Jpn. J. Appl. Phys. Vol. 42 (2003) pp. L 701–L 703
Part 2, No. 6B, 15 June 2003

Enhancement of Laser Trapping Force by Spherical Aberration Correction Using a Deformable Mirror

Taisuke OTA[1,*], Tadao SUGIURA[2], Satoshi KAWATA[1,3], Martin J. BOOTH[4], Mark A. A. NEIL[5], Rimas JUŠKAITIS[4] and Tony WILSON[4]

[1]*Department of Applied Physics, Osaka University, Suita, Osaka 565-0871, Japan*
[2]*Department of Bioinformatics and Genomics, Nara Institute of Science and Technology, Ikoma, Nara 630-0192, Japan*
[3]*Nanophotonics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan*
[4]*Department of Engineering Science, Oxford University, Parks Road, Oxford OX13PJ, U.K.*
[5]*Physics Department, Imperial College, London, SW7 2BW, U.K.*

(Received March 11, 2003; accepted for publication May 3, 2003)

We have developed a method to enhance axial trapping force in optical tweezers by aberration correction of a laser beam with a membrane deformable mirror. The axial trapping force is strongly dependent on the quality of the laser beam spot, which is deteriorated by aberration due to the refractive index mismatch between a cover glass and water. The aberration correction, therefore, is crucial for stable trapping of a particle and for weak-force measurement with laser trapping. We have evaluated spring constants of the trapping force in the axial direction with and without aberration correction. The enhancement factor of the spring constants by the aberration correction has been achieved as 1.35 for the case of 5-μm sample thickness and as 1.83 for the case of 10-μm sample thickness. The numerical simulation is coincident with the experimental results.
[DOI: 10.1143/JJAP.42.L701]

KEYWORDS: laser trapping, optical tweezers, trapping force, spherical aberration, aberration correction, wave front compensation, deformable mirror

A strongly focused laser beam exerts radiation pressure force on a microscopic particle. As a result, the particle can be trapped in the focal spot of the laser beam. This phenomenon is widely used for particle trapping and cell manipulation under a microscope, as called laser trapping or optical tweezers.[1)] This technique has been applied to hold a small probe particle for force measurement[2)] and for near-field optical microscopy.[3,4)] As a method to enhance the axial trapping force, a Laguerre-Gaussian mode beam or an annular beam has already been used for trapping a particle.[5–7)] In actual experiments of laser trapping, trapping force on the particle is strongly affected and is weaken by aberrations regardless of this enhancement technique. The aberrations are mainly caused by refractive index mismatch between a cover glass of a sample cell and aqueous medium surrounding the particles, besides residual aberrations in optical alignment.[8–11)] In this paper, we describe a method to correct the aberration caused by the index mismatch for the sake of enhancement of the axial trapping force. To perform the aberration correction, a wave front of the incident laser beam having a uniform intensity-profile is modified by deformation of surface shape on a deformable mirror.[12)] This mirror has already been utilized to confine the focal volume of a laser beam in a sample in a confocal microscope[11)] and to control position of a particle held by laser trapping.[13)]

The enhancement of the trapping force has been verified by comparison of spring constants of the trapping force with and without the aberration correction. The spring constant k_{LT} is defined as a proportional constant assuming that the trapping force is proportional to displacement of the particle from the most stably trapped position in the focus spot.[2,13)] Because the particle fluctuates thermally under the trapping force, the spring constant k_{LT} in z axis can be estimated from the relation $k_{\mathrm{LT}} = k_B T / \langle dz^2 \rangle$ by measuring $\langle z^2 \rangle$, where k_B is Boltzmann constant, T is absolute temperature and $\langle z^2 \rangle$ is a deviation of the particle position in z axis.

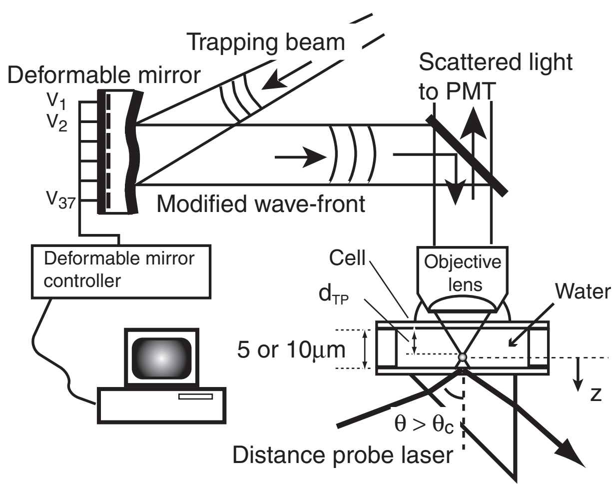

Fig. 1. Experimental setup for laser trapping with aberration correction system and for measuring the spring constant.

Figure 1 shows the experimental setup for laser trapping combined with the aberration correction system and for measuring the spring constant. A laser beam from a Nd:YAG laser at a wavelength of 1064 nm is reflected off a deformable mirror (OKO Technologies, Delft, Netherlands) with 95% reflectivity. The mirror consists of a 15-mm diameter aluminum coated silicon nitride membrane positioned above an array of 37 hexagonal electrodes that act as electrostatic actuators for deformation of the surface by applying DC voltage to electrodes. The two-dimensional phase-distribution on the section of the reflected laser beam is modified from that of the incoming beam according to deformation of the mirror's surface. The mirror's surface provides the desired phase-change and is controlled by the voltages applied to each electrode. The laser beam is finally focused by a microscope objective (NA = 1.4, 60×, Olympus) through an interface between the cover glass and water into the sample cell where the small object is

*E-mail address: ota@ap.eng.osaka-u.ac.jp

trapped. While the wave front changes, the beam reflects on the mirror, which keeps the continuous surface with the approximate 10-micron surface deformation at the center, without any deflection at the circular edge of 12-mm diameter. Therefore the diameter of the reflected beam and the amount of the laser power under the objective lens do not change.

The wave front of the focusing beam is deformed at the interface between the media of differing refractive index, namely the cover glass and the water. The aberrated wavefront $\Phi(\rho, \phi)$ defined over the circular pupil of the lens is a function of radius ρ and azimuth ϕ and can be represented by a series of Zernike polynomials $Z_j(\rho, \phi)$[14] as

$$\Phi(\rho, \phi) = \sum_{j=1}^{\infty} a_j Z_j(\rho, \phi), \quad 0 \le \rho \le 1, \quad 0 \le \phi < 2\pi, \tag{1}$$

where j is a polynomial order and a_j is the expansion coefficient or aberration coefficient. To correct the aberrations, the deformable mirror should introduce an equal but opposite aberration into the laser beam. In the case of the aberration caused by the refractive index mismatch, the induced aberration is described as the sum of the circularly symmetric polynomials of $j = 11, 22, 37, \ldots$, which represent spherical aberration modes.[10] The mode $j = 4$ corresponds to defocus, which simply causes an axial displacement of the focus and does not affect its quality.[10,13] In our experiment we correct the aberration by inducing the phase change described by the dominant spherical aberration mode, $a_{11}Z_{11}$. The control signals required to generate this mode Z_{11} with the deformable mirror were obtained from another experiment.[11,15] To measure the position of the particle in z axis for estimating the spring constant, we applied evanescent illumination using a He–Ne laser beam (632.8 nm wavelength) from the substrate of the sample cell.[2] We trapped a particle in the evanescent field generated on the substrate. Scattered light from the particle was detected with a photomultiplier tube. The particle position z was estimated from the relation $z = (\ln I - \ln I_0)/\beta$, where β was the decay constant of the evanescent field and I_0 and I were the scattered light intensities before and after the shift. The β was determined through the scattered light measurement as a function of the distance between the particle and the substrate. For each measurement, the scattered light intensity was accumulated at the sampling frequency of 20 kHz for 0.5 s. We used the temperature of 298 K for estimating spring constant.

We measured the spring constants k_{LT} under conditions of two different distances d_{TP} (see Fig. 1) from the upper glass of the cell to the trapping position, because the degree of the aberration changed as the distance d_{TP}. For making these conditions, we used two sample cells that had 5- or 10-μm separation between the upper glass and the bottom glass by sandwiching particles of 5- or 10-μm diameter to keep the separation. In the experiment a polystyrene particle of 1-μm diameter was trapped at 2 μm above the bottom glass surface. The distances d_{TP} in each cells were 2 μm and 7 μm, respectively. The spring constants before the aberration correction were 1.08 μN/m for $d_{TP} = 2$ μm and 0.672 μN/m for $d_{TP} = 7$ μm.

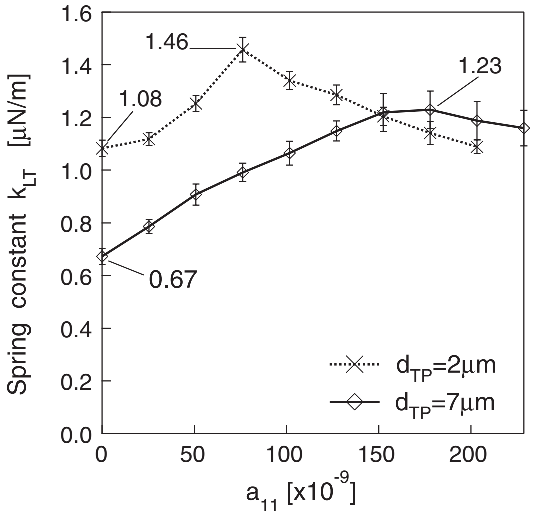

Fig. 2. Spring constants with aberration correction as functions of the magnitude of the 11th order polynomial a_{11}. (×)s with a dashed line are for $d = 2$ μm the spring constants and (◇)s with a solid line are for $d = 7$ μm.

To enhance the spring constant by the aberration correction, we induced the wave-front change described by the 11th order polynomial, $a_{11}Z_{11}$. While the coefficient of 11th order polynomial, a_{11}, was increased from 0 to 203×10^{-9}, the spring constants were changed as shown in Fig. 2. In the case of $d_{TP} = 2$ μm, the spring constant increased as a_{11} and was enhanced to 1.46 μN/m at $a_{11} = 76 \times 10^{-9}$. For further increase of a_{11}, the spring constant decreased. It is considered that the wave front was compensated the most at $a_{11} = 76 \times 10^{-9}$ and the inverted phase aberration was induced for a_{11} bigger than 76×10^{-9}. In the case of $d_{TP} = 7$ μm, the maximum spring constant was 1.23 μN/m at $a_{11} = 178 \times 10^{-9}$. The enhancement factors defined by the ratio of spring constants with/without aberration correction were 1.35 for $d_{TP} = 2$ μm and 1.83 for $d_{TP} = 7$ μm. These measurement of the spring constants were repeated 10 times for each a_{11}. The averages are plotted and the standard deviations are represented as error bars in Fig. 2. The trapping laser power was several tens mW under the objective lens in these measurements.

We evaluated the trapping force and the spring constant enhanced by the aberration correction using numerical simulations. In our simulation, an incident electromagnetic field with aberration caused by the index mismatch was calculated from the diffraction theory for high NA objective-lens proposed by Hell *et al.*[9] The wave front of the aberrated incident-field was compensated by adding the 11th order Zernike polynomial, $a_{11}Z_{11}$, to the phase term in the diffraction theory. The scattered field by a particle in the incident field was calculated by a method based on Mie scattering theory proposed by Barton *et al.*[16] The laser trapping force was calculated by the integration of electromagnetic stress tensor over the particle surface.[17] The spring constant was calculated as the differential of the force at the most stable trapped-position. We assumed that an aberration-free oil-immersion objective lens with 1.4 numerical aperture was used for focusing linearly polarized light of a 1064-nm wavelength for laser trapping. The immersion oil and the upper glass of the cell had same

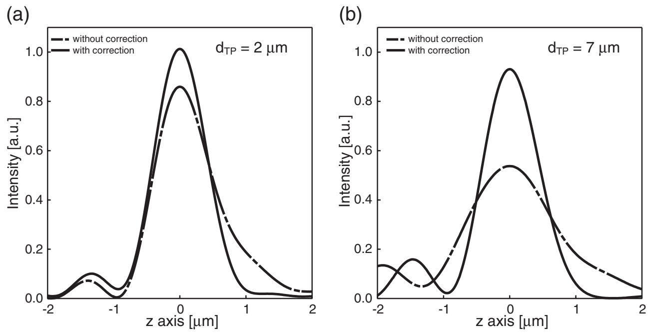

Fig. 3. Intensity distributions along the optical axis with and without the aberration correction for (a) $d_{TP} = 2\,\mu m$ and (b) $d_{TP} = 7\,\mu m$. Solid line; with the aberration correction, broken line; without the aberration correction.

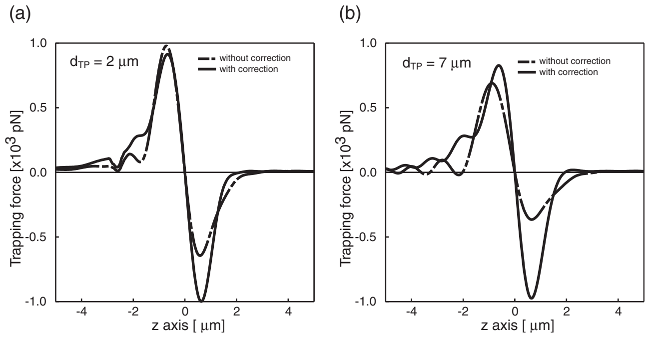

Fig. 4. Trapping forces on a 1-μm diameter-polystyrene particle in the incident fields with and without the aberration correction at (a) $d_{TP} = 2\,\mu m$ and (b) $d_{TP} = 7\,\mu m$. Solid line; with the aberration correction, broken line; without the aberration correction.

refractive indices of 1.51. The particle of 1.59 refractive index was surrounded by water of 1.33.

From the calculations of the spring constants for different a_{11}s, the spring constants were the biggest when the phase aberration was compensated the most. Figure 3 shows the intensity distributions of the incident fields along the z axis with and without the aberration correction for (a) $d_{TP} = 2\,\mu m$ and (b) $d_{TP} = 7\,\mu m$. It is clear that the maximum intensity without the aberration correction for $d_{TP} = 2\,\mu m$ is higher than that for $d_{TP} = 7\,\mu m$ because the aberration amplitude is proportional to the focusing depth d_{TP}. With the wave-front compensation, the maximum intensity is recovered from 0.86 to 1.01 for $d_{TP} = 2\,\mu m$ in Fig. 3(a) and from 0.54 to 0.93 for $d_{TP} = 7\,\mu m$ in Fig. 3(b). The coefficients a_{11} required for the compensation are 76×10^{-9} for $d_{TP} = 2\,\mu m$ and 191×10^{-9} for $d_{TP} = 7\,\mu m$. The intensity is normalized by the maximum intensity of ideal focal spot.

The trapping forces on a 1-μm-diameter polystyrene-particle are shown in Fig. 4. The incident laser power in the focal plane is normalized to 1 W. In both cases of (a) $d_{TP} = 2\,\mu m$ and (b) $d_{TP} = 7\,\mu m$, the maximum trapping forces are enhanced by the aberration correction. From these simulations, the enhancement factors of the spring constants are 1.20 for $d_{TP} = 2\,\mu m$ and 2.16 for $d_{TP} = 7\,\mu m$, while the corresponding results in the experiments were 1.35 for $d_{TP} = 2\,\mu m$ and 1.83 for $d_{TP} = 7\,\mu m$.

We have presented a method for enhancing trapping forces through aberration correction of the trapping beam. This was implemented using a membrane deformable mirror. By correcting the aberration due to the refractive index mismatch between the upper glass and water, the enhancement of the spring constant was successfully performed. The analysis by the numerical simulation was coincident with this experimental result. Although we have focused on the axial trapping force and axial spring constant, the enhancement of lateral force is also possible due to the aberration correction. The wave-front compensation technique has an ability to correct other aberrations simultaneously, although only spherical aberration was compensated in this paper. It is expected that this technique will be used for correcting the residual aberration in the optical alignment or the aberration caused by the refractive index distribution of the specimen and so on.

1) A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm and S. Chu: Opt. Lett. **11** (1986) 288.
2) T. Ota, T, Sugiura and S. Kawata: Appl. Phys. Lett. **80** (2002) 3448.
3) T. Sugiura, T. Okada, Y. Inouye, O. Nakamura and S. Kawata: Opt. Lett. **22** (1997) 1663.
4) M. Gu and P. C. Ke: Opt. Lett. **24** (1999) 74.
5) N. B. Simpson, D. Mcgloin, K. Dholakia, L. Allen and M. J. Padgett: J. Mod. Opt. **45** (1998) 1943.
6) R. Gussgard, T. Lindmo and I. Brevik: J. Opt. Soc. Am. A **9** (1992) 1922.
7) T. Sugiura and S. Kawata: Kougaku **24** (1995) 408 [in Japanese].
8) H. Felgner, O. Müller and M. Schliwa: Appl. Opt. **34** (1995) 977.
9) S. Hell, G. Reiner, C. Cremer and E. H. K. Stelzer: J. Microsc. **169** (1993) 391.
10) M. J. Booth, M. A. A. Neil and T. Wilson: J. Microsc. **192** (1998) 90.
11) M. J. Booth, M. A. A. Neil, R. Juškaitis and T. Wilson: Proc. Natl. Acad. Sci. USA **99** (2002) 5788.
12) G. V. Vdoin, P. M. Sarro and S. Middelhoek: J. Micromech. Microeng. **9** (1999) R8.
13) T. Ota, S. Kawata, T. Sugiura, M. J. Booth, M. A. A. Neil, R. Juškaitis and T. Wilson: Opt. Lett. **28** (2003) 465.
14) R. J. Noll: J. Opt. Soc. Am. **66** (1976) 207.
15) L. Zhu, P. C. Sun, D. U. Bartsch, W. R. Freeman and Y. Fainman: Appl. Opt. **38** (1999) 6019.
16) J. P. Barton, D. R. Alexander and S. R. Schaub: J. Appl. Phys. **64** (1988) 1632.
17) J. D. Jackson: *Classical Electrodynamics* (John Wiley & Sons, Inc., New York, 1975) 2nd ed.