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NANOPARTICLES SORTING AND ASSEMBLY BASED ON DOUBLE-AXICON IN AN OPTOFLUIDIC CHIP

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ABSTRACT

This paper presents a novel optofluidic system for nanoparticle sorting by using interference patterns generated through a double-axicon. The tightly confined Bessel beam is used to sort the 200-nm and 500-nm polystyrene nanoparticles massively and simultaneously by adjusting the flow rate and the laser power. Additionally, 2- μm polystyrene particles are assembled into a 2D array by utilizing the discrete interference pattern. This system first utilizes the interference patterns based on the on-chip double-axicon, and integrates the sorting and assembly abilities into a single chip. It has a great potential in bacterial and DNA sorting and cell assembly.

INTRODUCTION

Sorting and precise manipulating on micro/nanoparticles and biosamples such as cells and molecules in flowing streams is critical in the realm of biological and chemical analysis [1-4]. Optical tweezers, known as versatile and noninvasive tools, are able to manipulating particles from hundreds of micrometers to several nanometers efficiently [5, 6]. Conventional single beam optical tweezers are well known for sorting cells efficiently. They are also demonstrated to be capable of trapping and assembling nano-spheres and wires into 2D patterns one by one [5]. However, this assembly requires precise alignment and time-consuming manual works. Holographic optical tweezers have shown particularly success in sorting cells and assembling them into a designed array [7, 8]. Yet the sorting is only applicable to the microparticles, because of the small distinct gradient forces and relatively large hydrodynamic drag force on the nanoparticles. Besides, the assembly is only conducted in the still environment, and the samples are stick to the substrate, which causes samples contamination and measurement error. Recently, a novel optical switch is proposed to sort out two different cells with a high purity and yields [9]. The florescence of the samples are first detected and analyzed in the detecting zone, those with the chosen florescence signals will be pushed to a different outlet by the optical forces. This optical switch is widely used in the micrometer-sized biological sample separation. Meanwhile, many novel interference patterns in the optofluidic chips are used to sorting and assembly micro and nanoparticles. For example, Bessel beams and Laguerre-Gaussian beams are used to achieve 1D nanoparticle array in still water and flow stream, respectively [10, 11]. Nanoparticles and λ -DNA are trapped and transported on the "slot waveguide" by using evanescent

wave [12].

DESIGN AND WORKING PRINCIPLE

Figure 1: Illustration of optofluidic platform for nanoparticles sorting and assembly. (a) When gap is 30 μm , Quasi-Bessel beam is generated to retain large nanoparticles in the microchannel, whereas small nanoparticles are washed away by the flow. (b) When gap is 200 μm , the discrete interference pattern is formed to assembly large particles into a 2D array, whereas smaller particles are washed away.

The working principle of the optofluidic platform for particles sorting and assembly is illustrated in Fig. 1. The optofluidic chip consists of one inlet and two outlets. The aqueous suspension of particles is injected into the microchannel from the inlet. Light (532 nm) from a fiber (NA = 0.12) are coupled into the microchannel through a double-axicon optical elements. By increasing the gap between the fiber and double-axicon, the light beam can be switched from Bessel profile to different discrete interference patterns. When the gap is 30 μm , the interference pattern from the double-axicon is the quasi-Bessel beam. 500-nm polystyrene nanoparticles are trapped in the microchannel in

Figure 2: (a) Geometry of the double-axicon illuminated by a Gaussian beam. (b) Photography of the optofluidic chip.

the balance of the optical extinction forces and fluidic drag forces. Meanwhile, the 200-nm polystyrene nanoparticles are washed away by the flow, because they are seldom influenced by the optical field. When the gap is increased to 200 μm , the interference pattern switches to the discrete interference pattern. Large particles (e.g. 2- μm particles) will be assembled into a 2D array in the synergy of the optical extinction forces, optical gradient forces and fluidic drag forces. Nevertheless, the smaller polystyrene nanoparticles (e.g. 200-nm and 500-nm particles) are flushed out.

Figure 2(a) shows the geometry of a double-axicon illuminated by a Gaussian beam. The open angles (θ_1 and θ_2) of the two axicons are 8° and 55° , respectively. The lens length (from the left edge to the right edge) is 52 μm . The Gaussian beam is generated from the laser with a fiber coupled into the double-axicon. Figure 2(b) shows the fabricated optofluidic chip which is fabricated by polydimethylsiloxane (PDMS) utilizing the standard photolithography procedure.

DISTINCT INTERFERENCE FIELDS

The optical field in the microchannel is simulated based on the geometry in Fig. 2. Distinct interference patterns are generated by changing the gap between the optical beam waist and the double-axicon. Figure 3(a) shows that a Bessel profile beam is formed when the gap is 30 μm . Unlike the non-diffraction property of the Bessel beam, this beam diffracts slowly. The divergence of the beam is much smaller than that from the original low-NA (0.12) fiber. It is termed as quasi-Bessel beam. When the gap is increased to 200 μm , a discrete interference pattern emerges. This kind of discrete interference pattern is similar to the pattern in the optofluidic waveguide induced by the diffusion between two liquids

Figure 3: Simulated optical fields. (a) When the gap is 30 μm , a quasi-Bessel beam is generated. (b) When the gap is 200 μm , a discrete interference pattern is generated.

[13]. It is noticed that the length of the single light spot becomes larger as the light propagates.

OPTICAL FORCES AND HYDRONAMIC DRAG FORCE ANALYSIS

Optical forces mainly consist of the optical scattering force and the optical gradient force. The optical scattering force transfers the momentum of light to the particles, pushing particles as light propagates. The optical gradient force tends to draw particles into the maximum of the electrical field.

For Rayleigh particles, the optical forces can be expressed as [2]

$$\mathbf{F}_{grad}(\mathbf{r}) = 2\pi n_2^2 \varepsilon a^3 \left(\frac{m^2 - 1}{m^2 + 1} \right) \nabla |\mathbf{E}^2(\mathbf{r})|, \quad (1)$$

$$\mathbf{F}_{scat}(\mathbf{r}) = \frac{n_2}{c} \frac{128\pi^5 a^6}{3\lambda^4} \left(\frac{m^2 - 1}{m^2 + 2} \right)^2 I(\mathbf{r}), \quad (2)$$

where $\mathbf{r}$ is the position vector, ε is the dielectric constant in the vacuum, c is the speed of light, m is the ratio between the refractive index of the particle and that of the surrounding media n_2 , and a is the radius of the particle. For particles in the Mie regime (e.g. 2- μm particles), the generalized Lorenz-Mie theory (GLMT) is invoked. The optical force can be expressed as

$$\mathbf{F}(\mathbf{r}) = \frac{n_2}{c} I_0 \left[\hat{x} C_{pr,x}(\mathbf{r}) + \hat{y} C_{pr,y}(\mathbf{r}) + \hat{z} C_{pr,z}(\mathbf{r}) \right], \quad (3)$$

Figure 4 shows the calculated results of the optical forces induced velocity on 200 and 500-nm polystyrene nanoparticles. 200-nm polystyrene particles experience much smaller optical scattering force. Thus they will be washed away by controlling a proper flow rate. At the same time, 500-nm polystyrene particles, which are more susceptible to the optical field, will retain in a position where optical forces and fluidic drag force balance. The light intensity distribution in the direction that perpendicular to the

Figure 4: Optical forces on 200-nm polystyrene (a) and 500-nm polystyrene (b) nanoparticles induced velocity.

light propagating direction can be fitted well with Gaussian profile, forming an optical potential well. The form factor of a single Gaussian function is expressed as

$$f(\vec{r}) = \alpha a \exp\left(-\frac{\vec{r}^2}{2a^2}\right), \quad (4)$$

where a is the particle radius and $\alpha = 2\pi \frac{n_2}{c} \left(\frac{n_2^2 - n_1^2}{n_1^2 + 2n_2^2} \right)$.

Thus the effective potential is expressed as

$$V(\vec{r}) = -I(\vec{r}) \otimes f(\vec{r}) = -\int f(\vec{x} - \vec{r}) V(\vec{x}) d^2x. \quad (5)$$

Hence, the gradient force in the light propagating direction is

$$\begin{aligned} F_{grad} &= \vec{\nabla}(V(\vec{r})) = \vec{\nabla}\left[-(I(\vec{r}) \otimes f(\vec{x}))\right] \\ &= 2\pi\alpha I \frac{a^3 \omega}{\sigma^3(a)} x \exp\left(-\frac{(x-x_1)^2}{2\sigma^2(a)}\right). \end{aligned} \quad (6)$$

The hydrodynamic drag force on a particle is caused by the flow velocity difference between the flow and the particle. It can be expressed as

$$F_{drag} = 6\pi\eta va, \quad (7)$$

where η is the viscosity of the liquid, v is the velocity difference between the flow and the particles, and a is the radius of the particle.

EXPERIMENTAL RESULTS

The aqueous suspension which carries particles was injected into the microchannel using a syringe pump (Genie, Kent Scientific Corporation, CT, USA). The flow velocity is set to 200 $\mu\text{m/s}$. The simulation results show that the optical scattering force on the 200-nm polystyrene particles is much smaller than the hydrodynamic drag force, which is almost impervious to the optical fields. However, the 500-nm polystyrene particles experience much larger optical scattering forces, which can be balanced against the hydrodynamic drag force at an equilibrium position.

Figure 5 shows that the 200-nm and 500-nm polystyrene nanoparticles are under bidirectional sorting in the optofluidic chip with a gap of 30 μm . The 200-nm

Figure 5: 200-nm and 500-nm polystyrene nanoparticles under bidirectional sorting.

polystyrene nanoparticles which experience much smaller optical forces flow to the left driven by the flow. At the same time, the 500-nm polystyrene nanoparticles are pushed back by the optical forces, and eventually retain in an equilibrium position. The optical gradient force is responsible for the confinement of particles in the middle of the light spot.

When the gap is increased to 200 μm , the vertical confinement of light in the vertical direction is weaker, resulting in the smaller optical gradient force. In order to assemble the particles in the optical pattern, the laser power is increased to 500 mW, which generates strong enough optical gradient force to conquer the Brownian motion.

Figure 6 shows a 2D array formed by 2- μm polystyrene particles in the flow. The patterned particles are almost trapped at the same position when the 500-nm nanoparticles are flushed away. This is the result of the equilibrium of the optical scattering force and the fluidic drag force in the horizontal direction and the confinement due to the optical gradient force in the perpendicular and vertical directions. The equilibrium positions are corresponding to the hot spot in the discrete interference pattern as shown in Fig. 3(b). If the solute is dilute enough, there will be only one particle occupy one hot spot in the optical pattern. This phenomenon has a great potential on single cell analysis.

Figure 6: Assembly of 2- μm polystyrene particles into a 2D array in a flow stream.

CONCLUSIONS

In conclusion, an optofluidic chip with double-axicon is developed for sorting and assembling nanoparticles. The 200-nm and 500-nm polystyrene nanoparticles are massively and simultaneously sorted in the quasi-Bessel beam by controlling the flow rate and the laser power. The 2- μm polystyrene particles are successfully assembled into a 2D array in the discrete interference pattern in the flow stream. This optofluidic system can be applied to the single molecules sorting and single cells analysis and patterning.

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