Dynamic axial-position control of a laser-trapped particle by wave-front modification

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Received August 13, 2002

The axial position of a laser-trapped particle has been controlled by modification of the wave front by means of a membrane deformable mirror. The mirror gives wave-front modulation in terms of Zernike polynomials. By modulation of the Zernike defocus term we can modulate the particle position under conditions of laser trapping. A polystyrene particle of 1-μm diameter was moved along the optical axis direction for a distance of 2370 nm in minimum steps of 55.4 nm. We also demonstrated particle oscillation along the optical axis by changing the focal position in a sinusoidal manner. From the frequency dependency of the amplitude of particle oscillation we determined the spring constant as 91.7 nN/m.

OCIS codes: 140.7010, 010.1080.

Single-beam laser trapping is a tool for remote manipulation of micrometer-sized objects under a microscope[1] and has been utilized as a manipulator of biological cells[2] and single biomolecules[3–5] and as a nanometer-sized probe particle for scanning probe microscopy.[6–9] A 40-nm-diameter gold particle was manipulated for use in a near-field probe in near-field optical microscopy.[7] A particle suspended by laser trapping was used for measurement of surface force between the particle and the sample's surfaces in femtonewton order.[6,10] In such applications, control of the axial position of the trapped particle is crucial for precise manipulation of the particle on a nanometer scale. In this Letter we describe our control of the trapping position on an optical axis with wave-front modification by a membrane deformable mirror. Another application of wave-front modification to laser trapping has already been reported[11]: multiple trapping by use of a liquid-crystal spatial light modulator.

A membrane deformable mirror is a device that can modulate the wave front of an incoming laser beam by changing the shape of the mirror surface.[12,13] Figure 1 shows the experimental setup for controlling trapping position with a deformable mirror. A laser beam from a Nd:YAG laser at a wavelength of 1064 nm is reflected onto a deformable mirror's surface coated with aluminum (~95% reflection; OKO Technologies, Delft, The Netherlands). We can change the shape of the mirror surface slightly by applying voltage onto 37 electrodes of the deformable mirror. After reflection on the deformable mirror, the two-dimensional distribution of the phase in the reflected laser beam is modified because of deformation of the mirror's surface. By controlling the voltage applied to each electrode we can generate an arbitrary shape of the wave front of the reflected laser beam. The laser beam is finally incident onto a microscope optics and is focused in a sample cell by a microscope objective (N.A. = 1.4; 60× Olympus) to trap a small object. We control the wave front to shift the trap position of the object along the direction of the optical axis.

The desirable wave front for axial-position control of the trapping position is given by Zernike polynomials $Z_k(r,\theta)$.[14] The Zernike defocus (the fourth term of a Zernike polynomial) describes the focusing of light along the optical axis.[15,16] Therefore, when we modulate coefficient b_4 of Zernike defocus $b_4 Z_4$, we can change the spot's position along the optical axis without any degradation of the beam spot. The amount

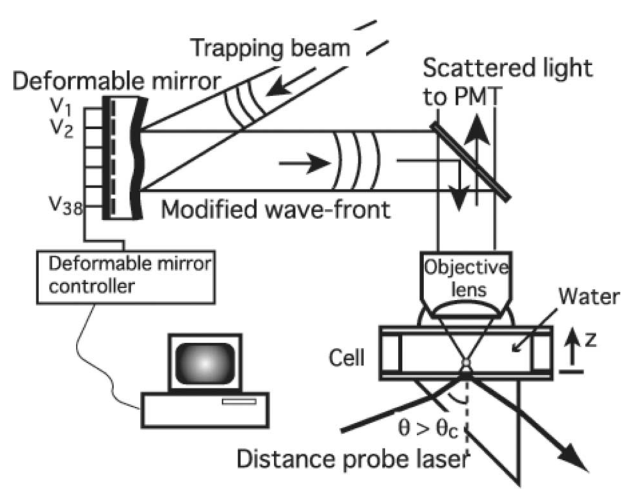

Fig. 1. Configuration of an experimental setup for control of trapping position.

of modulation dz is expressed with coefficient b_4:

$$\mathrm{d}z = 4\sqrt{3}\,(R/a)^2 b_4\,, \qquad (1)$$

where a is the radius of an exit pupil and R is the working distance of the focusing lens. The wave front is defined in Eq. (1) as the optical path length rather than phase, and therefore coefficient b_4 has the dimension of length. For modulation of coefficient b_4 we use control signal set $\mathbf{S} = (V_1{}^2, \ldots, V_{37}{}^2)$, which is a linear parameter of the deflection of the mirror surface, rather than applied voltage set $\mathbf{V} = (V_1, \ldots, V_{37})$, which is proportional to the square root of the mirror deflection. Control signal set $\mathbf{S}$ is transformed to applied voltage set $\mathbf{V}$ on electrodes of the deformable mirror through the deformable mirror's controller. Unit vector $\hat{S}_4$, which gives the unit change of the coefficient of the Zernike defocus, is determined from another experiment.[13] By use of unit vector $\hat{S}_4$ we can give the modulation of coefficient b_4 by inputting control signal set $\mathbf{S}$, expressed as $\mathbf{S} = b_4\hat{S}_4 + S_{\text{bias}}$, to the mirror controller. To achieve both positive and negative values of b_4 we apply the bias voltage that corresponds to S_{bias} to all electrodes at the initial state of the mirror.

To measure shift dz of a trapped particle, we engage evanescent illumination of a He–Ne laser beam from the substrate of the sample cell, as shown in Fig. 1.[10] The laser beam, at a wavelength of 632.8 nm, is incident upon the substrate through a prism under conditions of total internal reflection. We trap a particle in an evanescent field generated on the substrate. Scattered light from the particle is collected by the objective and detected by a photomultiplier tube. Shift dz of the trapped particle is estimated from the relation $\mathrm{d}z = -(\ln I - \ln I_0)/\beta$, where β is the decay constant of the evanescent field and I_0 and I are scattered light intensity before and after the shift. We determine β through measurement of the scattered light as a function of the distance between the particle and the substrate by changing the substrate's position by a piezoelectric stage and exponentially curve fitting the measured curve to an exponential function by the least-mean-square method.

A 1-μm-diameter polystyrene particle was trapped in water and was shifted by the wave-front modification. Figure 2 shows the shift in trapping position of the optical axis when coefficient b_4 was changed from -4.234×10^{-7} to $+3.387 \times 10^{-7}$. The change of coefficient b_4 was repeated 10 times, and the measured positions were averaged at each b_4 value. In Fig. 2, the dots are the average positions. The solid line is a linearly fitted line. From the fit, the gradient of the plots is given as 3.02, which corresponds to $R/a = 0.660$ in Eq. (1). The maximum distance of the position change was 2370 nm. The minimum increment of shift was 55.4 nm when coefficient b_4 was set at -3.810×10^{-7} to -3.387×10^{-7}. The variation of the measured data from 14 to 37 nm, which is caused mainly by drift of the position, is shown by error bars. In this experiment the particle was suspended at a mean distance of $\sim$2 μm from the substrate. The distance was set large enough to reduce the effect of surface force on the particle. The scattered light's intensity was detected at 20 kHz and was averaged for 0.5 s at each measurement position.

We caused the trapped particle to oscillate along the direction of the optical axis so we could investigate the frequency response of the particle-position control. We changed the focal position in time in a sinusoidal manner at frequency ω. We measured the particle's position in time by detection of scattered light and then filtered the position data with a bandpass filter that had a center frequency ω. The peak-to-peak amplitude of a trapped particle's position was determined from the amplitude of the signal at modulation frequency ω. Figure 3 shows the peak-to-peak amplitude of particle modulation at given frequencies induced by position shifts of the laser focus. The plot points indicated by crosses are the measured results. At a frequency less than 10 Hz, particle movement is

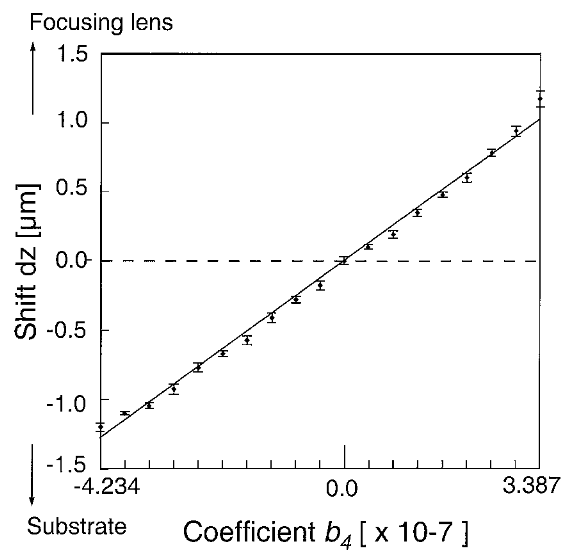

Fig. 2. Shift of trapping position when the wave front is modified by b_4Z_4. The shift was repeated 10 times, with b_4 changing from -4.234×10^{-7} to 3.387×10^{-7}. Dots, averge positions; error bars, variations. Solid line, a linearly fitted line.

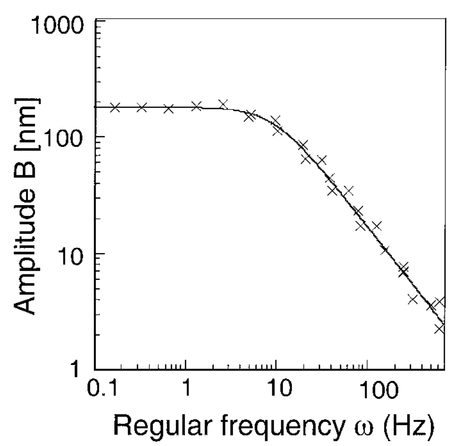

Fig. 3. Amplitude of trapped particle oscillation plotted by oscillation frequency. $\times$, measured results; solid curve, curve fitted from Eq. (3).

almost equivalent to oscillation of the focal position. The peak-to-peak amplitude at the lowest frequency is 180 nm. At higher frequencies, however, the amplitude decreases with increasing oscillation frequency.

The frequency dependence of modulation amplitude is explained as a dumping effect of particle movement by the viscous force of surrounding water. According to Stokes's law, drag force f on a spherical particle that has radius r and moves at velocity v in liquid is given as $f = Dv = 6\pi r\eta v$, where D is the viscous coefficient and η is the viscosity of the surrounding water. When the focal position is modulated as $A\sin\omega t$, the equation of motion of the trapped particle is

$$m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} + D\frac{\mathrm{d}z}{\mathrm{d}t} + k(z - A\sin\omega t) = F(t)\,, \qquad (2)$$

where m is the mass of the particle and $F(t)$ is a random force from water molecules, which vibrate thermally. We assume that the laser-trapping force is proportional to the displacement of the particle and that its spring constant is k in Eq. (2). Bandpass filtering eliminates the effect of the random force on the particle's position, and therefore $F(t)$ can be neglected. The motion of the trapped particle at frequency ω is described by $z = B\sin(\omega t - \Delta)$, where Δ is a phase response. From Eq. (2), the amplitude of particle movement is obtained as

$$B = \frac{k}{[(k - m\omega^2)^2 + D^2\omega^2]^{1/2}}A\,. \qquad (3)$$

In the experimental conditions m is 1.32×10^{-16} kg and D is 9.42×10^{-9} kg/s. The measured result, shown in Fig. 3, is fitted to Eq. (3) by the least-mean-square method, as shown by the solid curve in the figure. As a result of curve fitting, spring constant k of laser trapping is estimated to be 91.7 nN/m. The value 91.7 nN/m is small compared with the value reported previously[6,10] because laser power, 10 mW or less under the objective, was adopted in this experiment and was smaller than that in the research described in that report.

In this Letter we have described axial position control of a laser-trapped particle by modification of the wave front of a trapping laser beam with a deformable mirror. The advantage of this method is high frequency response of its modulation owing to the presence of a deformable mirror, which typically has a maximum operation frequency of several kilohertz. This oscillation frequency is barely achieved by high-speed lens movement, which may also cause mechanical vibration problems. In addition to this advantage, modification of the wavefront by a deformable mirror enables us to suppress aberrations of the microscope optics. For example, spherical aberration of a laser trapping beam, which often occurs as a result of an index mismatch between cover glass and water,[16,17] can be suppressed by adjustment of the coefficients of axisymmetric terms (e.g., 11th, 22th, ...) of Zernike polynomials.[16] By removing the aberrations we may recover the spring constant of laser trapping. Removing aberrations and controlling position can be done simultaneously because Zernike polynomials are orthogonal. Simultaneous operation of several terms of polynomials has already been applied in confocal microscopy.[13] Control of trapping position in an optical axis will be a strong tool for use with a near-field optical microscope that uses a laser-trapped particle. The near-field signal can be modulated by control of the probe position in the optical near field, and the signal-noise ratio can be enhanced by detection of the only modulated signal with a lock-in detection technique. Control of the trapping position also enables us to sense the surface force faster. The technique is important for fast distribution mapping of a surface force in two dimensions by scanning of the probe on the sample.

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