Crossed fiber optic Bessel beams for curvilinear optofluidic transport of dielectric particles

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Abstract: Due to its unique non-diffracting and self-reconstructing nature, Bessel beams have been successfully adopted to trap multiple particles along the beam's axial direction. However, prior bulk-optic based Bessel beams have a fundamental form-factor limitation for in situ, in-vitro, and in-vivo applications. Here we present a novel implementation of Fourier optics along a single strand of hybrid optical fiber in a monolithic manner that can generate pseudo Bessel beam arrays in two-dimensional space. We successfully demonstrate unique optofluidic transport of the trapped dielectric particles along a curvilinear optical route by multiplexing the fiber optic pseudo Bessel beams. The proposed technique can form a new building block to realize reconfigurable optofluidic transportation of particulates that can break the limitations of both prior bulk-optic Bessel beam generation techniques and conventional microfluidic channels.

OCIS codes: (060.2310) Fiber optics; (350.4855) Optical tweezers or optical manipulation; (140.3300) Laser beam shaping; (070.7345) Wave propagation; (230.3990) Micro-optical devices.

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1. Introduction

The gradient force in a tightly focused Gaussian laser beam has been applied to optical tweezers (OT) [1] for flexible manipulation of atoms in vacuum and Nano-bio particles in liquid [2–5]. Single optical trap technologies have been further expanded and multiple traps on the transverse plane have been successfully demonstrated by holographic technique, micro-mirror array imaging, and optical interference patterning [6–8], to name a few. In contrast, longitudinal traps have been realized mainly by laser beam shaping technology: transforming Gaussian beam into Laguerre-Gaussian and Bessel beams [9,10]. Despite independent successes, these transverse and longitudinal multiple optical trapping methods have not been fully compatible with one another to cast a fundamental limit in realizing arbitrary three dimensional OT capability.

Pseudo-Bessel beams have been on the center of recent OT research efforts due to their unique non-diverging and self-reconstructing characteristics, which enabled trapping of multiple particles along the axial length extending over a few millimeters [11]. These beams have been generated using bulk optics such as Fourier transformation of an annular slit and axicon lens [12–14], which require precise mechanical alignments and stability control. In recent reports, an Airy beam has been formed by a spatial light modulator to trap and transport particles [15], which can be applied in optical sorting and clearing of particles. However those results were still based on bulk optics, which have prevented OT technologies from finding in situ, in-vitro, and in-vivo applications in the microscopic environment. Preliminary efforts to shape the beam using fiber optics have been reported such as using Fresnel fibers or related specialty fibers [16–19].

In comparison to the precise single particle manipulation capability of OT, microfluidic technologies have shown an advantage in high throughput manipulation of particles along pre-defined channels using the liquid flow, or pressure [20,21]. However microfluidic channels should avoid long-range turbulences in the liquid flow [22], which casts a fundamental limitation in the radius of curvature of the fluid channels, liquid flow rate, and flexibility in transportation paths.

To take the advantage of compact and flexible guidance of light, fiber-optic based optical tweezers have been attempted [23–25]. Recently preliminary reports of fiber optic Bessel-like beams were reported by the authors utilizing both multimode interference (MMI) [26] and fiber optic Fourier transform [27,28] to experimentally demonstrate longitudinal trapping of multiple particles.

In this study, we report the first realization of spatially multiplexed fiber optic pseudo Bessel beam crossings to demonstrate true curvilinear optofluidic trapping and transportation of dielectric particles along a microscopic curvilinear optical route. The proposed technique can surpass the prior capabilities of conventional microfluidic channels and simultaneously overcome the fundamental limitations of prior bulk optic OT techniques. Beam forming mechanism will be briefly explained and subsequently description on multiplexing fiber optic pseudo Bessel beams is made, then we will discuss novel feature of 3-D optofluidic transportation provided by the propose technique.

2. Fourier transformation along a single strand of optical fiber in the microscopic scale

It was Durnin's first experimental demonstration that showed an optical beam, other than the ideal plane wave, can propagate over a macroscopic distance in a non-diffracting manner [12]. This pseudo-Bessel beam can be physically interpreted as the Fourier transformation of an annular aperture (AA) and its generation scheme is shown in Fig. 1(a), where the plane wave incident upon the AA is Fourier transformed by the focusing lens. The authors have preliminarily proposed implementing Fourier transformation along a single strand of hybrid optical fiber as depicted in Fig. 1(b) [28]. The device is composed of three segments of optical fibers: single mode fiber (SMF), hollow optical fiber (HOF), and coreless silica fiber (CSF), along with the integrated polymer lens (PL) at the end-facet of CSF. The fundamental mode in the SMF is adiabatically transformed to an annulus mode in the tapered hollow optical fiber (HOF), which has a central air hole surrounded by a high index ring core [29]. Note that the light confined in the ring core of HOF facet serves as a micro annular aperture, from which the light diffracted into the spatial frequency components along the CSF. The PL formed at the cleaved end-facet of CSF [30] completes Fourier-transform. Note that all the physical functions of bulk optic elements in Fig. 1(a), whose dimension is over a few centimeters, were realized along the single strand optical fiber with the common outer diameter of 125μm. The photograph of fabricated device is shown in Fig. 1(c) and its output beam inside a colloidal liquid is shown in Fig. 1(d) with the non-diffracting length ~1 millimeter.

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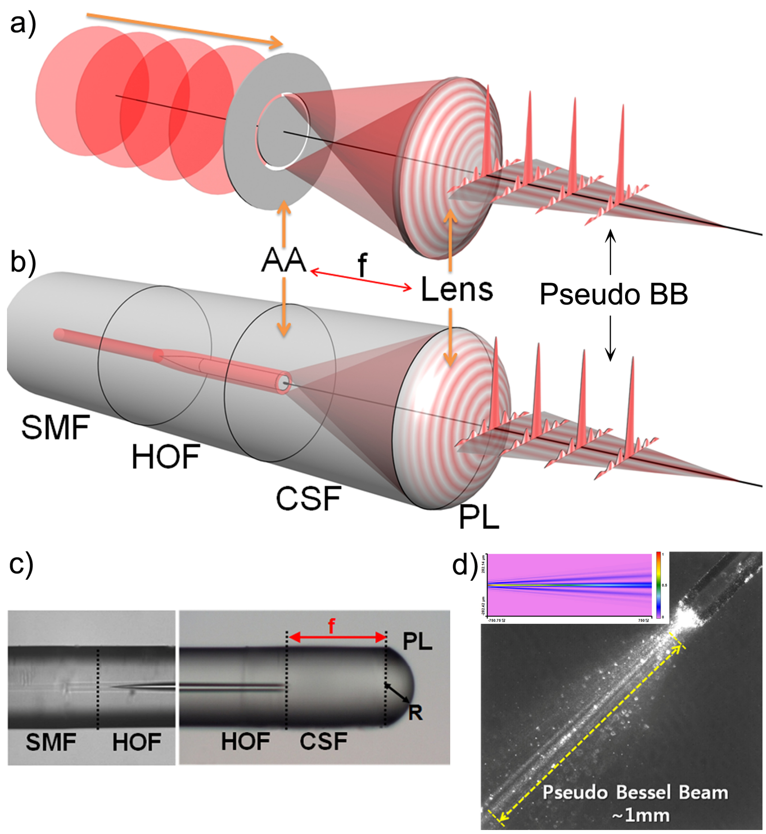

Fig. 1. (a) A schematic diagram of conventional Bessel beam generation by Fourier transform of a thin annular aperture (AA) using a focusing lens with focal length f [12], (b) Principle of implementing Fourier optics along a hybrid optical fiber. Here SMF, HOF [29], CSF, and PL are acronyms for single mode fiber, hollow optical fiber, coreless silica fiber and polymer lens, respectively. (c) Photography of fabricated device. (d) Side-view of the output beam from the fabricated device and (inset) simulation.

3. Microscopic curvilinear optofluidic route formed by pseudo-Bessel beam crossings

3.1 Curvilinear optofluidic experiment by pseudo-Bessel beam crossings

Flexible multiplexing capability in space, time, and spectral domains has been the key advantage in the all-fiber solutions [31]. Utilizing fiber optic probes, we successfully multiplex three pseudo Bessel-beams making angled crossings and furthermore demonstrated a unique reconfigurable curvilinear optical route that has not been achieved in prior reports. Schematic diagram is shown in Fig. 2 where three fiber optic Bessel beams were crossed sequentially making an angle of ~60°. A polystyrene dielectric particle was initially trapped by the pseudo Bessel beam-1 and subsequently transported along it. At the crossing of beams 1 and 2, marked as a dotted circle with a label 'Crossing 1', we were able to change the particle's path from the beam 1 toward the beam 2, utilizing the optical power difference between the beams. Due to competition in the trapping force between the beam 1 and 2, the optical crossing resulted in a unique curvilinear route. After being transported along beam 2, the particle's path was once again changed to beam 3 at the 'Crossing 2' along another curvilinear route. Finally the particle continued a linear motion along the beam 3.

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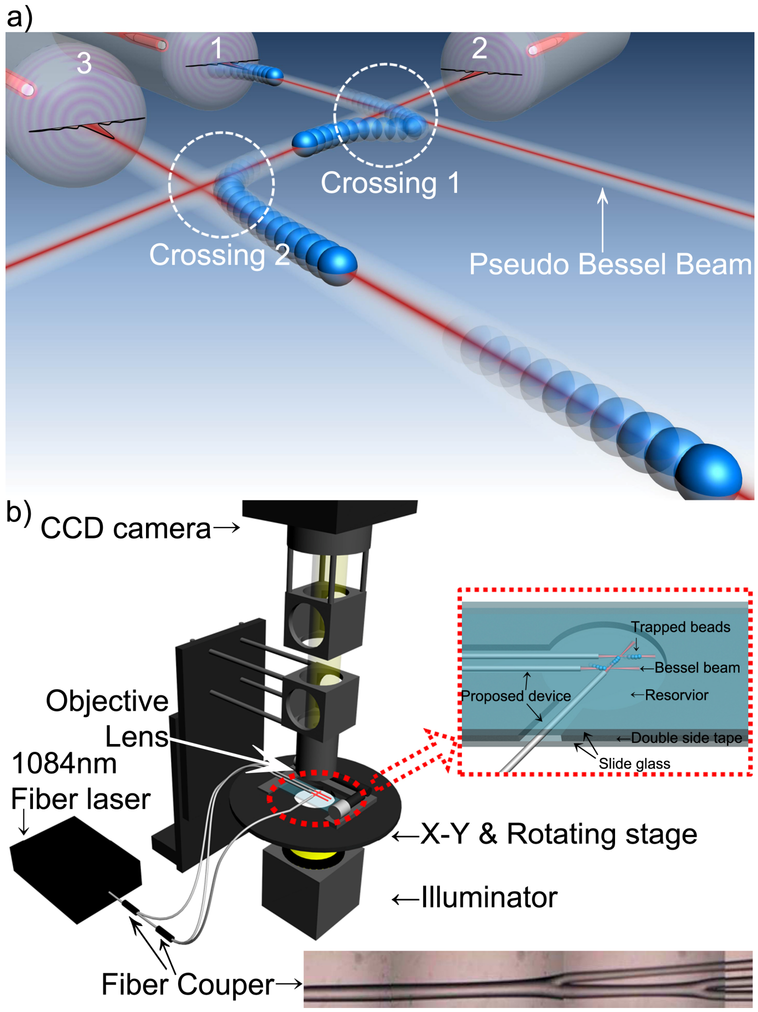

Fig. 2. (a) Schematics of the fiber-optic pseudo Bessel beam array for trapping and transporting of particles along curvilinear optical routes. (b) Monitoring setup of the pseudo Bessel beam and particle movement: trapping and transporting.

In experiment, we fabricated three identical fiber optic Bessel beam generators as in Fig. 1(c), whose performance was optimized at the wavelength of 1084nm, the output of an Yb-doped fiber laser. The non-diffracting length was about ~1mm and the central beam diameter was ~2μm. We fabricated a 1 × 3 fiber optic power splitter by fusion and tapering process to equally distribute the laser power at λ = 1084 nm to three fiber probes and the photograph of the device is shown in the bottom-right in-set diagram of Fig. 2(b) [32]. Three fiber probes were individually spliced to the outputs of the splitter with a negligible insertion loss of less than 0.1 dB. The fiber probes were then spatially multiplexed directly inside a sample reservoir where the polystyrene beads were dispersed, as shown in the top-right in-set diagram in Fig. 2(b).

The sample reservoir was fabricated using a double side masking tape, sandwiched between two slide glasses. The chamber had a form of a shallow cylinder with a radius of ~10mm, and a height of ~200 μm. Here we deliberately made an angle of 60° between probe 1 and 2, whereas probe 1 and 3 were arranged near parallel to each other. The output power from the probes was kept below 60 mW to inhibit local heating of liquid. Polystyrene beads with the diameter of 15 μm and the refractive index of 1.571 were dispersed in water and a volume of ~15.7 μl was dropped inside the reservoir. We did not use any of flow and pressure control of the liquid and the liquid was kept stagnant during the experiments. The assembled reservoir and fiber arrays were mounted on an inverted microscope with 10 times magnification and the images were recorded on a CCD camera mounted on the eye-piece. Note that all the fiber optic Bessel beam generators were directly immersed inside the liquid sample reservoir without using additional bulk optics, which has not been achievable in the prior Bessel beam applications. It is also noteworthy that the fiber probes were fed through narrow channels with a width less than 500 μm, which opened a further opportunity for syringe based optical trapping for in-vivo applications, which are being investigated by the authors.

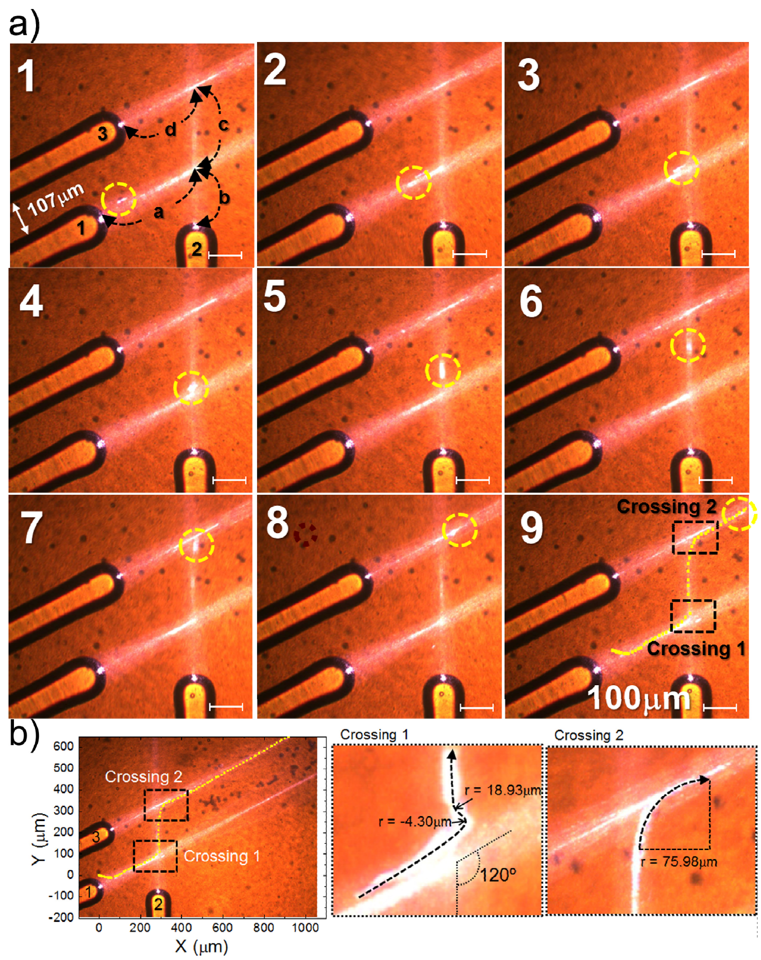

Fig. 3. (a) Captured frames from the pseudo-Bessel beam array experiment (: "a"-304.9μm, "b"-173.5μm, "c"-247.0μm, "d"-239.2μm at frame-1); Frames 3 to 5 correspond to "Crossing-1". Frames 7 and 8 correspond to "Crossing-2". (b) Detailed traces of trapped particle's curvilinear routes at the pseudo-Bessel beam crossings: "Crossing-1" and "Crossing-2" (Media 1).

Utilizing the axial beam intensity distribution of the proposed pseudo Bessel beam [28], the locations of the beam crossings were deliberately chosen to configure a curvilinear route and the actual fiber array configuration is shown in Fig. 3.

Captured frames are collected sequentially in Fig. 3(a). The frames from 3 to 5 correspond to the "Crossing 1" in Fig. 2(a) and the frames 7, 8 to the "Crossing 2" in Fig. 2(a). The trace of the trapped particle is denoted in the dotted circle in each frame, and the over-all optical route is marked as dotted line in the frame 9. These experimentally observed curvilinear

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optical routes confirm the unique potential of the proposed device and its arrays for all-optical trapping and transport of particles in macroscopic curvilinear routes. Real-time motions of the trapped particle along the curvilinear optical routes are shown in Media 1.

Magnified traces of the particle near the “Crossings” are shown in Fig. 3(b). The “Crossing 1” showed a composite motion; a unique transition from a counter-clockwise rotation with the radius curvature of 4.30 μm to the clockwise rotation with the curvature of 18.93 μm to result in an “S” shaped optical route. In contrast, the “Crossing 2” showed only the clockwise rotation with a much larger radius of curvature of 75.98 μm. Note that this optical route was formed by three identical pseudo Bessel beams with equal fixed optical power. The radii of curvature were controlled by the position of the beam crossing, where the attractive optical forces of two beams differed. Further complex routes can be readily formed by controlling the optical power of the beams individually, and the authors are investigating a multiplexed beams with a larger number counts.

3.2 Numerical calculation of curvilinear optofluidic route by optical forces

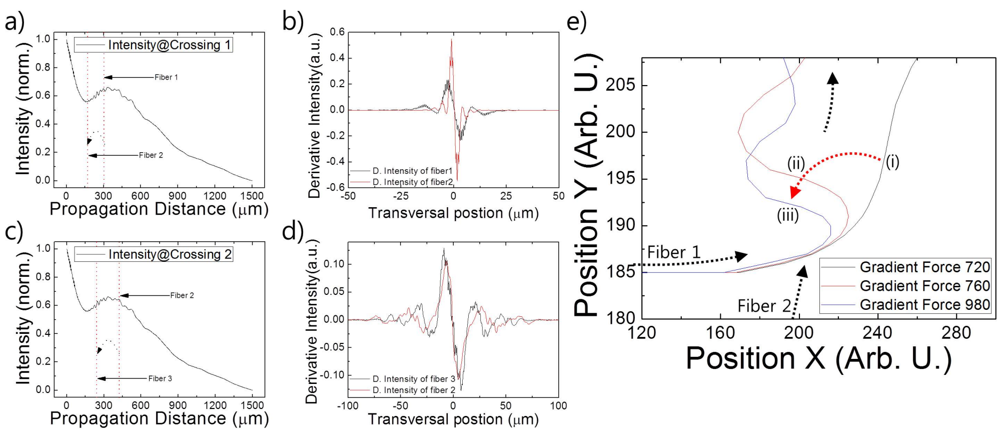

Fig. 4. (a)-(d)The comparison of the optical forces at crossings 1 and 2 (a) Optical intensity of fiber 1 and 2 at crossing 1 (b) Derivative of intensity of fiber 1 and 2 at crossing 1 (c) Intensity of fiber 2 and 3 at crossing 2 (d) Derivative of intensity of fiber 2 and 3 at crossing 2 (e) Numerical calculation of particle movement dependent on the gradient force at the crossing point. Here we assumed relative gradient force of 720, 760, and 980 for route (i), (ii), and (iii), respectively.

The experimental result of curvilinear optofluidic route was verified by theoretically analyzing the dynamics of the particle under the optofulidic dynamics [33–35]. We used the experimentally obtained a fiber optic Bessel beam intensity distribution on the x-z plane. To perform a simulation of crossed fiber optic Bessel beams, we formed a two-dimensional force field by placing two intensity distributions of the fiber optic Bessel beams in an angle of 60 degrees, which represented the crossing 1 and 2 in Fig. 3. Then we calculated the total optical forces near the crossing points and simulated the particle trajectories. Figures 4(a) and 4(c) show us the intensity distribution of the Bessel beams and locations at the crossing 1, and 2, respectively. Optical forces along a laser beam consisted of the scattering and gradient forces [4,9,34]. Although generated scattering forces from fiber 1 and 2, which induce the scattering forces, were not much different. However their derivatives, which induce the gradient forces, varied significantly at the crossing 1 and 2. Therefore, we fixed the scattering forces as in the experiments and only varied the gradient force of fiber 2 in this simulation.

We found that the magnitude of the gradient force from the fiber 2 significantly alter the radius of curvature at the crossing as summarized in Fig. 4(e). For a weaker gradient force, we could achieve a curvilinear route with a larger radius, as in the route (i) of Fig. 4(e). On the other hand, a stronger gradient force showed an abrupt change of radii of curvature with a smaller value as in route (ii) and (iii) in Fig. 4(e). Comparing the simulation and experimental data, we found the crossing 1, 2 in Fig. 3(b) correspond to the route (iii) and (i) in Fig. 4(e) and we could confirm the simulation agreed well with experiments.

4. Discussion

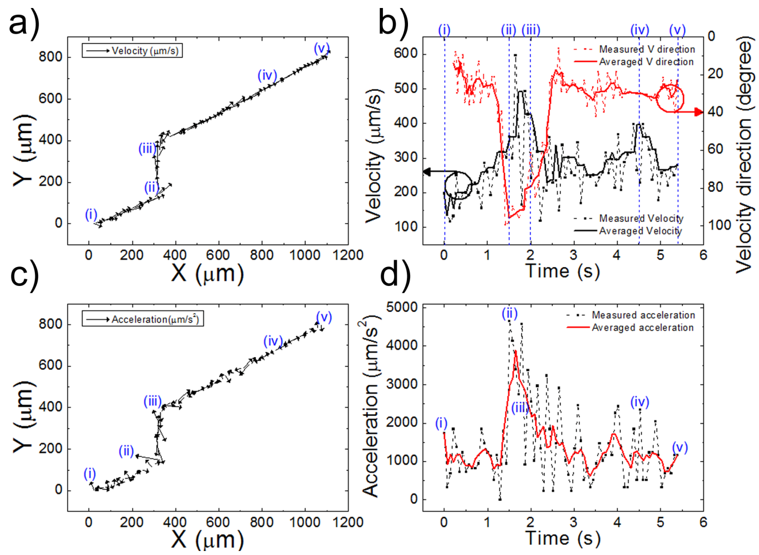

Fig. 5. (a) Velocity and (c) acceleration vectors of the particle along the curvilinear optical route. (b) Magnitude and direction of the velocity as a function of time. (d) Magnitude of the acceleration as function of time.

In order to investigate the kinetic perspectives of optical transport in the proposed Bessel beam arrays, we analyzed the tracks of the trapped particle frame by frame. The velocity and acceleration of the particle along the curvilinear optical route in Fig. 3 were calculated and their vectorial representations are plotted in Figs. 5(a) and 5(c), respectively. In Fig. 5(b) and 5(d), we plotted the magnitude and direction of the velocity vector and acceleration vector, respectively. Here we particularly marked 5 points of interests; (i) Initial trapping point, (ii) Crossing 1, (iii) Crossing 2, (iv) Normal transport point and (v) Final point in Fig. 5.

Near the point (i), we observed that the after the particle is trapped by the pseudo Bessel beam 1, its speed increased along the beam direction, which is attributed to the gradient force and radiation scattering force from the beam 1. Near the point (i) during the initial ~1.4 second, the particle had a linear motion with an average velocity of ~218 μm/s making an angle of ~30 degree. Along the section between point (i) and point (ii), the particle experienced an averaged acceleration of ~1000 μm/s^2, which corresponded to optical scattering force about 30 pN. When the particle's velocity continuously increased up to ~360 μm/s along the beam 1, the particle reached the Crossing 1, experiencing a more prominent influence from the beam 2. As show in Fig. 5(b) the particle direction significantly changed counter-clockwise with ~105 degree and then rapidly attracted to the beam 2 by turning the direction clockwise with ~44 degree. See Fig. 3(b), and Fig. 5(b) at the point (ii), Crossing-1, the proximately located beam 2 dominantly contributed to the acceleration of particle ~4000 μm/s^2, which corresponds to the optical force of 70 pN. The balance between two optical forces from the beam 1, and 2, provided a unique "S" shaped curvilinear route with radius curvature of ~4.30 μm in the counter clockwise and ~18.93 μm in the clockwise direction. Note that the radius of curvature of 4.3 μm in the "Crossing 1" is less than 1/3 of the particle's diameter and this level of abrupt and acute change in the particle motion has not been attainable in conventional micro-fluidic channels whose channel-width inevitably has to be larger than the particle diameter. After the point (ii), the particle maintained a linear motion with ~91 degree along the beam 2 until it reached the point (iii). The total displacement of this section was ~194.2 μm, and it took ~0.43 second for particles with an average velocity of ~451.6 μm/s. This segment, especially near the Crossing 1, corresponded to the high intensity region of the beam 2, consistent to prior fiber optic pseudo Bessel beam [28], to result in a higher acceleration than other segments. Velocity induced higher optical force than other sections. At the point (iii), the Crossing-2, the trapped particle had a velocity of ~420 μm/s and an acceleration of ~2500 μm/s^2 that corresponded to an optical force of ~35pN. Near this point, the particle's moving direction was changed from ~91 degree to ~30 degree with the counter clockwise radius of curvature of ~75.98 μm at "Crossing-2". Due to the characteristic of intensity profile of the fiber optic Bessel beam [28], the particle velocity slightly rose to ~400 μm/s. After the point (v) the particle followed the linear motion along the beam 3 with continuously decreasing scattering optical force.

The entire displacement from (i) to (v) was ~1.47 mm which took ~5.4 second. The average velocity along the entire curvilinear optical route was ~270 μm/s. The Reynolds number of the polystyrene particle's motion in the water was estimated as low as ~10^{-3} to ensure the laminar flow. This Reynolds number is less or equivalent to prior microfluidic channels and we confirmed that the optical routes formed by multiplexed pseudo Bessel beams can provide a non-turbulence transport along a macroscopic distance.

The velocity profile in terms of speed and direction can be flexibly controlled by the longitudinal optical power distribution of each pseudo Bessel beam and the geometrical configuration of multiplexing.

5. Conclusion

In conclusion, we successfully explored a new aspect of the modal intensity distribution in a hollow optical fiber as micro-apertures in order to generate pseudo Bessel beam using a monolithic optical fiber solution. Three pseudo Bessel beams were spatially multiplexed using fiber optic couplers to provide a unique curvilinear optical route for a dielectric particle. Along these routes, both counter-clockwise and clockwise rotations were achieved along with variable radius of curvature in the range from ~4.30 to ~75.98 μm. This type of curvilinear optical route can be a strong alternative to conventional micro-fluidic channels, providing unprecedented levels of control over the speed and angular motion of micro-particles in solution. Further applications of this technique to living cells are can provide a new level of precise control of motion in the microscopic in-vivo environment.

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