Dynamics of Optical Particle Transportation and Sorting in Brownian Liquids

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Abstract

In this study, particle sorting and transportation in Brownian liquids were explored by translating an optical standing wave. The standing wave is produced by crossing two coherent beams of light, and determining the resulting period by the angle of the intersection. Adjusting the period and velocity of wave ridges allows one to move particles of one size while leaving particles of another size behind — a noninvasive cell and virus sorting technique. The random nature of Brownian motion on these particles was also explored.

Introduction

Optical tweezing and particle sorting have proven to be powerful tools in the fields of physics and biology. Applications of these techniques include but are not limited to the sorting and manipulation of cancer and reproductive cells, as well as of viruses and bacteria.[1] Similar techniques can be used to study the physical properties of DNA and RNA and can be extended to nanometer-sized particles — including those smaller than the wavelength of light.[2] Because the forces on the sample are exclusively optical, the techniques of laser tweezing and particle sorting surmount conventional methods of particle manipulation, which often require physical contact with the sample.

Background

The technique of laser tweezing was first discovered in 1970[3,4] as a way of trapping and manipulating micron-sized particles using only light from a single laser beam. This beam is expanded and then tightly focused onto a sample, creating an optical force (roughly in the range of piconewtons to femtonewtons) on micron-sized particles. This optical force occurs when light changes momentum as it comes in contact with a sample having a higher refractive index than the medium in which it resides and is scattered or refracted by the particle (Figure 1). These forces are known as the scattering force and gradient force, respectively. Soon after the technique of optical tweezing was discovered, it began to be used for particle sorting.[5,6] Many techniques in this field have been established over the past several years,[7–19] and two groups have recently reported approaches for sorting different-sized particles using a translating optical standing wave.[15,16] The lateral force on a particle from a standing wave is determined by the wave spacing relative to the particle diameter. Adjusting these parameters allows one to sort particles by size — causing particles of one size to "slip" from one standing-wave intensity maximum to an adjacent trailing one because of a very small force acting upon them, while causing a particle of another size to move along with the wave as it is translated. In addition, the particles are subjected to Brownian motion, a physical phenomena observed with microscopic particles immersed in a liquid that cause them to move about randomly.

Approach

As previously discussed, creating an optical standing wave requires the interference of two coherent beams of light. In this experiment, a Spectra Physics Millenia laser (532 nm) with a full power of 4W operating in TEM00 mode is used. The laser output is split into two beams of equal amplitude with the nonpolarizing beam splitter (Figure 2).

These beams are reflected off an adjustable prism mirror. The beams are then focused with an objective lens (16X, NA 0.30), causing the beams to overlap one another at the Gaussian waist associated at the geometrical focal point. The overlapping coherent beams interfere with one another, creating a standing wave. The distance (d) between standing-wave ridges is $d = \lambda / (2\sin(\theta / 2))$, where λ is the wavelength of the laser beam (532 nm), and θ is the angle between the two converging beams. The adjustable mirror can be used to change the spacing between beams, thereby changing θ, which in turn changes the distance between standing waves.

The samples used in these experiments were 1.5, 2, and 3 μm diameter polystyrene particles, monodispersed to better than 4%, and diluted in deionized water. A hole was punched in double-sided Scotch Tape™ (~ 80 μm thick), and the sample was sealed inside this tape between two No. 2 microscope cover glasses (Fisherbrand 12-540A 18X18), preventing capillary or evaporative flows. In principle, a variety of samples can be used for this experiment, including silica, bacteria, viruses, and human cells; however, a sample must have a greater refractive index than its surrounding medium. Polystyrene samples are used

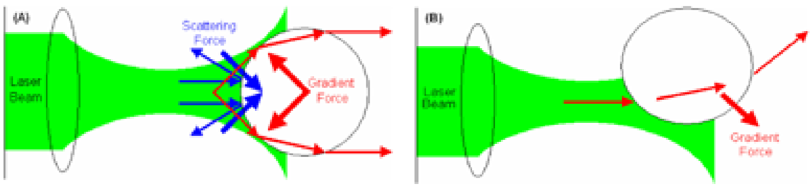


Figure 1: Diagram illustrating the gradient and scattering forces on a particle caused by the change in momentum of the light. (A) illustrates a particle in equilibrium. (B) illustrates the gradient force pulling the particle towards the center of the beam.

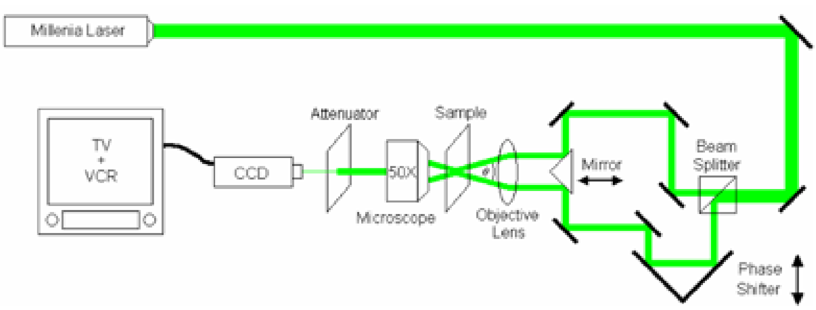


Figure 2: Schematic of the interferometery setup. The phase-shifting mirror is mounted on a piezoelectric displacer that is in turn mounted on an optical translator.

in this experiment because organic samples would be destroyed by the intense heat and energy given from the laser (Millenia 532 nm). Using an infrared laser is an easy fix to this problem; however, it is both inconvenient and dangerous in labs because it is not in the visible spectrum. The sample is placed at the focal point of the objective lens, and the optical standing wave created there can be observed through the microscope; small particles are attracted to the standing-wave intensity maxima.

Once this wave is established and the particles are trapped, the wave can be translated — bringing the particles along with it. The optical interference pattern is translated by applying a voltage to the piezoelectric displacer, which shifts the optical phase of one beam relative to the other (Figure 1), causing the interference pattern to move parallel to the cover slips.

This mode of particle transportation was applied to three particles of different diameters: 1.5 μm, 2 μm, and 3 μm. Particles with different sizes were individually observed in a series of differently spaced standing waves to find the maximum velocity at which they could be displaced before the viscous drag and Brownian forces caused them to slip from one ridge to the trailing adjacent ridge (only the center three fringes of the Gaussian beam where the intensity shift is less than 10% were used). The data gathered was used to determine the optical force on the three particle sizes versus their diameter. Note that there is a unique wave spacing for each particle size where the optical force vanishes; qualitatively this occurs when the diameter is such that the particle samples adjacent to maxima and minima such that the net force averages to zero.

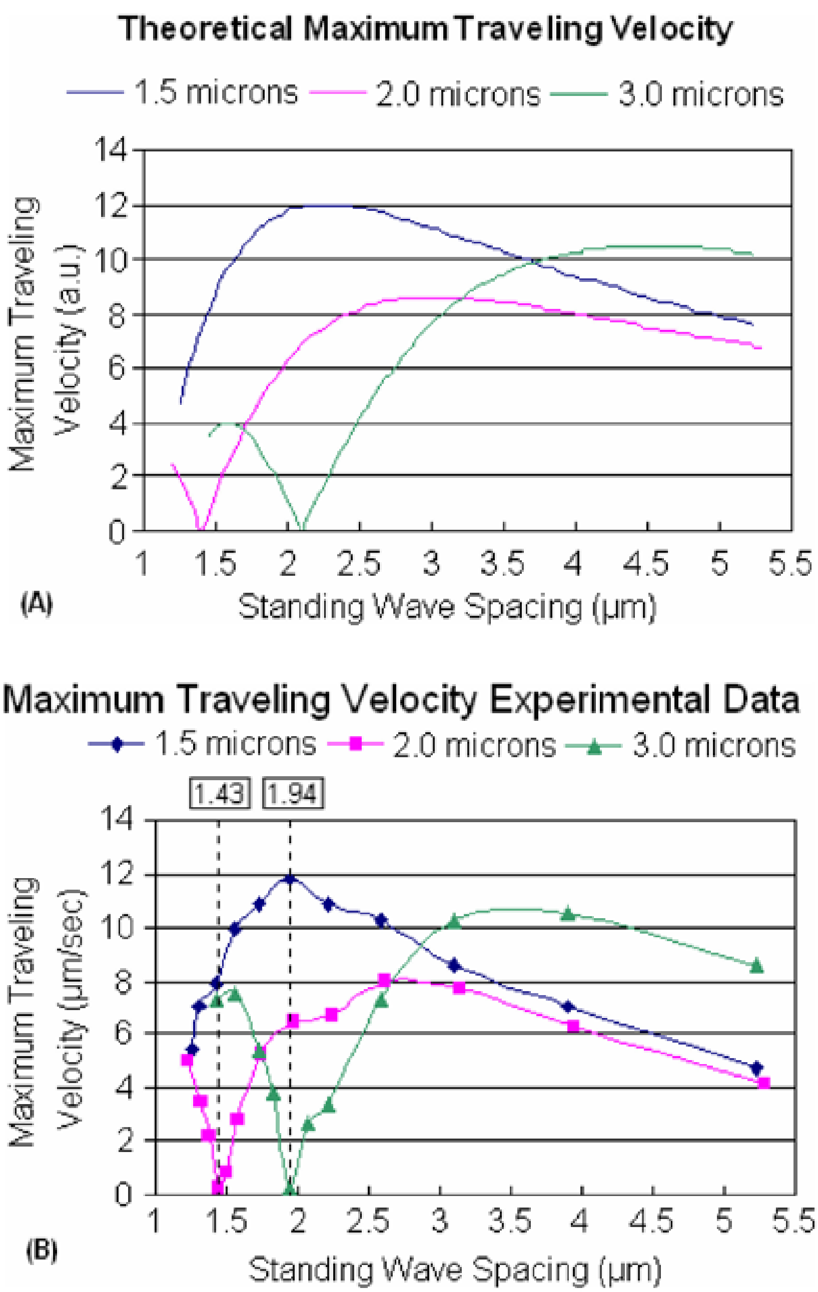


Figure 3: Graphical representation of the (A) theoretical and (B) experimental values for the maximum displacement velocity for differently sized particles. The theoretical curves show the absolute value obtained from the Rayleigh scattering theory. The dashed lines in (B) represent standing-wave spacings corresponding to a vanishing optical force on the particle (where it always slips). These standing-wave spacings are the basis of the optical sorting process.

At this same wave spacing, there is still a relatively large optical force acting on the particles that have a different diameter. This behavior is the foundation of our interferometric optical sorting technique.

Results

There are several different theoretical and experimental methods used to calculate the optical force arising from a standing wave on differently sized particles.[21–25] For particles with diameters of (D) >> 10λ, the force can be approximated using ray optics. For particles with diameters of D ~ λ, the force can be approximated using the Mie scattering theory; and for particles with diameters of D << λ, the force can be approximated using the Rayleigh scattering theory. The optical force on the particles used in this experiment most closely corresponds to the Mie scattering theory. Theoretical and experimental data for the maximum displacement velocity of the 1.5, 2, and 3 µm particles in differently spaced standing waves can be seen in Figure 3. The theoretical results were calculated using the absolute value obtained from the Rayleigh scattering theory, which may account for the minor differences between the theoretical and experimental results. The force on particles, according to the Rayleigh scattering theory, can be seen in the equation below.

$$F = \alpha I\left\{\left[\sin\left(\frac{D\pi}{d}\right) - \frac{D\pi}{d}\cos\left(\frac{D\pi}{d}\right)\right]d^2\right\}$$

In this equation, D is the particle diameter, d is the standing-wave ridge spacing, α is a constant dependent on the particle and solution, and I is the laser intensity.

Unfortunately, the objective lens was not large enough to obtain wave spacings small enough to find the zero force wave spacing for the 1.5 µm particle; it appears, however, to follow a similar trend to the 2 and 3 µm particles. As can be seen, there are two standing-wave spacings — 1.43 µm and 1.94 µm for the 2 µm and 3 µm particles, respectively, where the maximum displacement velocity is nearly zero. Thus, these optical standing-wave spacings exert virtually no force on the particles, and they nearly always slip to adjacent maxima. The equation also illustrates that when the optical force is zero on one particle size, there is still a sizable force on the particles of the other two sizes.

A sample was prepared containing both 1.5 and 3 µm particles mixed randomly in the solution. The adjustable mirror was fine-tuned to create a standing wave with spacings of 1.94 µm. Both sized particles tended to be attracted toward the center of the Gaussian beam where the optical force is strongest (Figure 4).

However, when a voltage was applied to the piezoelectric displacer, and the standing wave displaced, only the 1.5 µm particles moved, and the 3 µm particles stayed in the center of the beam. By modifying the function controlling voltage to the piezoelectric displacer, one can change the direction and speed at which the 1.5 µm particles travel while not affecting the 3 µm particles (Figure 5 A–F).

Discussion

The results shown in Figure 3 are interesting. The graphic representation of the maximum displacement velocity appears to show a relationship between zero force and maximum force points relative to their wave spacing/diameter ratio. The data were compiled and are shown in Figure 6.

The data clearly indicate there are several critical wave spacing/diameter ratios. The optical force vanishes when the ratio is approximately 0.68, whereas it is a maximum when the ratio is approximately 1.30. The data clearly indicate that particles with relatively similar diameters would follow this same trend and, according to the Rayleigh scattering theory, this trend would continue to much smaller particles.

Conclusion

The research described provides interesting experimental and theoretical behaviors related to optical displacement and sorting in Brownian particle systems. Interesting future research in this field might use similar techniques to sort differently sized biological cells, vesicles, viruses, etc. Of particular interest may be stretching or squeezing cells (or arrays of cells) using standing waves. While conventional methods of biological particle sorting and manipulation require physical contact, the techniques of laser tweezing are noninvasive and are therefore superior to traditional methods. Experiments in the lab have already begun using three and four coherent laser beams to create differently shaped optical standing wave interference patterns.

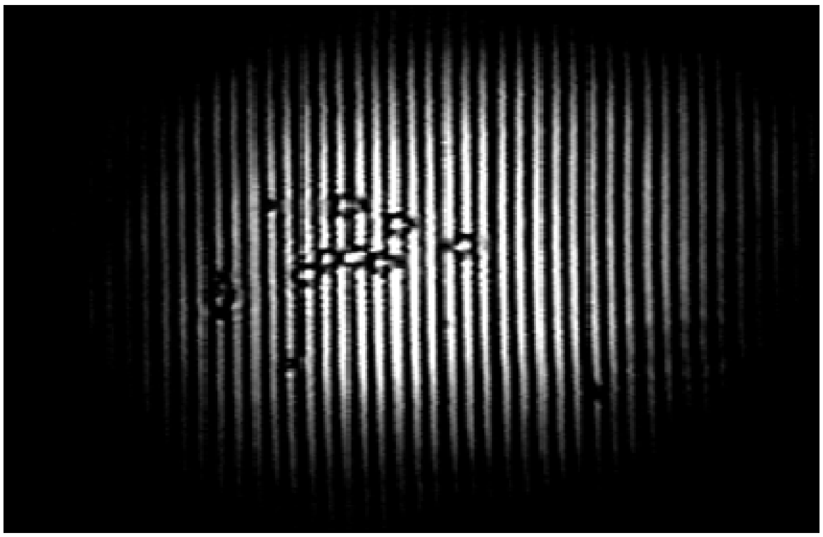


Figure 5: Image of the optical standing wave. Particles can be seen “trapped” on the white lines, which are the standing-wave intensity maxima.

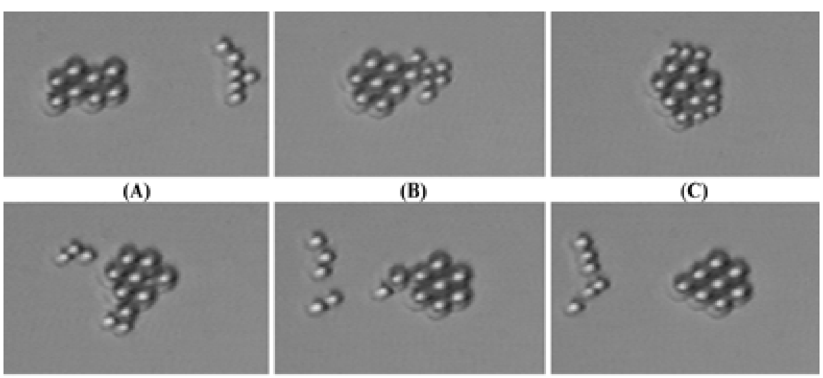
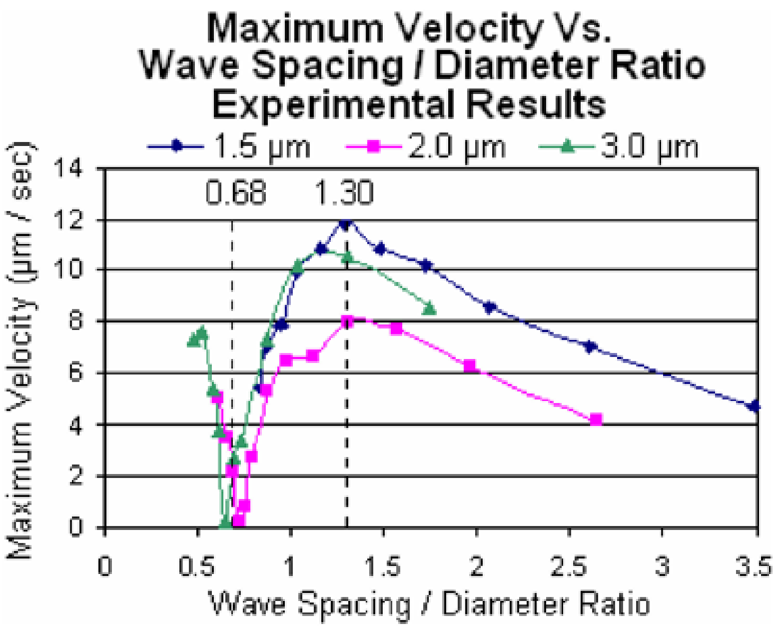
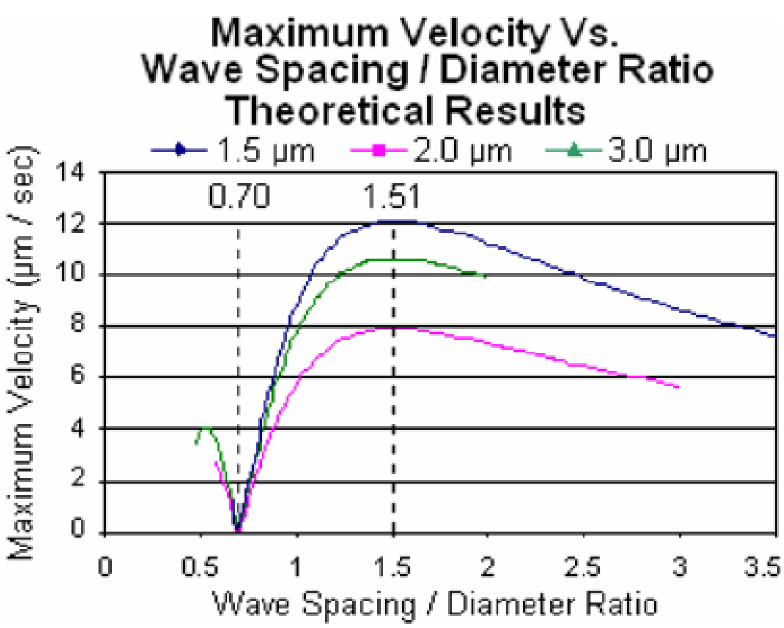


Figure 6: A 532 nm filter is used to block the laser light, while an external light source is used to illuminate a sample containing eight 3 µm diameter polystyrene particles and six 1.5 µm diameter particles. In frame A, the differently sized particles are already separated — the 1.5 µm particles on the right and the 3 µm particles on the left. In frames B and C, the 1.5 µm particles are dragged to the left by the standing wave, where they encounter a group of 3 µm particles. In pictures D and E, most of the 1.5 µm particles can be seen *moving around* the cluster, while one actually *passes through* the 3 µm particles. Picture F shows the particles sorted by size once again — this time with the 1.5 µm particles on the left and 3 µm particles on the right.



A



B

Figure 7: (A) Experimental and (B) theoretical representations of the maximum displacement velocity of differently sized particles relative to their wave spacing/diameter ratio. The theoretical results were calculated using the Rayleigh scattering theory. The dashed lines represent standing-wave spacings corresponding to the optical force minimum and maximum on each particle. Although complete data on the 1.5 μm particle could not be gathered due to physical limitations, it appears to follow the same curve as the 2 μm and 3 μm particles.

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