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An all fiber apparatus for microparticles selective manipulation based on a variable ratio coupler and a microfiber

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A B S T R A C T

We propose an all fiber apparatus based on a variable ratio coupler which can transport microparticles controllably and trap particles one by one along a microfiber. By connecting two output ports of a variable ratio coupler with two end pigtails of a microfiber and launching a 980 nm laser into the variable ratio coupler, particles in suspension were trapped to the waist of microfiber due to a gradient force and then transported along the microfiber due to a total scattering force generated by two counter-propagating beams. The direction of transportation was controlled by altering the coupling ratio of the variable ratio coupler. When the intensities of two output ports were equivalent, trapped particles stayed at fixed positions. With time going, another particle around the micro fiber was trapped onto the microfiber. There were three particles trapped in total in our experiment. This technique combines with the function of conventional tweezers and optical conveyor.

1. Introduction

Optical tweezers was proposed by Ashkin in 1986 [1], since then it has been widely used for particles manipulation in the fields of physics and biology due to the noncontact manipulation of objects. In the early days, much work was done mainly based on a highly focused laser beam through a high numerical aperture microscope objective. In these systems, optical manipulation are quite complicated and costly. In order to simplify the trapping system, optical fiber tweezers based on etched fiber tips have been developed since 1993 [2]. Compared to conventional tweezers, optical fiber tweezers are more low cost and convenient to realize particles levitating [3], moving [4] and rotating [5]. However, a much short focal depth of optical fiber turns the continuous transportation of particles into a challenge. To overcome such limitation, microparticles manipulation using the evanescent field of planar waveguides appeared [6]. Compared to planar waveguides fabricated on substrates, optical fibers is more freestanding, and the small size makes it compatible to be integrated on a chip. As a result, works about trapping and continuous transportation of particles by the evanescent field of optical fibers have been reported [7,8]. Nevertheless, in these works, transportation of particles is usually unidirectional. There have been several reports on the bidirectional optical transportation of particles. Grujic et al. reported a dielectric microsphere manipulation by counter-propagating waves in a channel waveguide [9]. Zhao et al. reported an optical trapping by counter-propagating beams in nanofiber theoretically [10]. Lei et al. reported a bidirectional optical transportation by using two incoherent beams [11].

In this paper, we not only achieve bidirectional particles transportation but also selective particles trapping based on a variable ratio coupler. Two output ports of the variable ratio coupler and two end pigtails of a 1 μm diameter microfiber were connected into a loop. Due to the evanescent field of a microfiber, particles around the waist of microfiber in suspension were trapped and then transported along the microfiber. The direction of transportation can be controlled by altering the intensity ratio of two counter-propagating beams through adjusting the coupling efficiency of the variable ratio coupler. Once the intensities of two counter-propagating beams were equivalent, the trapped particles kept still at fixed positions. At the same time, particles not trapped may run into the potential well of the microfiber and then be trapped onto the microfiber. There were three particles trapped one by one in the following experiment. In such a way, we achieved a selective trapping of particles. Such manipulation can apply to particles ranging in size from hundreds of nanometers to several micrometers.

2. Theory of force calculation

The optical force acting on a particle is defined as:

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$$F = \oint_s (\langle T_M \rangle \cdot n_s) dS \tag{1}$$

where n_s is the normal vector of the surface around the particle pointing outward, T_M is the Maxwell stress tensor which is given by:

$$\langle T_M \rangle = DE^* + HB^* - \frac{1}{2}(D \cdot E^* + H \cdot B^*)I \tag{2}$$

where E, D, H and B denote the electric field intensity, the electric displacement, the magnetic field intensity and the magnetic flux, respectively. I is the isotropic tensor, and E^* and B^* are the complex conjugates. Fig. 1a shows the variation of gradient force and scattering force versus diameters of particles when there is only one laser beam is launched. For the simulation, the gap between particle and microfiber is assumed to be 100 nm. A 980 nm laser is launched, the refractive index of the microfiber, water and silica particles are 1.445, 1.33 and 1.46, respectively.

A microfiber of 1 μm in diameter is illuminated by two counter-propagating beams, beam 1 and 2, which propagate along $+z$ and $-z$ direction, respectively. It is assumed that the length of the microfiber is L and the left end face of the microfiber is set to be $z = 0$. The electric fields of beam 1 and 2 at $z = z_0$ are presented as E_1 and E_2, respectively.

$$E_1 = A_1 \exp j(\omega t + \varphi_0 + (2\pi/\lambda)z_0) \tag{3}$$

$$E_2 = A_2 \exp j(\omega t + \varphi_0 + \pi/2 - (2\pi/\lambda)(z_0 - L) \tag{4}$$

where A_1 and A_2 are amplitudes of beam 1 and 2, respectively, ω is the angular frequency of beams, λ is the wavelength of the laser beam, φ_0 is the initial phase of beam 1 at $z = 0$.Therefore the total interference electric field is

$$E = A \exp(j\varphi t) \tag{5}$$

where

$$A = \left[A_1^2 + A_2^2 + 2A_1A_2 \cos(\pi/2 + (2\pi/\lambda)\mathrm{L} - (4\pi/\lambda)z_0)\right]^{1/2} \tag{6}$$

$$\varphi = \frac{A_1 \sin(\omega t + \varphi_0 + (2\pi/\lambda)z_0) + A_2 \sin[\omega t + \varphi_0 + \pi/2 - (2\pi/\lambda)(z_0 - \mathrm{L})]}{A_1 cos(\omega t + \varphi_0 + (2\pi/\lambda)z_0) + A_2 cos[\omega t + \varphi_0 + \pi/2 - (2\pi/\lambda)(z_0 - \mathrm{L})]} \tag{7}$$

Generally, there are two kinds of optical force acting on a dielectric particle due to the interaction between the evanescent field of the microfiber and the object. The gradient force used to trap an object is caused by the intensity gradient in a nonuniform field. The other force, namely the scattering force, is generated due to the scattering and absorption of the incident field by the dielectric particle. Scattering force is the reason for transportation of particles along the microfiber. In the Rayleigh regime, scattering force is proportional to the energy flux and points along the direction of propagation of the incident light. In the Mie regime, scattering force depends on the deflection of incident light. There is an analytic solution for Mie spherical objects, which describes the scattering of a plane wave by a dielectric sphere. However, much complicated computation is needed to find the full solution. For simplicity, the direction of Mie particles can be explained by the energy flux qualitatively. Fig. 1b shows the variation of energy density flux versus positions in z axis when the intensity ratios of two counter-propagating beams are 10:1, 1:10 and 1:1. As the figure shows, the variation of energy density flux in such interference fields is sinusoidal. However, the large diameters of micro particles used in our experiment compared to the wavelength in the medium cancel such a variation trend. The total scattering force is an

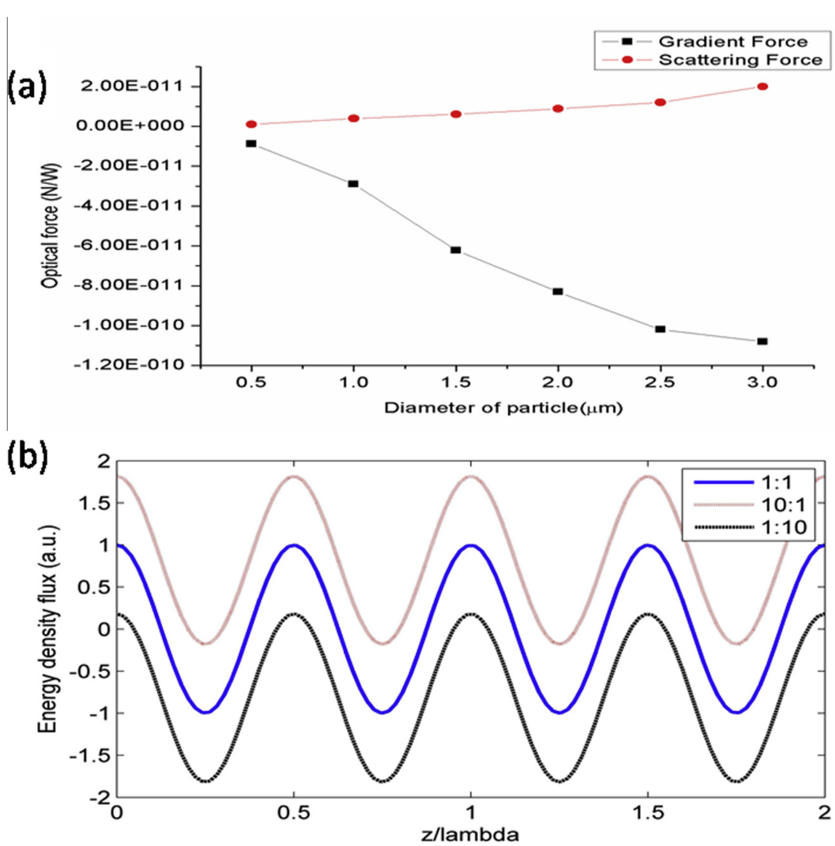

Fig. 1. (a) The variation of gradient force and scattering force acting on particles versus diameters of particles with one beam launched. (b) The variation of energy density flux along the microfiber corresponding to different power ratios of two counter-propagating beams.

average effect. That is to say, in an interference field, the direction of scattering force depends on the direction of total energy density flux. When the intensities of two counter-propagating beams are same, the total scattering force along microfiber is zero. When there is an intensity difference between two counter-propagating beams, the total scattering force is along the direction of the beam with bigger intensity.

3. Experimental procedure

A sketch of the experiment setup is shown in Fig. 2. Microfibers used in this experiment were manufactured using the so called flame brushing technology from a standard single mode optical fiber. The waist diameter of the microfiber was about 1 μm. The microfiber was positioned on a cover glass without touching the substrate by fixing their extremities with adhesive tapes. Two pigtails of the microfiber were connected to output ports of a variable ratio coupler. A 980 nm laser of 100 mW in power was used as trapping source. A water based suspension of SiO_2 spheres of 2 μm in diameter was used to surround the waist of the microfiber. The index of these particles is around 1.45. An optical microscope with a 40 times objective lens was used to observe the behavior of particles. A computer interfaced charge coupled device (CCD) camera is used to record experimental phenomena.

There are many ways to fabricate a various ratio coupler in the laboratory, for example, it can be fabricated from two twisting single mode optical fibers by a flame brushing method [12]. The coupling ratio can be adjusted by changing the wavelength of injecting laser and stress distribution in the coupling region. Moreover, two polished fibers can be combined to be a directional coupler and it can be tuned by adjusting their separation. Here we choose a stable commercial various ratio coupler (F-CPL-1550-N-FP, Newport) based on two polished fibers, which can adjust the coupling ratio from 0 to 100% with a high accuracy. The coupling of light is accomplished by putting two fiber cores close for evanescent field coupling. The precise control of the coupling ratio is realized by adjusting the relative lateral positions of the mated fibers with a micrometer. Fig. 3 shows the optical power ratio of two output ports corresponding to different relative lateral positions of the mated fibers.

4. Results

4.1. Controllable particles transportation

When there is only one laser beam injected to a microfiber, particles in suspension will be trapped onto the microfiber due to a gradient force and then transport along the propagation direction. When there is another counter-propagating laser beam, the direction of transportation could be controlled by changing the intensity ratio of the two counter-propagating beams. Fig. 4 shows the images of one particle transportation at different intensity ratios.

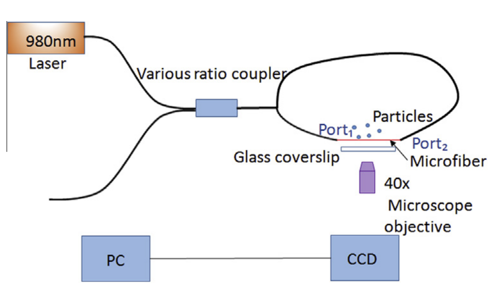

Fig. 2. Schematic of the experimental setup.

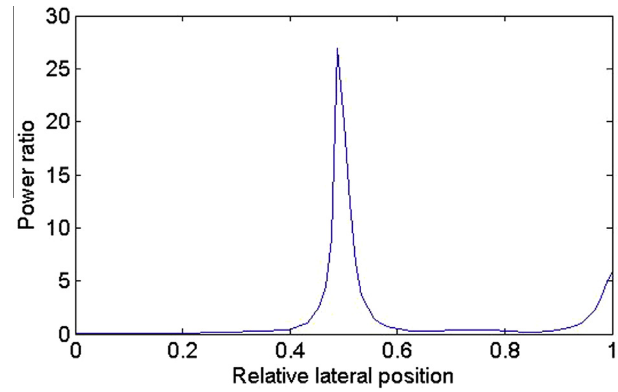

Fig. 3. Optical power ratio corresponding to different relative lateral positions of the mated fibers.

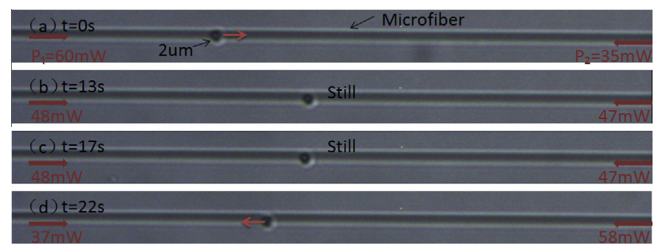

Fig. 4. Microscope images of controllable transportation for a single particle (Media 1). (a) A 2 μm particle was trapped and transported from the left to the right with P_1 larger than P_2. (b and c) The particle was still at a position with roughly same P_1 and P_2. (d) The particle transported from the right to the left with P_1 smaller than P_2.

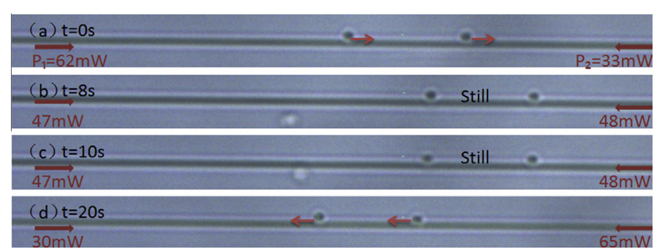

Fig. 5. Microscope images of controllable transportation for two particles (Media 2). (a) Two particles were trapped and transported at the same time from the left to the right with P_1 larger than P_2. (b and c) The two particles kept still with roughly same P_1 and P_2. (d) The particles transported from the right to the left with P_1 smaller than P_2.

At the beginning of recording ($t = 0$ s), power P_1 was larger than power P_2, the particle transported from the left to the right side. At $t = 13$ s, we tune the coupler to make the particle stop with roughly same power P_1 and P_2. Fig. 4(c) further shows the particle kept still at $t = 17$ s. Fig. 4(d) shows the particle transported from the right to the left when P_1 was smaller than P_2. Figs. 5 and 6 show the simultaneous transportations of two particles and three particles, respectively, and the transportation rule of multiple particles is similar to that of a single particle. However, when more particles were trapped, it was harder to make the particles stop at a fixed position stably, which may be caused by the interaction effect between particles.

4.2. Selective particles manipulation

Once a particle was trapped and transported along the microfiber, we tuned the micrometer to force the particle to stop at a

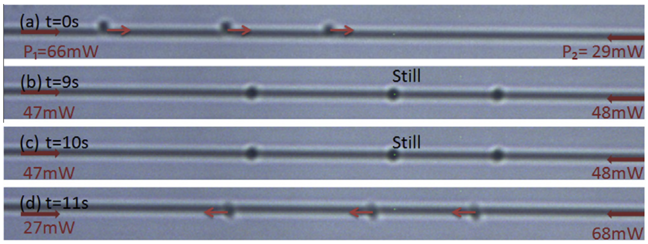

Fig. 6. Microscope images of controllable transportation for three particles (Media 3). (a) Three particles were trapped and transported simultaneously from the left to the right with P_1 larger than P_2. (b and c) The three particles kept still with roughly same P_1 and P_2. (d) The particles transported from the right to the left with P_1 smaller than P_2.

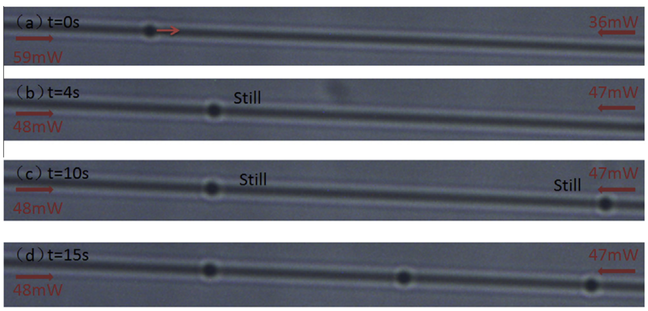

Fig. 7. Selective trapping of three particles one by one (Media 4). (a) A particle was trapped and transported along the microfiber from the left to the right. (b) The first trapped particle was kept still under the almost same power. (c) After six seconds, another particle was trapped onto the microfiber due to a gradient force and stayed still. (c) At $t = 15$ s the third particle was trapped.

desired position, and then we maintained this power ratio. With time going, another particle near the microfiber may be trapped onto the microfiber because of a gradient force. Fig. 7(a) shows at $t = 0$ s a particle was trapped and transported from the left to the right. For $t = 4$ to 9 s, the first particle kept still. At $t = 10$ s the second particle was trapped onto the micro fiber. With the second particle trapped onto the microfiber, the distribution of optical field around the second particle was changed by the first one and there was a bonding effect between these two particles, so there was a small deviation from the previous positions when the third one was trapped at $t = 15$ s.

5. Conclusion

In conclusion, bidirectional particles transportation and selective particles trapping were experimentally demonstrated through an all fiber apparatus based on a various ratio coupler. When a 980 nm laser was launched into the variable ratio coupler, particles around the microfiber were trapped and transported along the fiber in the evanescent field of two counter-propagating beams. By altering the intensity ratio of two counter-propagating beams through changing the coupling efficiency of the variable ratio coupler, the direction of transportation was controlled. Moreover, particles were selectively trapped one by one when the intensities of two counter-propagating beams were roughly same.

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References

[1] A. Ashkin, J.M. Dziedzic, J.E. Bjorkholm, Steven Chu, Observation of a single-beam gradient force optical trap for dielectric particles, Opt. Lett. 11 (5) (1986) 288–290.
[2] A. Constable, Jinha Kim, J. Mervis, F. Zarinetchi, M. Prentiss, Demonstration of a fiber-optical light-force trap, Opt. Lett. 18 (21) (1993) 1867–1869.
[3] K. Taguchi, K. Atsuta, T. Nakata, R. Ikeda, Levitation of a microscopic object using plural optical fibers, Opt. Commun. 176 (2000) 43–47.
[4] G. Brambilla, G.S. Murugan, J.S. Wilkinson, D.J. Richardson, Optical manipulation of microspheres along a subwavelength optical wire, Opt. Lett. 32 (32) (2007) 3041–3043.
[5] L.B. Yuan, Z.H. Liu, J. Yang, C.Y. Guan, Twin-core fiber optical tweezers, Opt. Express 16 (7) (2008) 4559–4566.
[6] T. Tanaka, S. Yamamoto, Optically induced propulsion of small particles in an evanescent field of higher propagation mode in a multimode channeled waveguide, Appl. Phys. Lett. 77 (20) (2000) 3131–3133.
[7] G.S. Murugan, G. Brambilla, J.S. Wilkinson, D.J. Richardson, Optical propulsion of individual and clustered microspheres along sub-micron optical wires, Jpn. J. Appl. Phys. 47 (8) (2008) 6716–6718.
[8] M.C. Frawley, I. Gusachenko, V.G. Truong, M. Sergides, S. Chormaic, Selective particle trapping and optical binding in the evanescent field of an optical nanofiber, Opt. Express 22 (13) (2014) 16322–16334.
[9] K. Grujic, O.G. Helleso, Dielectric microsphere manipulation and chain assembly by counter-propagating waves in a channel waveguide, Opt. Express 15 (10) (2007) 6470–6477.
[10] L.H. Zhao, Y.D. Li, J.W. Qi, J.J. Xu, Q. Sun, Quasi 3-dimensional optical trapping by two counter-propagating beams in nano-fiber, Opt. Express 18 (6) (2010) 5724–5729.
[11] H.X. Lei, C. Xu, Y. Zhang, B.J. Li, Bidirectional optical transportation and controllable positioning of nanoparticles using an optical nanofiber, Nanoscale 4 (21) (2012) 6707–6709.
[12] Y.M. Jung, G. Brambilla, D.J. Richardson, Optical microfiber coupler for broadband single-modeoperation, Opt. Express 17 (7) (2009) 5273–5278.