Light Fields Can Tailor the Microscopic World

Holographic shaping of laser light fields opens new perspectives in optical micromanipulation

The manipulation of microscopic particles solely by light has reached a high level of sophistication and versatility. While simple optical tweezers have become a standard technology in many laboratories nowadays, in particular the holographic shaping of laser light fields has dramatically increased potential applications of optical micromanipulation. In this article, we briefly introduce the basic concepts of holographic beam shaping, and show a selection of cutting-edge applications in the field of optical micromanipulation.

The optical manipulation of microscopic particles has a long and prosperous history. With the simplest and perhaps most elegant implementation, known as optical tweezers, it has found its way into many laboratories around the world [1]. Since Arthur Ashkin's early work on the basic concepts of optical micromanipulation about 40 years ago, optical tweezers have developed to a standard technique where smallest forces are applied to microscopic particles or measured with highest precision [2]. Especially interdisciplinary applications in the fields of biophysics and biomedicine benefit from this development, which revolutionized the investigation of single cells and living organisms. Optical tweezers, however, are usually limited to the simultaneous manipulation of one single particle at a time. The dynamic movement and positioning of multiple particles is facilitated by specific technical extensions. Besides the obvious approach of using several optical tweezers, time-sharing single optical tweezers with, for example, acousto-optic deflectors is a practicable way for more advanced applications in optical micromanipulation [3].

The highest degree of versatility in optical micromanipulation, however, can be achieved by holographic shaping of a laser light field [4,5]. It is well known from the classical theory of optical holography that any arbitrarily shaped light field can be recorded in and restored from a suitable holographic medium. In the following we will discuss recent concepts that enable shaping of an incident light field by means of computer-generated holograms which are displayed on liquid crystal spatial light modulators (SLMs). When the boundaries imposed by the fundamental Maxwell equations are respected, highly complex light distributions can be created in the manipulation plane in the vicinity of a microscope objective's focal plane. These field distributions can resemble a number of discrete focused beams – and thus discrete optical tweezers – which can be steered at will through the microscopic sample [5]. As a complementary approach, continuous, three-dimensional energy potential landscapes can be created by the light field, which can be tailored in a versatile way to a specific application [6].

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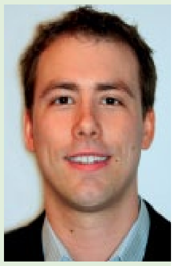

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Holographic optical tweezers

Diffraction gratings are well known to deflect light into diffraction orders, i.e. by certain angles which can be tuned by the grating parameters. For example, a so-called blazed grating deflects mpst light into exactly one diffraction order and hence can re-position an optical tweezers in the focal plane, depending on the grating periodicity. The blazed grating can be considered as a particularly simple kind of hologram. Displayed on a computer-controlled SLM, the grating can be updated following the user input and thus an optical tweezers can be moved dynamically. A superposition of multiple, differently prepared blazed gratings can deflect parts of the incident light into many diffraction orders at the same time and hence create multiple optical tweezers which are not time-shared but actually exist simultaneously. The blazed gratings can be complemented with diffractive Fresnel lenses which shift the focal spots and the respective optical tweezers along the optical axis. With this gratings and lenses approach [7], basic holograms can be designed that allow creating a multitude of optical tweezers in parallel which can be freely positioned in the sample volume. This is the concept of holographic optical tweezers. The computational efforts are reasonable and even standard hardware nowadays is sufficient to compute holograms in real-time. Figure 1 gives an impression of the capabilities of holographic optical tweezers. All the individual tweezers can be controlled independently and interactively and make advanced applications possible, including the simultaneous control of many particles, the defined handling and alignment of non-spherical particles, or driving of lab-on-chip devices [8,9,10]. The top left image stack in Figure 2 provides a few examples of holograms calculated with the gratings and lenses approach.

Advanced holographic beam shaping

The hologram design described so far has the virtue of being computationally efficient. Moreover, it exhibits the optical principles behind a complex hologram as this can be decomposed into the constituting elementary gratings. However, holograms obtained by the gratings and lenses approach in general are not optimal and can suffer from inhomogeneous intensity distributions of the optical tweezers. Furthermore, additional unwanted equilibrium positions at symmetry dependent locations can occur, known as ghost traps [11]. The most flexible and from the computational viewpoint most expensive way to improve the quality of the holograms and hence the generated optical tweezers is an iterative approach [12]. As the propagation of any light field is governed by the well-known wave equations, the light field resulting from a hologram under test can be estimated numerically. In the common case that only the light distribution in the vicinity of a focal plane is of interest, the propagation can be described directly by Fourier transformations [13]. The key towards an optimal hologram, starting from a given hologram or a random distribution, is the iterative numerical propagation of the light field from the hologram plane to the optical trapping plane and back. At either plane, the physical constraints are implemented and the modified light field is fed back into the algorithm for the next iteration. Typical constraints in the optical trapping plane are the position, number and homogeneity of the optical tweezers, while the phase usually serves as a free parameter. In the hologram plane, the incident light field can be accounted for, as well as possible discretisations of the modulation. In general, using iterative approaches nearly arbitrary two-dimensional – and to some extend even three-dimensional – intensity distributions can be realized in the vicinity of the focal plane [14].

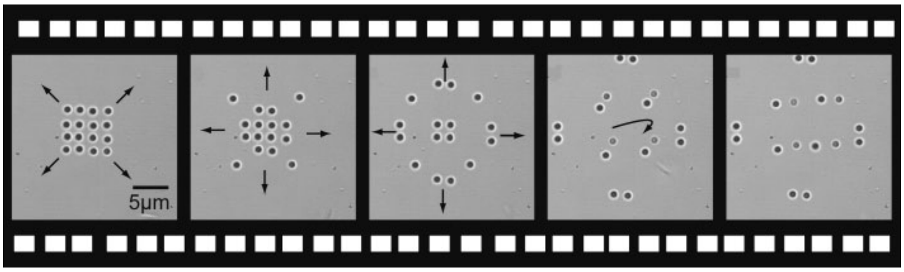

FIG. 1: **Optical manipulation of 16 spherical polystyrene microspheres. The particles are ordered and rearranged in the focal plane and finally the structure is rotated three-dimensionally.**

The creation of continuous, three-dimensional energy potential landscapes

Discrete optical tweezers, i.e. a number of discrete optical potential wells for micro-

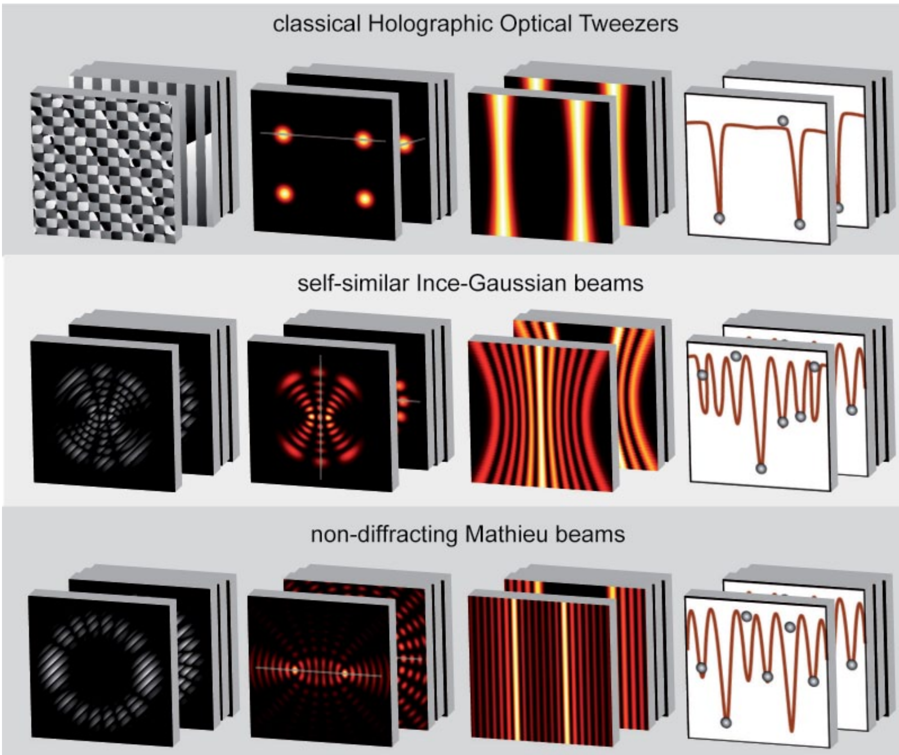

FIG. 2: **Overview of key properties of holographically shaped light fields. From left to right, typical holograms, transverse intensity distributions, axial intensity distributions (obtained along indicated transverse line), and transverse optical potential landscapes are shown.**

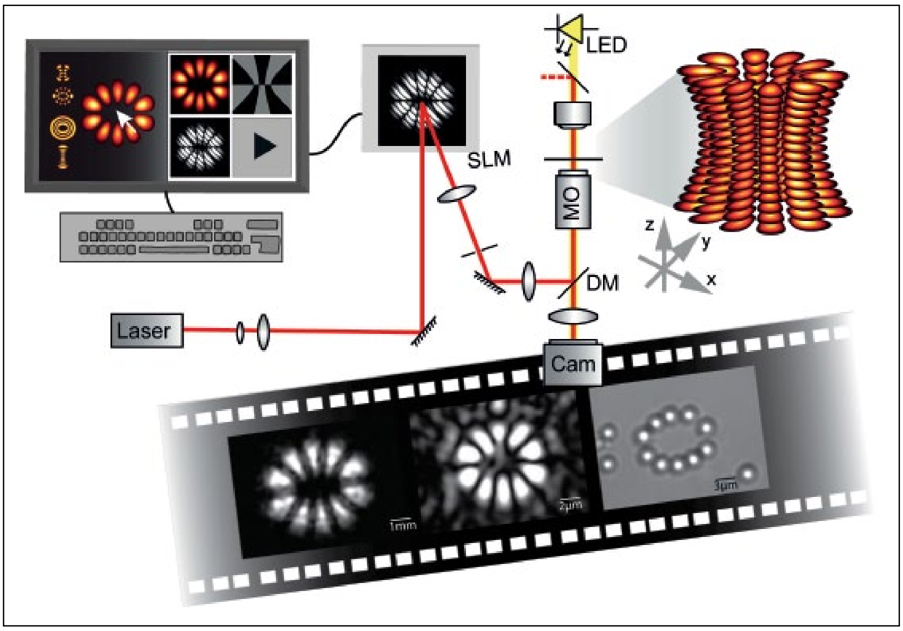

FIG. 3: **A scheme of the experimental setup used for optical micromanipulation with self-similar Ince-Gaussian beams. A computer-generated hologram displayed on a phase-only SLM is used to tailor the incident Gaussian laser beam to a higher-order Ince-Gaussian mode, which is used for optically guided self-assembly in vicinity of the focal plane of the microscope objective (MO). The propagation behaviour of the $IG^{o}_{5,5}$ beam is shown at the top right. The three images at the bottom are taken by the camera (Cam) and show (from left to right) the transverse beam intensity in an image plane of the SLM, the focal plane and the particle structure under bright field illumination.**

scopic particles, are only a special – even though the most common – case in optical micromanipulation. Recent developments show that more sophisticated light fields, e.g. in the form of higher-order solutions of the (paraxial) Helmholtz equation can open a complete new branch in the field of optical micromanipulation [6,16,17]. These analytic light modes also offer a high diversity of transverse modes, as already provided by previously described methods. But at the same time, they provide defined propagation behaviour, resulting in extended longitudinal potential landscapes. When the desired light field is known analytically, the complex-valued hologram required for the beam shaping is readily calculated. Unfortunately, this hologram cannot be displayed by a phase-only SLM which by definition cannot alter the amplitude of the incident light field directly [15]. There are, however, a number of different concepts available to modulate the amplitude as well as the phase with a phase-only modulator. The basic idea is to use a carrier grating with a high spatial frequency which diffracts most of the light into a higher diffraction order [19,20]. For those portions of the light field that are supposed to have lower amplitude

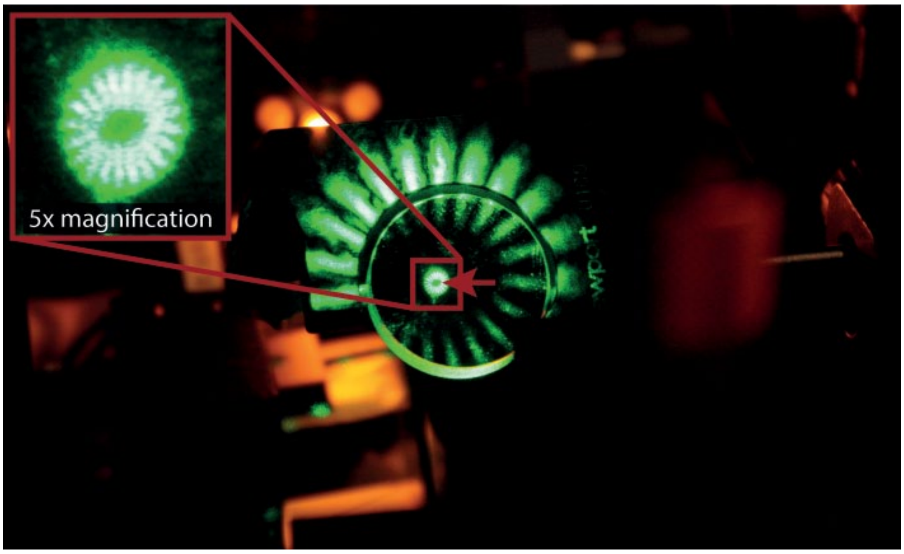

FIG. 4: **This detailed view of one mirror (DM in Figure 3) in the optical micromanipulation system reveals interesting insights into the propagation properties of the employed Ince-Gaussian light modes. An Ince-Gaussian $IG^{e}_{10,10}$ beam is reflected off the mirror (red arrow) and hits the mounting of the mirror again (large light pattern) after propagation through the microscope objective, reflection off a test sample and, again, propagation through the objective. Despite of the long propagation distance in between, the beam has maintained its shape except for a scaling factor.**

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The Institute of Applied Physics (IAP) of University of Münster combines applied physics with principles of nonlinear phenomena, thereby developing novel techniques and devices for the technical demands of today. The institute focuses on photonics and magnonics, where control of electrocmagnetic wave propagation is an actual challenge for applications in information processing and biomedicine. Among recent achievements of the institutes researchers are Bose-Einstein condensation of magnons at room temperature, magnonic waveguides, nonlinear CARS microscopy workstation, ultrafast optics in nonlinear optical fibres, complex holographic optical tweezers, and the realization of light confinement in space and time in photonic lattices.

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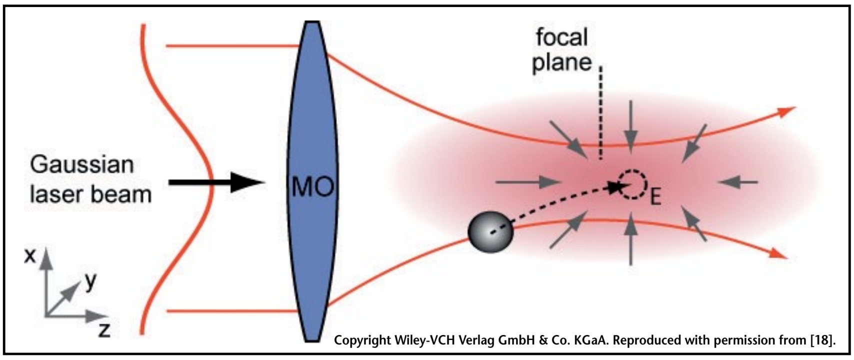
than others, the efficiency of the diffraction grating is degraded locally. For this purpose, the modulation depth of the grating is reduced, resulting in lower diffraction efficiency. This kind of "pseudo" amplitude modulation can be combined with the phase-modulation inherent to the SLM, resulting in complex-valued modulation of amplitude and phase at the SLM plane. Utilising complex-valued modulation, any arbitrary light field can be generated at the cost, however, of a reduced spatial bandwidth [20]. The two lower image stacks in the leftmost column of Figure 2 provide a number of examples, showing holograms that create highly structured light fields when being reconstructed.

Higher-order light modes

Looking at the various light fields that have been investigated in the past for different applications, there are a number of candidates which have particularly advantageous properties in optical micromanipulation. In classical optical tweezers, for example, a tightly focused fundamental Gaussian beam is employed. It has a flat wave front and the well known properties of a Gaussian envelope of the transverse beam shape which is maintained even after focusing. The Gaussian beam, however, is the fundamental and most common lowest order mode of the families of self-similar beams, which include the Hermite-Gaussian and Laguerre-Gaussian beams. Higher-order modes from these families feature highly interesting transverse beam profiles which can have extended, highly structured intensity and phase distributions. With the family of Ince-Gaussian beams, a third complete class of higher order solutions to the paraxial Helmholtz equation has been proposed relatively recently [21]. Since Ince-Gaussian beams are general solutions of the paraxial Helmholtz equation in elliptical coordinates, they are characterised by the additional ellipticity parameter and thus include all Hermite-Gaussian as well as Laguerre-Gaussian modes as limiting cases of infinite or zero ellipticity, respectively. A selection of different Ince-Gaussian modes is shown in Figure 2, middle row , and in Figure 3. They possess a huge variety of different transverse intensity distributions. Furthermore, the wave front can be tilted in a helical way which associates orbital angular momentum with the light wave. Most interesting, however, are the propagation properties of Ince-Gauss-



Optical tweezers utilise the strong intensity gradients of a tightly focused Gaussian laser beam in order to hold and move suitable dielectric microscopic and nanoscopic particles. In the vicinity of the focal spot, there are two forces acting on a particle. The gradient force is proportional to the spatial change of the light intensity and thus accelerates the particle in direction of the focal spot. Additionally, a scattering force accelerates the particle along the beam axis. If the laser beam is focused strongly enough, the gradient force can surpass the scattering force and a stable equilibrium position (E) arises close to the focal plane [1].

ian beams. Similar to the fundamental Gaussian mode, Ince-Gaussian beams exhibit the very same intensity distribution in any plane during propagation – even in the far field – except for a scaling factor. Thus, Ince-Gaussian beams are said to be self-similar [17]. All these exciting properties make Ince-Gaussian beams promising candidates for advanced applications in optical micromanipulation.

A second family of higher-order light modes are the so-called Mathieu beams which are solutions of the Helmholtz equation without paraxial approximations. These beams are nondiffracting in a sense that their central features do not undergo any spreading when they propagate [22]. Similar to Ince-Gaussian beams, Mathieu beams are solutions in elliptical cylinder coordinates and thus include more established solutions in polar and Cartesian coordinates, respectively, like the fundamental non-diffracting beam, the zeroth order Bessel beam. Looking at the transverse beam profile, Mathieu beams feature a high diversity of intensity and phase distributions, similar to Ince-Gaussian beams [16]. Their propagation properties, however, are exactly complementary. Figure 2 contrasts the transverse beam structures and propagation properties of light fields employed in classical holographic optical tweezers with Ince-Gaussian and Mathieu beams, respectively.

Self-similar beams in optical micromanipulation

Holographically generated higher-order light modes are ideally suited for the creation of continuous, complex optical potential landscapes in contrast to the discrete potential wells induced by classical holographic optical tweezers. A selection of typical transverse optical potential landscapes is sketched in the rightmost column of Figure 2. Using the example of Ince-Gaussian beams, we will highlight the concept and show the impact in the field of optical micromanipulation.

Figure 3 shows a schematic sketch of the basic optical setup utilised in our laboratories [17]. It is based on a standard holographic optical tweezers system, integrated in an inverted optical microscope for simultaneous observation of the manipulated microscopic objects. The major difference to conventional holographic optical tweezers implementations is the design of the hologram. A liquid crystal phase-only SLM displays the pre-calculated phase pattern which constitutes the tailored hologram. The SLM is illuminated by a laser light source with sufficient output power, in the order of a few watts, and subsequently imaged onto the back focal plane of the microscope objective. In the vicinity of the focal plane, the Ince-Gaussian beam shows strong but continuous spreading. The self-similarity of the employed Ince-Gaussian beams during propagation can be observed in a visually appealing way in Figure 4, showing a close-up from one mirror in our experimental setup.

Tailoring the microscopic world

Holographically shaped light fields have found a vast number of applications in optical micromanipulation, ranging from the dynamic control of single cells [9] over the hierarchical assembly of nano-container particles [10] to the optically guided self-assembly of extended two- and three-dimensional particle structures [17]. In particular the optically guided self-assembly is a promising approach which could bridge the gap between classical optical micromanipulation of a few individual particles and chemical self-assembly techniques which are well suited for the assembly of huge particle numbers but lack of fine control of individual particles.

Extended, continuous optical potential landscapes, induced by holographically shaped light fields, can be the basis for optically guided self-assembly. In contrast to the discrete potential wells of classical holographic optical tweezers, Ince-Gaussian or Mathieu beams, for example, enable continuous, highly structured and extended optical potential landscapes. Diffusing or sedimenting particles can find equilibrium positions within these potential landscapes as it is indicated in Figure 2. Hence they assemble themselves within the framework imprinted by the light field. Figure 3 shows an example of ten silica glass microspheres, reproducing the structure of an Ince-Gaussian $\mathbf{IG}^{o}_{5,5}$ beam. This optically guided self-assembly on the one hand enables the creation of more extended particle assemblies compared to classical holographic optical tweezers. On the other hand, each particle can be controlled individually at any time by appropriate adjustments of the holographically shaped light field. Depending on the desired three-dimensional properties of the constructed micro-assemblies, the propagation properties of the light field and thus the axial extension of the optical potential landscape can be tuned.

Exciting examples for particularly ingenious utilisations of tailored propagation properties include the demonstration of an "optical snow-blower" where particles are accelerated along a curved trajectory [23], the simultaneous manipulation in multiple planes [24], and the stacking of many particles along a structured beam [16].

The versatility of holographically generated light fields is once more evident if absorbing particles are to be manipulated. In contrast to optically transparent particles, these cannot be trapped directly in a laser focus. Using a superposition of self-similar beams, it is possible to generate a "bottle beam", i.e. a region of low intensity surrounded by high intensity, which can confine absorbing particles by means of photophoretic forces [25].

Most interestingly, higher-order light modes can feature significantly smaller features in their transverse intensity substructures compared to the fundamental Gaussian beam. This suggests innovative applications in the highly structured assembly of nanoparticles with sizes below a few hundred nanometres. There is no other straightforward way to assemble particles of this size with classical optical tweezers because the particles' dimensions are small compared to the laser beam focus and hence multiple particles cannot be arranged in close defined positions.

Summary

The holographic shaping of a light wave significantly widens the potentials of optical micromanipulation methods. While in this article we were only able to hint at a very few promising applications which are in focus of topical research, there have been demonstrated an uncountable number of applications in the past couple of years and there might be even more aspects still to discover in the future. The most striking benefit of holographically shaped light fields in optical micromanipulation certainly is their flexibility and versatility.

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