Higher-order micro-fiber modes for Escherichia coli manipulation using a tapered seven-core fiber

QIANGZHOU RONG,1,* YI ZHOU,1 XUNLI YIN,2 ZHIHUA SHAO,1 AND XUEGUANG QIAO1

1Department of Physics, Northwest University, Xi’an 710069, China
2School of Science, Xi’an Shiyou University, Xi’an 710065, China
*qzrong2010@gmail.com

Abstract: Optical manipulation using optical micro- and nano-fibers has shown potential for controlling bacterial activities such as E. coli trapping, propelling, and binding. Most of these manipulations have been performed using the propagation of the fundamental mode through the fiber. However, along the maximum mode-intensity axis, the higher-order modes have longer evanescent field extensions and larger field amplitudes at the fiber waist than the fundamental mode, opening up new possibilities for manipulating E. coli bacteria. In this work, a compact seven-core fiber (SCF)-based micro-fiber/optical tweezers was demonstrated for trapping, propelling, and rotating E. coli bacteria using the excitation of higher-order modes. The diameter of the SCF taper was 4 µm at the taper waist, which was much larger than that of previous nano-fiber tweezers. The laser wavelength was tunable from 1500 nm to 1600 nm, simultaneously causing photophoretic force, gradient force, and scattering force. This work provides a new opportunity for better understanding optical manipulation using higher-order modes at the single-cell level.

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1. Introduction

Escherichia coli (E. coli) bacteria form a large and diverse group of bacteria that are commonly found in food, the environment, and the intestines of people and animals. Although most strains of E. coli bacteria are harmless, others can cause illnesses, such as diarrhea, urinary tract infections, respiratory illness, and pneumonia. To completely study the properties of E. coli, the motion of the bacteria needs to be controlled.

Optical manipulation is an efficient and precise method for controlling and delivering microscopic objects to a desired position by providing stable, accelerated, or directional control on the motion of micro- or nanoparticles. Specifically, this method applies high local confinement to specimens of biological interest using an optical trapping field. Conventionally, optical tweezers use a microscope objective with a high numerical aperture to focus a laser beam for producing an optical force on microscopic objects and consequently controlling the activities of the objects. Recently, the use of fiber optics has produced more flexible optical tweezers than those produced with conventional space-optics methods [1, 2].

On the other hand, photophoresis can be used to create a non-uniform distribution of temperature for an illuminated particle in a fluid medium, yielding a larger trapping volume than the small waist of the focused beam in optical tweezers. Small particles suspended in liquids start to migrate when illuminated by a sufficiently intense beam of light [3, 4]. Similar to Crookes radiometer [5], light can be used to heat the region on one side of the particles, hence using the temperature gradient to push the particle away from the light source. Under certain conditions, namely when particles have a diameter comparable to the wavelength of...
light, the phenomenon of negative indirect photophoresis occurs. In negative indirect photophoresis, a temperature gradient is produced in the medium around the particle such that particles far from the light source heat up more, causing the particles to move towards the light source [6–8]. To strongly couple the light from the fiber to the liquid, the fiber is usually tapered to have nanometer-order diameter [9, 10]. Because the photophoretic force is usually orders of magnitude larger than optical gradient force, the particles can be moved to the fiber light source at the large scales. Therefore, this technology is effective at trapping larger amounts of particles and moving them to the different positions, but photophoresis is unable to be used for optical manipulation on a single particle [1–3, 11–14].

The evanescent field of a waveguide can also create strong optical forces, not only producing a larger trapping volume at its surface than that of an optical tweezers but also overcoming limitations imposed by the Rayleigh range. Such optical waveguides are capable of offering long-range controllable transport of micro- and nano-objects [15–18]. Among waveguides, optical micro/nanofibers (MNFs) are usually easily formed with a flexible structure and are readily integrated into other optical fiber systems [19, 20]; thus, optical MNFs are rapidly developing as a common tool for controlling particles in a liquid. The single mode fiber can easily be tapered to the nanoscale diameters, in which the evanescent field of the fundamental core mode is strongly coupled and surrounds the taper tip and waist. Recent studies have used high-order modes for particle manipulation due to advances in accessing the higher-order modes in MNF fabrication [15, 21]. These studies exploited the extension of the longer evanescent field from the fiber surface that occurs in the high-order mode, the three-dimensional (3D) arrangement of the field, and the larger cut-off waist diameter of the fiber compared to that needed for high-order mode propagation.

Most fiber-optics tweezers applications have been mainly concerning with realizing particle trapping and propulsion, rather than micro-particle rotation, because of the symmetrical evanescent field distribution and symmetrical body of the objects. Recently, the rotation operation has been realized by multiple optical-fiber tweezers with the support of multiple micromanipulation motors [22–24]. Another simple method adjusted the optical field distribution to change the position of the particle in the liquid. For example, the distribution of light power was controlled by changing the light coupling in a taper-assisted four-core fiber tip [25], resulting in a rotation torque on the micro-particle that realized controllable particle rotation. However, achieving an optimal fiber splice (large offsets may create strong light polarization that influence the rotation torque) and symmetrical fiber tip (a key factor influencing the power distribution surrounding the tip) has been challenging.

In this study, we took advantage of the photophoretic force and the evanescent field illuminated by tapered seven-core fiber (SCF) and realized several interesting observations on E. coli trapping, propelling, and rotation. In the SCF structure, the high-order mode was excited, which effectively improved the optical manipulation ability and mechanical strength of fiber tweezers compared to the fundamental-mode-based nano-fiber. The optimal wavelength of the light of 1560 nm simultaneously produced a large photophoretic force, gradient force, and scattering force, enabling the high-order SCF to be used as a new tool for optical manipulation on E. coli bacteria.

2. Theory analysis and experiment setup

When the laser with a wavelength near 1550 nm is launched into the vivo system, the radiated E. coli bacteria will experience negative photophoretic force $F_p$ [14]. Meanwhile, due to the strong absorption of the 1550-nm light by water, which has absorption coefficient $\alpha = 10.9$ cm$^{-1}$ [26], the temperature of water will increase by

$$\Delta T = \frac{\eta f \tau}{c pd}$$  \hspace{1cm} (1)
where \( d \) is the effective depth of water for light absorption, \( \rho \) is the density of water, \( \tau \) is the thermal relaxation time, \( f \) is the power flow, and \( \eta \) is the light absorption ratio of water. The temperature distribution is mainly caused by the light intensity distribution in the water. This temperature gradient will generate force \( F_T \) that acts on E. coli against \( F_p [1] \). Thus, the joint force \( F_{pT} \) will be exerted on the E. coli bacteria. Far from the fiber, the temperature gradient distribution is weak, so the \( F_p \) is the main force acting on E. coli bacteria. When the E. coli bacteria are close to the fiber region, which provides stronger light illumination, the temperature gradient becomes more dominant, resulting in stronger \( F_T \).

When the E. coli bacteria are close to the surface of the fiber, the interaction between the surface evanescent field of the optical micro-fiber and the dielectric micro-object (i.e., the E. coli bacteria) produces three different optical forces on the objects [17]. The trapping force, also called the gradient force \( F_g \), is generated because of the temporary polarization of a dielectric particle in a non-uniform field. The other forces are the results of radiation pressure. In particular, the scattering \( F_s \) and absorption \( F_a \) forces are responsible for the movement of particles along the optical axis of the fiber. As particles are transported over a timescale much longer than the optical period of the incident fields coupled into the fiber, the total optical force \( F \) and fluidic drag force \( F_D \) (the microfluidic effect on particles near the micro-fiber surface) exerted on the E. coli bacteria can be obtained by integrating the time-independent Maxwell stress tensor \( T_M \) and the flow stress tensor \( T_F \) along the enclosing surface of the E. coli bacteria, respectively. The time-independent Maxwell stress tensor can be written as [27]

\[
\langle T_M \rangle = D E^* + H B^* - \frac{1}{2} \left( D \cdot E^* + H \cdot B^* \right) I
\]  

(2)

where \( D \) and \( H \) are the electric displacement and magnetic field, respectively, \( E^* \) and \( B^* \) are the complex conjugates of the electric field \( E \) and magnetic flux field \( B \), respectively, and \( I \) is the isotropic tensor. The total force \( F \) can be given by [28]

\[
F = \oint_S \left( \langle T_M \rangle \cdot n \right) dS
\]  

(3)

where \( n \) is a normal vector pointing in the outward direction from the surface \( S \). Note that \( T_M \) can be written as

\[
T_M = -p I + \mu \left( \nabla v + \nabla v^T \right)
\]  

(4)

where \( p \) is the pressure, \( \mu \) is the viscosity, and \( v \) is the flow velocity vector. Thus, the fluidic drag force can be given by

\[
F_D = \oint_S \left( \langle T_F \rangle \cdot n \right) dS
\]  

(5)

For a non-absorptive particle, the force acting on the particle can be derived as the sum of the scattering force \( F_s \) along the fiber axis and the gradient force \( F_g \) perpendicular to \( F_s \):

\[
F = F_g + F_s
\]  

(6)

Here,

\[
F_g = \frac{1}{4} \Re(\alpha) \nabla |\varepsilon|^2
\]  

(7)

where \( \alpha \) is the electric polarizability of the particle (the conventional Mie coefficient), and \( \varepsilon \) is the complex amplitude of the electric field.

If we assume that the spin component of the field contributing to the force is negligible, the scattering force can be described as
$F_s = \sigma_{\text{ext}} \frac{n^2_2}{c} S$  \hspace{1cm} (8)

where $S$ is the Poynting vector, $\sigma_{\text{ext}}$ is the extinction cross-section of the Rayleigh particle, and $n^2$ is the refractive index of the medium.

Because the E. coli bacteria is normally ellipsoidal, the optical momentum density $g = nS/c$ on E. coli differs (such as that at point A, shown in Fig. 5(b)), resulting in the time average change of momentum density given by [29]

$$\langle \Delta g \rangle = \langle \Delta g_{\text{ad}} \rangle - \langle \Delta g_{\text{al}} \rangle$$ \hspace{1cm} (9)

According to momentum conservation theory, the force acting on the $ds$ region of point A can be described by

$$F_A = \langle \Delta g_{\text{ad}} \rangle - \langle \Delta g_{\text{al}} \rangle \cdot ds$$ \hspace{1cm} (10)

The force acting on E. coli along the $x$-direction and $y$-direction can be given, respectively, by

$$F_x = \int F_{x, ds} \cdot ds \quad \text{and} \quad F_y = \int F_{y, ds} \cdot ds$$ \hspace{1cm} (11)

As a result, the E. coli cell can be rotated by torque

$$\tau = F_z \cdot z - F_x \cdot x$$ \hspace{1cm} (12)

Fig. 1. Experimental schematic and characterization of the modified tapered fiber and E. coli bacteria: (a) schematic illustration of the experimental setup, (b) magnified image of the interaction region, (c) photograph of the SCF cross-section, (d) and (e) simulations on gradient and scattering forces on rod-shaped E. coli with different positions in the microfiber evanescent field, (f) schematic illustration of the optical trapping and single E. coli motion, (g) SEM image of the fiber taper, and (h) and (i) SEM images of two E. coli.
Figure 1 schematically shows the stable trapping, direct propelling, and rotation of E. coli bacteria. The experimental setup was designed as shown in Fig. 1(a). A tunable laser (Santec, 710) with 100-kHz linewidth, 0.1-µm tunable resolution, up to 80-mW tunable output power, and wavelength range of 1500 nm to 1600 nm was employed as the light source. The light source was coupled into the micro-fiber (MF) immersed in the water dispersion. A computer was connected to charge-coupled device (CCD) for capturing images. Figure 1(c) shows an optical microscope image of the cross-section of the SCF before the tapering operation. There are seven cores over the fiber cladding, in which six cores surround a center core. The fiber cladding has a diameter of 125 µm, the fiber cores have the same diameter of 6 µm, and the separation between the cores is 35 µm. A 5-mm-long SCF was spliced between two single-mode fibers (SMFs) and was drawn using a flame-heating technique. The diameter of taper waist region was $d = 4 \mu m$, which is several times larger than that of the MNF-based tweezers [2, 15–20]; however, the SCF functions as a good tool for optical manipulation thanks to the strong coupling effect of the multiple-core structure. Figure 1(d) and 1(e) show simulations for $F_g$ and $F_s$ exerted on rod-shaped E. coli with different positions in the evanescent field. Figure 1(g) shows a scanning electron microscope (SEM) image of the tapered SCF with a 1.3-µm waist diameter, in order to verify the smoothness of the tapered SCF surface. To avoid fiber-bending influence on the light power, both sides of fiber taper were mounted on a glass plate, and the taper region was suspended in the E. coli liquid. Figures 1(h) and 1(i) respectively show SEM images of E. coli bacteria with two shapes (produced by Shanghai Ruichu Biotech Co., Ltd., China): a diameter of 0.3 µm and a length of 1.8 µm, and a diameter of 0.4 µm and a length of 0.6 µm. The initial concentration of E. coli sample is approximately $5 \times 10^5$/mL. In the experiment, to observe few E. coli motions, the initial sample was diluted to approximately $10^5$/mL. Before SEM imaging, the E. coli bacteria were pre-processed following the method in [20].

To explain the results in the following sections, a finite-element method (FEM) was used to simulate the $E$-field distribution along the micro-fiber. Here, the light wavelength was set to 1550 nm. At the 1550-nm wavelength, the corresponding refractive indices were set to 1.445 for the fiber cladding, 1.578 for the seven-core region, 1.333 for the surround medium of water, and 1.39 for the E. coli bacteria. Light propagates from left to right. The optical momentum transfer that causes the particle to be trapped and propelled is equal to the momentum difference between the surrounding medium and the particle. Figure 1(d) shows the forces acting on the rod-shaped E. coli cell (black rectangle) lying on the fiber surface, namely $F_i$ (parallel to the fiber surface) and $F_g$ (perpendicular to the fiber surface). The E. coli bacterium is kept 10 nm from the fiber surface. Figure 1(e) shows the forces acting on the E. coli standing on the fiber; however, these forces will be weaker due to the smaller interaction region between the object and resonant field. When any E. coli bacterium is trapped in a random position (not lying on the fiber surface), the unbalanced optical momentum density acting on the E. coli body will result in torque, making the bacterium rotate to a more stable state.
According to the weakly guiding approximation, modes of a standard fiber approximated as linearly polarized modes or LP_{nm} modes (where the subscripts n and m indicate the radial and azimuthal order, respectively). However, when the fiber was tapered down and immersed in water, the fiber was simplified as a three-layer structure: fiber cores region, fiber cladding and surround water. Figure 2(a) shows the relationship between effective refractive indices of propagation modes and tapered fiber diameter. The result shows the 4 μm-diameter fiber allows LP_{01} mode and LP_{11} propagation (owing to the none-circular symmetrical cross section of fiber) and set cut-off to other higher-order modes. Moreover, the E-field distributions of the two modes were calculated, as shown in Figs. 2(c) and (d), where if x-y plate was set for cross-section of fiber, only x-direction degenerated mode, LP_{11}(x) was considered here. As can be seen from the numerical profiles, the E-field distribution region of LP_{11} mode is much larger than that of LP_{01} mode. Accordingly, when one considers the normalized intensity distribution along the horizontal direction, as shown in Fig. 2(b), the total evanescent field of the LP_{11} mode has longer evanescent field extensions when compared to the LP_{01} mode at a given distance from the surface of a 4 μm fiber. Therefore, the E-field distribution of LP_{11} mode extends out fiber to water much more so that it mainly contributes to trap and move the E. coli bacteria.

The calculation and analysis can be identified by spectral information of the sandwiched SCF structure. Because of the center core-mismatching between SCF and SMF, the weak coupling of core-to-cladding modes occurs in the splicing interface. The partial of cladding modes within the fiber cladding may radiate out the fiber and loss. The transfer of the field from the SMF to the SCF is non-adiabatic. As the SCF was tapered to 4 μm, the surround cores approached to the center one and modulated the refractive index around it, resulting in
the strong coupling of core-to-cladding modes. Because of the effective refractive index difference between fundamental mode and high-order mode, resulting in a phase difference after propagating along the SCF, eventually, a well-defined interference spectrum was observed, as shown in the following Fig. 3(a), which was with a fringe contrast of larger than 15 dB. In order to confirm what high-order modes were excited and participated into the interference, the spatial spectrum was transformed into frequency spectrum by the Fourier transform algorithm. As shown in Fig. 3(b), there is a strong high-order mode, mainly participating into the interference. Except for it, there are also some weak high-order modes, which mainly take part into modulating the interference. Here for the fiber tweezers, the stronger mode mainly provides the potential for the E. coli motions. The order of the mode can be judged as LP_{11} by two ways: the effective refractive index difference between it and fundamental mode based on the equation of 
\[ \Delta n_{\text{eff}} = \frac{\xi \lambda_{0}}{2} \text{L} [30], \]
where \( \xi \) is the spatial frequency, \( \lambda_{0} \) is the wavelength of light, \( L \) is the length of SCF; the non-axisymmetric fiber cross-section structure, coupling will be predominantly to the mode with the nearest propagation constant to the fundamental mode, i.e. to the second mode [31]. The experimental testing is well agreed with the theoretical analysis mentioned above.

3. Results and discussion

3.1 Photophoresis effect for mounts of E. coli bacteria trapping

At the beginning of the process with the laser off, the E. coli suspended in the liquid were able to move freely, as shown in Fig. 4(a). When the laser (50-mW power and 1550-nm wavelength) was turned on, the E. coli bacteria were quickly absorbed to the fiber because of the negative \( F_{p} \) that accumulated at the taper region. Since the water strongly absorbs the 1550-nm light, \( F_{T} \) also appears with the opposite direction of \( F_{p} \). When the two forces were in non-equilibrium, i.e. \( F_{p} \) is larger than \( F_{T} \), E. coli trapping occurred. We then recorded a time-lapse image with a time step of 15 min (shown in Fig. 4(b)), which clearly show hundreds of E. coli bacteria moving toward the fiber taper region. The relative slow trapping speed was attributed to the small laser power. More particles were trapped over time, as shown in Fig. 4(c). The E. coli bacteria agglutinated and formed a thin coating over the fiber taper. After 45 min, fewer E. coli could be found far away from the fiber taper, and the trapping process reached a saturation state, as shown in Fig. 4(d). The E. coli bacteria were stably suspended (trapped) in the liquid (no absorbing or escaping processes occurred) because of the balance of \( F_{p}, F_{T} \), and the bacterial motility. Finally, the E. coli were symmetrically distributed on both sides of fiber due to the uniform structure of the SCF taper. In the experiment, we have found, in the suitable range, for each laser power, correspondingly, there would be relative balance state, i.e. the amount of suspend E. coli bacteria could be adjusted by laser power.
3.2 E. coli bacteria trapping and propelling

To observe the motion of E. coli close to the surface of the fiber, the original liquid was further diluted to a lower concentration, allowing few E. coli to exist near the fiber. Figure 5(a) shows consecutive images of fewer E. coli along the optical axis of the fiber, mainly caused by joint of $F_g$ and $F_s$. In the conditions: the laser power was kept at 50 mW, the wavelength was set as 1560 nm, and the microfluidic effect on particles near a microfiber surface was ignored, according to the Eqs. (7) and (8), the gradient force ($F_g$) and scattering force ($F_s$) were calculated as 0.065 pN and 0.0017 pN for LP$_{01}$ mode, and 0.35 pN and 0.012 pN for LP$_{11}$ mode. As can be seen in the experiment demonstration, in the time-lapse sequence from 0 s (beginning observation point) to 15 s, a single E. coli bacterium was propelled a distance of about 110 µm. The average speed of movement was calculated as 7.3 µm/s. Moreover, the bacteria accelerated from the right side of the fiber to the fiber taper waist because of the increasing $F_s$. Figure 5(b) shows the consecutive images of two propelled E. coli bacteria of different dimensions. The larger E. coli bacterium moved stably along the fiber axis with a slower speed of 6.7 µm/s compared to the faster speed of 7.5 µm/s of the smaller bacterium. Under the same light momentum conditions, the smaller E. coli should show higher velocity. As a result, the distance between the two E. coli increased from the 68 µm to 81 µm. This phenomenon suggested that multiple E. coli of different dimensions could be simultaneously propelled in a line along the fiber.
In the experiment, we found that the speeds of the E. coli bacteria strongly depended on the laser power and wavelength. In Fig. 6(a), the average speed of a single E. coli was plotted as a function of power for different wavelengths, as measured from the recorded video files. For a given lasing wavelength, as the power increases from 10 mW to 50 mW, the average speed of the particle linearly increases since the increasing laser power enhances $F_s$. Thus, the speed of motion of E. coli can be controlled by adjusting the laser power. Figure 6(a) also shows the change in the speed of E. coli with varying laser wavelengths for a given laser power. The laser wavelength dependence could be attributed to two effects: E. coli size certainly does influence light scattering, i.e. particles with diameters that are larger than the wavelength of the laser will scatter light with a different pattern than E. coli bacteria that are smaller than the wavelength of the laser, and then resulting in the different scattering force formations, and then induce the different driving speeds; with E. coli of diameter comparable to the wavelength of light, the phenomenon of a negative indirect photophoresis occurs, due to the unequal heat generation on the laser irradiation between the back and front sides of E. coli bacteria, this produces a temperature gradient in the medium around the E. coli, causing the particle to move towards faster [32].

| Parameters | Diameters | Refractive indices |
|------------|-----------|--------------------|
|            | Core      | Clad               | Core | Clad |
| SMF        | 9μm       | 125μm              | 1.450 | 1.445 |
| MMF        | 105μm     | 125μm              | 1.464 | 1.458 |
| SCF        | 6μm       | 125μm              | 1.578 | 1.445 |

In Fig. 6(b), the speed of the E. coli was plotted as the function of different wavelengths at a fixed laser power of 50 mW. With increasing wavelength from 1500 nm to 1600 nm, the speed of motion first increases and then decreases. The maximum speed (denoted as $V_m$) occurs at the laser wavelength of 1560 nm. For comparison, SMF and multiple-mode fiber (MMF) tapers were fabricated, and the diameters were the same as that of SCF. The performance parameters of the three fibers are shown in Table 1. Light from the SMF could
not draw E. coli close to the fiber owing to its weak resonant field extension in the water. On the other hand, the light from MMF could draw the E. coli and slowly propel them along the fiber (blue points in Fig. 6(b)). The speed of E. coli also showed laser wavelength dependence similar to that in the SCF condition. As the wavelength increased, the speed increased to the maximum value of 1560 nm and then decreased. In Fig. 6(b), although the MMF could be a good tool for high-order evanescent field coupling, the unique cross sectional structure of SCF is a much stronger candidate for high-order evanescent field coupling.

3.3 Rotation activity of rod-shaped E. coli bacterium

In addition to optical trapping and propelling of the E. coli bacteria, rotational motion of the E. coli around its body was observed, as shown in Fig. 7(a). The imperfect symmetric shape of the E. coli in our sample caused an optical momentum density difference over its body, and the resulting torque causes the bacterium to rotate toward a more stable state, as shown in the schematic in Fig. 7(b). Here, the position of a bacterium with a relative angle of 30° to the fiber axis was recorded as the origin state, and the E. coli bacterium rotated on its own axis in a clockwise direction. The rotation direction depended on the laser launching direction, which determined the orientation of optical momentum on the E. coli. The rotation process was completed in less than 3.5 s, moving successively from the original state to the vertical state and to the final flat state, as shown in Fig. 7(a). However, because of the limitation of the magnification of the microscope, the detailed shape of the bacterium could not be observed in the process. Moreover, based on the recorded images, the rotation angles were plotted as a function of time in Fig. 7(c). The E. coli rotated with a non-uniform speed, i.e., the speed of rotation in first 1.25 s was greater than that in the last 2 s owing to the E. coli state gradually toward a more stable state.
4. Conclusion

In summary, a strategy for the optical manipulation of motile bacteria was demonstrated using a modified tapered optical fiber. Several motions of E. coli bacteria were controlled by the optical forces, such as trapping, propelling, and rotation. Due to the high-order mode acting as the evanescent field, the robust SCF taper facilitated individual particle propulsion, trapping and rotation. The mainly improved performance in this work is providing a new possibility for manipulating the particles of E. coli bacteria in a relatively thicker and sturdier fiber structure than traditional nano-fiber tweezers techniques. In the same fiber diameter, we believe the SCF will provide larger forces. Moreover, this work provided a simple method for the manipulation of motile nanoscale organisms that could be further extended to applications of single bacterium dynamics observation and energy estimation.

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