Optical vortex trapping of particles

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We demonstrate three-dimensional trapping of low-index particles (20-μm-diameter hollow glass spheres in water) by using a single, strongly focused, stationary dark optical vortex laser beam. The holographically generated vortex, which is similar to a TEM_{01}^{*} mode beam, was also used to trap and form ring patterns of high-index particles.

A three-dimensional gradient-force optical trap for microscopic dielectric particles was demonstrated in 1986 by Ashkin *et al.*[1] They showed that low-absorbing, dielectric spherical particles with an index of refraction (n_p) higher than that of a surrounding liquid (n_0) could be trapped in three dimensions by use of a strongly focused Gaussian laser beam. This phenomenon was suggested earlier for moving atoms[2] and more recently has led to biomedical and related applications involving micromanipulation of living cells,[3] chromosomes,[4] spermatozoa,[5] and motor proteins.[6,7] However, the conventional gradient-force trap based on the design of Ashkin *et al.* has some limitations. Trapped particles are susceptible to optical damage by absorptive heating because the center of the trap is located in the high-intensity focal region of the beam.[3,5] Another limitation is that multiple particles may be attracted into the same trap; thus isolating a single particle requires dilute samples. What is more, the trapping of low-index particles such as bubbles and droplets or of absorbing particles such as metallic fragments requires a rotating beam when a conventional gradient-force trap is used.[8] To circumvent such limitations various schemes have been proposed, including the use of higher-order Gaussian mode beams[9] and unusually shaped particles.[10] Here we investigate the trapping of a low-index particle with the aid of a computer-generated hologram of an optical vortex.

We demonstrate that a hollow glass sphere in water can be stably trapped in three dimensions. If the glass shell is thin compared with the particle radius, the sphere can be approximated as a low-index particle with an effective refractive index near unity. This study is, to our knowledge, the first demonstration of three-dimensional trapping of a low-index particle by use of a single, stationary beam. Furthermore, this trap is also capable of trapping high-index particles, as was previously demonstrated with one type of vortex, the TEM_{01}^{*} lasing mode.[9]

An optical vortex can be characterized by a scalar electric field, $E = A\exp(i\mathbf{k}\cdot\mathbf{z})$, where the envelope is given by $A = G(\rho,\phi,z)\exp(iM\phi)$, where (ρ,ϕ,z) are the polar coordinates of a beam propagating in the z direction with wave vector $\mathbf{k}$ in a medium of index n_0 and $M=\pm 1$ is the topological charge. Owing to destructive interference, the envelope vanishes on the z axis (the optical axis), i.e., $G(\rho=0)=0$ for all z. The intensity profile of a vortex is depicted in Fig. 1(a), where we have assumed an initial Gaussian envelope of size w_0 containing a concentric vortex core of size w_v: $G \simeq E_0\exp(-r^2/w_0^2)\tanh(r/w_v)$. In general, the center of the beam need not coincide with the vortex core, and, what is more, several vortices may be placed within a single beam to produce multiple traps. Control over these degrees of freedom can be achieved with computer-generated holography.[11]

The trapping of dielectric particles can be described with a ray-optics analysis[9,12] if the particle diameter is much larger than both the wavelength of light and the focal spot size of the beam. The focused beam is treated as a collection of individual light rays directed toward a single focal point. Each ray incident upon the particle undergoes multiple reflections and refractions. The net wave vector of a reflected and refracted ray, $\mathbf{k}' = \sum C_i\mathbf{k}_i'$, differs from the incident wave vector $\mathbf{k}$ by an amount $\Delta\mathbf{k} = \mathbf{k}' - \mathbf{k}$. The coefficients C_i are products of the Fresnel coefficients. The ray exerts a force on the particle that is proportional to $-\Delta\mathbf{k}$. This force has two components: the scattering force $\mathbf{F}_s = -(n_0\delta P/ck^3)[(\Delta\mathbf{k}\cdot\mathbf{k})]\mathbf{k}$ parallel to $\mathbf{k}$ and the gradient force $\mathbf{F}_g = (n_0\delta P/ck^3)[\mathbf{k}\times(\mathbf{k}\times\Delta\mathbf{k})]$ normal to $\mathbf{k}$, where δP is the incident power of the ray [see Fig. 2(a)]. The direction of $\mathbf{k}$ subtends a different angle θ with respect to the optical axis for each ray, and thus it is useful to decompose these forces with respect to this axis. The transverse components are given by $F_{s\perp} = F_s\sin\theta$ and $F_{g\perp} = \pm F_g\cos\theta$, and the longitudinal components are given by $F_{sz} = F_s\cos\theta$ and $F_{gz} = \pm F_g\sin\theta$. The net force is calculated by integration of these forces over the solid angle of rays that intersect the particle.

To trap a particle successfully in three dimensions requires a position of stable equilibrium where the

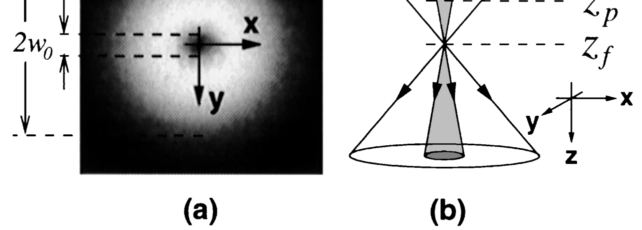

Fig. 1. (a) Intensity profile at $z = z_{\mathrm{obj}}$ of a vortex beam with a dark central core. (b) Cone of light formed by a focused vortex beam.

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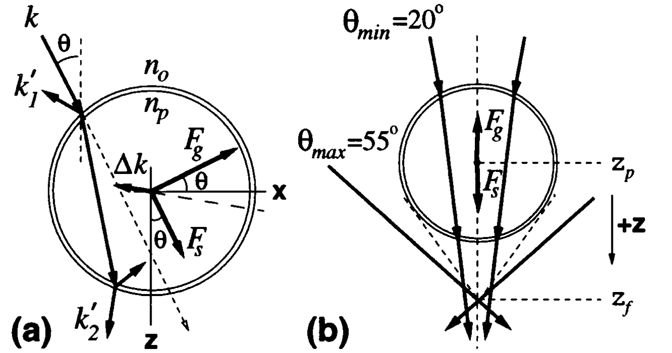

Fig. 2. Gradient and scattering forces exerted on a low-index particle (a) by an arbitrary ray and (b) at the equilibrium position.

net gradient and scattering forces are balanced. For a low-index particle ($n_p < n_0$) in a strongly focused vortex beam this equilibrium position occurs on the optical axis a short distance above the focal plane [Fig. 2(b)]. To see this, consider first the characteristics of the gradient force in this region.

In general, the gradient force acts to repel a low-index particle away from regions of high intensity. In the vicinity of the vortex core (with $z_p < z_f$) the large gradient force pushes the particle into the dark core and in the $-z$ direction (upward). Assuming an azimuthally symmetric intensity distribution and circularly polarized rays, the superposition of the transverse components $F_{g\perp}$ for all rays will cancel when the particle is centered on the optical axis. If the particle is displaced off axis but still within the vortex core, this "dark force" pushes the particle back toward the axis. For larger transverse displacements the direction of the net gradient force is reversed, and the particle is pushed out of the beam. The latter case represents a potential barrier that is desirable for isolating a single particle inside the vortex trap.

The net scattering force has a longitudinal component directed in the $+z$ direction and a transverse component directed toward the optical axis for a particle above the focal plane ($z_p \leq z_f$). Transverse trapping occurs within the vortex because both the scattering and the gradient forces are directed toward the core. Longitudinal trapping can occur at an axial position where the gradient and the scattering forces are balanced. Consideration of the ratio of longitudinal forces exerted by an individual ray incident at angle θ, $|F_{gz}/F_{sz}| = (F_g/F_s)\tan\theta$, shows that the scattering force will increase relative to the gradient force as the solid angle of rays intersecting the particle decreases. Thus, when the particle is above (below) the equilibrium position and the solid angle is small (large), the scattering (gradient) force will dominate. The scattering force plays an important role in providing a downward restoring force as the particle moves away from the focus. This situation differs from that of the conventional gradient-force optical trap (used only for high-index particles) in which the restoring force both above and below the equilibrium position is primarily the gradient force. The vortex trap also differs from an optical levitation-type trap (for a low-index particle) in which the particle is trapped below the focal plane and the upward longitudinal restoring force is the buoyant force.[12]

The experimental apparatus that we used to create the optical trap is shown in Fig. 3. A Gaussian beam from an argon-ion laser (Ar^+) at wavelength $\lambda = 514$ nm is directed through a computer-generated hologram of an optical vortex. The collimated first-order diffracted beam, which has a measured vortex-core to beam-size ratio of $w_v/w_0 \approx 1/4$, is directed into a 100×, N.A. 2.5, semi-plan oil-immersion microscope objective with an input aperture of diameter $\sim 2w_0$. A sample cell containing deionized water ($n_0 = 1.33$) and hollow glass spheres is placed at the focus of the objective and backlighted with a white-light source. The cell is viewed through the same 100× objective by use of a beam splitter, a video camera, and a television monitor. Video sequences were recorded with a Macintosh computer and a video cassette recorder.

When they are placed in water, the hollow glass spheres experience a buoyant force and reside on the upper surface of the cell. The net buoyant–gravitational force $F = 4\pi R^3 g(\rho_w - \rho)/3$ can be estimated by use of the manufacturer-specified average density of the hollow spheres, $\rho = 0.2$ g/cm^3, where R is the radius of the sphere, g is the gravitational acceleration of the Earth, and ρ_w is the density of water. The minimum power required for trapping a particle can be written as $P_{\min} = cF/n_0 Q$, where c is the speed of light in vacuum. We estimate a maximum longitudinal trapping efficiency Q in the range 0.03–0.1, based on preliminary calculations with the methods discussed in Ref. 9. For a 20-μm-diameter particle we estimate $F \approx 30$ pN, $P_{\min} \approx 70$ mW, and an effective index of $n_p \approx 1.1$.

We accomplished three-dimensional trapping of hollow glass spheres in the 20-μm-diameter range by moving the beam focus up from below the particle until the particle was pushed downward into the trap by scattering forces. We estimate that $z_p - z_f \approx 20 \pm 10$ μm at the equilibrium position, a value consistent with preliminary calculations. Once freed from the upper surface, the trapped particle could be moved through the entire 120-μm height of the cell. The power necessary to trap these particles was roughly 80 mW, in close agreement with the estimated minimum power.

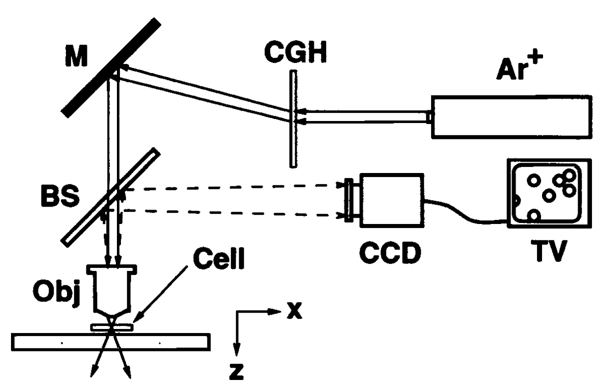

Fig. 3. Setup for vortex trapping using a microscope objective (Obj) and a cell containing hollow glass spheres in water and monitored with a CCD camera: BS, beam splitter; M, mirror; CGH, computer-generated hologram; TV, television monitor.

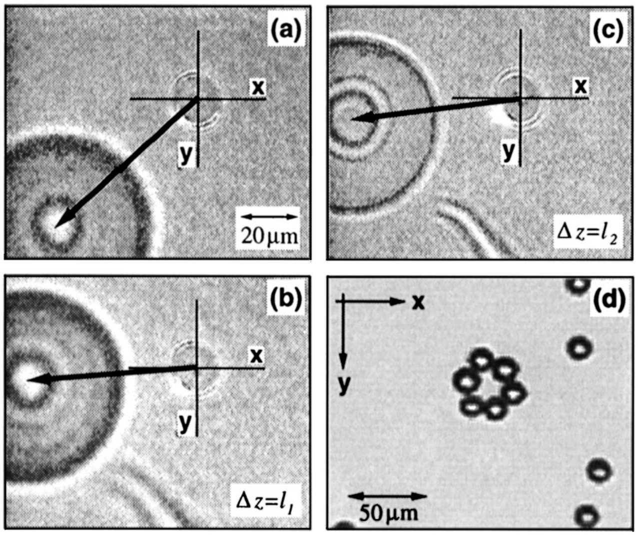

Fig. 4. 20-μm-diameter hollow glass sphere trapped within an optical vortex beam (not visible) (a), (b) transversely and (b), (c) longitudinally translated with respect to a larger untrapped particle. (d) Ring of 10-μm-diameter high-index polystyrene particles formed near the perimeter of an optical vortex beam.

Robust three-dimensional translation of a trapped 20-μm-diameter hollow glass sphere in the vicinity of a larger untrapped particle is depicted in Fig. 4. A comparison of the arrows in Figs. 4(a) and 4(b) shows transverse translation of the well-focused trapped particle with respect to the larger out-of-focus untrapped particle. We achieved this effect by translating the sample cell in the $x-y$ plane. Longitudinal translation along the optical axis is evident in a comparison of Figs. 4(b) and 4(c); in the latter case, the larger untrapped particle is moved into focus with the trapped particle. We observed, in addition to the foregoing dynamics, that particles outside the trap were pushed away from the beam. Only particles aligned along the optical axis can be trapped, as discussed above.

We believe that the upper axial boundary of the trap can be attributed to scattering forces' pushing the particle downward, whereas the lower axial boundary is due to gradient forces' repelling the particle away from the beam focus. Indeed, when lower-power (10× and 20×) objectives were used to achieve weaker longitudinal gradient forces, only transverse trapping was observed. What is more, when the beam focus was brought up from below a buoyant particle, the scattering forces would push the particle off the upper surface and down through the focal plane. This phenomenon occurred when the distance between the 20-μm hollow sphere and the beam focus was 10–20 μm. This remarkable fountain effect may be sustainable because the particle floats back to the upper surface.

In addition to three-dimensional trapping, we also employed the optical vortex to generate a two-dimensional pattern of solid 10-μm-diameter polystyrene spheres in water. For this application a low-power (10×) objective was used to focus the incident beam to a point just below the bottom surface of the cell where the particles reside. As shown in Fig. 4(d), a ring pattern was formed owing to the attraction of high-index particles to intensity maxima.

In conclusion, we have demonstrated three-dimensional radiation pressure trapping of a low-index (hollow) spherical particle in water, using a Gaussian beam containing an optical vortex. The point of stable equilibrium was observed to be located on the axis and slightly above the focal plane. Transverse trapping is attributed to gradient and scattering forces directed toward the vortex core, whereas longitudinal trapping resulted from balanced scattering and gradient forces, even in the presence of buoyancy. Owing to (1) both the greater efficiency and the lower peak intensity of vortex traps for high-index particles compared with those of a conventional Gaussian beam trap[9] (permitting opportunities to minimize laser damage effects) as well as to (2) the ability to trap low-index particles, we suggest that dark traps are often more useful than bright traps. We also believe that computer-generated holographic techniques open new opportunities to create customized particle arrangements with a single beam.

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