Front. Optoelectron. 2019, 12(1): 97–110
https://doi.org/10.1007/s12200-017-0755-z

REVIEW ARTICLE

Fiber-based optical trapping and manipulation

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Abstract An optical fiber serves as a versatile tool for optical trapping and manipulation owing to its many advantages over conventional optical tweezers, including ease of fabrication, compact configurations, flexible manipulation capabilities, ease of integration, and wide applicability. Here, we review recent progress in fiber-based optical trapping and manipulation, which includes mainly photothermal-based and optical-force-based trapping and manipulation. We focus on five topics in our review of progress in this area: massive photothermal trapping and manipulation, evanescent-field-based trapping and manipulation, dual-fiber tweezers for single-nanoparticle trapping and manipulation, single-fiber tweezers for single-particle trapping and manipulation, and single-fiber tweezers for multiple-particle/cell trapping and assembly.

Keywords optical trapping, photothermal effect, optical force, cell trapping and assembly

1 Introduction

Optical trapping and manipulation was first reported in 1970 by Ashkin [1]; it has since exhibited rapid progress and been widely used in interdisciplinary applications such as micro-/nanophotonics, biophotonics, biochemistry, and biomedicine [2–4]. Most applications are achieved using the most common optical trapping and manipulation tool, i.e., conventional optical tweezers (COTs), which are based on a standard microscope with free-space light beams focused by a high-numerical-aperture objective [5]. Samples with sizes ranging from tens of nanometers, such as DNA [6] and protein molecules [7], to tens of micrometers, such as microparticles [8] and cells [9], can be trapped and manipulated using COTs. Because they are targeted and noninvasive, COTs are extensively used in biophysical and biochemical research. However, the structure of COTs, with a bulky focusing objective and optical system, has many disadvantages, including an inflexible manipulation (moving) process, diffraction limitations for nanoparticles, difficulty in penetrating thick samples, and limited integration functions.

With the advantages of commercial availability, easy fabrication, and high flexibility, optical fibers have been used for optical trapping and manipulation [10–12]. The introduction of fiber-based optical trapping and manipulation has overcome many of the limitations of COTs. Commercial single-mode optical fiber can be fabricated into structures such as subwavelength-diameter optical fibers (SDFs) [13], optical fiber rings [14], and tapered optical fibers (TFs) [15]. These structured optical fibers can be fabricated using various methods including polishing [16], chemical etching [17], high-resolution micromachining [18], and flame heating [19]. Among them, flame heating is widely used because it can easily be used for fabrication within a short time. Use of optical fibers with different configurations and structures has enabled optical trapping and manipulation with many different functions to be realized with high flexibility, high precision, and high levels of integration. When laser beams with different wavelengths are launched into the fiber, depending on the optical absorption of the laser by the solution, optical trapping and manipulation based on both the photothermal effect and the optical force can be achieved, as shown in Fig. 1. For photothermal-effect-based optical trapping and manipulation, massive trapping, assembly, and manipulation can be achieved. For optical-force-based trapping and manipulation, both the evanescent fields at the SDF surface and the light output from the TF end can be used. Trapping and manipulation methods that use the optical force based on the light output from the TF end can be classified as dual-fiber tweezers (DFTs) or single-fiber tweezers (SFTs). Using SFTs, stable trapping of single particles in both contact and noncontact modes can be realized. In addition, SFTs can also be used for multiple-particle trapping and cell assembly, and the cells can be further used to assemble biophotonic components and devices. Many review papers

Received August 31, 2017; accepted October 9, 2017

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have already comprehensively discussed the development of optical trapping and manipulation using COTs as well as many newer methods such as nanoplasmonic tweezers [2–5,12]. In addition, Ribeiro et al. also reviewed recent trends in optical fiber tweezers [10]. However, they focused only on single-particle trapping and manipulation. In this review, we will discuss recent progress in fiber-based optical trapping and manipulation based on all of the above applications.

2 Massive photothermal trapping and manipulation

The photothermal effect is induced by absorption of light by a liquid or by particles suspended in the liquid. When a laser beam with high absorption is launched into an optical fiber, the photothermal effect can be observed in the solution. Depending on the light absorption by water and by the particles, the photothermal effect can be classified as the photophoresis effect or the temperature gradient effect. When a light beam irradiates a particle suspended in a liquid, the incident light may be focused and absorbed by the particle, causing uneven heat distribution around the particle volume. This uneven heat distribution will increase the movement of surrounding water molecules and eventually result in a force driving the particle to move either toward (negative photophoresis) or away from (positive photophoresis) the light source [20]. When light is strongly absorbed by water, a temperature gradient will be generated in the water. Strong temperature gradients can result in isotropic diffusion of particles or molecules in a large area. These particles move along the direction of the temperature gradient, typically from the hot region to the cold region [21].

By combining the photothermally induced negative photophoresis and temperature gradient effect, massive particle trapping and manipulation can be achieved using optical fibers with a laser beam at a wavelength of 1.55 μm because of the strong absorption of light at this wavelength by water and weak absorption by many particles such as SiO_2 and TiO_2 particles (where the imaginary parts of their refractive indices are less than 1×10^{-3}). Far from the light source, for example, the light output from a TF and leaked light from an SDF, particles will move toward the light source under the negative photophoretic force. However, near the light source, because of the strong light absorption by water, particles will be slowed by the temperature gradient effect. These two effects will ultimately result in massive particle trapping and assembly. According to a theoretical study presented by Soong et al. [20], both the photophoretic velocity and photophoretic force of a particle in liquid are linearly proportional to the light intensity and the temperature distribution asymmetry factor, which describes the uneven heat distribution in the particle volume during light irradiation. When light irradiates particles having a very low absorption coefficient, each individual particle acts as a microlens and

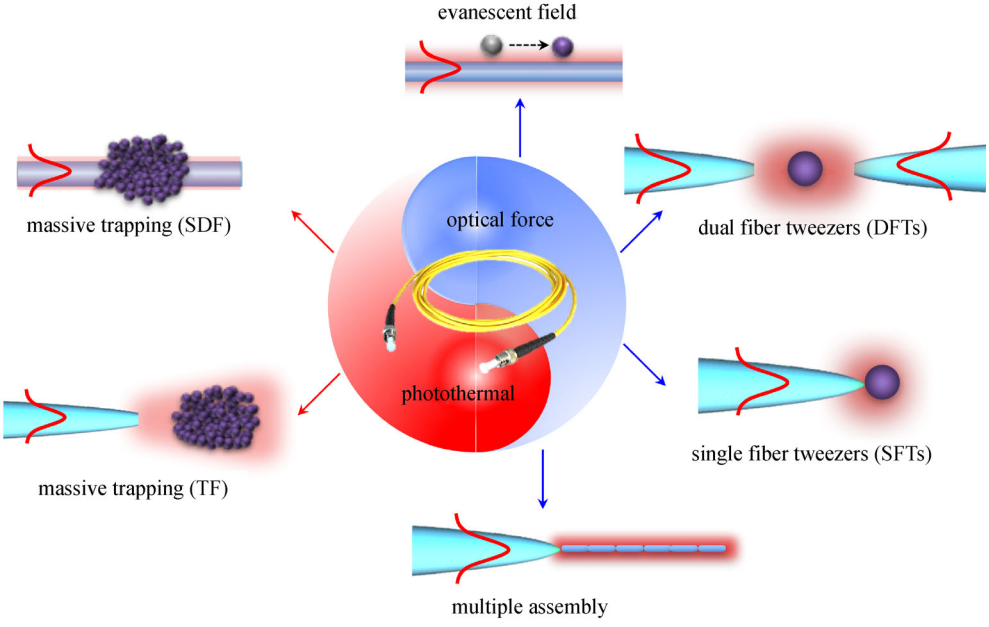

Fig. 1 Overall description of fiber-based optical trapping and manipulation. Both photothermal effect and optical force can be used for optical trapping and manipulation. Massive photothermal trapping and manipulation can be achieved using subwavelength diameter optical fiber (SDF) and tapered optical fiber (TF). For optical force based trapping and manipulation, the evanescent field at the surface of SDF can be used, and the optical force from dual fiber tweezers (DFTs) and single fiber tweezers (SFTs) can be used for single particle trapping and manipulation, and SFTs can be used for multiple trapping and assembly

focuses the incident radiation onto the rear side of the particle, leaving part of the surface hotter and generating a photophoretic force. The particles are driven by the resulting force and move toward the light source, resulting in massive particle trapping and assembly.

Optical fibers with different structures such as TF [22], SDF [13], and ring [14] structures have been used for massive photothermal trapping and assembly. Figures 2(a) and 2(b) shows massive trapping and assembly using a TF [22]. Particles suspended in water were irradiated by light output from the TF end. Owing to the negative photophoresis and temperature gradient effects, particles were assembled at the location at which the two forces reached equilibrium. At an optical power of 170 mW, more than 10000 SiO_2 particles were assembled into a spindle-shaped region approximately 380 μm from the TF end after 15 min. Using an SDF, massive trapping and assembly have also been achieved using the leaked light from the fiber surface, as shown in Figs. 2(c) and 2(d) [13]. At an optical power of 200 mW at t_{on} = 360 s, approximately 4300 particles were assembled around the SDF, and saturation was achieved. When the laser was switched off, the photothermal motion of the particles stopped, and the assembled particles began to diffuse back to the dispersed state via Brownian motion (Fig. 2(d)IV). This method is also useful for the assembly of microbes such as *Escherichia coli*.

After trapping and assembly, massive migration of the assembled particles can be achieved simply by moving the fiber, as shown in Fig. 3. Within only approximately 1 min, the assembled particles are migrated by a distance of 112 μm by moving the TF (Fig. 3(a)) [22]. When the TF is moved back, the particles migrate by a distance of 172 μm after approximately 2 min. Similarly, the assembled particles can also be migrated by moving the SDF (Fig. 3(b)). Compared with migration using an SDF, TF-based migration is more effective and more convenient. This massive assembly and effective migration of particles is very important for future applications in microbe removal in a limited space and drug screening and separation.

By using two different TFs, effective separation of different-sized particles by the photothermal effect has also been demonstrated [23]. By inducing a flow in the SDF-based photothermally assembled particles, particle separation and microbe removal processes can be realized [24,25]. A microbe removal efficiency as high as 99.9% has been demonstrated using this method [25]. When a fiber tip is placed on the surface of a particle suspension, a vortex flow can be induced by the photothermal effect and can then be used for particle manipulation [26–28]. Massive trapping and assembly provide an effective method for local water purification and quick collection and removal of microbes in biological environments. Recently, by employing the synergy between the optical force and photophoretic force in a TF, optical pulling and oscillation of a single metallic plate have also been realized, opening exciting possibilities for optical driving and energy conversion applications [29].

The above subsection discussed optical-fiber-based massive trapping and manipulation of microparticles and microbes using the photothermal effect. These methods will provide many new possibilities for biomedical and biochemical applications including drug screening, drug separation, and microbe removal.

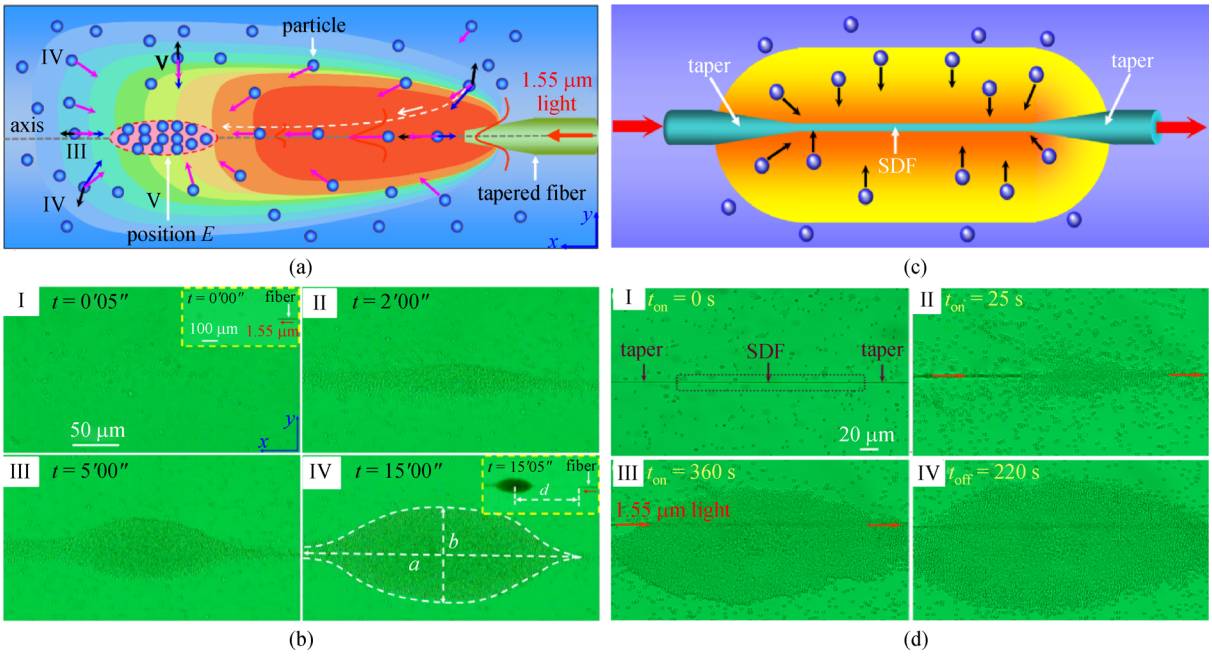

Fig. 2 Massive photothermal trapping and assembly of microparticles. (a) Schematic and (b) experimental results of massive trapping and assembly using TF [22]. (c) Schematic and (d) experimental results of massive trapping and assembly using SDF [13]

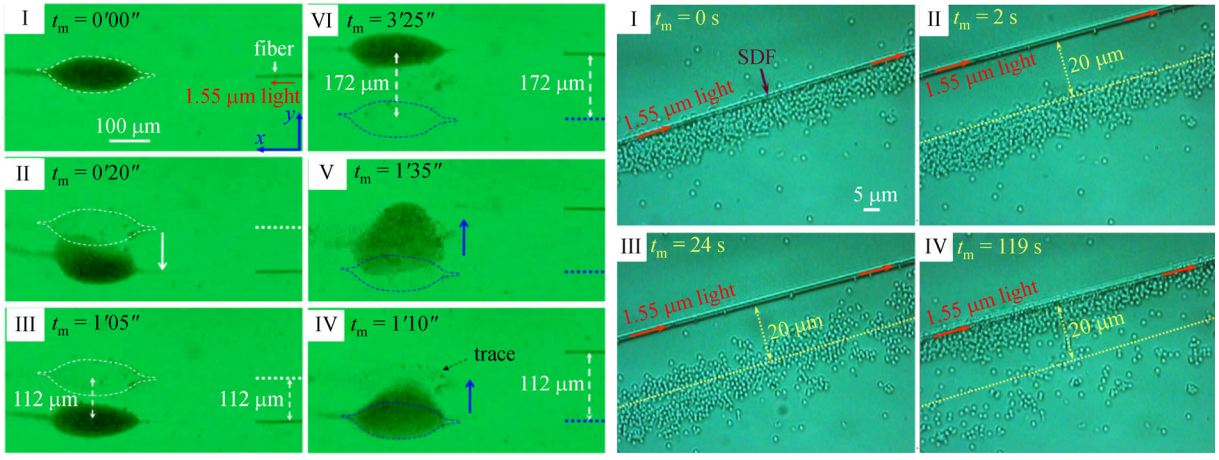

Fig. 3 Massive migration of photothermal assembled particles using (a) TF [22] and (b) SDF [13]

3 Evanescent-field-based trapping and manipulation

Evanescent fields were first used for optical trapping and manipulation in 1992 [30]. Since then, interest in optical trapping and manipulation of particles and biological cells using surface evanescent fields has increased because they afford long-range manipulation [31–33]. Objects are trapped at the waveguide surface by the optical gradient force, which is directed toward the surface, and are then propelled along the surface by the optical scattering force, which occurs in the direction of light propagation. Since 2007, SDFs have also been widely applied to optical trapping and manipulation based on the use of the evanescent fields that occur on the fiber surface [34]. Compared with the use of optical waveguides, SDF-based evanescent manipulation provides many advantages. For example, evanescent wave fields exist on the entire surface of the SDF, which is a larger area than that of a conventional optical waveguide, with one side confined by the substrate. Light can be directly launched into an SDF from the input port, so the coupling loss is smaller than that in a conventional optical waveguide that is coupled with other optical components. Further, an SDF can be flexibly moved and manipulated in three dimensions by manipulating the microstages, so it is much more flexible than fixed optical waveguides. Because of these advantages, the SDF is widely used for optical trapping and manipulation using evanescent fields [35–37]. The evanescent field that occurs around an SDF can also interact with the surrounding atoms through absorption, and the resulting gradient force can balance each atom's centrifugal force. This phenomenon has thus been widely applied in atom trapping, cooling, and detection [38–40], and has led to new approaches to the development of quantum technologies.

Figures 4(a)–4(d) show the electric field distributions of polystyrene particles with different diameters on the surface of an SDF with a diameter of 600 nm [41]. The evanescent fields around the SDF exert an optical force on the particles. The optical force ($\boldsymbol{F}_o$) can be calculated by integrating the Maxwell stress tensor ($\boldsymbol{T}_M$) around a particle as follows:

$$\boldsymbol{F}_o = \int_S (\langle \boldsymbol{T}_M \rangle \cdot \boldsymbol{n}) \mathrm{d}S. \quad (1)$$

$\boldsymbol{F}_o$ consists of two components; one is the gradient force F_g, which is directed to the fiber surface for particle trapping, and the other is the scattering force F_s, which is in the direction of light propagation and can propel the particle. The calculated F_g and F_s for particles with different sizes are shown in Fig. 4(e) [41]. The calculated scattering force magnitude at unit power is one order higher than that for a planar waveguide, which indicates that the SDF is more efficient for long-range particle delivery.

In fact, both a straight SDF [41] and an arbitrarily bent SDF [42] have demonstrated excellent particle delivery performance using evanescent fields on the SDF surface. More importantly, evanescent-field-based trapping and manipulation using an SDF are also applicable for controlled manipulation of biological samples such as bacteria. Figures 5(a) and 5(b) show the controlled trapping of three randomly swimming *E. coli* bacteria using an SDF at an optical power of 30 mW [43]. By increasing the power to 60 mW, long-range delivery of trapped *E. coli* is achieved, as shown in Fig. 5(c), and the delivery velocity increases linearly with the optical power (Fig. 5(d)) [43]. When the SDF is integrated into a microfluidic channel, trapping and delivery in a flowing environment are also realized [44]. By fabricating a defect at a target position of the SDF, nanoparticles can be delivered to the defect position in a targeted manner, and particles trapped at the defect can be released in a

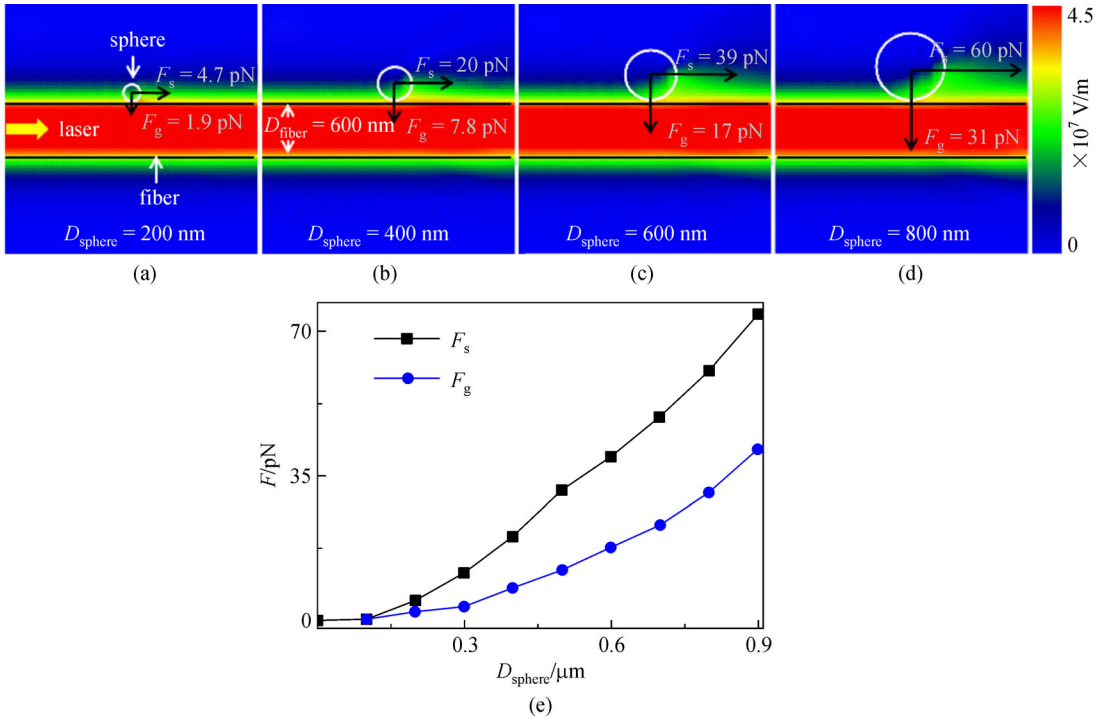

Fig. 4 Numerical calculation results of optical force on nanoparticles by the evanescent fields on surface of SDF [41]. (a)–(d) Examples of calculated optical force exerted on particles with different sizes. (e) Calculated optical force for particles with different diameters

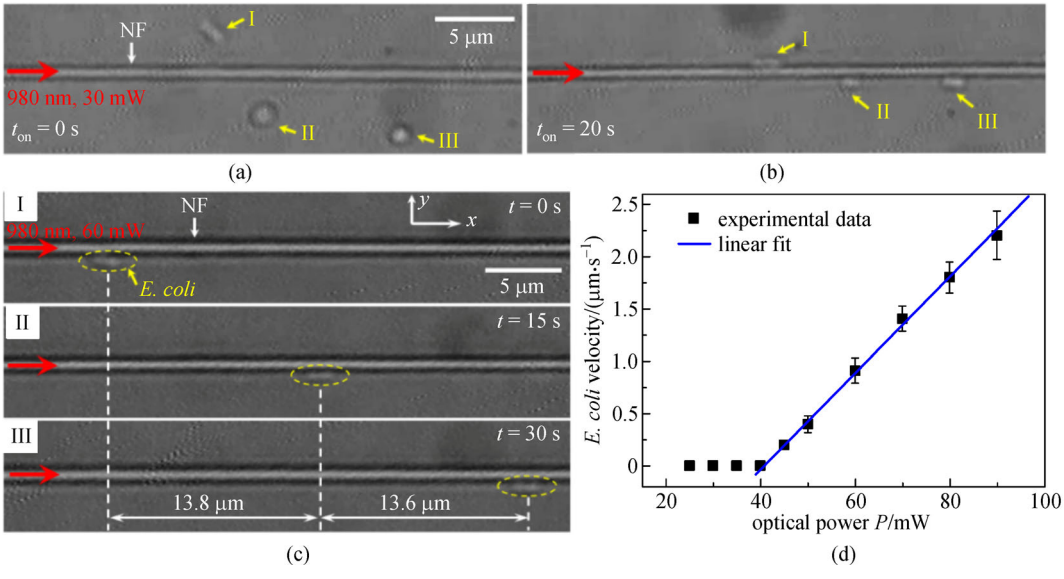

Fig. 5 Evanescent fields-based trapping and delivery of bacteria (*E. coli*) using SDF [43]. (a) and (b) Stable trapping of individual *E. coli* bacteria. (c) Long-range delivery of individual *E. coli* bacteria. (d) Delivery velocity as a function of optical power

controllable manner [45,46]. An SDF with this function provides a new platform for targeted delivery and controlled release of drugs. This defect-decorated SDF can also perform particle extraction in a microfluidic channel [47]. When coupled with plasmonic nanorods (either at the fiber surface or immersed inside the fiber), this SDF structure can support enhanced plasmonic trapping and manipulation [48,49].

In addition to one-direction delivery, the SDF also affords an excellent platform for bidirectional manipula-

tion when both ends of the SDF are coupled with separate laser beams. Depending on the optical power at either end of the SDF, direction-controlled delivery along the SDF is possible [50]. When laser beams at different wavelengths are launched into each end of the SDF, the optical force exerted on particles of different sizes or materials is different. On the basis of this phenomenon, the SDF is also used to sort particles of different sizes and materials [51,52]. This optical sorting method using a simple arrangement of a static fluid with static optical components is promising for practical application in sorting of colloidal particles or living cells for laboratory-on-a-chip chemical analyses.

The above subsection discussed SDF-based trapping, long-range delivery, and controllable release using evanescent fields at the surface. This platform will provide new insights into many physical and biomedical applications, including atom trapping, target drug delivery, drug screening, and single-bacteria analysis.

4 Dual-fiber tweezers for particle trapping and manipulation

In addition to trapping and manipulation of particles using evanescent fields on the SDF surface, single-particle trapping can also be achieved using the light output from a TF, which exerts an optical force on particles. The first demonstration of TF-based single-particle trapping and manipulation was based on dual DFTs and was reported by Constable et al. [53]. They used two flat-cut optical fibers that allowed small dielectric spheres and living yeast to be held and manipulated. Counterpropagating focused laser beams were first used for particle trapping by cooperation between the radiation pressure forces [1]. Similarly, two oppositely placed optical fibers forming DFTs for particle trapping and manipulation can also be realized using two oppositely placed optical fibers, eliminating the need to use focusing objectives and thus making the system much more flexible and simple. To increase the degree of light focusing and the resulting optical force while also reducing the fiber size, DFTs based on tapered and lensed optical fibers were demonstrated. Lyons and Sonek demonstrated confinement and bistability using DFTs formed from two tapered hemispherically lensed optical fibers [54]. Taguchi et al. demonstrated rotational manipulation of a yeast cell using DFTs [55]. Additionally, Taguchi et al. used DFTs to demonstrate levitation of a single particle [16]. However, all these reported results of particle manipulation using DFTs are limited to particles several microns in size. In fact, the DFT method can also be used to manipulate nanometer-scale objects; for example, the method enables controllable manipulation of one-dimensional nanostructures. The Li group demonstrated flexible trapping, orientation, and moving of single nanoparticles, including nanospheres and nanowires, using DFTs [56,57], as shown in Fig. 6. Using DFTs for trapping and flexible manipulation of nano-objects will provide new possibilities for nanoassembly.

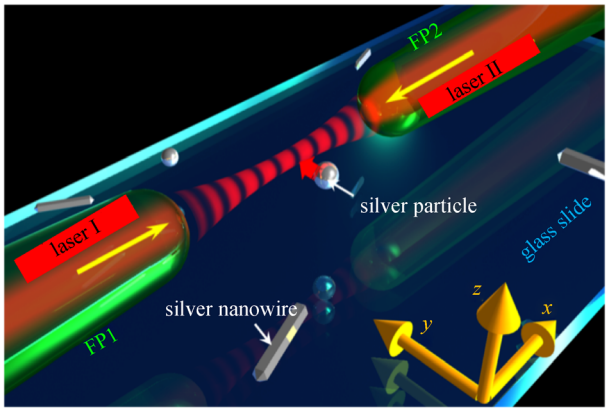

Fig. 6 Schematic for optical trapping and manipulation of particles using DFTs [57]

5 Single-fiber tweezers for single-particle trapping and manipulation

Although DFTs can perform particle trapping, among many other manipulation functions, the configuration of the two optical fibers is not flexible. To realize a compact, miniaturized, and flexible manipulation platform, SFTs, which are formed using only a single optical fiber, have been introduced [15,18,58–61]. Light output from the fiber end is focused at the end and exerts an optical gradient force for particle trapping, similar to that in COTs. When compared with the DFT method, the SFT method offers the advantages of manipulation flexibility and compact size. In comparison with COTs, in addition to having the advantages of manipulation flexibility and compact size, SFTs can also be inserted into particle suspensions in different directions and to different depths.

In addition to trapping by an optical gradient force, the scattering force from the output light can also be used for particle manipulation, for example, for pushing and driving [19,62], as shown in Fig. 7. For a single TF probe, Xin et al. calculated the region for particle trapping to be within a distance of approximately 13 μm from the fiber end along the axis (Fig. 7(c)), where the gradient force is larger than the scattering force. At a distance larger than 13 μm, the scattering force is larger than the gradient one, and particles can be driven away. For particles near the fiber axis, the force is directed toward the axis, and particles can be trapped at the axis with minimum trapping potential [19]. Combining the optical gradient and scattering forces, as well as offering flexibility in fiber manipulation, SFTs have been widely used for trapping and manipulation of

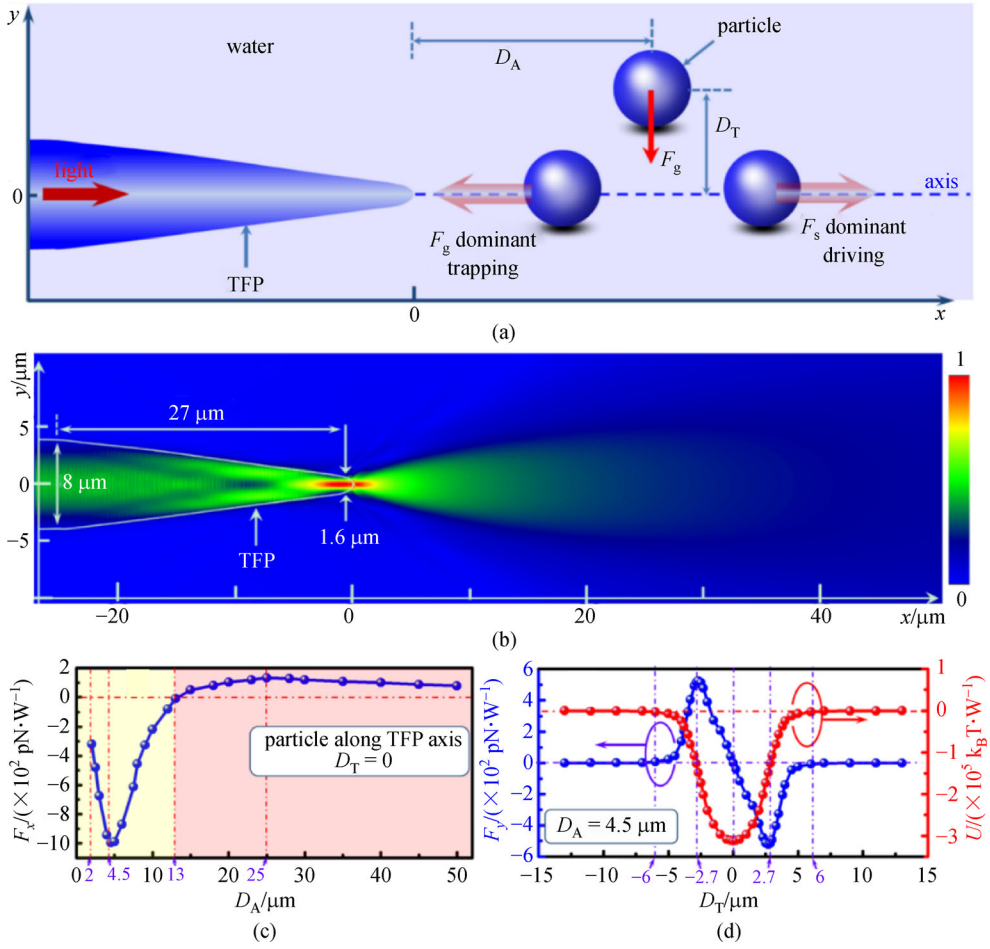

Fig. 7 SFTs for single particle trapping and manipulation [19]. (a) Schematic for particle trapping and manipulation. Particles in gradient force (F_g) dominant region near the fiber end can be trapped, while those in the scattering force dominant region are driven away. (b) Simulated field distributions output from SFTs. (c) Calculated optical trapping along the longitudinal axis of the SFTs. (d) Calculated optical force and trapping potential along the transverse axis of the SFTs with distance of 4.5 μm to the fiber end

various particles and biological cells with different functions in various environments such as microfluidics [19,63]. For example, by combining the trapping and driving ability, flexible arrangement of different particles into various structures and patterns has been realized [19]. The use of traditional SFTs for trapping of biological cells is based on mechanical contact, where the cells are in direct contact with the fiber. This will inevitably cause mechanical damage to the trapped cells. By changing the shape of the fiber end, noncontact trapping of single cells [64] and even motile bacteria has also been achieved [65]. This noncontact trapping provides many possibilities for better understanding of the dynamics and energetics of motile bacteria.

Controllable manipulation of nanosized particles using traditional COTs and SFTs remains a major challenge, particularly for particles with sizes as small as 100 nm. One example of such particles is carbon nanotubes, which are considered to be a promising building block for various applications because of their exceptional optical and electronic properties [66]. The challenge arises because the reduced size of the trapped object means that both the Brownian motion and the rotational diffusion coefficient are dramatically increased. Orientation and shifting of individual carbon nanotubes are extremely important processes in the assembly of building blocks for nanodevices and in the development of one-dimensional materials for interdisciplinary applications. By fabricating a nanotip at the end of a tapered fiber (Fig. 8(a)) [67], Xin and Li demonstrated controllable orientation and shifting of a single multiwalled carbon nanotube (MWCNT) by the optical torque and optical scattering force, respectively, as shown schematically in Fig. 8(b). Figure 8(c) shows an example of the orientation and shifting of a single MWCNT using this method. By introducing a second fiber nanotip to form a dual-fiber nanotip structure, precise control of the orientation and shifting of a single MWCNT has been achieved [67]. The ability to orient and shift a single MWCNT represents a new approach to the manipulation of one-dimensional materials with controlled

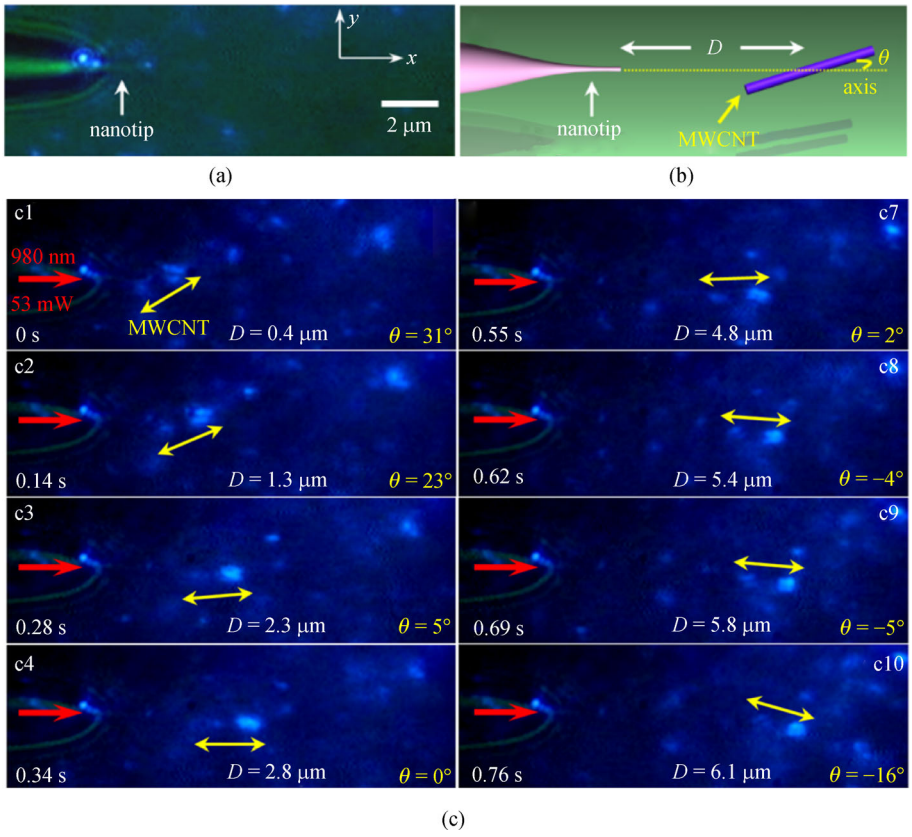

Fig. 8 Optical orientation and shifting of single MWCNTs using optical fiber nanotip [67]. (a) Optical microscope image of an optical fiber nanotip. (b) Schematic of optical orientation of a single MWCNT. (c) Dark-field optical microscope images showing the orientation and shifting of a single MWCNT along the nanotip axis

arrangements and should facilitate the development of high-precision MWCNT assemblies. By attaching a microparticle that serves as a microlens to the end of a tapered fiber, the output light can be further focused by the microlens, forming a photonic nanojet that overcomes the diffraction limit [68]. This SFT-supported photonic nanojet enables stable trapping of single sub-100-nm particles as well as single biomolecules such as plasmid DNA. Attaching multiple microlenses to a flat fiber end facet produces a parallel photonic nanojet array that enables multiple trapping and detection of nanoparticles and cells with high throughput [69]. These results demonstrate that SFTs are applicable not only for microparticle trapping and manipulation, but also for nanoparticle manipulation, thus overcoming the diffraction limit of COTs.

In addition to simple trapping and manipulation of single micro-/nanoparticles and biological cells, SFTs can also afford co-trapping of different particles and bacteria. For example, Xin et al. realized co-trapping of single upconversion nanoparticles (UCNPs) and bacteria [70], as shown in Fig. 9. Because UCNPs have the intrinsic ability to emit green light upon 980-nm laser excitation, this method offers a new approach to precise single-bacterium labeling and analysis, with huge potential for single-pathogenic-bacterium labeling, detection, and real-time analysis at the single-particle and single-bacterium level.

The above subsection showed that the focused output light at the fiber end makes the SFT an excellent tool for trapping and manipulation of single particles (including micro-/nanoparticles, nanotubes, cells, and bacteria). This will provide many possibilities for single-nanoparticle manipulation and single-cell analysis, which will afford many new insights into cell biology.

6 Single-fiber tweezers for multiple-particle/cell trapping and assembly

Trapping and organized assembly of multiple particles or cells is of great importance for a wide range of applications, including general biophotonic devices [71], cell-to-cell interactions and communications [72], tissue engineering [73], and genetic engineering [74]. Various methods, such as optical tweezers [2], dielectrophoresis [75], and acoustic tweezers [72], have been used for particle/cell trapping and assembly applications. Because optical trapping is noninvasive and precise, it has huge

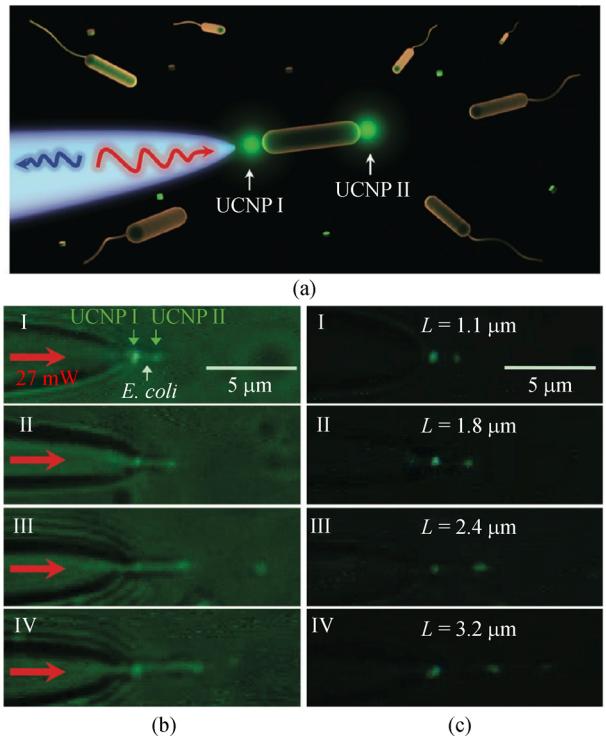

Fig. 9 Optical cotrapping of single UCNPs and bacteria for single bacteria labeling [70]. (a) Schematic for cotrapping and labeling. (b) Bright-field optical microscope imaging of cotrapping and labeling. (c) Dark-field imaging of cotrapping and labeling

potential for use in particle/cell trapping and assembly applications. Although COTs are normally used for single-particle trapping and manipulation, SFTs have provided new possibilities for multiple-particle/cell trapping and assembly by the extended output light.

There are two typical methods of using SFTs for multiple-particle/cell trapping and assembly. The first is optical binding in the driving region of SFTs [76], which results from cooperation of the optical scattering force with the optical gradient force, as shown in Fig. 10(a). Light can propagate along the trapped particles; consequently, more particles are trapped and form particle chains, as shown in Fig. 10(b). Calculation results show that the optical force at the end of the particle chain changes from a driving force to a trapping force as the particle number increases, which differs from the situation for a single particle (Fig. 10(c)). The transverse force is larger than that for a single particle (Fig. 10(d)). Therefore, it is easier for the trapping of more particles in a particle chain, when compared with a single particle. This method can be used for assembly and patterning of dielectric particles and cells into both one-dimensional chains and two-dimensional arrays (Fig. 10 (e)) [76] and for intracellular organelle assembly [77]; it can also be used in particle and cell separation [78].

Although cooperation between the optical scattering force and the gradient force can result in optical binding, which can then be used for multiple-particle/cell trapping and assembly applications, the particle and cell chains and patterns that are formed are not sufficiently stable or flexible for three-dimensional manipulation and biophotonic integration applications. The second method of multiple-particle/cell trapping using SFTs is optical gradient force trapping, in which the extended optical gradient force produced by a TF is used. As shown in Fig. 11(a), after a single cell is trapped by SFTs, light can propagate along the trapped cell and is refocused at the cell ends; it then exerts an extended optical gradient force to trap more cells and form bacterial cell chains with different cell numbers and chain lengths (Fig. 11(b)) [79]. The formed cell chains show high stability even in a flowing environment and can be flexibly moved and manipulated in three dimensions. This multiple-cell trapping and cell alignment provide a flexible method to control cell–cell contact, which is very important for the study of cell–cell interaction and communication. When another tapered fiber with a laser beam launched into it is used, the orientation of a single cell in the formed cell chain can be flexibly controlled by the optical force exerted by the additional fiber [80]. In addition to being used to orient a single cell at the end of a cell chain, the second fiber can also be used to regulate the locations of individual bacteria at other positions in the cell chain. This includes the removal of a targeted cell from a cell chain, addition of a targeted cell to a cell chain, and even adjustment of a targeted cell inside a cell chain [81]. Regulation of the orientation, contact sequence, and interaction distances

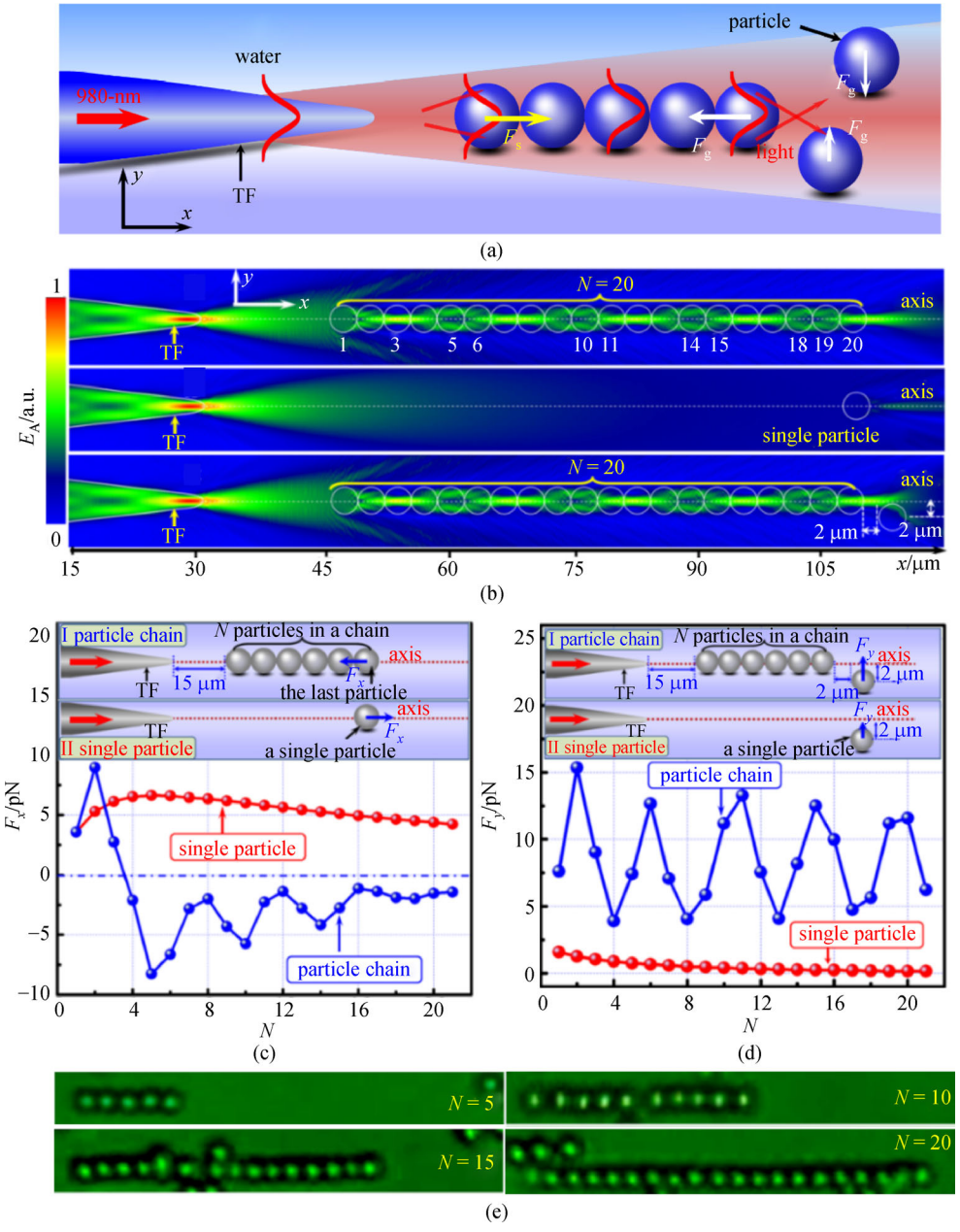

Fig. 10 Optical trapping and assembly of multiple particles by optical binding using SFTs [76]. (a) Schematic for the trapping and assembly. Particles are bound together by the cooperation of scattering force and gradient force. (b) Simulated light distributions along the assembled particle chains. (c) Calculated optical force at the end of particle chains along the central axis with different particle numbers. (d) Calculated transverse optical force at the end of the chain. (e) Examples of assembled particle chains

using this method will allow the effects of different extracellular cues on the cell interaction processes to be investigated.

The formed highly ordered cell chains show excellent light propagation performance. Using this phenomenon, the formed cell chains were used as biophotonic waveguides, as shown in Fig. 12 [71]. Waveguides with lengths up to 40 μm were formed using this method and showed a propagation loss of approximately 0.23 dB/μm for light at a wavelength of 644 nm. These bacteria-based biophotonic waveguides provide biocompatible and disposable photonic components, which are important for biological and biomedical applications [82]. Direct formation of biophotonic components using live cells is also more convenient for biomedical applications because the cells can simultaneously serve as both samples and optical elements for signal sensing and detection in real time. This multiple-cell trapping and assembly method is also applicable for assembly of many different biophotonic components. For example, using different cells, one-

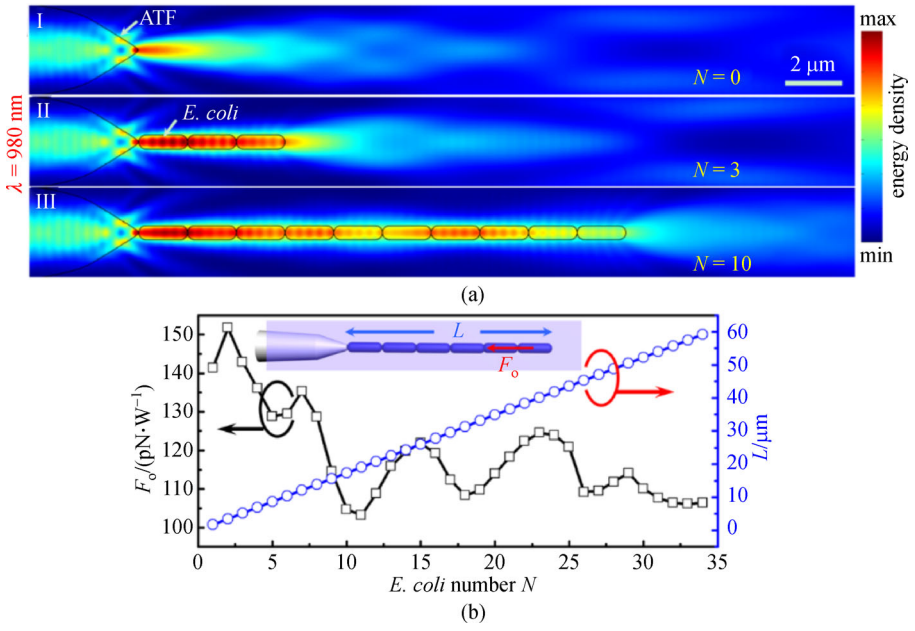

Fig. 11 Simulation and calculation results for multiple cell trapping and assembly by optical gradient force using SFTs [79]. (a) Simulated light distributions along the assembled multiple cell chains, light can propagate along the cell chains. (b) Calculated optical trapping force for the end cell of each cell chain with different lengths

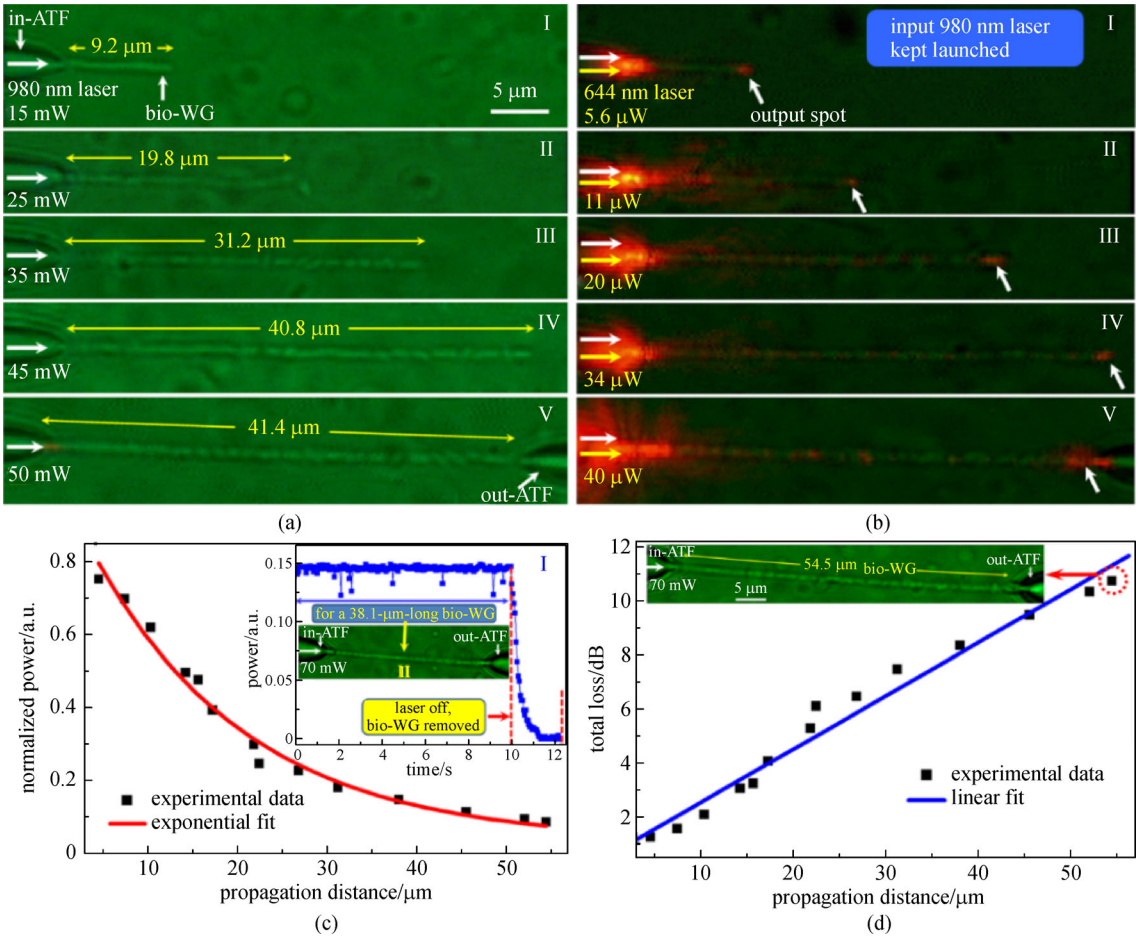

Fig. 12 Optical formation of bacteria-based biophotonic waveguides (bio-WGs) using SFTs [71]. (a) Formed bio-WGs with different lengths. (b) Bio-WGs with different lengths for red light propagation. (c) Measured normalized optical power as a function of propagation distance. (d) Total loss as a function of propagation distance

dimensional periodic cell structures and periodic biophotonic waveguides have been assembled [83]. By modifying the tapered fiber end, light output from the fiber can be divided into three beams, allowing individual cell chains to be formed by each beam. These branched cell chains have been formed for use as multidirectional biophotonic waveguides as well as biophotonic beam splitters [84]. Because these bionanophotonic components are assembled from natural living biomaterials, all the resulting bionanophotonic components can be integrated directly into biological systems. These results further show that the applications of optical trapping extend far beyond simple particle trapping and show huge potential for optical component and device assembly and integration.

The above subsection discussed multiple-particle/cell trapping and assembly, as well as biophotonic device assembly. This flexible method will provide many new applications for biophotonics using natural materials, which afford a seamless interface to the biological world.

7 Conclusions

Optical-fiber-based optical trapping has allowed multiple types of functional manipulation of micro-/nanoparticles, as well as biological cells and biomolecules. The photothermal effect of microstructured optical fibers allows for massive trapping, assembly, migration, and separation of different particles and cells with high efficiency. The evanescent fields of subwavelength fibers allow for long-range and targeted delivery. TF-based optical tweezers allow for flexible trapping and manipulation of different single particles as well multiple-particle/cell assembly. Optical-trapping-based multiple-cell assembly provides a new method for biophotonic component assembly. All of these optical-fiber-based trapping and manipulation methods provide many new possibilities as well as new insights for biomedical and biophotonic applications.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 11774135).

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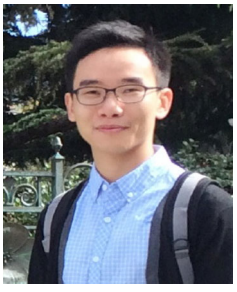

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