Fully-structured counter-propagating optical trap sculpted by spherical aberration

Eileen Otte* and Cornelia Denz

Institute of Applied Physics, University of Muenster, Corrensstr. 2/4, 48149 Muenster, Germany
E-mail: eileen.otte@uni-muenster.de

Received 14 December 2020, revised 3 March 2021
Accepted for publication 15 March 2021
Published 27 April 2021

Abstract
Aberrations of light are commonly known as undesired effects in different applications, including optical trapping. However, here we demonstrate how to take advantage of controlled spherical aberration in order to shape extended optical trapping landscapes, fully-structured in three-dimensional (3D) space and embedding transverse as well as longitudinal electric field contributions. We numerically analyze the light field customization by the simple means of including glass plates in a counter-propagating trapping configuration, presenting sculpted intensity as well as 3D polarization ellipse structures. Experimentally, we prove the realized counter-propagating optical structure by particle velocimetry as well as the analysis of scattered light of optically guided micro-particles. Finally, we demonstrate the potential of our approach by creating extended 3D particle assemblies.

Supplementary material for this article is available online

Keywords: Counter-propagating trapping, structured light, singular optics, fully-structured light, polarization modulation, vector beam, tight focusing

(Some figures may appear in colour only in the online journal)

1. Introduction
Structured light fields are characterized by a spatial variation in its different properties, more precisely, its amplitude, phase, and/or polarization. Due to its spatial structure, it enabled the advancement of various fundamental as well as applied fields of research [1], ranging from fundamental singular optics [2, 3], optical material machining [4, 5], and classical as well as quantum communication [6–11], to high-resolution imaging technologies [12–14]. Also the constantly developing field of optical trapping benefits significantly from structured light [15] enabling complex trapping potentials of customized features unavailable in standard optical traps.

In optical trapping, we make use of the optical scattering as well as gradient forces being proportional to the applied light field’s intensity (F_{scat} ∝ I(x,y,z)) and its gradient (F_{grad} ∝ \nabla I(x,y,z)), respectively [16]. In the equilibrium of these acting forces, transparent dielectric particles can be trapped. The probably most established configuration for optical trapping is the single-beam optical gradient trap—‘optical tweezers’—in which the typically dominating scattering force of light, exerted in beam propagation direction, are balanced by increasing counter-acting gradient force by tightly focusing the trapping beam. Today, this configuration benefits from the implementation of structured light as trapping beams, since a modulation in the spatial degrees of freedom of the light field, e.g. its intensity, is directly related to a spatial customization of optical trapping features. Scalar trapping potentials, customized in amplitude and phase in two- (2D) as well as
three-dimensional (3D) space, have been implemented, facilitating like-wise 2D or 3D particle assemblies and control (see e.g. [15, 17–23]) including the transfer of phase-related orbital angular momentum (OAM) [24, 25]. Additionally, the polarization of light allows for the transfer of spin angular momentum (SAM) to trapped birefringent objects [26]. Recent advances in methods to structure light have even enabled the spatial customization of polarization and, therefore, SAM as well as the joint modulation of amplitude, phase, and polarization, shaping ‘fully-structured’ light [27–33]. This ability has paved the way to novel focal trapping potentials of, e.g., adaptable spatial shape or trapping stiffness [15, 34–36]. This is particularly due to the unique tight focusing behavior of polarization-structured, i.e. vectorial light fields, enabling longitudinal in addition to transverse focal electric field contributions (3D polarization) [37–40].

Even though structured light has thus significantly advanced optical tweezers, trapping potentials in a single-beam gradient trap are typically limited in their longitudinal extent due to the requirement of strong longitudinal gradient forces. To enable longitudinally extended trapping landscapes, the original version of an optical trapping scheme [16], namely, a counter-propagating trapping configuration consisting of two on-axis counter-propagating beams can be applied. In this case, confinement of particles is realized by the balance of counter-acting dominant scattering forces of the two light fields. As the two beams are typically only weakly focused (numerical aperture NA ≪ 0.7) into the sample solution, gradient forces play a minor role in this case. Although this configuration could allow for extended trapping potentials, its further development is not yet as advanced as that of the single beam gradient trap—especially considering the advancement by structured light. Till now mainly scalar light fields have been implemented, for instance, Bessel or Laguerre–Gaussian beams for creating an optical conveyor belt or the customized transfer of OAM in extended potentials [41–44]. Hence, there is still huge unexploited potential not only considering the implementation of more sophisticated scalar structures, but also of (3D) polarization structures or even fully-structured light landscapes for tailored, extended counter-propagating trapping landscapes.

We present an easy-to-implement, affordable approach to tailor 3D fully-structured trapping potentials in a counter-propagating configuration, sculpted in its amplitude, phase, and 3D polarization and based on an effect commonly avoided in optical trapping: aberrational effects of light. Our approach does neither require any pre-shaping of the input fields, nor expensive optical components as a spatial light modulator or digital mirror device, while enabling complex trapping landscapes of significant longitudinal extent. By including a simple glass substrate of defined thickness \( d \) and refractive index \( n_{\text{glass}} \), mismatching with the surrounding medium \( n_1 \), within each of the weakly focused counter-propagating light fields, we 3D modulate the trapping beams by spherical aberration controllable by \( d \) as well as the refractive indices. By combining partially coherently on-axis counter-propagating beams, we generate a trapping light field \( \vec{E}(x,y,z) = [E_x(x,y,z), E_y(x,y,z), E_z(x,y,z)]^T \) modulated in its intensity, phase as well as 3D polarization in 3D space. We numerically analyze these 3D structured fields, highlighting its adaptability and broad longitudinal extent. In experiment, we first enable the visualization and analysis of aberration effects by the means of optical guiding of micro-particles (1 µm-polystyrene-beads) in solution. Thereby, we analyze the realized light structure by particle velocimetry as well as its scattered light. Subsequently, we demonstrate 3D assemblies of particles trapped in different stable, distant positions of the created potential and analyze its relation to the intensity and Poynting vector distributions.

### 2. Spherical aberration by a glass substrate

For shaping the counter-propagating trapping beams by aberration, we apply a simple common component existing in optical trapping systems: a glass substrate. By focusing light through this kind of substrate, applying an objective focusing faultlessly in air, aberrations will occur [45, 46]. This effect is illustrated in figure 1(a). Due to the refractive index mismatch of the surrounding medium of index \( n_1 \) and the substrate of thickness \( d \) and refractive index \( n_2 \), focused rays of light passing the substrate are refracted such that they do no longer meet in a joint focal point. Even for a non-structured plane wave input, this results in a structured focal field different from the ideal Airy disk. The structuring of intensity, e.g. on the optical axis, is caused by constructive as well as destructive interference of rays, dependent on different propagation paths of meeting rays (among them, the on-axis ray and outer rays) and respective phase differences. Following the description in [45], the effect of the substrate on the focal field distribution can be described by the phase function \( \phi_{ab} \) at the back aperture of the focusing microscope objective (MO; numerical aperture NA = \( \sin\alpha_{0,\text{max}} \) and focal distance \( f \), both in \( n_1 \)-medium). This function is given by [45]

\[
\phi_{ab}(r) = \frac{\pi d}{\lambda} (1 - n_1) \cdot \left[ r_0^2 \cdot (1 - n_r) - r_0^4 \cdot \frac{3}{4} (1 - n_r^2)^2 \right],
\]

with radial coordinate \( r \), wavelength \( \lambda \), relative refractive index \( n_r = n_1/n_2 \), tangent \( \theta_0 = \tan(\alpha_0) = r/f \), and focal distance \( f \) (for detailed derivation see [45]). By comparison of this equation to Zernike’s polynomials, one sees that the first term in square brackets corresponds to a focal longitudinal shift (defocusing), while the second represents third-order spherical aberration. The latter is responsible for spatial variations in the focal light field distribution. Obviously, for fixed NA and \( n_1 \), the aberrations and, thus, the resulting focal field can be controlled by the properties of the glass plate \( d \) and \( n_2 \).

To numerically determine the focal field distribution \( \vec{E} = [E_x, E_y, E_z]^T \), we apply a fast Fourier transform (FFT) based approach [47] (details available in cited reference) to solve Richards and Wolfs diffraction integrals [48] with \( \vec{E}_{in} = \hat{\vec{e}} \cdot \exp(i\phi_{ab}) \) as input light field at the back aperture of the focusing objective, simulating focusing a plane wave through a glass substrate. The polarization of the paraxial input field is given by \( \hat{\vec{e}} = [e_x, e_y]^T \) (Jones vector; linear polarization basis). As an example, matching out later experimental
settings, we assume focusing a plane wave by a MO of NA = 0.7, positioned in air (n_{air} = 1), through a glass substrate of d = 2 mm and n_{glass} = 1.534, into a probe solution of refractive index n_{sol} = 1.34. For simplicity, we approximate n_1 as the mean of n_{sol} and n_{air}, i.e. n_1 = 1.167 and n_r = 0.7608. The chosen NA of 0.7 creates focal fields at the border between paraxial and non-paraxial light: It is known that, for a larger NA, the resulting focal field is clearly non-paraxial including significant electric field contributions in z-, i.e. propagation direction. These longitudinal contributions are formed by radial polarization components of the input field, which are tilted in propagation direction when being focused (see orange polarization arrows in figure 1(a)). Further, with increasing NA the longitudinal extend of the focal spot is decreasing (for Gaussian/plane wave input). For the intended counter-propagating configuration, longitudinally extended fields are desirable to provide an extended trapping landscape. By the choice of NA = 0.7, considerably extended focal light structures are still enabled while simultaneously providing longitudinal in addition to transverse polarization components, offering an additional degree of freedom for customized fields.

In figures 1(b)–(d) we present the numerical results for (b, d) horizontal linear (\vec{e} = [1, 0]) and (c) vertical linear (\vec{e} = [0, 1]) input polarization. The intensity contributions I_j = |E_j|^2 per polarization component j = \{x, y, z \} with the corresponding phase \phi_j \in [0, 2\pi], as well as the total intensity I \in [0, 1] and polarization ellipticity \varepsilon \in [-1, 1] (calculation see section 3.2) are shown in the transverse (x, y)- or longitudinal (x, z)-plane for z = z_{max} (longitudinal position of maximal intensity) or y = 0 (see white dashed line in (b), I), respectively.

In the transverse plane (b), (c), as expected for focusing these uniformly polarized fields, the strongest focal field contributions I_j is of the same polarization as the input field, i.e. (b) x- (horizontal linear) or (c) y- (vertical linear) polarized. The transverse intensity is distributed circular symmetrically. In contrast, orthogonal (b) y- or (c) x-components are negligible. Since radially polarized input field components are tilted...
when being focused, longitudinal $z$-components are formed at the (b) $y = 0$ or (c) $x = 0$ axis, reflecting the orientation of the respective input polarization. Matching respective distributions, $\phi_y$ shows areas of discrete phase values, whereby neighboring areas have a $\pi$-phase difference. Due to a difference in Gouy phase shift [49], longitudinal components are shifted by $\pi/2$ in comparison to transverse ones. As $I = \sum I_j$, the total intensity distribution $I$ is of slightly elliptical shape due to non-negligible longitudinal field contributions. This contribution also affects the polarization ellipticity $\varepsilon$ within this transverse plane: states of polarization are linear ($\varepsilon = 0$) along the (b) $x = 0$ or (c) $y = 0$ axis. For (b) $y = 0$ or (c) $x = 0$, thus, at the positions where $E_z$ contributes significantly, the ellipticity varies between $-1$ (left-circular polarization) and $+1$ (right-circular polarization).

In propagation direction, exemplarily illustrated by (d) the intensity distributions in the $(x, z)$-plane for the focused $x$-polarized input field, the expected behavior due to spherical aberration can be observed. Namely, the total intensity $I$ as well as its contributions $I_{1,2}$ oscillate in its magnitude upon propagation in $+z$-direction. This behavior is highlighted by the white curve within $I$, depicting the evolution of the on-axis total intensity. Reflecting the transverse distributions in (b), $I_z$ represents the strongest contribution the the focal field intensity and also $I_x$ contributes significantly, whereas $I_y$ is negligible. Due to the thick glass plate and the respective refractive index mismatch, strong aberrational effects are created, that enable shaping a significantly elongated focal field. Considering the on-axis total intensity (white curve), the local minimum on the very right still represents approximately 62% of the maximum intensity (first maximum). Note that, since the total intensity of the input field is distributed to several local intensity spots, the maximum intensity of this field is lower than for an non-aberrated focus. Within the structured light field, the transverse shapes of $I$ and $I_{1,2}$ do not change significantly, e.g. $I_z$ keeps its petals-appearance upon propagation. In total, taking advantage of these induced spherical aberrations, we create an extended focal light field sculpted in 3D space.

3. Shaping extended, fully-structured trapping potentials

In order to implement the above presented beam shaping approach to sculpt a 3D fully-structured trapping potential, we realize a counter-propagating trapping scheme of two light fields, both structured by aberration as presented above and superimposed with a distance of $\Delta z$ between their intensity maxima. In this scheme, the dominant scattering forces of an elongated 3D structured beam, such as the one tailored by aberration, will be compensated by a second beam of similar scattering force, counter-propagating on-axis, such that particle trapping is enabled within an equilibrium of optical forces. Thereby, we are able to fully exploit of the longitudinally extended volume of each beam for shaping a likewise extended trapping potential. Further, the counter-propagating scheme facilitates to advance from a mainly intensity structured light field (figure 1) to an extended fully-structured field, customized in its intensity (amplitude), phase, as well as 3D polarization. For this purpose, both beams are shaped by focusing a linearly polarized input field through the glass substrate into a probe solution (parameters as in section 2), applying an objective with NA = 0.7 to realize fields close to the non-paraxial regime. Thereby one beam (beam 1) is of horizontal linear input polarization (see figures 1(b) and (d)), propagating in $+z$-direction, while the second beam (beam 2) is of vertical linear input polarization (see figure 1(c)), propagating in $-z$-direction. We superimpose the respective focal fields such that the distance between their total intensity maxima is given by $\Delta z = 60.5 \mu m$. Since the input fields for beam 1 and 2 are of orthogonal polarization, the corresponding focal light fields are superimposed in a partially coherent way: the focal fields are mainly polarized orthogonally to each other, following their respective input fields, however both also include longitudinal $z$-polarization components, making the superposition partially coherent (see figures 1(b) and (c)). This partially coherent superposition represents the key for the realization of a 3D fully-structured light field $E(x, y, z) = E_{1, 2}(x, y, z)$, $E_j = E_{j, 0} e^{i \phi_j}, j = \{x, y, z\}$, as we will prove in the following.

3.1. Partially coherent superposition for customized intensity

First, we investigate the intensity and phase distribution of the partially coherent, counter-propagating superposition of beam 1 and beam 2. The respective normalized (total) intensity $I_{1,2}$ of both beams (beams 1, 2) as well as of their superposition $I$ in the $(y, z)$-plane is illustrated in figure 2(a) with the evolution of the on-axis intensity depicted by white curves. These distributions finally define the scattering and gradient forces within the shaped trapping potential (see section 4). The intensity distributions $I_1$ and $I_2$ show the oscillatory behavior as discussed in section 2, with mirror symmetric curve evolution. Consider that, since significant $z$-polarization contributions of beam 2 are found along the $y$-axis (see figure 1(c)), whereas beam 1 does not have $z$-polarization contributions along this axis (see figure 1(b)), the $(y, z)$-distribution of $I_1$ and the mirror image of $I_2$ slightly differ from one another. The partially coherent superposition of 3D structured beam 1 and beam 2 gives a likewise 3D structured, extended intensity landscape, as visible in figure 2(a). $I$. This spatial variation in total intensity in connected to a spatial change in its electric field contributions $E_j = E_{j, 0} e^{i \phi_j}, j = \{x, y, z\}$, as illustrated in (b).

Figure 2(b) shows the transverse intensity (contributions) $I \in [0, 1]$ ($I_j = |E_j|^2 \in [0, 1]$) and phase $\phi_j \in [0, 2\pi)$ distributions in chosen $z$-slices of the superposition. The intensity images are normalized to the superposition’s maximum intensity. The slice positions $z_0, u = \{1, 13\} \in \mathbb{N}$, are marked by white dashed lines in (a), $I$; the black line indicates the size of the $(x, y)$-section studied in (b). The total intensity $I$ reveals slight variations in its transverse shape for different $z$-distances, including some elliptical deformation. This variation is due to the variation of its contributions, particularly $E_z$. The intensity contribution $I_z$ of the superposition represents the $x$-(y-)polarized contribution of beam 1 (beam
Figure 2. Superposition of counter-propagating aberrated light fields. (a) Longitudinal intensity distribution of beam 1 ($I_1 \in [0, 1]$, $+z$-propagation), beam 2 ($I_2 \in [0, 1]$, $-z$-propagation), and their superposition ($I \in [0, 1]$) in the $(y,z)$-plane, each normalized according to their own intensity maximum. White graphs illustrate the on-axis intensity profile. Beam 1 and beam 2 are superimposed with a longitudinal distance $\Delta z = z_{12} - z_2 = 60.5 \mu m$ of their intensity maxima. White dashed lines at $z = z_u, u = [1, 13]$, and black line in $I$ indicate position and size, respectively, of transverse planes presented in (b). (b) Transverse total intensity $I \in [0, 1]$, intensity contributions $I_j = |E_j|^2 \in [0, 1]$, and respective phase distributions $\phi_j \in [0, 2\pi], j = \{x, y, z\}$, of total field $\vec{E} = [E_x, E_y, E_z]$, in different $z_u$-planes.

2), since beam 2 (beam 1) does not contain contributing $x$-polarized components. Similar to its discrete phase distribution at $z_{\text{max}} = z_2$ or $z_{12}$, discussed by figure 1(b) or (c), respectively, also for other $z_u$ the phase $\phi_{x, z}$ in figure 2(b) shows the ring-shaped discrete distribution. Dependent on the $z$-position, propagation gives an additional phase factor to $\phi_x$ and $\phi_y$. Due to the opposed propagation direction of beam 1 and beam 2, the relative phase between these beams changes with $z$.

Most striking changes with $z$-position can be observed for $E_z$ of the counter-propagating superposition, since $z$-polarized contributions appear in orthogonal directions, i.e. along the $y$- or $x$-axis, for beam 1 or beam 2, respectively. Additionally, due to aberrations, the magnitude of the beams’ contributions vary upon propagation in $\pm z$-direction and the relative phase varies. As a consequence, the transverse intensity distribution $I_z$ of the superposition shows not only changes in maximum intensity, but also in shape. A clear variation between (smeared) diagonal ($z_{(1,6)}$,$z_{(7,13)}$) or (smeared) antidiagonal ($z_{(2,10)}$,$z_{(4,12)}$) petal-structures, and ring-shaped distributions ($z_{(3,5,9,11)}$) is observed. Interestingly, clear petal structures correspond to discrete phase $\phi_z$ distributions ($z_{(3,4,10)}$) with $\pi$ phase jumps between neighboring regions. For a clear ring structure, $\phi_z$ reveals a central continuous phase vortex with on-axis phase singularity of topological charge $\ell =+1$ ($z_{(3,11)}$) or $\ell =-1$ ($z_{(5,9)}$)—the topological charge represents the counter-clockwise change of phase around the central point divided by $2\pi$ [2, 3]. Outer rings show a similar continuous phase variation with a $\pi$ phase shift to the neighboring rings. At $z$-positions between clear petals and clear ring-structures
(smeared petal structures), the corresponding phase distribution shows the transition between the discrete and vortex phase distribution. This obvious variation of the transverse appearance of the \( z \)-polarized contribution \((I_\text{z}, \phi_\text{z})\) is mainly responsible for the change in the transverse distribution of the total intensity of the superposition.

In figure 2, we considered a distance of \( \Delta z = 60.5 \mu m \) between the maximum of beam 1 and beam 2. Due to the electric field contributions of each beam and their phase relation, the presented 3D structured intensity landscape of the superposition is formed. We can easily adapt this 3D landscape by changing the distance between superimposed beams, since this change varies the relation between interfering electric field components of beam 1 and 2, i.e. between respective amplitudes and phases. We exemplify this customization tool for the 3D landscape by graphs in figure 3. Here, the on-axis profile of the total intensity of beams 1 (grey, solid), beam 2 (light grey, dashed), and their superposition (red) is shown for different \( \Delta z \), each normalized to their own maximum. For (a)\textendash}(p) the distance \( \Delta z \) is varied between (a) 57.3 \( \mu m \) and (p) 79.7 \( \mu m \) in 1.4 \( \mu m \) steps. Obviously, the profile of the superposition clearly varies with distance \( \Delta z \). This behavior enables the customization of, e.g. the number of local maxima within the total intensity (see e.g. (a) 4 maxima vs. (p) 6 maxima) or the depth of minima in between of them (see minima in (a) vs. minima in (c)). The latter also affects the strength of longitudinal intensity gradient and, thereby, the strength of gradient forces in optical trapping (see section 4.3). Note that, for weak intensity gradients, the influence of the longitudinal intensity structure on particle trapping positions will be decreased (see section 4.4). Hence, by changing \( \Delta z \), we are able to adapt the 3D intensity landscape of the counter-propagating superposition and, thus, the trapping potential.

### 3.2. 3D polarization states in custom fields

The spatial modulation of contributions \( E_{x,y,z} \) does not only shape the transverse as well as longitudinal intensity landscape of the counter-propagating superposition, but also corresponds to a spatial variation in 3D polarization ellipses. For the example of \( \Delta z = 60.5 \mu m \), in figure 4 the (absolute) ellipticity \(|\varepsilon| \in [0,1]\) \( \varepsilon \in [-1,1] \) of the 3D polarization ellipses in the (a) \((y,z)\)-plane as well as in (b) the chosen transverse plane at \( z_m \) is shown. The (absolute) ellipticity of 3D polarization states is determined by the semi major axis \( p_0 \), minor axis \( q_0 \), and normal vector \( \vec{N} \) of the respective polarization ellipse with [50]:

\[
\vec{p}_0 = [p_{0x}, p_{0y}, p_{0z}]^T = \frac{1}{\sqrt{EE}} \Re \left( \vec{E} \vec{E}^* \right), \tag{2}
\]

\[
\vec{q}_0 = [q_{0x}, q_{0y}, q_{0z}]^T = \frac{1}{\sqrt{EE}} \Im \left( \vec{E} \vec{E}^* \right), \tag{3}
\]

\[
\vec{N} = \Im \left( \vec{E} \times \vec{E}^* \right) = 2\vec{p}_0 \times \vec{q}_0. \tag{4}
\]

The absolute ellipticity \(|\varepsilon| \in [0,1]\) is calculated from the ratio of the length of minor and major axis \(|\vec{q}_0|/|\vec{p}_0|\). The handedness of the polarization state, thus, the sign of the ellipticity \( \varepsilon \) is defined by the normal vector of the ellipse with respect to the plane of oscillation: if \( \vec{N} \) is parallel (anti-parallel) to the normal vector \( \vec{n}_{osc} \) of the oscillation plane...
The graphical representation of spatially varying polarization states emphasizes the found variation of electric field contributions. The 3D ellipses visualize the change in 3D orientation of polarization as well as in ellipticity, resulting from the counter-propagating, partially coherent superposition of aberrated light fields. Consider that, by changing the distance Δz and, thereby, the amplitude and phase relation between beam 1 and beam 2, we could spatially tailor the 3D polarization states, their orientation and ellipticity, as well as the related SAM distribution within the designed trapping potential.

4. Experimental verification and application

In the following, for the example of Δz = 60.5 μm, we experimentally demonstrate the features imparted in each of the two counter-propagating beams, shaped by spherical aberration, by analyzing optically guided micro-particles, and present the capability of the respective counter-propagating trapping potential for optical particle assembly. For this experimental study, we solve 1 μm-particles (polystyrene) in water (n_{sol} = 1.34) and place our sample solution into the square channel of a square glass cuvette (base: 4.25 × 4.25 mm²; n_{glass} = 1.534) with a wall thickness of d = 2 mm, thus, channel width of 250 μm. To create the partially coherent superposition of the two spherically aberrated light fields in the solution, we focus the two on-axis counter-propagating, orthogonally polarized beams (colimitsed, λ = 532 nm, 90 mW power each) by two MOs of NA = 0.7 (100 ×, working distance WD = 6.5 mm, focusing error-free in air), positioned in air (n_{air} = 1), through the glass walls (upright cuvette) into the probe solution (see figure 6(a)). Note that the backapertures of MOs are over-saturated to realize approximately plane waves as input while optimally exploiting the technically provided NA. We observe the sample-light interaction in the (y, z)-plane (beams are propagating along z-axis, y = 0) by an imaging system, set up orthogonal to beam propagation direction (along x-axis) by a MO (100 ×, NA = 0.4), a tube lens (focal distance: 200 mm) and a camera. The sample is illuminated by a blue LED, such that by the inclusion of a spectral filter, scattered laser light can be removed from the camera image.
Figure 5. 3D polarization states in fully-structured light landscape in vicinity of the maximum of (a)–(b) beam 1 or (c)–(d) beam 2. Polarization ellipses (black) are shown on normalized total intensity $I$ (left) or absolute of ellipticity $|\varepsilon|$ (right) in the $(y, z)$-plane at positions where $I$ is at least 7.5% of the maximum intensity. White lines indicate positions of $z_u$ (see previous figures).

Figure 6. Experimental system (a) and velocity (b) of 1 $\mu$m-particles (in water, solution refractive index $n_{\text{sol}} = 1.34$) optically guided by spherically aberrated light field of beam 1 ($\text{NA} = 0.7$, $d = 2\text{ mm}$, $n_2 = 1.534$). Beam propagates in $+z$-direction. Velocity is determined by tracking the positions of six exemplary particles (corresponding to colors of data points) in each camera frame (frame rate: 42 frames s$^{-1}$).

4.1. Particle velocimetry

To validate the desired aberration of the focal fields (beam 1 and beam 2) in the sample solution, we optically guide microparticles by each of the beams separately and analyze the velocity of particles, accelerated longitudinally. Particle velocity is related to the intensity-dependent optical scattering as well as gradient forces of the guiding beam, such that particle velocimetry can be applied to confirm the aberrated intensity structure and demonstrate its optical manipulation features.

First, we block beam 2 and observe particle movement caused by beam 1 ($+z$-propagation direction) by our imaging system (camera frame rate: 42 frames s$^{-1}$; spectral filter included). The beam intensity causes particles to move on-axis, into regions of high intensity (transverse gradient forces due to transverse intensity gradient); here, dominant scattering forces push particles along the beam propagation axis. Velocimetry is performed by tracking the on-axis movement of six exemplary optically guided particles. Respective results are presented in figure 6(b), depicting the particles’ momentary
velocity dependent on its \(z\)-position. The data points of the same color correspond to the same particle. We observe an oscillatory behavior for the velocity with \(z\)-position, which matches the expected intensity structure of aberrated beam 1. In general, the scattering force of beam 1 pushes and, with \(z\)-distance, accelerates the particles in beam propagation direction. The gradient forces corresponding to each of the local longitudinal intensity maxima (see figure 2(a), \(I_1\)) slightly increase or decrease this acceleration in propagation direction due to a positive or negative longitudinal intensity gradient. Note that, as the beam is not focused tightly as in a single-beam gradient trap, scattering forces dominate in the counter-propagating configuration. For higher local intensity maxima, particles can reach higher momentary velocities due to the intensity-dependency of forces. Hence, spatially varying optical forces cause the oscillatory behavior in the speed of particles with a decrease in the local velocity maxima with \(z\)-distance, which reflects and, therefore, confirms the aberrated intensity structure of beam 1. An equivalent particle behavior is found for beam 2, also confirming the aberrated structure for this light field.

Note that the particle velocimetry can be applied to identify the position of maximum intensity per beam and, hence, to adjust the distance of beam 1 and beam 2 for the desired superposition. Here, we exemplarily realized \(\Delta z = 60.5 \, \mu m\) for our subsequent analyses.

### 4.2. Scattered light analysis of counter-acting beams

To directly visualize the created structure of light within our sample solution we can analyze the laser light scattered from optically manipulated particles. For this purpose, we remove the spectral filter from the imaging system and turn off surrounding light sources including the illuminating LED. Hence, only scattered laser light is observed on the camera if particles interact with beam 1, beam 2 or their superposition \((y, z)-\text{plane}\).

Investigating the light field distribution of each beam individually, we block beam 1 or 2 and observe light scattered from one to two particles optically guided through the camera image by beam 2 or 1, respectively. By performing a maximum intensity projection (via ImageJ), with each of its pixels containing the maximum value over all camera frames in the video (grey scale) at the particular pixel location, a representative image of the beam’s intensity distribution along the particles’ propagation trajectory is created. Results are presented in figure 7(a). Note that we decreased the camera’s field of view to a minimal area of interest to increase the frame rate for better resolved representative intensity images (longitudinally). Further, we adjusted the propagation axis of beam 1 and 2 to be parallel but with a slight transverse \(y\)-distance, such that intensity representations of beam 1 and 2 can be visualized in a joint image without superimposing them.

The top image in figure 7(a) reveals the expected oscillatory intensity distribution per beam, confirming the aberrated field structures. Emphasizing this result, the graph below presents the scattered light intensity \(I_{\text{scat}}\) (normalized for each beam along the observed particles propagation trajectory (solid/dashed line: beam 1/beam 2). Results clearly show the longitudinally extended, structured intensity distribution of the on-demand aberrated beams, matching the numerical calculations presented in (b) (normalized intensities \(I_1, I_2\)) and confirming the set distance \(\Delta z = 60.5 \, \mu m\) between the absolute maxima.

### 4.3. Optical particle assembly

Beam 1 and 2 both being confirmed experimentally, next, we combine them to the on-axis, counter-propagating superposition (numerics of \((y, z)\)-intensity \(I\) in figure 7(c)) as fully-structured trapping potential in our sample solution. First, by scattered light analysis, we identify the most probable particle position within the intensity landscape. Analyzing multiple particles, the position is found to be in the middle of superimposed beams, as visualized by the bright area in figure 7(d), top row. This observation matches the expectations for a counter-propagating optical trap. However, additional stable trapping positions can be found within the tailored 3D structured trapping potential. These positions are identified by imaging the particles while excluding the scattered light (include spectral filter; turn on LED illumination). Here, particles are found as dark spots in camera images. Thus, to visualize stable positions, we perform a minimum intensity projection (ImageJ) of multiple video sections showing stably trapped particles at various positions. The resulting image is shown in (d), bottom row, with each pixel containing the minimum value over all camera frames in the video sections at the particular pixel location. Note that, by including the spectral filter in the imaging system, the observation on the camera is slightly shifted transversely. In our presentation in (d), this movement is considered by shifting the illustration in relation to the other experimental results (white box and dashed grey line).

The minimum intensity projection in (d), bottom row, clearly shows multiple stable trapping positions with considerable distance to each other along the \(z\)-axis within the tailored trapping potential (dark spots). Obviously, the 3D extended fully-structured trapping potential, formed by counter-propagation of focal aberrated light fields, enables the 3D assembly of particles in like-wise extended structures. Particles are accumulated on-axis due to the transverse intensity gradient, thus, transverse gradient forces of the extended 3D structured light field (see figure 7(c)). The longitudinal distribution of multiple stable trapping spots can be considered a result of counter-acting, spatially varying longitudinal forces of beam 1 and 2 and optical binding [43, 51, 52] (see next section). The effect of dominant scattering forces is sketched by arrows in figure 7(c). Empty/filled arrows correspond to forces of beam 1/beam 2 acting in \(+z/-z\)-direction with the arrow size representing its relative strength and the arrows’ starting point being the exerting point. Considering these and, additionally, some longitudinal gradient force per intensity maxima of the total intensity structure (see white curve in (c)), stable trapping positions are formed as presented in figure 7(d).
Figure 7. Visualization and application of fully-structured trapping potential ((y, z)-plane illustrations). (a) Top: illustration of light scattered from particles, guided by beam 1 (top) or beam 2 (bottom). Background illumination is turned off, such that scattered light originates from the interaction of particles with aberrated beams 1 or 2, depicting the beams’ intensity distribution. Bottom: graph shows intensity profiles of scattered light $I_{\text{scat}}$ (solid or dashed line: beams 1 or 2). (b) Longitudinal intensity distributions $I_{1,2}$ and its on-axis profile (white curve) for comparison. (c) Top: total intensity distribution $I$ (white curve: on-axis intensity profile) with arrows depicting counteracting scattering forces of beam 1 (non-filled arrows) and 2 (filled arrows) at different positions. Arrow size indicates its strength. Bottom: absolute of Poynting vector $\vec{P}$ (x, y, z)-plane (in addition to (y, z)-plane; transverse dimension: black bar in $I$). (d) Trapping of 1 $\mu$m-particles. Top: scattered light analysis showing most probable central trapping position. Bottom: different stable trapping positions revealed by superposition of multiple camera images of stably trapped particles (black; background illumination turned on). Inclusion of wavelength filter (filtering green trapping light) causes camera image to shift (see grey dashed lined).

This observation is confirmed by calculated Poynting vectors $\vec{P}(x, y, z) = [P_x, P_y, P_z]^{T}(x, y, z)$ in the 3D volume, describing the energy current/flow of light. We determine the time-averaged Poynting vector distribution according to [53]

$$\vec{\bar{P}} \propto \Re \left[ \vec{E}^* \times \vec{H} \right] \propto \Im \left[ (\vec{E}^* \cdot \nabla)\vec{E} \right] + \frac{1}{2} \nabla \times \Im (\vec{E}^* \times \vec{E}), \quad (5)$$

with $\vec{H}$ as magnetic field and $\nabla = [\partial/\partial x, \partial/\partial y, \partial/\partial z]^T$. The absolute of Poynting vectors $P = |\vec{P}|$ in the (x, z)- and (y, z)-plane, representing the strength of energy current, is presented in figure 7(c) (bottom). The chosen transverse dimension is indicated by black bar in $I$ (figure 7(c), top). Overall the energy current matches the above described interaction of beam 1 and 2. Due to differences in focal distributions of beam 1 and 2, with beam 1 (beam 2) dominating in (x, z)-plane ((y, z)-plane) (see figures 1(b)–(d)), we can observe a mirror symmetry between the $P$ distributions in (x, z)- and (y, z)-plane. The absolute energy current shows valleys for stable trapping positions, matching the equilibrium positions of optical forces.

In figure 8, calculated Poynting vectors are presented in more detail in comparison to (a) the stable trapping positions. In addition to the absolute of the Poynting vector $P$, in (b), the $x$-, $y$-, and $z$-contributions $P_{x,y,z}$ are shown in longitudinal $(x, z)$-plane (top) and $(y, z)$-plane (bottom) each. In (c), the selected transverse $(x, y)$ distributions for $P_{x,y,z}$ at $z = z_u$ are depicted; respective $z$-positions are marked by dashed white lines in (b). $P_{x,y,z}$ are normalized to their overall maximum. For $P_z$...
**Figure 8.** Poynting vector $\vec{P} = [P_x, P_y, P_z]^T$ ($P = |\vec{P}|$) distribution of counter-propagating superposition of beam 1 and beam 2, affecting (a) stable trapping positions (see figure 7). (b) Longitudinal distribution in $(x,z)$- and $(y,z)$-plane and (c) transverse distributions at selected $z = z_u$, $u \in [1, 13]$ positions (see figure 2), marked by white dashed lines in (b).

| $P_x$ | $P_y$ | $P_z$ |
|-------|-------|-------|
| $z_1$ |        |       |
| $z_2$ |        |       |
| $z_3$ |        |       |
| $z_4$ |        |       |
| $z_5$ |        |       |
| $z_6$ |        |       |
| $z_7$ |        |       |
| $z_8$ |        |       |
| $z_9$ |        |       |
| $z_{10}$ |       |       |
| $z_{11}$ |      |       |
| $z_{12}$ |     |       |
| $z_{13}$ |    |       |

we clearly observe the longitudinally counter-acting nature of energy flow, reflecting the counter-acting scattering forces of beam 1 and beam 2. Also in this case we see the dominance of beam 1 (beam 2) in the $(x,z)$-plane ($(y,z)$-plane), revealing a positive (negative) energy flow contribution in $z$-direction. Additionally, vector components $P_x$ and $P_y$ reveal no contribution on the propagation axis, but show contributions pointing azimuthally around the propagation axis at some locations in the $(y,z)$- and $(x,z)$-plane, respectively. The absence of on-axis contributions confirms the stable, on-axis trapping positions at the equilibrium of optical forces. The azimuthal components result in an orbital flow around the optical axis for the total transverse energy flow, as indicated by black arrows with white heads in exemplary planes of (c). This behavior is connected to the change in phase of the tailored light structure, visualized in figure 2(b).

$P_x$ and $P_y$ do not always contribute equally to the orbital flow for different $z$-positions. Approximately equal contribution is given for $z_{3,5,9,11}$, with right-handed (left-handed) energy flow for $z_{3,11}(5,9)$. This matches the found phase vortices and their handedness identified for the $z$-polarized electric field contribution of the trapping light field (figure 2(b), $\phi_z$). For unequal contributions of $P_x$ and $P_y$ (e.g. $z_{1,13}$), the $\phi_z$ still shows a vortex-like configuration but with azimuthally non-linear increase. This observation manifests in an orbital Poynting flow with higher strength in $x$- ($z_{1,3}$) or $y$-direction ($z_{1}$). For discrete $\phi_z$ structure, no significant transverse Poynting vector contribution is found ($z_{4,7,10}$). Note that due to the particle size in relation to trapping field and its spherical shape, we do not observe an effect of orbiting transverse Poynting vector flow on the particles. We see particles being trapped, centered on-axis, where the transverse flow is zero, and arranged according to the 3D valleys of Poynting vectors $\vec{P}(x,y,z)$.  

### 4.4. Optical binding

In the center between beam 1 and 2, an elongated stable trapping region is shaped in an extended weak intensity and Poynting vector valley. Here, forces act similar to a standard counter-propagating trap with a positive distance between the intensity maxima of counter-propagating Gaussian beams. This light field distribution does not only allow optical trapping of single objects in its center, but also enables the formation of elongated longitudinal particle chains due to optical binding between trapped objects. Note that optical binding might also affect other stable trapping positions, however, in the case at hand, the spatially varying forces of counter-propagating, aberrated beams are considered being dominant. Only for significantly larger $\Delta z$ (around $\Delta z > 100\mu m$), the spatial variation/gradient in intensity and, thus, dominating forces might decrease in an extended area between superimposed beam (only weaker local minima). In this case, the increasing importance of optical binding can be observed, as exemplified in supplementary video 1 (available online at stacks.iop.org/JOPT/23/064002/mmedia). In this video, we observe $1\mu m$-particles trapped within a customized trapping
landscape for \( \Delta z = 131.3 \, \mu \text{m} \). Particles are arranged in stable trapping positions, however, these positions are significantly influenced by optical binding: if a new particle enters the assembly, its entrance changes the trapping position of the neighboring, but distant particle, initiating a chain reaction to the other particles. The seemingly repulsive behavior is due to light being focused behind each particle, affecting its neighbors, namely, optical binding.

5. Conclusion

We proposed an easy-to-implement, affordable approach to include the till now unexploited potential of fully-structured light in counter-propagating optical trapping. Our approach does neither require any pre-shaping of the input fields, nor expensive optical components as a spatial light modulator or digital mirror device. We took advantage of the typically undesired effect of aberrations in order to shape adaptable 3D extended, fully-structured trapping landscapes in a counter-propagating configuration by the simple means of glass plates. We analyzed its 3D intensity structure, its adaptability as well as its spatially varying transverse as well as longitudinal field contributions. The respective 3D polarization ellipses are structured in their orientation as well as ellipticity in 3D space, corresponding to a spatial variation of spin angular momentum. We experimentally confirm the extended, aberrated structure of counter-propagating beams by means of particle velocimetry and scattered light analysis of optically guided micro-particle and prove our light fields’ benefit for assembling particles in 3D space. Due to its additionally embedded 3D polarization structure, our approach for adaptable extended trapping landscapes will be of specific interest for next-generation confinement and arrangement of polarization-sensitive micro- and nano-objects.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors acknowledge partial support by the German Research Foundation (DFG), under Project No. DE-486/23-1, as well as by the European Union (EU) Horizon 2020 program, in the framework of the European Training Network ColOpt ITN 721465. Further, the authors acknowledge experimental support by Dr. Mike Woerdemann, University of Muenster, Germany.

ORCID iDs

Eileen Otte https://orcid.org/0000-0002-3109-5837
Cornelia Denz https://orcid.org/0000-0002-7292-2499

References

[1] Rubinsztein-Dunlop H et al 2017 J. Opt. 19 013001
[2] Dennis M R, O’Holleran K and Padgett M J 2009 chap 5 Singular Optics: Optical Vortices and Polarization Singularities Progress in Optics vol 53 (Amsterdam: Elsevier) pp 293–363
[3] Soksm M S and Vanaetsov M V 2001 chap 4 Singular Optics Progress in Optics vol 42 (Amsterdam: Elsevier) pp 219–77
[4] Nivas J et al 2017 Sci. Rep. 7 42142
[5] Rahimian M G, Bouchard F, Al-Khazraji H, Karimi E, Corkum P B and Bhardwaj V R 2017 APL Photonics 2 086104
[6] Mair A, Vaziri A, Weihs G and Zellinger A 2001 Nature 412 313
[7] Mirhosseini M, Magaña-Loaiza O S, O’Sullivan M N, Rodenburg B, Malik M, Lavery M P, Padgett M J, Gauthier D J and Boyd R W 2015 New J. Phys. 17 033033
[8] Gibson G, Courtial J, Padgett M, Vanaetsov M, Pas’ko V, Barnett S and Franke-Arnold S 2004 Opt. Express 12 5448–56
[9] Otte E, Nape I, Rosales-Guzmán C, Denz C, Forbes A and Ndagano B 2020 JOSA B 37 A309–23
[10] Ndagano B et al 2017 Nat. Phys. 13 397–402
[11] Nape I, Otte E, Vallés A, Rosales-Guzmán C, Cardano F, Denz C and Forbes A 2018 Opt. Express 26 26946–60
[12] Hell S W and Wichmann J 1994 Opt. Lett. 19 780–2
[13] Santi P A 2011 Nature 419 145
[14] Voic A H, Burns D and Spelman F 1993 J. Microsc. 170 229–36
[15] Otte E and Denz C 2020 Appl. Phys. Rev. 7 041308
[16] Ashkin A 1970 Phys. Rev. Lett. 24 156
[17] Sato S, Ishigure M and Inaba H 1991 Electron. Lett. 27 1831–2
[18] Jesacher A, Fürhapter S, Bernet S and Ritsch-Marte M 2004 Opt. Express 12 4129–35
[19] Alpmann C, Schöler C and Denz C 2015 Appl. Phys. Lett. 106 241102
[20] Alpmann C, Bowman R, Woerdemann M, Padgett M and Denz C 2010 Opt. Express 18 26084–91
[21] García-Chávez V, McGloin D, Melville H, Sibbett W and Dholakia K 2002 Nature 419 145
[22] Ruffner D B and Grier D G 2012 Phys. Rev. Lett. 109 163903
[23] Baumgartl J, Mazilu M and Dholakia K 2008 Nat. Photon. 2 675
[24] He H, Friese M E J, Heckenberg N R and Rubinsztein-Dunlop H 1995 Phys. Rev. Lett. 75 826–9
[25] Friese M, Enger J, Rubinsztein-Dunlop H and Heckenberg N 1996 Phys. Rev. A 54 1593–6
[26] Friese M, Nieminen T, Heckenberg N and Rubinsztein-Dunlop H 1998 Nature 394 348–50
[27] Alpmann C, Schlickriede C, Otte E and Denz C 2017 Sci. Rep. 7 8076
[28] Otte E, Alpmann C and Denz C 2016 J. Opt. 18 074012
[29] Marrucci L, Manzo C and Paparo D 2006 Phys. Rev. Lett. 96 163905
[30] Piccirillo B, D’Ambrosio V, Slussarenko S, Marrucci L and Santamato E 2010 Appl. Phys. Lett. 97 241104
[31] Desiatov B, Mazurski N, Fainman Y and Levy U 2015 Opt. Express 23 22611–18
[32] Gibson C J, Bevington P, Oppo G L and Yao A M 2018 Phys. Rev. A 97 033832
[33] Otte E, Tekke K and Denz C 2018 J. Opt. 20 105066
[34] Bhebhe N, Williams P A, Rosales-Guzmán C, Rodriguez-Fajardo V and Forbes A 2018 Sci. Rep. 8 1–9
[35] Nieminen T A, Heckenberg N R and Rubinsztein-Dunlop H 2008 Opt. Lett. 33 122–4
[36] Skelton S, Sergides M, Saia R, Iati M, Maragó O and Jones P 2013 Opt. Lett. 38 28–30
[37] Dorn R, Quabis S and Leuchs G 2003 Phys. Rev. Lett. 91 233901
[38] Quabis S, Dorn R, Eberler M, Glöckl O and Leuchs G 2000 Opt. Commun. 179 1–7
[39] Otte E, Tekce K and Denz C 2017 Opt. Express 25 20194–201
[40] Bauer T, Banzer P, Karimi E, Orlov S, Rubano A, Marrucci L, Santamato E, Boyd R W and Leuchs G 2015 Science 347 964–6
[41] Čižmár T, Garcés-Chávez V, Dholakia K and Zemánek P 2005 Appl. Phys. Lett. 86 174101
[42] Carruthers A E, Walker J S, Casey A, Orr-Ewing A J and Reid J P 2012 Phys. Chem. Chem. Phys. 14 6741–8
[43] Čižmár T, Romero L D, Dholakia K and Andrews D 2010 J. Phys. B: At. Mol. Opt. Phys. 43 102001
[44] Donato M G, Brzobohatý O, Simpson S H, Ireresa A, Leonardi A A, Lo Faro M J, Sváček V, Maragó O M and Zemánek P 2018 Nano Lett. 19 342–52
[45] Iwaniuk D, Rastogi P and Hack E 2011 Opt. Express 19 19407–14
[46] Vijayakumar A and Bhattacharya S 2013 Appl. Opt. 52 5932–40
[47] Boruah B and Neil M 2009 Opt. Commun. 282 4660–7
[48] Richards B and Wolf E 1959 Electromagnetic diffraction in optical systems. II. Structure of the image field in an aplanatic system Proc. R. Soc. A 253 358–79
[49] Pang X, Visser T and Wolf E 2011 Opt. Commun. 284 5517–22
[50] Berry M V 2004 J. Opt. A: Pure Appl. Opt. 6 675
[51] Mohanty S, Mohanty K and Berns M 2008 Opt. Lett. 33 2155–7
[52] Burns M M, Fournier J M and Golovchenko J A 1989 Phys. Rev. Lett. 63 1233
[53] Berry M V 2009 J. Opt. 11 094001