Optical trapping of nanoparticles and microparticles by a Gaussian standing wave

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The optical trapping of nanoparticles and microparticles by a Gaussian standing wave is experimentally demonstrated for the first time to the authors’ knowledge. The standing wave is obtained under a microscope objective as a result of the interference of an incoming laser beam and a beam reflected on a microscope slide that has been coated with a system of reflective dielectric layers. Experimental results show that three-dimensional trapping of nanoparticles (100-nm polystyrene spheres) and one or more vertically aligned micro-objects (5-μm polystyrene spheres, yeast cells) can easily be achieved by use of even highly aberrated beams or objectives with low numerical apertures. © 1999 Optical Society of America

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The transfer of momentum between focused laser light and microparticles has been investigated in a number of experiments during the past 30 years. It has been proved that focusing laser light facilitates the trapping of particles whose sizes range from tens of nanometers to tens of micrometers that are immersed in water, ethanol, or air. It also permits the trapping of living cells and uncoiled DNA molecules and the rotation of micro-objects. In this Letter we propose efficient modification of a single-beam trap (SBT) built in a classic optical microscope. A SBT is based on the focusing of the laser beam to a diffraction-limited spot by a microscope objective of high numerical aperture (NA). In this case the optical force coming from the axial intensity gradient can be stronger than and of opposite direction from the force caused by the radiation scattered by the object. The enhancement that we suggest is based on the use of a Gaussian standing wave (GSW) that is created by the interference of an incident beam passing through the objective and a beam reflected back from the coated microscope slide.

Previously the behavior of a Rayleigh particle (RP) in a GSW had been studied only theoretically. It is generally accepted that the radius of a RP is less than \( \lambda/20 \) (\( \lambda \) is the radiation wavelength in the medium) and that the RP can be treated as an induced dipole oscillating in phase with the field. The forces acting on such a small object are of two kinds: gradient force, which is the time-averaged Lorentz force acting on the dipole induced by the electromagnetic field, and scattering force, which is generated by scattering of radiation on the particle (radiation pressure) and which is proportional to the energy flux represented by the Poynting vector. A RP placed in a GSW in the vicinity of the beam waist, which moreover is located near the reflective slide, feels a strong axial gradient force caused by the steep intensity gradients between the standing wave’s nodes and antinodes. It has been calculated that this axial gradient force can be 2 orders of magnitude higher than a SBT if the Gaussian beam is in the paraxial range [i.e., beam waist \( \omega_0 \approx 8a \) (Ref. 11)]. The axial scattering force (which is proportional to the difference between the Poynting vectors of the incoming and the reflected beams) is negligible for a RP located near the beam waist and highly reflective slide. The gradient force can easily overcome the scattering force, and three-dimensional (3-D) confinement of a RP can be obtained even for paraxial beams produced by low-NA objectives (NA = 0.55). The interference of counterpropagating beams creates a number of particle equilibrium positions, i.e., standing-wave traps (SWT’s) that are located at the standing-wave antinodes and that are separated axially by \( \lambda/2 \). Consequently, simultaneous 3-D manipulation of several RPs confined in these axially aligned traps is possible.

The experimental setup for particle manipulation with a GSW is shown in Fig. 1. We use a Nd:YLF laser (Spectra-Physics T20-W-105c; \( \lambda_0 = 1053 \) nm, \( P_{\text{max}} = 4 \) W at TEM\( _{00} \) mode), an Olympus BX-50 microscope, and an Olympus UPLFL 100X OI oil-immersion objective (NA = 0.6–1.3). The same objective was used for both trapping and observation. We used two telescopes to magnify the beam and to permit lateral and axial positioning of the beam waist and consequently of the optical traps. The first telescope comprised Geltech lenses \( F_1 \) and \( F_2 \) (\( f_1 = 2.75 \) mm and \( f_2 = 8 \) mm), and axial motion of lens \( F_1 \) provided axial positioning of the beam waist under the objective. The second telescope consisted of doublets \( F_3 \) and \( F_4 \) (Edmund Scientific, \( f_3 = 60 \) mm and \( f_4 = 175 \) mm). Lens \( F_4 \) was placed in a plane conjugate to the objective’s back aperture plane and at a distance equal to \( f_2 \) from lens \( F_2 \), and its transverse motion provided lateral trap...
On the basis of our theoretical conclusions it should be possible to confine a RP in a SWT even in the vicinity of an ordinary uncoated microscope slide. Therefore we replaced the 99% reflecting slide with an ordinary slide (reflectance $R = 0.4\%$), and we succeeded in 3-D confinement of 100-nm polystyrene particles near the slide. The particles moved laterally over a larger distance, but the mean displacement was only approximately one third of the distance traveled by free particles. Their vertical movement was confined within one antinode because they stayed sharp in the CCD image and did not touch the slide (see Fig. 2). We increased the power threefold, and no acceleration or shift upward was observed, which proves that the influence of radiometric forces was negligible.

The behavior of optically trapped particles that are out of the Rayleigh scattering regime can be described by one of two methods: geometrical optics for particles of radii $a \geq 100\lambda/2\pi$ (Ref. 13) and electromagnetic theory for particles from the intermediate region $a \sim \lambda$. The electromagnetic theory is based on the generalized Lorenz–Mie theory, and the force calculations are quite laborious. A simple intuitive method was presented recently\textsuperscript{14} that permits easy prediction of the particle behavior in an electromagnetic field with strong intensity gradients. It is assumed that the relative refractive index of the object is close to unity and therefore that the total field confinement of 100-nm polystyrene particles near the slide ($99\%$ total reflectivity). The absorption of the trapping beam wa...
configuration with a simplified trap and particle shapes (sphere, cube),\textsuperscript{14} and an analytical formula for optical forces was obtained for the general particle size. The same approach can be applied to a GSW, and the particle equilibrium position can be found as the location of minimal dipole interaction energy of the particle. In this case the particle covers a maximal number of GSW antinodes. Again a number of axial equilibrium positions can be found for the particle trapping.

We succeeded in experimental trapping of polystyrene spheres of diameters 0.295, 1, 5, and 15 \(\mu\)m in a SWT with a 0.6-NA objective. Although it was possible to trap the objects mentioned above in a SBT, we had to use a higher NA of 1.3 and work near the cover glass for smaller spheres. We also succeeded in simultaneous manipulation of three \(5-\mu\)m axially aligned polystyrene spheres. A different objective (Meopta; oil, 100\% \(N_A 1.25\)) was immersed directly into the water, which led to higher optical aberrations that resulted in a beam waist equal to 1.57 \(\mu\)m (measured by the knife-edge method\textsuperscript{15}). Employing a GSW, we easily achieved 3-D trapping of polystyrene spheres of diameters from 0.3 to 15 \(\mu\)m and of yeast cells (see Fig. 3). 3-D trapping of all these objects failed for the same power and NA if a SBT was employed (ordinary microscope slide).

In this Letter we have demonstrated successful 3-D trapping of micrometer- and submicrometer-sized particles by using standing-wave traps that were produced by the interference of incoming and reflected Gaussian beams under the objective of a classic optical microscope. The classic single-beam setup was modified by use of a 99\% reflective microscope slide as the bottom of the trapping cell. The axial optical force was modulated by a gradient force component coming from the steep intensity gradients between the standing-wave nodes and antinodes. This force was strong enough to ensure successful confinement of 3-D micro-objects near the mirror, even when low-NA or aberrated objectives were used. Experiments have revealed that a number of micro-objects can be collected in a vertical line along the optical axis and moved together within the sample. We experimentally proved the existence of a SWT in the vicinity of an ordinary uncoated microscope slide through the successful 3-D confinement of 100-nm particles.

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