Trapping and rotating microparticles and bacteria with moiré-based optical propelling beams

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Abstract: We propose and demonstrate trapping and rotation of microparticles and biological samples with a moiré-based rotating optical tweezers. We show that polystyrene beads, as well as *Escherichia coli* cells, can be rotated with ease, while the speed and direction of rotation are fully controllable by a computer, obviating mechanical movement or phase-sensitive interference. Furthermore, we demonstrate experimentally the generation of white-light propelling beams and arrays, and discuss the possibility of optical tweezing and particle micro-manipulation based on incoherent white-light rotating patterns.

OCIS codes: (350.4855) Optical tweezers or optical manipulation; (170.4520) Optical confinement and manipulation; (120.4120) Moiré techniques.

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#169107 - $15.00 USD Received 22 May 2012; revised 4 Jul 2012; accepted 15 Jul 2012; published 18 Jul 2012

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1. Introduction

Optical trapping and particle manipulation have aroused great interest over the past four decades following Ashkin’s pioneering work [1,2]. Nowadays optical tweezers serve as useful tools across many branches of science, including molecular biology, medicine, nanotechnology, atmospheric science and colloidal physics [3–5]. In addition to linear translations in three dimensions, rotation of trapped particles offers another important degree of freedom for optical manipulation, with promising applications in biotechnology. Over the years, a variety of techniques have been proposed for rotating trapped particles, including the alteration of optical angular momentum [6,7]; the holographic optical tweezers (HOT) [8,9]; specially designed electric or magneto-optic manipulators [10,11]; or the more popular, rotating, non-symmetric trapping beams (as obtained with higher-order transverse laser modes, cylindrical lenses, rectangular apertures, revolving interference patterns, and so on) [12–19]. Most of these techniques rely on either mechanical rotation of beam-shaping components or phase-sensitive interference, thus deterring stabilized control of the tweezers against ambient vibrations or perturbations.

Recently, we proposed a novel approach to generate rotating intensity blades (optical propelling beams) by employing the moiré technique [20]. These optical propelling beams can be generated with controllable rotation speed and direction without the need for any mechanical movement or phase-sensitive interference. In this work, we show how such optical propelling beams can be utilized to achieve dynamic control of trapped particles, establishing moiré-based rotating optical tweezers. With intelligent beam design, we obtain a well-resolved multi-blade intensity structure, even when the whole beam is tightly focused, and demonstrate stable two-dimensional trapping and controlled rotation of *Escherichia coli* bacteria and polystyrene micro-beads. We show that in principle our technique for rotating tweezers can be implemented with incoherent light sources, as multi-blade white-light propelling beams are readily demonstrated in our experiment. These computer-controlled, rotating multi-traps that do not require time-share may open new avenues for optical trapping and manipulation.

2. Experimental setup and generation of optical propelling beams

When implementing moiré-based rotating optical tweezers, the key is to generate the rotating multi-blade intensity patterns and keep the blades well separated even after tight focusing, so that each blade turns into an optical gradient trap, similar to the single-beam tweezers. Such

#169107 - $15.00 USD Received 22 May 2012; revised 4 Jul 2012; accepted 15 Jul 2012; published 18 Jul 2012

multi-blade intensity patterns are created by overlapping a moving straight-line grating with a fork-type grating (as from interference between a plane wave and a vortex beam) [20]. The number of intensity blades is determined by the topological charge of the vortex, while the direction of beam rotation depends on the direction of the grating movement and/or the sign of the topological charge. The rotation speed is proportional to the speed of the grating motion. One advantage of this technique is that the number of blades and their angular velocity can be changed with ease by a computer-controlled spatial light modulator (SLM). More importantly, because no phase-sensitive interference is involved, the resulting pattern is remarkably stable during rotation and immune to environmental vibrations.

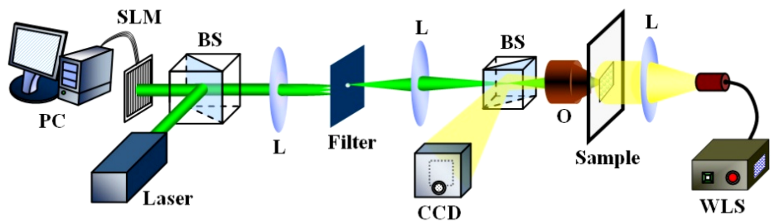

Fig. 1. (a) Experimental setup for moiré-based rotating optical tweezers. SLM: spatial light modulator; BS: beam splitter; L: lens; O: objective lens; WLS: white light source; CCD: charge-coupled device.

Our experimental setup is sketched in Fig. 1, similar to earlier setups used for particle manipulation with optical bottle beams and morphing autofocusing Airy beams [21,22]. A collimated Gaussian beam (λ = 532 nm) is reflected from a SLM reading out the overlapped gratings. With appropriate spatial filtering through a typical 4f-system, the designed moiré patterns can be retrieved. By simply setting the straight-line grating into linear motion, the propelling beams are generated, and then sent into a setting typically used for optical tweezers, as shown on the right side of Fig. 1. To form a multi-trap rotating tweezers with our propelling beams, we use an objective lens (60X, NA = 0.85) with relatively low magnification so to match the size of individual traps with the typical size of the particles used in our experiments. The power of the trapping beam is about 20 mW. The sample consists of either 2-μm polystyrene beads or *E. coli* cells (with an average length of 2 μm) suspended in aqueous solution and sandwiched between two thin glass plates. The sample is illuminated with a white-light source from the opposite direction and imaged with a CCD camera.

With the above setup and the technical approach detailed in [20], multi-blade rotating patterns can be readily achieved. A typical example for generating of 3-blade rotating beams is illustrated in Fig. 2, where (a)-(c) show the gratings configured onto the SLM, and (e)-(g) show numerically and experimentally retrieved transverse intensity patterns from the moiré fringes in (a) with a single input Gaussian beam, corresponding to snapshots taken at different

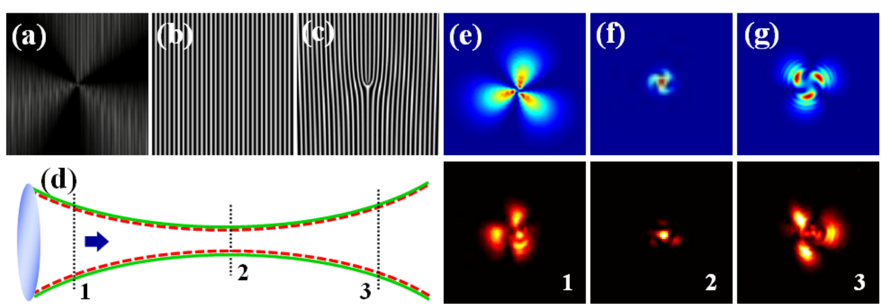

Fig. 2. (a) Moiré pattern used for generating 3-blade rotating beams by overlapping (b) a straight-line grating and (c) a fork-type vortex grating of topological charge m = 3. (d) Illustration of beam focusing and propagation of the Gaussian (solid) and vortex (dashed) components exiting from (a). (e)-(g) Numerical (top) and experimental (bottom) transverse intensity patterns taken at different longitudinal positions marked in (d), as retrieved from (a) with a single input Gaussian beam.

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longitudinal positions. Now that the 3-blade rotating pattern is established, forming rotating 3-trap tweezers seems trivial. However, with the moiré fringes [Fig. 2(a)] resulting from overlapping a simple straight-line grating [Fig. 2(b)] and a fork-type vortex grating [Fig. 2(c)], the rotating blades readily merge into a single spot at the focal point [Fig. 2(f)]. This can be better seen from the illustration in Fig. 2(d), which shows how the Gaussian beam (solid) and vortex beam (dashed) focus after retrieval from the moiré fringes in Fig. 2(a). Although the 3-blade structure is clearly visible at locations away from the focal point, it loses its fine feature in its intensity pattern at the focal point, where the intensity gradient is needed for forming the trap. As such, when tightly focused for optical tweezing, the 3-blade pattern generated in Fig. 2 is in essence no different from a single Gaussian beam trap.

To overcome the above problem, we employ a curved fork-type vortex grating [shown in Fig. 3(b)] as opposed to the straight-line fork-type grating [shown in Fig. 2(c)]. By overlapping the curved fork-type vortex (m = 3) grating [Fig. 3(b)] with the straight-line simple grating [Fig. 2(b)], a spiral-type moiré fringe is obtained, as shown in Fig. 3(a). Translating the line grating still leads to rotation of the beam passing through the two gratings. When the spiral moiré pattern is retrieved by sending through a single Gaussian beam, the output vortex component (from the curved vortex grating) has different wavefront convergence as compared to that of the Gaussian component (from the straight-line grating). Therefore, the fine feature of 3-blades is preserved even after tight focusing, as the Gaussian component is now focused at a different longitudinal position. A typical example for generating well-resolved 3-blade rotating beams is illustrated in Fig. 3, where (a) and (b) show the moiré pattern and the curved fork-type grating, (c) illustrates that the Gaussian beam (solid) and the vortex beam (dashed) have different focal points, and (d) and (e) show retrieved moiré intensity patterns with a single input Gaussian beam taken at different longitudinal positions. Clearly, the 3-blade pattern now can be tightly focused (at plane 2) without losing the fine structure (3 blades) needed for forming the rotating multi-traps. Similarly, other numbers of blades can be readily reconfigured by setting the curved vortex grating with different numbers of singularities.

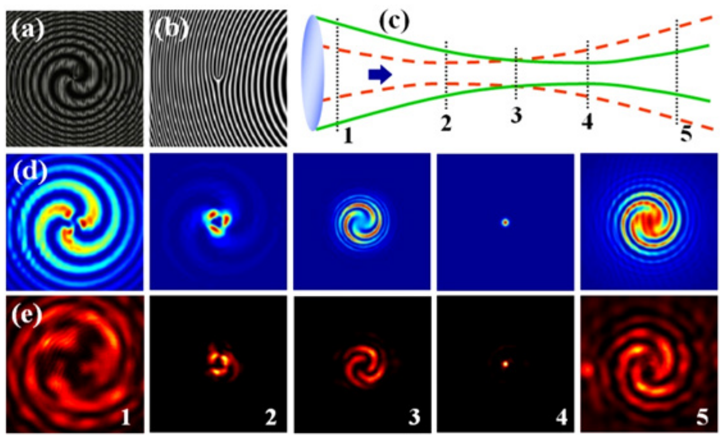

Fig. 3. (a) Moiré pattern used for generating 3-blade rotating beams by overlapping (b) a curved fork-type vortex grating (m = 3) with the straight-line grating shown in Fig. 2(b). (c) Illustration of beam focusing and propagation of the Gaussian (solid) and vortex (dashed) components exiting from (a). (d)-(e) Numerically (top) and experimentally (bottom) retrieved moiré patterns with a single input Gaussian beam at different longitudinal positions marked in (c).

3. Experimental results: controlled rotation of micro-particles and bacteria

To demonstrate optical trapping and manipulation with the propelling beams generated above, we employ an objective lens to tightly focus the beams down to several microns as in a typical setting for optical tweezers (Fig. 1). To prove the feasibility of our rotating traps, a sample of

#169107 - $15.00 USD Received 22 May 2012; revised 4 Jul 2012; accepted 15 Jul 2012; published 18 Jul 2012

2-μm polystyrene beads suspended in water is used. The motion of beads under the influence of the rotating beams is monitored from backscattered white light with a CCD camera. As expected, a rotating beam with a particular number of blades can trap and rotate the same number of particles by the optical gradient force, as shown in Fig. 4. By reversing the rotation of the propelling beam (achieved by reversing either the sign of vortex topological charge or the translation direction of straight-line grating), the rotation direction of the particles is also reversed. As seen in the media files, the polystyrene beads follow the propelling beam at the same frequency (about 0.1Hz). We emphasize that, since no interference or mechanical motion is involved in this technique, the dynamic multi-trap established here is very stable, not susceptible to ambient perturbations.

Next, we demonstrate stable trapping and rotation of biological specimens using the above setup. One sample we used involved live *E. coli* bacteria suspended in de-ionized water. The experimental results are shown in Fig. 5, where several snapshots of a rotating bacterium are displayed in different panels. Similar to the case for polystyrene beads, the trapped bacterium can rotate either in a clockwise or counter-clockwise direction, depending on the rotation direction of the trapping beam. The rotation speed of the bacterium is the same as that of the input rotating beam, with a period of roughly 40 seconds for a full 360° turn. Since the *E. coli* cell is somewhat rod-like, its shape does not appear the same in every picture as the bacterium moves in and out of the imaging plane. Trapping and rotating other bacteria of different shapes with our dynamic tweezers is currently underway, and issues such as the optimal beam configurations (2-blade, 3-blade, etc.) for trapping a specific bacterium or a particular cell

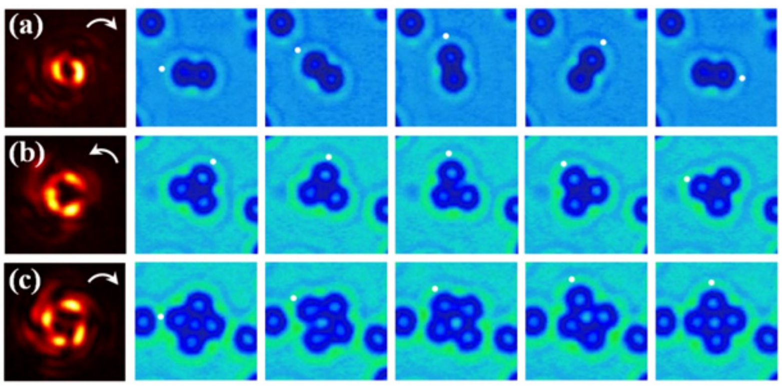

Fig. 4. Trapping and rotation of 2-μm polystyrene beads. Left column: generated multi-blade propelling beams (Media 1, Media 2, and Media 3); right columns: snapshots of trapped beads as driven by the rotating tweezers. (a) to (c) correspond to tweezing with propelling beams of 2-blades (Media 4), 3-blades (Media 5), and 4-blades (Media 6), respectively.

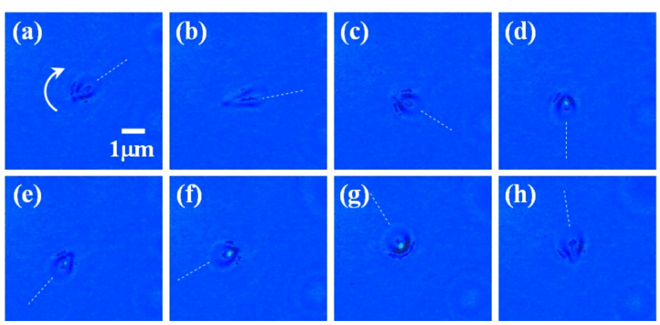

Fig. 5. Experimental demonstration of optical trapping and rotation of an *E. coli* bacterium (Media 7). (a)-(h) show snapshots of the *E. coli* cell in different orientations during rotation. The bacterium is about 2 μm in length and 1 μm in width. The white dashed line serves as a visual guide for the orientation of the bacterium, and the white arrow shows the direction of rotation.

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shape will be studied. These studies may lead to biological applications for our moiré-based rotating tweezers, such as sorting and separation of bacterial cells.

4. Optical propelling beam arrays generated with coherent and incoherent light

Finally, as a future development for this technique, we discuss the possibility of generating arrays of propelling beams. Simply by switching the fork-type grating associated with a single vortex into an array of fork-type gratings associated with a multi-vortex array, propelling beam arrays can be generated. The geometry of this arrangement, as well as the rotating direction of individual rotating beam in an array, can be readily controlled by the configuration and topological charges of the vortex array. Figure 6 (top panels) exemplifies a square array of rotating beams resulting from an array of triply-charged (m = 3) vortices, where (a) shows the grating design for the vortex array and (b) shows the corresponding moiré pattern, while (c) and (d) are results obtained from numerical simulation and experiment, respectively. Furthermore, by taking advantage of the fact that the moiré technique does not depend on the coherence of the illuminating light beams [23], we can generate all aforementioned propelling beams simply with an incoherent white-light source. This is quite different from the technique of the holographic optical tweezers [8,9], leading to the possibility of dynamic optical tweezers or tweezer arrays that are not only free from phase-sensitive vibrations but also totally based on incoherent light [24,25]. Figure 6 (bottom panels) shows some typical examples of white-light propelling beams and arrays of such beams, as demonstrated in our experiments. To obtain intensity profiles of the generated rotating beam arrays with a single uniform input, we have encoded periodic modulations onto the overlapped gratings [see Figs. 6(b), 6(e), and 6(g)]. Such white-light propelling beams may be useful in developing multi-functional dynamic white-light tweezers.

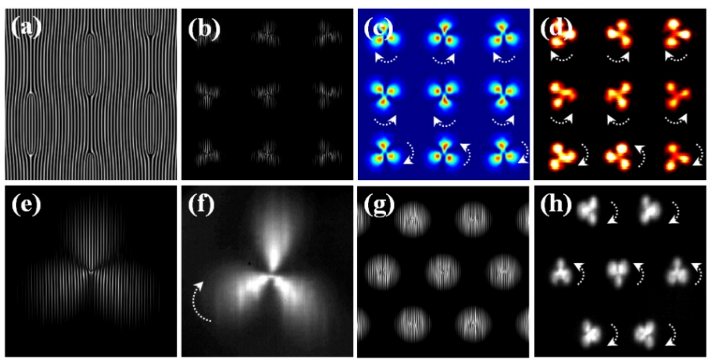

Fig. 6. (a-d) Generation of optical propelling beam arrays with coherent light. (a) shows the grating design corresponding to a desired optical vortex array; (b) moiré pattern created by overlapping the grating in (a) with a straight-line grating as shown in Fig. 2(b); (c, d) Numerically (Media 8) and experimentally (Media 9) reconstructed array of rotating beams. (e-h) Experimental demonstration of (e, f) a single optical propelling beam and (g, h) an array of such beams with incoherent white light, where (e) and (g) are the moiré patterns, and (f) and (h) show one snapshot of the generated rotating beams (Media 10 and 11).

5. Summary

We have proposed and demonstrated trapping and rotation of microparticles and bacteria with moiré-based rotating optical tweezers. We show that such dynamic multiple-traps based solely on the moiré technique are inherently immune to environmental perturbations. Our findings may have applications in multifunctional tweezing for biological research. In addition, the technique proposed here for rotating beam generation based on coherent and incoherent light sources may be useful for studying stirred Bose-Einstein condensates [26] or investigating complex nanofluidic dynamics [27].

#169107 - $15.00 USD Received 22 May 2012; revised 4 Jul 2012; accepted 15 Jul 2012; published 18 Jul 2012

Acknowledgments

This work was supported by NSF (PHY-1100842), AFOSR (grant nos. FA9550-10-1-0561 and FA9550-12-1-0111), and NIH (SC2GM082318).

#169107 - $15.00 USD Received 22 May 2012; revised 4 Jul 2012; accepted 15 Jul 2012; published 18 Jul 2012