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Parallel alignment of bacteria using near-field optical force array for cell sorting

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ABSTRACT

This paper presents a near-field approach to align multiple rod-shaped bacteria based on the interference pattern in silicon nano-waveguide arrays. The bacteria in the optical field will be first trapped by the gradient force and then rotated by the scattering force to the equilibrium position. In the experiment, the *Shigella* bacteria is rotated 90 deg and aligned to horizontal direction in 9.4 s. Meanwhile, ~150 *Shigella* is trapped on the surface in 5 min and 86% is aligned with angle < 5 deg. This method is a promising toolbox for the research of parallel single-cell biophysical characterization, cell-cell interaction, etc.

Keywords: rod-shaped bacteria, near-field, trap, align

1. INTRODUCTION

Optical manipulation utilizes the combination of optical force, fluidic drag force, and particle's Brownian motion to achieve manipulation functionalities such trapping, sorting and patterning [1]. In recent years, optical manipulation has grown enormously benefitting from the advance in nanofabrication, optofluidics, metamaterials, etc. [2] The development of optical manipulation boosts the research in many areas such as cell biology [3, 4], atom physics [5], microscopy [6], and many others [7-9].

Immobilizing individual living cells at the specific location is important for cell biologists to study cellular behaviours such as growth, interaction and metabolism. In conventional optical tweezer, a bacterium tends to align itself with the light propagation which prevents the direct in-plane observation [10, 11]. Near-field methods is demonstrated based on localized surface plasmon resonance in nano-antennas [12]. However, the available methods still have substantial limitations in manipulating massive bacteria for bacterial motility characterization and intercellular interaction study.

This paper proposes a near-field approach is proposed based on the interference pattern in silicon nano-waveguide arrays. This method is anticipated to benefit the research of single-cell biophysical characterization, cellular heterogeneity, and cell-cell interaction.

2. PRINCIPLE AND FORCE ANALYSIS

Figure 1(a) illustrates the trapping and alignment of multiple bacteria in the system. When a bacteria flows into the optical field, it will be trapped on the surface, aligned to the x-direction, and pushed along the waveguide. The bacterial motion can be decomposed into the out-of-plane rotation, in-plane rotation, and translation motion. The out-of-plane rotation occurs when a bacteria flows through the optical field, one end of the bacteria is first trapped on the surface, and then the bacteria is rotated by the out-of-plane gradient force until fully contact with the surface as shown in Figure 1(b). Similarly, the in-plane rotation occurs when the axial direction of a bacteria is noncoincident with the waveguide-length direction, the bacteria is rotated by the in-plane gradient force and aligned to the waveguide-length direction as shown in Figure 1(c). The translation motion occurs when a bacteria is partially or fully trapped on the surface, it is pushed by the optical scattering force along the waveguide as shown in Figure 1(d). The three types of motions may occur

simultaneously. For example, when a bacteria flows into the optical field, it may rotate in the in-plane and out-of-plane directions, and in the meanwhile, moves towards along the waveguide.

Figure 1. (a) Schematic illustration of bacteria trapping and alignment in the optofluidic system. The bacterial motion can be decomposed into: (b) out-of-plane rotation, (c) in-plane rotation, and (d) translation motion.

Figure 2. Simulated light intensity in a waveguide-pair. (Vertical direction is magnified by 5-fold)

Since the size of bacteria is comparable with the optical wavelength [17], the optical force on a bacteria cannot be calculated using Rayleigh model. Here a commercial FDTD software (Lumerical FDTD) is used to calculate the optical force instead. The FDTD calculation is extremely resource-intensive and time-consuming in dealing with large simulation region. Meanwhile, the optical force field is the array of the force in two sequential hotspots. Therefore, only the optical force in the first three hotspots is calculated to reduce the computational complexity.

In the simulation, the bacteria is modeled as a cylinder with a dimension of $0.8\ \mu\text{m}$ (diameter) $\times$ $2.0\ \mu\text{m}$ (length). The cylinder is placed 50 nm above the surface and the axial direction is parallel to the waveguide length-direction. The refractive index of the bacteria is set to 1.422 [17]. The guided power in the waveguide-pair is set to 3mW. The center position of the bacteria is swept in the x - y plane. Figure 5.33 shows the simulated x -component, y -component and z -component of the optical force distribution. The black dashed line denotes the direction of the energy flow. The force distribution in the x - y plane indicates the bacteria will follow the energy flow and move along the waveguide to the right direction. In the z -direction, the bacteria is subjected to an attractive force to the surface ranging from 0.15 - 1.0 pN.

3. RESULTS AND DISCUSSIONS

Here the rotational motion of an individual *Shigella* is studied experimentally. The laser power coupled into the device is $\sim 100\ \text{mW}$ and the flow velocity is set to $5\ \mu\text{m/s}$. The length and diameter of *Shigella* are reported to be $2.74 \pm 0.67\ \mu\text{m}$ and $0.77 \pm 0.10\ \mu\text{m}$, respectively. The *Shigella* in the experiment is $3.1\ \mu\text{m}$ in length and $0.8\ \mu\text{m}$ in diameter. As shown in Figure 3, the bacteria at $t = 0$ is perpendicular to the waveguide, while at $t = 9.4\ \text{s}$, the bacteria is aligned to horizontal direction, just as the other bacteria in the images.

Figure 3. The rotational movement of a single *Shigella* bacteria in the optical field.

Figure 4. Optical image of accumulated *Shigella* bacteria on the surface.

The parallel trapping and alignment of *Shigella* is also experimentally demonstrated. The *Shigella* concentration is $\sim 1 \times 10^3$ CFU/ μ L. Figure 4 shows the optical image of the waveguide surface when the optical field is switched on for 5 min. We can clearly see ~ 150 *Shigella* is trapped on the surface and $> 86\%$ of them are aligned with angle < 5 deg. Meanwhile, the trapped *Shigella* exhibits varied length and width, which indicates the different growth phase of individual *Shigella*.

4. CONCLUSIONS

In conclusion, an optical approach is developed to trap and align rod-shaped bacteria based on the near-field interference pattern in nano-waveguide arrays. The *Shigella* bacteria is rotated 90 deg and aligned to horizontal direction in 9.4 s. Meanwhile, ~ 150 *Shigella* is trapped on the surface in 5 min and 86% is aligned with angle < 5 deg. This near-field approach is a promising toolbox for parallel single-cell analysis.

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