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Aberration correction in holographic optical tweezers using a high-order optical vortex

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Abstract

Holographic optical tweezers are a powerful optical trapping and manipulation tool in numerous applications such as life science and colloidal physics. However, imperfections in the spatial light modulator and optical components of the system will introduce detrimental aberrations to the system, thereby degrading the trapping performance significantly. To address this issue, we develop an aberration correction technique by using a high-order vortex as the correction metric. The optimal Zernike polynomial coefficients for quantifying the system aberrations are determined by comparing the distorted vortex and the ideal one. Efficiency of the proposed method is demonstrated by comparing the optical trap intensity distribution, trap stiffness, and particle dynamics in a Gaussian trap and an optical vortex trap, before and after aberration corrections.

Keywords

(050.4865) Optical vortices; (090.1000) Aberration compensation; (140.7010) Laser trapping; (260.6042) Singular optics; (350.4855) Optical tweezers or optical manipulation

1. INTRODUCTION

Optical tweezers (OTs) have found wide application in life sciences [1] and fundamental physics [2] by providing applicable force (from several piconewtons to hundreds of piconewtons) to probe microscopic interactions. Compared with single point-trap OTs [3], holographic OTs (HOT) implemented with a commercial spatial light modulator (SLM) have shown high flexibility in optical micro-manipulations [4,5]. Dynamic manipulation of multiple microparticles in three dimensions can be easily realized by updating the predesigned computer-generated holograms (CGHs) displayed on the SLM [6]. Furthermore, a HOT provides the possibility to manipulate microparticles with novel beams,

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such as Bessel beams [7], Airy beams [8], and more complex optical fields [9]. These features make HOT a powerful tool to address some scientific problems [10–12].

However, wavefront aberrations—introduced by defects in the surface curvature of the liquid crystal panel of the SLM; the imperfection of the optical components; and the mismatch of an optical system such as refractive index mismatch when using an oil-immersion objective—will inevitably lead to degradation of beam quality, resulting in reduced trapping efficiency [13,14]. Considerable progress on aberration correction has been made in recent years to correct these issues [15–25]. The interferometric approach, which accurately measures wavefront distortion, has been met with a lot of interest [16–18]. However, as it needs an additional interferometer to measure the aberration, the system becomes more complicated and inconvenient.

The non-interferometric method is a reliable option that does not require extensive system modification [16,20]. As is well known, optical vortices have been applied broadly to optical trapping and stimulated excitation depletion microscopy. An ideal optical vortex has a symmetric doughnut shape with zero intensity at the center, and is very sensitive to phase irregularity. Even slight distortions in the wavefront, especially astigmatism, will destroy its rotationally symmetric intensity distribution. For this reason, Jesacher *et al.* developed an iterative method using the Gerchberg–Saxton (GS) algorithm to extract the wavefront aberration from a distorted first-order vortex [20]. While the focal spot size of the vortex field is proportional to the magnitude of the topological charge of the vortex, the size of the focused first-order vortex is small and therefore unfavorable to experimental observation. Especially, the dark region in the center is smaller than one-half of the wavelength, which is hard to be resolved by the camera. An additional problem is that the GS iterative algorithm is generally time consuming.

In this paper, we present a non-iterative program that permits aberration correction in a SLM-based HOT system *in situ*. A high-order Laguerre–Gaussian (LG) vortex is used as the aberration correction metric instead of a first-order LG vortex because it is easier to observe. To achieve this, a sequence of precalculated CGHs comprising various Zernike polynomials combined with a high-order spiral phase are loaded onto the SLM, and the difference between the produced vortex and the ideal one is calculated to find the optimal Zernike polynomial coefficients. Using this approach, the first- and second-order astigmatism introduced by the SLM are corrected [17,19,20]. We provide a detailed analysis of the entire aberration correction procedure and evaluate the performance of the approach by measuring the trap stiffness and rotation trajectory of the uncorrected and corrected HOT systems. We demonstrate that trap stiffness is improved by a factor of (2.35, 1.44) in (x , y) direction, respectively. In addition, the rotation trajectory of the particle in the vortex is optimized from an elliptical orbit to a circular one. We anticipate that the proposed approach can be applied to SLM-based systems as a fast optimization procedure.

2. METHODS AND EXPERIMENT DESCRIPTION

A. Description of Aberration

Before performing the aberration correction, we provide a description of the aberration with Zernike polynomials. In an optical system, any imperfection of optical elements would result in a wavefront aberration, W , which denotes a change in the phase, i.e.,

$$\Delta\phi = \frac{2\pi W}{\lambda}. \quad (1)$$

The wavefront aberration can be expanded as a linear combination of normalized Zernike circle polynomials of order (n, m) , Z_n^m , with coefficients C_n^m :

$$W = \sum_{n,m} C_n^m Z_n^m, \quad (2)$$

where n and m denote, respectively, the highest order of the radial polynomial and the angular frequency of the sinusoidal component. The Zernike circle polynomials in polar coordinates (ρ, θ) within the ranges of $0 < \rho < 1$ and $0 < \theta < 2\pi$ are defined as

$$Z_n^m(\rho, \theta) = \begin{cases} N_n^m R_n^{|m|}(\rho) \cos(m\theta) & \text{for } m \geq 0, 0 \leq \rho \leq 1, 0 \leq \theta \leq 2\pi \\ -N_n^m R_n^{|m|}(\rho) \sin(m\theta) & \text{for } m < 0, 0 \leq \rho \leq 1, 0 \leq \theta \leq 2\pi \end{cases}, \quad (3)$$

where the normalization factor and radial polynomial are expressed, respectively, as

$$N_n^m = \sqrt{\frac{2(n+1)}{1+\delta_{m0}}} \quad \delta_{m0} = 1 \quad \text{for } m = 0, \quad (4)$$

$$\delta_{m0} = 0 \quad \text{for } m \neq 0$$

and

$$R_n^{|m|}(\rho) = \sum_{s=0}^{(n-|m|)/2} \frac{(-1)^s (n-s)!}{s! [(n+|m|)/2 - s]! [(n-|m|)/2 - s]!} \rho^{n-2s}. \quad (5)$$

Among the aberrations represented by Zernike polynomials, the second-order modes ($n = 2$, $m = [-2, 2]$) and the fourth-order modes ($n = 4$, $m = [-2, 2]$) characterize the first- and second-order astigmatism, respectively. As demonstrated previously, these four

astigmatisms are the primary system aberrations that exist in a HOT utilizing SLMs [17,19,20].

B. Experimental Setup

The experiments were carried out with a home-built HOT system (Fig. 1). The trapping light source is a linearly polarized CW laser ($\lambda = 1064$ nm) with maximal power of 2 W. The collimated beam is modulated by a reflection-type pure-phase SLM (Pluto-NIR-II, HOLOEYE Photonics AG Inc., Germany), which has resolution of 1920×1080 pixels and a pixel pitch of 8 μm . Then, a quarter-wave plate (QWP) is used to convert the linearly polarized beam into a circularly polarized one. The QWP is used here for the reason that, under tight focusing condition, a circularly polarized vortex has a uniform intensity distribution along the azimuthal direction, whereas the focused linearly polarized vortex has two hot spots on the ring [26,27]. After the QWP, the beam is directed to a $60\times$ water-immersion objective ($60\times/\text{NA } 1.27$; Nikon Inc., Japan) by a dichroic mirror (FF700-SDi01-25 $\times$ 36; Semrock Inc., USA) and focused into the sample cell where the beam power is measured to be approximately 150 mW. A CCD camera (60 fps at full resolution; Thorlabs Inc., USA) with resolution of 1280×1024 pixels is employed to record the focal field intensity distribution and trapping dynamics. An LED is used as the illumination source.

C. Aberration Correction Procedure

The LG vortex has a spiral phase term $\exp(i\ell\theta)$, where ℓ denotes the topological charge and θ denotes the azimuthal angle in polar coordinates. This phase singularity makes the intensity at the center of the beam profile null and leads to rotational intensity symmetry, which is very sensitive to the off-axis wavefront aberration. The significant deviation of a distorted vortex from its rotational symmetry can be utilized to extract the phase errors.

Aberration is searched by loading a CGH consisting of the high-order spiral phase combined with a varying aberration phase represented by the Zernike polynomials, i.e.,

$$\phi_n^m = 2\pi C_n^m Z_n^m / \lambda. \text{ Here, we use a fourth-order vortex. The correction coefficient } C_n^m$$

quantifying the aberration of mode (n, m) is determined by finding the minimal error between the recorded vortex, I_{CCD} , and the ideal fourth-order LG vortex, I_{ideal} . This error is defined as

$$\epsilon = \sum_M \sum_N (I_{\text{CCD}} - I_{\text{ideal}})^2, \quad (6)$$

where $M \times N$ denotes the pixel number of the images. In Eq. (6), a smaller value of ϵ corresponds to a more accurate aberration correction. The aberration correction procedure follows two steps (Fig. 2):

1. In the first step (Fig. 2, step 1), we measure the error for various aberrations by varying the Zernike coefficients to find the primary aberration existing in the system. The hologram displayed on the SLM comprises only one kind of

aberration at one time, i.e., $\phi = l\theta - \phi_n^m$. Here, we choose to correct the first- and second-order astigmatism mainly caused by the SLM. The optimal correction coefficients $(C_2^{-2}, C_2^2, C_4^{-2}, C_4^2)$ are (2.33, 0.78, -0.87, -0.02). Therefore, the primary aberration in our system is the astigmatism of mode (2, -2). It should be noted that the four astigmatism with these correction coefficients should not be simply superposed and displayed on the SLM. Otherwise, it will cause a larger error ε , of 0.651.

2. In the second step, we correct the four astigmatism sequentially. The rule is that, once one of the correction coefficients is determined, the corresponding correction phase of the determined aberration is added to the previous hologram. Then the correction procedure is repeated. We start the procedure from the primary aberration, i.e., the astigmatism of mode (2, -2), and its correction coefficient C_2^{-2} is 2.33. Then we continue to correct the astigmatism of modes (2, 2), (4, -2), and (4, 2) in order (Fig. 2, step 2), and calculate the corresponding error. The final correction coefficients $(C_2^{-2}, C_2^2, C_4^{-2}, C_4^2)_{\text{optimal}}$ for the four astigmatism are (2.33, 0.62, -0.03, 0.21) and the final error is measured to be 0.0931. Here, we choose the primary aberration as the first one to be corrected. As a result, this produces the smallest error.

The time for correcting each aberration is about 24 s in our system. There are two aspects that can be improved to enhance the speed of aberration correction: the consumption time for loading the holograms onto the SLM and the exposure time of the camera. It needs about 30 ms (33.3 Hz in use) to load a hologram onto the SLM, leading to a total loading time of 18 s for 600 holograms. This can be significantly decreased by using a faster SLM. The acquisition time for each image is about 5 ms when the camera is operated in region of interest mode, leading to a total acquisition time of 3 s for 600 images. This can be improved by using a camera with a faster acquisition rate. In addition, it takes about 3 s to calculate the error ε .

The fourth-order LG vortices before and after aberration correction are shown in Fig. 3. Figures 3(a) and 3(b) show, respectively, the LG vortices with topological charges of 4 before and after aberration correction. Figures 3(c) and 3(d) show, respectively, the cut-line intensity profiles of the vortices along the dashed lines marked in Figs. 3(a) and 3(b). Before aberration correction, the vortex is severely elongated and two hot spots exist in the vortex [Fig. 3(a) and 3(c)]. This will surely hinder the rotation of particles in the vortex. In contrast, the corrected vortex shows a more symmetric intensity pattern [Fig. 3(b) and 3(d)]. After aberration correction, the ratio between the vortex diameters in the perpendicular directions (L3 versus L4) is about 1.02, whereas the value of the uncorrected vortex is about 1.49 (L1 versus L2). In addition, the intensity distribution is more uniform. These results show significant improvement on the rotational symmetry of the LG vortex following aberration correction.

3. RESULTS AND DISCUSSION

A. Improvement of Particle Trapping Stiffness for Gaussian Beams

To verify the effectiveness of our approach, we first compare the intensity distribution of the focused Gaussian spot before and after aberration correction. The cut-line intensity profiles [Fig. 4(c) and 4(d)] along the dashed lines [Figs. 4(a) and 4(b), respectively] show that the maximal intensity following aberration correction increased from 0.522 to 0.857. This indicates a higher modulation efficiency for beam tailoring due to aberration correction. In addition, the uncorrected focal spot shows a slightly elliptical profile, where the full width at half-maximum (FWHM) is 0.824 and 0.707 μm in the orthogonal directions. In sharp contrast, the FWHM of the corrected spot is 0.659 and 0.624 μm , demonstrating that a sharper and more symmetric spot is obtained.

We then investigate the trapping performance of the uncorrected and corrected Gaussian spots using beads with a diameter of 1 μm . The Brownian motion of the trapped beads is measured with digital video microscopy [28]. A particle's position chart over 5 s is shown in Fig. 4(e) and 4(f), demonstrating that the position of the bead is confined more significantly in the corrected trap, as indicated by the size of the two dashed circles.

Finally, trap stiffness was calibrated using equilibrium theory to determine whether trapping performance is also improved using our approach [29]. Results show that the trap stiffness in (x, y) direction is increased from (94.61, 133.02) pN/ μm to (222.06, 192.17) pN/ μm , corresponding to a factor of ratio of (2.35, 1.44).

B. Improvement of Particle Rotating Dynamics for LG Vortex Beams

The transfer of orbit angular momentum from the laser beam to trapped particles will result in rotation of the particles. There is immense interest in exploring the mechanical manifestation of this technique in experimental scenarios. Therefore, we further study the effectiveness of our method on the particle rotating performance of the high-order vortex.

Here, the topological charge of the vortex is 10. We compare the particle dynamics of 1 μm beads in the uncorrected and corrected vortices (Fig. 5 and Visualization 1). The rotation trajectory of a sphere in the corrected vortex clearly shows a quasi-circular profile [Fig. 5(b)]. In contrast, the sphere rotates in an ellipsoid-shaped orbit in the uncorrected vortex [Fig. 5(a)]. Improvement in the rotating performance of the vortex is notable as ellipticity decreases from 25.1% to 1.2% following aberration correction. Here, ellipticity is defined as where a and b denote, respectively, the lengths of the long and short axes of an ellipsoid.

$$e = \frac{a-b}{a} \times 100\%, \quad (7)$$

Improvement of the rotation orbit is anticipated to improve the particle dynamics in the vortex. To demonstrate this, we measure the relationship between a particle's angular velocity and the topological charge of the vortex before and after aberration correction. The dependence of the angular velocity of the 1 μm diameter polystyrene sphere on the

topological charge of the vortex is plotted in Fig. 6. This analysis shows that, before aberration correction, the sphere does not rotate until topological charge l increases to 9, whereas it begins to rotate at $l = 6$ when aberration is compensated for. When the topological charge is large (say $l > 13$ in Fig. 6), aberration correction shows little improvement in the overall rotation velocity. The reason might be that the size of the vortex is much larger than the size of the particle, making the averaged velocity of the sphere over a rotation period at large rotation orbit changes very little.

4. CONCLUSION

We have presented an efficient aberration correction program using a high-order LG vortex. We use a fourth-order LG vortex rather than a first-order LG vortex as the beam quality metric to perform the correction procedure. Using this approach, the first- and second-order astigmatism introduced by the SLM are corrected effectively. The trap stiffness for the Gaussian trap is increased (2.35, 1.44) folds in the (x , y) direction, respectively. The particle rotation trajectory and velocity in the vortex trap are both improved, resulting in a higher efficiency of transfer of orbital angular momentum from the vortex to the trapped particle. The improvements of trap stiffness and particle rotation dynamics are critical for precise holographic optical micro-manipulation. The method developed for aberration correction using a high-order LG vortex is simple and efficient. It has great potential in system optimization for SLM-based HOTs and microscopes without modification of the system.

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Fig. 1. Schematic of the home-built holographic OTs. SLM, spatial light modulator; CGH, computer-generated hologram; QWP, quarter-wave plate.

Fig. 2.

Diagram of the aberration correction procedure using a high-order LG vortex. The correction time for each aberration is about 24 s. The range of the coefficient for each astigmatism is set in $[-3.0, 3.0]$ with an interval of 0.01. The correction procedure is carried out on a PC (Intel Core i5-3470 CPU at 3.2 GHz and 16 GB RAM) by using MatLab.

Fig. 3.

Intensity distributions of the fourth-order LG vortex before and after aberration correction. (a) Uncorrected LG vortex. (b) Corrected LG vortex. (c) Cut-line intensity profiles along the dashed lines marked in (a). (d) Cut-line intensity profiles along the dashed lines marked in (b). The inset in (a) shows the spiral phase with a topological charge of 4 for generation of the fourth-order LG vortex. The inset in (b) shows the phase superposed by the spiral phase and correction phase.

Fig. 4.

Comparison of the focused Gaussian spot before and after aberration correction. (a) Uncorrected focal spot. (b) Corrected focal spot. (c) Cut-line intensity profiles along the dashed lines marked in (a). (d) Cut-line intensity profiles along the dashed lines marked in (b). (e) The lateral (xy) position chart of the trapped particle in the uncorrected Gaussian spot trap. (f) The lateral (xy) position chart of the trapped particle in the corrected Gaussian spot trap.

Fig. 5. Rotation trajectory of the trapped 1 μm bead in the 10th-order LG vortex (a) before and (b) after aberration correction.

Fig. 6. Angular velocity of the rotated sphere against the topological charge of the vortex before and after aberration correction.