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ABSTRACT

Particle jumping between optical potentials has attracted much attention owing to its extensive involvement in many physical and biological experiments. In some circumstances, particle jumping indicates escaping from the optical trap, which is an issue people are trying to avoid. Nevertheless, particle jumping can facilitate the individual trap in each laser spot in the optical lattice and enable sorting and delivery of nanoparticles. Particle hopping has not been seen in fluid because Fluidic drag force dramatically reduce the dwell time of particle or break the potential well. Here, we observe particle hopping in the microchannel by three reasons, e.g., particle collision or aggregation, light disturbing by pre-trapped particle and fake trapping position. We show that commonly ignored particle influence to the light could create a new isolated trapping position, where particle hops to the adjacent potential well. The hopping happens in an optofluidic fishnet which is comprised of discrete hotspots enabling 2D patterning of particles in the flow stream for the first time. We also achieve a 2D patterning of cryptosporidium in the microchannel. Our observed particle hopping in the flow stream completes the family of particle kinetics in potential wells and inspires new interests in the particle disturbed optical trapping. The 2D patterning of particles benefits the parallel study of biological samples in the flow stream and have potential on cell sorting and drug delivery.

Keywords: Particle jumping, optical manipulation, particle collision, optofluidics

1. INTRODUCTION

Particle hopping between optical potentials has attracted much attention owing to its extensive involvement in many physical and biological experiments. In some circumstances, particle hopping indicates escaping from the optical trap, which is an issue people are trying to avoid. Nevertheless, particle hopping facilitates the individual trap in each laser spot in the optical lattice and enable sorting and delivery of nanoparticles. Previously, early investigations dates back to 1940s and most of them stay in the theoretical level. Experimentally, a dual optical trap was used to investigate the transition rate of the particle and shows a good consensus with Kramer's theory. A standing wave saves as a one-dimensional optical lattice which was used to investigate the free particle drifting inside. However, either the dual trap or standing wave configures only a 1d lattice which allows a random drifting of the particle only in the still water. Moreover, previous investigations, both in theory and experiment, only investigate the kinetics of a single particle in the potential well, which has a great gap between the real works, e.g., multiple-particle transition between potential wells.

Investigation of the 2D particle hopping in the flow stream relies on the creation of a 2D particle array in the microchannel. During the last two decades, there has been several methods to pattern particles. Examples are the laser printing single gold nanoparticles, plasmonic and holographic patterning. Some intriguing beams, such as LG and Airy beams, also have the ability to pattern particle in their isolated hotspots. However, those beams are not feasible in the flow stream because they do not have components of forces that compete with the fluidic drag force. In the flow stream, 1D patterning of particles in the flow stream has been achieved using two counter-propagating interfering Bessel beams and two interfering LG beams. Nevertheless, the 2D pattering of particle in the flow stream is still a big challenge.

Here, we develop a 2D optofluidic lattice in the microchannel. Each hotspot in the optofluidic lattice (also called discrete interference pattern) traps a single particle in the synthesis of the optical and fluidic forces. Three types of hopping trigger by particle-particle interaction in lattice, e.g., extra trapping position, particle collision, particle aggregation are

observed in the flow stream for the first time. Our theoretical investigation shows that the particle residence time in the potential well can be largely reduced by the interaction of other particles. 2D patterning of cryptosporidium is also demonstrated using this optofluidic lattice, which has a great potential in the biological studies.

2. OPTOFLUIDIC CHIP AND JUMPING MECHANISMS

Illustrated in Figure 1, the optofluidic chip comprises a microchannel with three inlets and two outlets. Light (532 nm) is coupled into the microchannel by a single-mode fiber (NA 0.12) and generates a 2D optical lattice after a built-in micro-quadrangular lens [1−3]. The lens can be regarded as a combination of two axicons with two open angles. Particles which are dispersed in the deionized water are injected into the microchannel by the hydrodynamic focusing. Particles in the optofluidic lattice experience the optical scattering force F_{sca} which points to the energy transfer direction, the optical gradient force F_{grad} that draws particles to the spot center, the drag force F_{drag} which is along the flow direction and the Brownian force F_{th} [4−7]. The particle jumping can be delicately controlled by the coordination of the optical and fluidic forces. And the particle trajectory can be tweaked as a loop by the optical jumping as shown in Figure 1. We show two jumping mechanisms in the optofluidic lattice, e.g. extra trapping position (Figure 2a) and particle collision (Figure 2b). Shown in Figure 2a, the extra trapping position induced hopping happens when the initial position of the green particle is on the top of the x-z plane. The red particle is previously trapped in the central potential well. After trapping, the red particle generates an extra trapping position on the right because of the focusing of light by the red particle. The green particle surpasses the red particle without collision and trapped in the extra trapping position. It then jumps to the adjacent potential well because the potential energy of the extra potential well is shallow which is unable to hold the particle for a long time. As shown in Figure 2b, the collision happens when the green particle comes from the side of the central potential well. It is gradually attracted to the central line of the potential well, and collides with the pre-trapped red particle. The collision eventually causes the red particle jumps to the adjacent potential well. The reason of the jumping lies in that the collision generates a particle wall and extrudes the red particle to the adjacent potential well.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

As mentioned previously, the pre-trapped red particle generates an extra trapping position for the subsequent particles. The extra trapping positions (blue particle) is approximately 3.5 μm away from the original trapping position (red ball). The potential well in the extra trapping position is shallow and unable to hold the particle for a long time. The particle will eventually jumps to the adjacent potential well. The mean first passage time (MFPT) which characterize the mean residence time in the potential well can be expressed as [8],
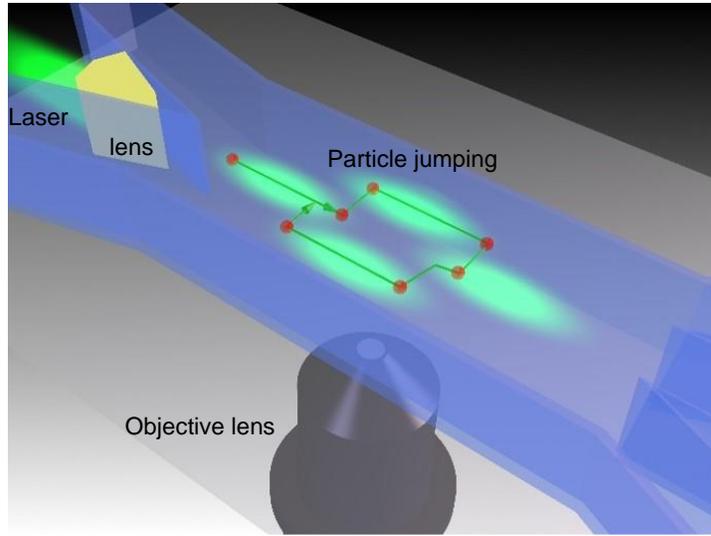
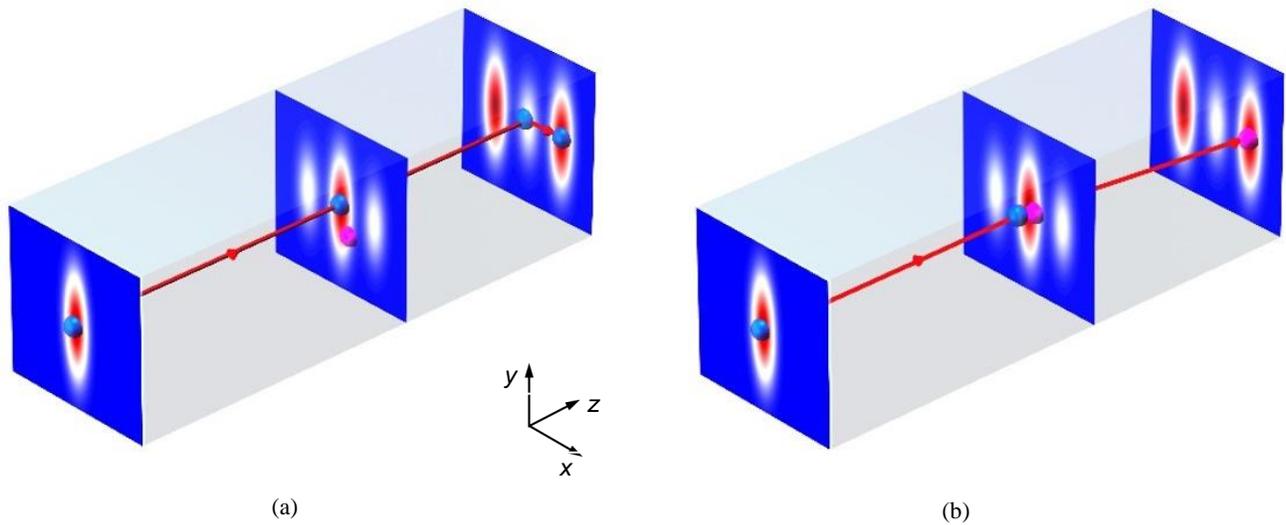Figure 1. Illustration of particle hopping and looping in the optofluidic chip.

(a)

(b)

Figure 2. Mechanisms for the (a) pre-trapping and (b) collision induced jumping.

$$T = \frac{2\pi\gamma}{\sqrt{\left\|U''(A)\right\|\left\|U''(B)\right\|}} \exp\left(\frac{U(B)-U(A)}{k_B T}\right) \tag{1}$$

where $U(A)$ and $U(B)$ denote the potential energy at point A and B, respectively. $U''(A)$ and $U''(B)$ denote the second
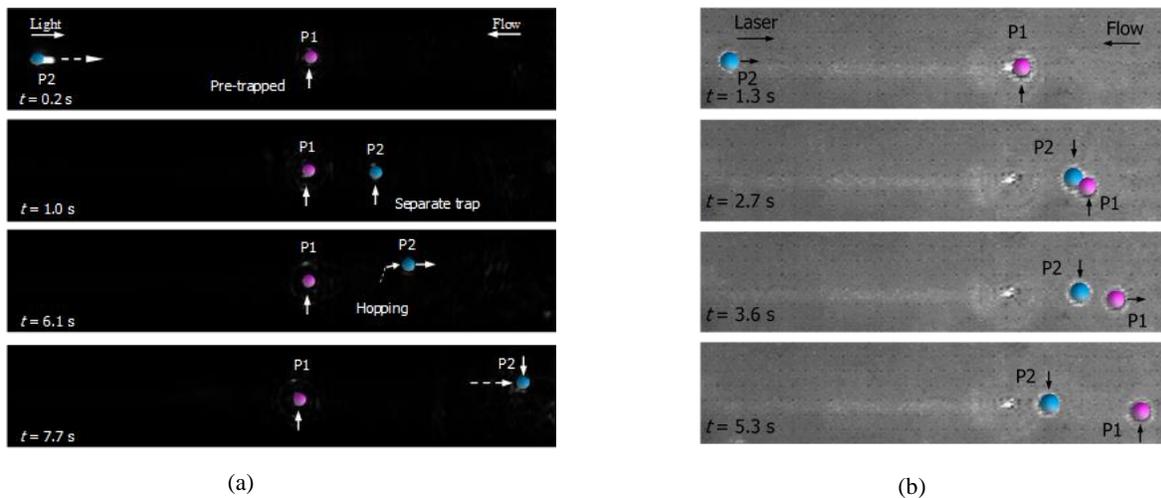
(a)

(b)

Figure 3. Experimental observation of the (a) pre-trapping and (b) collision induced jumping. (a) Moving illustrating the hopping of the 1μm particle induced by the pre-trapped particle. At $t = 0.2$ s, particle P1 is trapped in the potential well 1 and P2 is pushed to the right against the flow stream. P2 passed P1 and trapped on the right side of P1 in the potential well 1 at $t = 1.0$ s. P2 begins to hop to potential well 2 at $t = 6.1$ s. It is trapped in the potential well at $t = 7.7$ s. (b) Experimental demonstration of the particle collision induced hopping between potentials. At $t = 1.3$ s, particle P1 is previously trapped and particle P2 is pushed against the flow stream by the optical force. P2 collides with P1 and causes particle 1 shift away from the central of the beam at $t = 2.7$ s. P1 is attracted by the optical gradient force in potential well 4 and pushed to the right by the optical scattering force at $t = 3.6$ s. P1 then resides on its new equivalent position in the adjacent potential well at $t = 5.3$ s.

derivative of the potential energy profile at points A and B, respectively. And γ and kB are the fluidic damping constant and Boltzmann constant, respectively. The activation energy of the potential barrier $E=U(A)−U(B)$) is 2.25×10^{-20} J. The experimentally measured MFPT is approximately 7 s which is in good consensus with the calculated MFPT 8 s. The experimental observation of the particle hopping from the extra trapping position was shown in Figure 3a. At $t = 0.2$ s, particle P1 (1 μm) is already trapped in the potential well. Particle P2 (1 μm) comes from the left side pushing by the optical scattering force. P2 is trapped in the extra trapping position bypassing P1 at time 1.0 s. P2 stays in the potential well for 5.1 s before it hops to the potential well upside. It is eventually pushed to the further right by the optical scattering force at $t = 6.4$ s.

The collision of two particles in the optofluidic lattice occurs when the red particle is pre-trapped in the potential well and the green particle comes from the side of the potential in the x-z plane. The green particle eventually hit on the side of the red particle and extrude the red particle to the adjacent potential well (shown in Figure 3b). The red particle is pushed to the right by the optical scattering force in case of hopping back to the original potential well. The potential energy plot of the original trapping position in Figure 3a indicates that the The activation energy of the potential barrier $E=U(A)−U(B)$) is 7.5×10^{-19} J, which is 181 fold of the thermal energy of the particle (k_BT). This means the red particle can be stably trapped in the potential well if there is no collision with the green particle. At $t = 1.3$ s, particle P1 is pre-trapped and particle P2 comes from the same x-z plane and pushed to the right by the optical scattering force. P2 makes contact with P1 at $t = 2.7$ s and extrude P1 from the potential well.

4. CONCLUSIONS

In conclusion, our optofluidic chip offers an unparalleled paradise for investigation of the particle-particle interaction induced jumping in the optofluidic lattice. Two mechanisms for the jumping, e.g. extra trapping position and particle collision were demonstrated in the microchannel, which fills the gap of 2D, controllable, particle interaction and in the flow stream comparing to previously proposed 1D, random walk, single particle and still environment. Our demonstration inspires a burgeoning interest in the particle-particle interaction in the 2D even 3D optical lattice in either

the still environment or the flow stream. In addition, our optofluidic chip may also facilitate the 2D untangled patterning of biological samples in the flow stream, which benefits the simultaneous investigation of their biological properties and chemical reactions.

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