Continuous separation of nano-sized molecules has great importance in biomedical applications. This paper represents a near-field optical approach to separate nanoparticles using speckle patterns. Near-field random light patterns (speckle pattern) are generated by the repeated coupling and interference of light in nano-waveguide arrays. The movements of 2-μm and 0.5-μm particles are studied under the co-action of Brownian motion and the exerted optical force. The experimental results show that the 2-μm particle has an average lateral displacement of 10 μm, which is considerably larger than that of the 0.5-μm particle. This method avoids the stringent optical systems and broadens the perspectives of optical manipulation in real-life applications.
Figure 1 shows the working principle of particle manipulation using near-field speckle patterns. In order to generate the near-field speckle pattern, a focused laser beam with a wavelength of 1550 nm is coupled into a single waveguide as shown in Figure 1(b). The light wave is coupling back and forth from one waveguide to adjacent waveguides, forming a large number of optical waves with random phases. Then the waves interfere with each other and eventually form a complex and random light pattern. Here the speckle pattern is reconfigurable by changing the source position, laser wavelength or the surrounding medium. The background image in Figure 1(a) is a typical speckle pattern. The red spots stand for high-energy positions, while the blue areas stand for low-energy regions. Each optical potential will exert an optical gradient force and a scattering force to nearby particles. The exerted optical force on a Rayleigh particle is shown in Figure 2. It clearly shows that the scattering force is larger than gradient force for large particles, whereas is smaller than gradient force for small particles.

\[
F_{\text{sc}} = \frac{k_B T}{\gamma} \frac{\pi a^4}{3} \left( \frac{m_i}{m} \right)^{\frac{1}{2}} n_i \\
F_{\text{gr}} = \frac{2\pi n a^2}{c} \left( \frac{m_i}{m} \right) dI
\]

where \( D_{\text{sc}} = \frac{k_B T}{\gamma} \) is the Stokes-Einstein’s diffusion coefficient of the Brownian particle.

When the particle is in a single optical potential as shown in Fig. 1(c), the gradient force for both the large and small particles is smaller than the scattering force in the longitudinal direction. That is because the light is loosely focused in this direction. Therefore, all the particles will move rightwards. However, in the transverse direction, the light spot has a length of only 200 nm, i.e. tightly focused, and the gradient force is comparable with the scattering force for small particles. Therefore, the second term of small particles in Eq.(2) is smaller than that of large particles. This relationship theoretically indicates that large particles will have a larger transverse Brownian displacement than small particles. In this way, different-sized particles can be separated when flowing through the speckle pattern.

![Figure 3: Simulated near-field speckle patterns 40 nm above the waveguide surface.](image)

Three-dimensional simulations are conducted in RSoft 8.01 to investigate the light patterns. Figure 3 shows the simulated speckle patterns 40 nm above the waveguide surface. The random pattern is reconfigurable by changing the light source position and wavelength. Figure 4 shows the force analysis of the zoom-in region of Figure 3. The white
arrow represents the magnitude and direction of the resultant force, which clearly shows that the 2-μm particle experiences constantly downward force, whereas the 0.5-μm particle experiences either upward or downward force depending on its location.

**FABRICATION AND EXPERIMENTS**

The silicon nano-photonic device is fabricated on a silicon-on-insulator wafer with a device layer of 220 nm and a buried-oxide layer of 2 μm. Figure 5(a) and (b) show the SEM images of waveguide array with 11 and 5 waveguides, respectively. The fabrication steps include: (1) silicon etching using SiO₂ as hard mask, (2) 2-μm cladding HDP SiO₂ deposition and (3) etching to release the window region [16]. The microchannel is fabricated with polydimethylsiloxane (PDMS) using soft-lithography technology. Then the silicon and PDMS chips are bonded together after careful surface treatment. The dimension of the final hybrid chip is 16 mm (length) × 3 mm (width) × 2 mm (height).

**RESULTS AND DISCUSSIONS**

Figure 7 shows the trajectories of 0.5-μm and 2-μm particles, respectively. Here the particle positions are superposed into a single image for illustration purpose. The 1550 nm laser is applied into the waveguide array from its left port. When particles diffuse onto the edge of the array, they move under the action of Brownian motion and the exerted optical force. The particle trajectories show that in the transverse direction, the 2-μm particle diffuses downward considerably at a certain time, whereas the 0.5-μm particle basically vibrates around its original position. Figure 8 shows the statistical analysis of the transverse displacement of different sized particles. It indicates that larger particles generally move further in the speckle pattern, which can be potentially used for particle fractionation.

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Figure 5: SEM images of the fabricated waveguide arrays with (a) 11 waveguides and (b) 5 waveguides.

Figure 6: Experimental setup to generate and control the required light patterns.

Figure 7: Position superposition of (a) 2-μm and (b) 0.5-μm particle. Green and yellow line: motion trajectory. Scale bar: 20 μm

![Figure 8](image_url)

**Figure 8:** Statistical analysis of the transverse displacement of different sized particles.
CONCLUSIONS

In conclusion, a near-field speckle pattern is generated in nano-waveguide arrays and the motion trajectory of 0.5-μm and 2-μm particles are studied. The experimental results show that the 2-μm particle has a considerably larger transverse displacement than the 0.5-μm particle. This technique is anticipated to have a high potential in nano-sized particle fractionation such as DNA and virus molecules.

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