binding helped rods 1 and 3 remain stationary, while the water was moved in the $+x$ [(c) and (d)] and $-y$ [(d) and (e)] directions. The scale bar is $10\ \mu\text{m}$ in length. (f) Sketch shows the optical bound rods on the yz plane. The rods are $\sim 3.5\ \mu\text{m}$ in diameter and $8\text{--}15\ \mu\text{m}$ in length. The silica bead is $3.5\ \mu\text{m}$ in diameter.

The experiments discussed above demonstrate that the inclined DFOTs have the ability of trapping cylindrical particles and performing multiple functionalities. With two fibers assembled on a block, control of the positions as well as the separations of the traps can be realized easily. With a single actuator, in this case, a 3D translational stage, attached to the fiber block, optical alignment, rotation, stacking, and optical binding of microscopic glass rods can be achieved.

V. NUMERICAL SIMULATIONS AND DISCUSSION

Although the experimental results on rod manipulations have been explained qualitatively in Sec. IV, to achieve an enhanced understanding of the experimental results, numerical simulations on the optical forces and torques are carried out based on a ray-optics model.^{8,12,24} The parameters (the optical power, wavelength, beam waist and location, fiber separation and inclination angle, and rods diameter and refractive index) are chosen to be the same as those used in the experiments. The rods used in the simulations are considered to have perfect flat ends and a length of $10\ \mu\text{m}$. The vertical distance between the beam intersection and the rod plane is $3.36\ \mu\text{m}$ in the simulations. Note that some simulation parameters, such as rod length, end face shape, and height of the beam intersection, are difficult to determine due to the fact that these parameters were either constantly changed within a range or hard to measure in the experiments. The influence of these parameters will be discussed at the end of this section. Since all the rods in the experiments lied on the substrate except those in the optical binding experiment, the axes of the rods considered in the modeling always lie in the xy plane.

A. Optical force and torque fields of a single 2D trap applied on a y -oriented rod

As seen in Figs. 3–8, the rods were always aligned along the y axis. In the simulations, it is considered that the rod is initially oriented along the y axis, and further it is assumed that only a single 2D trap (trap 3 in Fig. 1) takes effect. This is true when the two 2D traps are far ($>10\ \mu\text{m}$) from each other. It is noted that the influence of the rod orientation and the forces when two 2D traps exist in the same area will be studied later in this paper.

The optical force field applied on a single y -oriented rod by a single 2D trap is obtained, as shown in Fig. 9(a). It can be clearly seen from Fig. 9 that a 2D trap of the rod exists near the beam axis, which is located on the yz plane and intersects the xy plane at $(0, 0)$. By plotting the optical force along the y axis (data not shown), the trap is found to be at $(0, 0.074\ \mu\text{m})$. The fact that the trap is slightly shifted from the beam axis toward the $+y$ direction is because the gradient force

FIG. 9. Simulation results of (a) the optical force field and (b) the z -axis optical torque field of a single 2D trap (trap 3 in Fig. 1). Each arrow in (a) stands for the optical force applied on a glass rod when the center of the rod is located at the start point of the arrow. The origin of the coordinate system is located at the intersection of the optical beam axis and the horizontal plane passing the rod center. The rod is $3.5 \mu\text{m}$ in diameter, $10 \mu\text{m}$ in length, and is oriented along the y axis. The optical power is 7.65 mW .

needs to have a $-y$ component to balance the scattering force, which is always along the beam propagation direction and has a $+y$ component. The same reason can be used to explain why the trapping force is stronger in the $-y$ direction than in the $+y$ direction. When the rod is located in the $-y$ area, both the gradient force and the scattering force have $+y$ components and hence contribute to the trapping force. However, if the rod is located in the $+y$ area, the gradient force has a $-y$ component, but the scattering force still has a $+y$ component that pushes the rod away from the trap, resulting in weaker trapping forces.

The optical torque field applied on a single y -oriented rod is shown in Fig. 9(b). As discussed in Sec. IV, the elliptical shape and the nonuniform intensity distribution can cause torques on the rod. Depending on the position of the rod, it will be rotated clockwise (by the negative torques) or counterclockwise (by the positive torques). Since the intensity field is symmetric about the y axis, there is no torque when the y -oriented rod is located on the y axis. On the other hand, the intensity field is not symmetric about the x axis (with stronger intensity in the $-y$ area). As a result, the optical torque is not zero on the x axis, unless the rod is far from the optical beam so that it does not feel the optical intensity.

B. Optical torque field of a single 2D trap applied on an arbitrarily oriented rod

In order to fully understand the principles of rod trapping and alignment, the relationship between the optical torque and the rod orientation is obtained and shown in Fig. 10. Here, we consider a rod with an arbitrary orientation and located at three positions $(0, -1 \mu\text{m})$, $(0, 0.074 \mu\text{m})$, where the rod is stably trapped, and $(0, 1 \mu\text{m})$. It is noted that the angle θ (see Fig. 1) increases when the rod is subject to a positive z -axis torque. There are four orientations, namely, $\theta=0$, $\pi/2$, π , and $3\pi/2$, with zero optical torques. The orientations of $\theta=\pi/2$ and $3\pi/2$ are not stable. If the rod rotates slightly away from, for example, $\theta=\pi/2$, due to the Brownian motion, the optical torque will drive the rod further away from $\pi/2$ until it reaches $\theta=0$ or π , depending on the direction in which the rod initially deviates. However, at $\theta=0$ or π , the restoring torque will pull the rod back when it rotates slightly away. In other words, $\theta=0$ or π are potential wells, while $\theta=\pi/2$ and $3\pi/2$ are potential hills. The stable orientations of $\theta=0$ or π correspond to the conditions in which the rod axis is aligned with the y axis. Although only three positions ($y=-1$, 0.074 , and $1 \mu\text{m}$) are shown in Fig. 10, the stable orientations are always 0 and π as long as the rod is located on the y axis and not too far away ($<10 \mu\text{m}$) from the beam axis (data not shown).

FIG. 10. Simulation results of the dependence of the z-axis optical torque on the orientation of a rod. The torque is applied by a single 2D trap (trap 3 in Fig. 1). θ is the angle between the rod axis and the y axis, as shown in Fig. 1. The rod is $3.5 \mu\text{m}$ in diameter, $10 \mu\text{m}$ in length, and is located on the y axis ($x=0$). The optical power is 7.65 mW.

C. Optical force and torque fields of two 2D traps applied on a y-oriented rod

When two 2D traps are close to each other, the force field will change from that with a single 2D trap. The optical force and torque fields on a y-oriented rod applied by two 2D traps are shown in Figs. 11(a) and 11(b), respectively. Here, the vertical distance between the beam intersection and the rod plane (xy plane) is $3.36 \mu\text{m}$, and the corresponding separation between the two intersections of the beam axes and the xy plane is $8 \mu\text{m}$. It is noted that different from Figs. 9 and 10, the origins of the coordinate systems in Fig. 11 is located right below the beam intersection, with equal distances from the two 2D traps. It can be seen from Fig. 11 that the trap position is at the origin, which is in between the two 2D traps. Due to the symmetry of the system about both x and y axes, the optical torque is zero on both the x and y axes.

D. Explanation of optical trapping, alignment, rotation, and stacking of glass rods

Combining the simulation results shown in Figs. 9 and 10, we can quantitatively explain the experimental results of the rod trapping and alignment. If a y-oriented rod is located off the y axis, it will be pushed toward the y axis [see Fig. 9(a)], while being rotated under the optical torque with a direction depending on its initial position [see Fig. 9(b)]. Once the rod reaches the y axis, it will quickly settle down at the stable position of $(0, 0.074 \mu\text{m})$ (see Fig. 9) as well as align itself along the y axis (see Fig. 10). After it is trapped, although the Brownian motion or the moving water causes the rod to deviate from the stable position and orientation, the restoring force and torque retain the stable trapping and alignment of the rod, just as the experimental results shown in Fig. 3.

If the water is moved along the $+x$ axis at a speed fast enough to drag the rod away from the trap, the rod will be rotated clockwise by a negative torque [see Fig. 9(b)]. When the rod is brought back to the trapping area by the moving water, it will be further rotated clockwise and will align its axis again along the y axis. This process is the same as the one shown in Figs. 4(a)–4(e). It is noted that the rotation directions in Figs. 4 and 9(b) are opposite. This is because the simulation results shown in Fig. 9(b) are obtained with trap 3 (see Fig. 1), while the experimental rotation results shown in Fig. 4 were obtained with trap 2.

FIG. 11. Simulation results of (a) the optical force field and (b) the z axis optical torque field of two 2D traps (traps 2 and 3 in Fig. 1). Each arrow in (a) stands for the optical force applied on a glass rod when the center of the rod is located at the start point of the arrow. The origin of the coordinate system is located at the center of the line segment connecting the two traps. The intersections of the optical beams and the xy plane are at $(0, -4 \mu\text{m})$ and $(0, 4 \mu\text{m})$. The rod is $3.5 \mu\text{m}$ in diameter, $10 \mu\text{m}$ in length, and is oriented along the y axis. The optical power is 7.65 mW from each fiber.

If there are two rods in the optical field formed by two 2D traps, according to Fig. 11, both rods are pushed toward the origin. The rods still try to align themselves along the y axis, and hence they will tend to stay on either x or y axis, where the torque is zero [see Fig. 11(b)]. Depending on their initial positions, the two rods can be pushed against each other along the x axis (side by side) or along the y axis (end to end). This explains why the bottom two rods in the experiment were either side by side [see Fig. 6(a)] or end to end [see Fig. 6(b)]. If there is a third rod existing in the optical field, it will also be pushed toward the origin. However, since there is not enough space left for it to stay on the xy plane, it will be stacked onto the first two rods by the force field with its axis aligned along the y axis (see Fig. 11). When the third rod was sandwiched by the other two rods along the y axis, the third rod can be lifted up by the forces coming from both sides, and maintain this orientation by the support of the two rods on both sides, as shown in Fig. 6(c).

E. Discussion

There are some parameters used in the simulation that do not match exactly the ones in the experiments. The influence of these parameters is discussed here. The rods used in the experiments have different lengths ranging from 8 to $15 \mu\text{m}$. In the simulations, only a rod length of $10 \mu\text{m}$ is used. If a different rod length is used in the simulations, the results shown in Figs. 9–11 would change slightly. For example, the stable trapping position will be displaced by a small amount ($<0.5 \mu\text{m}$), and the amplitude of the optical forces and torques will also change slightly. However, the important conclusions and the behaviors of the rods in the optical trap, such as the alignment along the y axis and stable trapping positions located on the y axis, will not change. As a result, the understanding of the experimental results through the simulation results will still hold for slightly changed rod lengths. Another issue that was not considered in the simulation is the influence of the end face shape of the rods. As seen in the experimental results, most of the rods do not have a perfect flat end face. However, since the end faces have much smaller areas than the

sidewall, the optical forces applied on the end faces are much smaller than those on the sidewalls. Therefore, the end face shapes will have little influence on the simulation results as long as the rod length is much larger than its radius. This issue of the influence of end face shapes has also been studied in the previous work.²⁴ The height of the beam intersection with respect to the xy plane (the rod plane) is another parameter that constantly changed in the experiments. In our simulations, the value of $3.36\ \mu\text{m}$ is used, while the height of the beam intersection ranged from 0 to $20\ \mu\text{m}$ in the experiments. According to our experience in the experiments, the effects of two 2D traps (rods trapped in between the 2D traps, as shown in Fig. 11) are dominant if the beam intersection is close ($<3\ \mu\text{m}$) to the xy plane. With a higher beam intersection, the distance between the two 2D traps is larger. In this case, the influence of the other beam on the rods trapped by one beam is smaller, resulting in more profound effects of a single 2D traps (rods trapped separately by one of the 2D traps, as shown in Figs. 9 and 10). To facilitate different functionalities, proper beam intersection height might be chosen. A high beam intersection is preferable in the case of rod alignment, while a low beam intersection is necessary for rod stacking.

Furthermore, the trapped rods were not perfectly aligned along the y axis in the experiments [see Figs. 4(h) and 6], while a perfect alignment is predicted in the simulations. This is mainly because there always exists an error of the fiber alignment in the experiments. It is difficult, if not impossible, to align the two optical beams in exactly the same plane. This alignment error can cause the force field shown in Fig. 9 to be twisted (data not shown), resulting in an imperfect alignment of the rod along the y axis.

It has been demonstrated that the inclined DFOTs have the ability to control both the orientations and the positions of the microscopic glass rods. As discussed in our previous work,¹² the inclined DFOT system can be used as a system block in a microfluidic system. In the current setup, manual 3D stages are used to fix the fibers on the common board. However, the stages can be removed if the board is replaced with a silicon wafer with etched V-grooves. In this case, the fibers can be aligned well along the V-grooves and the block size can be significantly decreased. The position control of the trapped glass rods can be realized by controlling the position of the fiber block with a single actuator. The separations between the trapped glass rods can be adjusted by tuning the height of the fiber block. The orientations of the glass rods can be adjusted by rotating the fiber block about the z axis. However, because the single actuator on the fiber block cannot provide enough degrees of freedom, the trapped glass rods cannot be adjusted independently. They are both oriented along a line while lying on the substrate, unless they are tilted by the optical binding effects. Although multiple rods cannot be rotated independently, the ability to rotate the glass rods makes it feasible to control the orientation of the multiple rods simultaneously. Moreover, by controlling the motion of the fibers, the rods can be controlled to rotate by a fixed angle (e.g., 180° in an entire cycle and 90° in half a cycle).

The ability of aligning, positioning, stacking, and optically binding cylindrical particles, as well as spherical particles as previously reported,¹² makes it possible to create periodical structures with each node being one particle. These artificial lattice structures are also called “optical matter,”²⁰ which are in analogy with the lattices of natural crystals. Since the periods and crystal-line structures can be designed, the resulting optical matter may serve as artificial materials with unique properties, which are not available in nature. Along the x axis, multiple fiber blocks can be introduced to create multiple layers of the trapped particles. However, there will be a minimum achievable separation between the adjacent layers due to the physical size of the optical fibers. To further reduce the layer separation along the x direction, the optical fibers can be thinned with hydrofluoric acid etching. In this sense, it is possible to realize a large number of traps by integrating multiple inclined DFOTs, thanks to the flexibility and compact size of this setup. Moreover, unlike the objective-based OTs that require thin, transparent substrates, the multiple traps created by the inclined DFOTs can work with any substrate, including silicon or other lightproof substrates.

VI. CONCLUSIONS

In this paper, we report on the optical manipulation and optical binding of microscopic cylindrical particles with the multiple traps created by an inclined dual-fiber optical tweezer system. To the best of our knowledge, this is the first time that cylindrical particles are optically trapped and bound with fiber optical trapping systems. We experimentally demonstrated optical alignment, rotation, and stacking of microscopic glass rods. Optical binding of glass rods and silica beads were also observed in the experiment. Furthermore, a numerical study on the optical force and torque fields was carried out to achieve better understanding of the experimental results. While spherical particles are readily employed in various optical trapping systems,¹ trapping of nonspherical particles is essential for addressing long-reaching implications of assembling and driving microstructures²⁵ in optofluidic systems as well as studying biological samples that are mostly nonspherical.¹³ The ability of manipulating multiple differently shaped particles with a compact system setup bestows the inclined dual-fiber optical tweezers the potential to find applications in microfluidic systems.

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