Digital holographic visualization of microparticles retained by an optical spatial trap

N V Shostka¹, B V Sokolenko¹, O S Karakcheva², A V Prisyazhniuk¹, V I Voytitsky³, D A Poletaev¹ and S I Halilov¹

¹Institute of Physics and Technology, V.I. Vernadsky Crimean Federal University, Simferopol 295007, Russia
²Department of Science and Research, V.I. Vernadsky Crimean Federal University, Simferopol 295007, Russia
³Taurida Academy, V.I. Vernadsky Crimean Federal University, Simferopol 295007, Russia

E-mail: simplexx.87@gmail.com

Abstract. We propose a convenient method for generating optical traps based on a spatially structured beam. The proposed method of optical trap shaping utilizes interference of few Gaussian beams which waists, inclination angles and beam number are chosen for controllable trapping of micron-sized particles in three-dimensional space. In addition to implementing non-contact trapping, optical visualization in all planes was performed with digital holographic microscopy. This method contributes to the accurate localization of the studied specimens inside the cuvette over whole volume.

1. Introduction

The task of forming arrays of two- and three-dimensional (3D) optical traps based on gradient forces [1,2] consists in choosing the optimal method for generating complex optical fields for transparent particles trapping. Commonly, the method of holographic reproduction on spatial light modulators (SLM) is used [3–5]. Based on this approach, it is possible to separate single incident coherent beam into independent partial beams using diffractive optical elements, which may be adjusted dynamically with SLM or micro mirrors devices and stationary (metasurfaces, diffraction gratings and amplitude masks) [3].

Another solution of spatial trapping beam shaping explores wave front singularity, known as optical vortex [6,7]. Vortex beams allows to capture particles with a refractive index lower than the refractive index of the environment, as well as objects with a fully reflective surface. In contrast to conventional traps which based on gradient forces, an optical tweezers with optical vortex performs trapping to its intensity minima, which has a two-dimensional (2D) distribution.

One of the highly efficient methods for generating spatially 3D structured vortex beams is a method based on polarization filtering after birefringent crystal [8,9]. When the outgoing beam after crystal is focused by a lens located after the crystal, two intensity maxima are formed at the Fourier plane: a complex spatial distribution of the electromagnetic field between foci [10] has a form of well-known “bottle” beam with intensity minimum on the axis uniformly surrounded by a high-intensity area [11–12]. The intensity distribution of “bottle” beam may be adjusted using a polarizer and a quarter-
wave plate, which allow to switch a trap from “opened” to “closed” state [13] which differ by intensity maxima in longitudinal direction. This approach is well suitable for trapping of single particles into intensity minima, while it is practically important to increase number of traps and to adjust its spatial alignment. This work demonstrates the use of few Gaussian beams interference for generating fully three-dimensional optical trap for absorbing microparticles.

Our paper organized as follows: in section 2 we describe two methods of spatial traps shaping by Gaussian multibeam superposition generated with amplitude screen. In section 3 we demonstrate the capabilities of integrated non-contact trapping and digital holographic microscopy.

2. Spatial trap shaping with coherent beams superposition

A method of forming a “bottle” beam structure is based on the interference of several Gaussian beams. Recently, it was shown, how two-dimensional light quasiperiodic structures could be produced by the interference of three Gaussian beams converging at different angles. Before spatial light manipulators became widespread, the use of one- and two-dimensional diffraction gratings and wave-front division interferometers was the simplest way to create a quasiperiodic grid of intensity minima [12,13]. The resulting field after Gaussian beams superposition was used exclusively for trapping of silica beads in intensity maxima. As a result, optical tweezers were formed to trap an ensemble of microparticles in a certain plane. The implementation of spatial trapping and controlled manipulations of an array of particles absorbing light energy, or with a refractive index less than the refractive index of the medium is not fully solved yet [14,15]. The developed method of generating spatially structured quasi-periodic fields using interference of three, four and five Gaussian beams allowed creating the necessary conditions for the formation of areas of the light field with a "bottle" structure [16–18].

In this section, we present a method to achieve stable in-plane optical trapping and full control of a set of microparticles in liquid medium. A control of initial phase, polarization, and the inclination angle \( \alpha \) to the propagation axis of each beam makes it possible to adjust the position of the “bottle” structure in space of light lattice and, as a result, to manipulate the coordinates of the captured particle in all planes. Numerically calculated spatial intensity distributions are shown in figure 1 (a-c).

To describe a trapping beam shaping with amplitude screen with holes which is shown in figure 2 (b), let us introduce the transformation of the coordinates of an output beam at the plane \( x0z \) as [19]: \( X = x + i\alpha z_0 \), and at the plane \( y0z \): \( Y = y + i\alpha z_0 \), where \( z_0 = k\alpha_0^2 / 2 \), \( \alpha_0 \) is the radius of the waist of the Gaussian beam and \((x, y)\) is the Cartesian coordinates of the beam in the focal plane \( z = 0 \) as it was shown in figure 2 (b). Additionally, we suppose rotational transformation of coordinates: let \( \varphi \) to be the beam precession angle around the z axis, and \( d \) is the displacement of the axis of an arbitrary beam in the transverse plane \( z = 0 \) from the central axis. The resulting transformation for the beam coordinates is written as: \( X = (x + i\alpha z_0)\cos(\varphi) + (y + d)\sin(\varphi), \ Y = (i\alpha z - x + d)\sin(\varphi) + y\cos(\varphi). \)

A propagation of each Gaussian beam after amplitude screen in vicinity of micro-objective (MO) focal plane at the distance \( z \) can be described as a complex amplitude:

\[
E_i(X, Y, z) = \frac{1}{1-iz/z_0} \exp\left[\frac{-\left(X^2 + Y^2\right)}{\alpha_0^2 (1-iz/z_0)}\right] \exp(-\alpha^2 k z_0)\exp(-ikz). \tag{1}
\]

The interference between pairs of Gaussian beams \((i, j)\) with a complex amplitude (1) produce a dynamic multiple dark optical trap in form of quasi-periodic light lattice in intensity distribution \( I(X, Y, z) \):

\[
I(X, Y, z) = \sum_{i=1}^{N} |E_i|^2 + \sum_{i<j} E_i E_j, \tag{2}
\]

where \( N \) denotes the number of superposed beams, \((i, j)\) – beam indexes, \( i, j = 1 \pm 5 \).
Figure 1. Numerically simulated transverse intensity distribution of five Gaussian beam superposition (a1–b1, a2–b2, a3–b3) and its longitudinal spreading (c1–c3) in free space. Transverse intensity distribution of four beams interference (a4–b4) and their longitudinal spreading section (c4). Beam parameters are: $\lambda = 535 \text{ nm}$, $\omega_0 = 200 \mu\text{m}$, $z = \pm 2 \text{ cm}$ from focal plane.

A numerically calculated spatial intensity distributions for case of four (opened trap) are shown in figure 1 (bottom row) and for five Gaussian beams (closed trap). In particular case, amplitudes of each beam may be equal. Thus, the geometric spatial structure of the resulting interference pattern could be shaped by an appropriate set of parameters $\varphi$, $d$ and $\alpha$ for each beam. The result of numerical simulation of the interference process of five Gaussian beams oriented at equal angles to a central beam propagating which spreads without inclination is shown in figure 1 (a1–c1 and a3–c3), whereas frames in figure 1 (a2–c2) correspond to the case of different inclination angles of two beam pairs.

An arbitrary displacement of a trapped particle in 3D lattice cells leads to heating of that part of its boundaries that falls into an intensity maximum. The resulting pressure difference on the hot and cold parts of the particle returns absorbing particle to the equilibrium within the area of a minimum intensity. The reproducing of fields with localized minimum intensity – “bottle” beams in practice is possible with
the use of diffraction elements – amplitude screens with shaded edges by a Gaussian envelope for preventing the undesirable diffraction effects occurrence as it is shown in figure 2.

Figure 2. (a) Schematic sketch of optical trapping beam shaping with digital holographic microscopy part (top view). TL–trapping diode laser, L_{1,2}–lenses, (b) S–amplitude screen, MO–micro-objective, C–cuvette, CMOS–imaging camera, HL–He-Ne laser, PH–pinhole of 25 μm diameter. (c) Experimentally captured images of few microparticles trapped by “bottle” beam lattice in transverse plane (x, y) of the trapping beam. Other beam parameters are following: \( \omega_o = 200 \) μm, \( \lambda = 535 \) nm, \( z = 2 \) cm. Each frame (c1–c4) corresponds to rotation of amplitude mask by the angle \( \varphi \) with step of 10° in anticlockwise direction.

The lattice shape and positions of minima and maxima may be changed by waist radius of beams \( \omega_o \) via diameters of holes in amplitude screen, inclination angle \( \alpha \) and rotation of amplitude screen around z-axis for each beam to configure an arbitrary number of microparticles in the specified coordinates. An inclination angle is adjusted by the distance \( d \) between holes and by focal length \( f_3 \) of trapping MO.
In current experimental setup, a beam of trapping diode laser (TL) with operating wavelength \( \lambda = 535 \text{ nm} \) and output power 500 mW after spatial filtering by lenses \( L_1 \) with focal length \( f_1 = 1 \text{ cm} \). \( L_2 \) with \( f_1 = 10 \text{ cm} \) and diaphragm D is expanded to overlay amplitude screen S, which splits input beam into five separate beams as shown in figure 2, (b). A microscope lens MO with numerical aperture 0.2 is used to project spatial trapping field into cuvette with studying specimen. In Figure 2 (c1–c4) the experimental trapping process is illustrated. The specimen is marine diatoms in deionized water was trapped and arranged at the same \( z \)-plane. The image sequence (c1–c4) corresponds to the different angles of particles orientation, controlled with revolving of amplitude mask by the angle \( \varphi \). Any deviation from symmetry in beam waist or inclination angle results on spatial composition of 3D trapping lattice, which used for adjusting size of trapping areas and its shape. By closing central beam on amplitude screen, an optical trap may be easily switched from “closed” to “opened” state.

3. Digital holographic analysis of optically trapped objects

Basically, any trapped microparticle is an amplitude-phase object, which phase properties are determined by refractive index of the media. Using of digital holographic microscopy as a tool sensitive to spatial variations of refractive index makes it powerful solution for this task. Digital holographic microscopy is based on the interference of two coherent or partially-coherent light beams with phase differences [20]. The beams are usually generated by a single source and have been separated by a beam splitter [21,22]. In case of in-line digital holography, the point source of light is used for illumination of specimen, wherein superposition of wave is diffracted by the microparticle and the spherical diverging reference wave, which passes in free space, occurred on the camera sensor as it shown in figure 2 (a).

To obtain a process of recording a digital hologram, a three-dimensional specimen, in our case – a cuvette with marine diatoms, where an imaging plane is located at a distance \( h \) from the camera. To obtain the object wave of the specimen in digital holography, a numerical calculation of the optical field \( I(x, y) \) propagation from the hologram plane \((\xi, \eta)\) to the image plane is used.

Numerical reconstruction of a digitally recorded hologram is carried out in accordance with the scalar diffraction theory in the Fresnel approximation for the Rayleigh-Sommerfeld diffraction integral. In our research we chosen an angular spectrum approach for hologram reconstruction as a method which has no limitations to distances \( z \) from a specimen to image plane, as well as size of each pixel of reconstructed image corresponds to the pixel size of original hologram [23]. Emitted the field \( E(\xi, \eta) \) at the hologram plane \(( z = 0)\), its angular spectrum is defined as Fourier transform:

\[
A(k_x, k_y) = \mathcal{F} [E(\xi, \eta)] = \frac{1}{2\pi} \int_{-\infty}^{+\infty} d\eta d\xi E(\xi, \eta) \exp[-i(k_x k_x + k_y \xi)],
\]

where wave vector \( k = (k_x, k_y, k_z) \), \( k = \frac{2\pi}{\lambda} \), \( k_x = k \frac{x}{z} \), \( k_y = k \frac{y}{z} \), \( k_z = \sqrt{k_x^2 + k_y^2 + k_z^2} \). After propagation over a distance \( z \) to the image plane \((x, y)\), the diffracting wave acquires an additional phase \( \exp(i k_z z) \), thus we receive a wave amplitude at the plane \((x, y)\) at the distance \( z \):

\[
E(x, y) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} dk_x dk_y A(k_x, k_y) \exp[i(k_x x + k_y y + \sqrt{k_x^2 + k_y^2 + k_z^2})].
\]

We may rewrite equation (4) as a double Fourier transform of the object field \( E(\xi, \eta) \):

\[
E(x, y) = \mathcal{F}^{-1} \left\{ [\mathcal{F}[E(\xi, \eta)] \times \exp(i\sqrt{k_x^2 + k_y^2 - k_z^2}) z]] \right\},
\]

where \( k_z = \sqrt{k_x^2 + k_y^2 - k_z^2} \). In equations (4) and (5) we assumed \( k_z \) to be real, so the condition \( k^2 \geq k_x^2 + k_y^2 \) should be met. The recorded hologram contains information about the entire depth of the
field of captured area and, after reconstruction, the amplitude and phase components are available for analysis. Intensity $I(x, y; z)$ and phase $\phi(x, y; d)$ of reconstructed images may be obtained from the complex field $E(x, y)\,z$ at a distance $z$ using the following relations:

$$I(x, y; z) = |E(x, y)\,z|^2,$$

$$\phi(x, y; d) = \arctg \left( \frac{\text{Im}[E(x, y)\,z]}{\text{Re}[E(x, y)\,z]} \right) = \arg[E(x, y)\,z].$$

Phase values $\phi(x, y; z)$, which was obtained by equation (7) correspond to a modulo $2\pi$. One of the well-known phase unwarping algorithms can be applied to restore a continuous unfolded image of phase values, but we restrict to describing of $I(x, y; z)$ only.

The scheme of axial lensless digital holographic microscopy setup is shown in figure 2 (a): He–Ne laser light source (HL) with wavelength $632.8 \text{ nm}$ and $2 \text{ mW}$ power is collimated onto a $25 \mu\text{m}$ pinhole (PH). The emerging diverging spherical wave illuminates a cuvette (C) with observing specimen. The interference pattern as a hologram is recorded on the screen of CMOS camera. The red-colored cone corresponds to the reference undiffracted wave and blue filled cone is a scattered wave, respectively. The imaging layer inside the cuvette is positioned at the distance $h$ from a pinhole and distance $z$ from a specimen to CMOS, which are used for further calculations. Magnification in reconstructed image had a value no less than $20\times$. In figure 3 (a–c) two particles are manipulated simultaneously: initial position in figure 3 (a) is shown with red circles, were red arrows denote direction of translation movement. In figure 3 frames (b) and (c) show the rotational movement of diatoms and their final placement. All particles are trapped into intensity minima while strong intensity spots surround the particles behind and in front of them in focal plane area along the optical axis, thus 3D “bottle” beam traps are realised.

Figure 3. Numerically reconstructed digital hologram of diatoms in water (a), trapped by “bottle” laser beam; the cropped frame to $50 \times 50 \mu\text{m}$ was extracted from original hologram with dimensions of $4.30 \times 3.50 \text{ mm} (1024 \times 768 \text{ pix.})$. The traps configuration can be changed using screen adjustment (b) or by movement of the cuvette towards focal plane of micro-objective. By rotation of amplitude screen all particles experiences simultaneous revolving around centre of symmetry (c).

The operational power of beam at the trapping plane is estimated near $80 \text{ mW}$ and distributed among the all trapping lattices. Increasing of holes size of amplitude screen directly relates to growth of trap power and size of lattice proportionally. A current scheme of lensless axial holographic visualisation enables computational scanning along excitation beam axis within $5 \text{ mm}$ range and overlap $1 \text{ ml}$ volume of the cuvette. Each particle positions in all directions are calculated from image dimensions and distances $h$ and $z$ from pinhole to trapped object and reconstruction distance respectively. The micron-scale resolution makes possible to observe geometrical form and localization of particles.

4. Conclusion

In this work, we studied the scheme for generation of volumetric optical trapping structures which are similar to “bottle” beam and perform absorbing particles capturing into intensity minima. In our
approach, a three-dimensional field structure is shaped with parametric multibeam interference via amplitude screen. This method offers easy calculating, adjustable and practically valuable non-contact optical trapping functionality for micron-sized biological specimen in large volume. During this study, it was found that the optical lattice which generated by superposition of five Gaussian beams with axial one determines the condition of “closed” 3D trap. When central beam was diaphragmed, an optical trap switched to “opened” state along z-direction. The positions of zero amplitude spots observed in the interference experiment are controlled by beam waist radius, shape of amplitude screen, number of superposed beams and their inclination angle in focal plane. A digital holographic visualization allows studying of specimen under relevant conditions in much larger volumes in comparison to conventional microscopy and provides access to extended observation times of each particle size, position and mutual orientation at static and dynamic processes.

Acknowledgments
The reported research was supported by RFBR and Council of Ministers of the Republic of Crimea (research project 19-42-910010) in part of trapping beam shaping and was funded by Russian Science Foundation grant (project No 20-72-00065) in part of optical microscopy and digital image retrieving.

References
[1] Stuhrmann B, Jahnke H-G, Schmidt M, Jahn K, Betz T, Muller K, Rothermel A, Kas J and Robitzki A A 2006 Rev. Sci. Instrum. 77 063116–11
[2] Simpson S H and Hanna S 2011 J. Opt. Soc. Am. A. 28 850–8
[3] Rosales-Guzman C, Bhebhe N A and Forbes A 2018 Opt. Soc. Am. 227 25697–706
[4] Bhebhe N, Williams Peter A, Rosales-Guzman C and Rodriguez-Fajardo V 2018 Sci. Rep. 8 1–9
[5] David G, Esat K, Thanopulos I and Signorell R 2018 Commun. Chem. 1 1–9
[6] Kiselev A D and Plutenko D O 2016 Phys. Rev. A. 94 013804
[7] Eckerskorn N, Bowman R W, Kirian R A and Awel S S 2015 Proc. SPIE, Opt. Trapp. Opt. Micromanipulation XII 9548 95480H
[8] Shostka N V, Karakchieva O S, Sokolenko B and Shostka V I 2019 J. Phys. Conf. Ser. 1400 1–5
[9] Shostka N, Karakchieva O and Sokolenko B V 2018 J. Phys. Conf. Ser. 1124 1–6
[10] Shostka N V, Sokolenko B V, Karakchieva O S, Poletaev D A, Titova A O, Prisyazhniuk A V and Ismailov I A 2019 J. Phys. Conf. Ser. 1410 1–6
[11] Shvedov V G, Hnatovsky C, Rode A V and Krolikowski W 2011 Opt. Express 19 273–75
[12] Shvedov V, Hnatovsky C, Shostka N and Krolikowski W 2013 J. Opt. Soc. Am. B 30 1934–36
[13] Yang Z, Lin X, Zhang H, Ma X, Zou Y, Xu L, Xu Y and Jim L 2019 Appl. Opt. 58 2471–80
[14] Porfiriev A P, Dubman A B and Porfiriev D P 2020 Opt Lett 45 1475–78
[15] Ghebjaogh S G, Fischer D and Sinzinger S 2019 Appl. Opt. 58 8943-49
[16] Shvedov V G, Hnatovsky C, Shostka N, Rode A V and Krolikowski W 2012 Optics Letters 37 1934–36
[17] Turpin A, Shvedov V C, Hnatovsky C, Loiko Yu V, Mompart J and Krolikowski W 2013 Opt. Express. 21 26335–40
[18] Ivanov M and Shostka N. 2014 Proc. SPIE, Laser Beam Shap. XV. (San Diego) vol 9194 ed. by A. Forbes, T. E. Lizotte (SPIE—International Society For Optics and Photonics) p 91941C
[19] Fadeyeva T, Rubass A, Sokolenko B and Volyar A 2009 J. Opt. A-Pure Appl. Op. 11 1–8
[20] Pavani S R P and Pietsten R 2008 Opt. Express 16 3484–89
[21] Masajada J, Popiolek-Masajada A, Augustyniak I and Sokolenko B 2013 Proc. SPIE, Optical Measurement Systems for Industrial Inspection VIII (Munich) vol 8788 ed P H. Lehmenn et al (SPIE—International Society For Optics and Photonics) p 87882V
[22] Plociniczak L, Popiole-Masajada A, Masajada J and Szatkowski M 2016 Appl. Opt. 55 B20–7
[23] Sokolenko B, Shostka N, Karakchieva O, Poletaev D, Voytitsky S, Halilov S, Prisyazhniuk A, Ilyasova A and Kolosenko E 2018 J. Phys.: Conf. Ser. 1062 012004

7