Dynamic multiple-beam counter-propagating optical traps using optical phase-conjugation

Mike Woerdemann,* Konrad Berghoff, and Cornelia Denz

Institute of Applied Physics, Westfälische Wilhelms-Universität Münster, Corrensstraße 2, 48149 Münster, Germany
*woerde@uni-muenster.de

Abstract: Counter-propagating optical traps are widely used where long working distances, axially symmetric trapping potentials, or standing light waves are required. We demonstrate that optical phase-conjugation can automatically provide a counter-propagating replica of a wide range of incident light fields in an optical trapping configuration. The resulting counter-propagating traps are self-adjusting and adapt dynamically to changes of the input light field. It is shown that not only single counter-propagating traps can be implemented by phase-conjugation, but also structured light fields can be used. This step towards more complex traps enables advanced state-of-the-art applications where multiple traps or other elaborated trapping scenarios are required. The resulting traps cannot only be used statically, but they can be rearranged in real-time and allow for interactive dynamic manipulation.

OCIS codes: (020.7010) Laser trapping; (350.4855) Optical tweezers or optical manipulation; (070.5040) Phase conjugation.

References and links

1. A. Ashkin, "History of optical trapping and manipulation of small-neutral particle, atoms, and molecules," IEEE J. Sel. Top. Quantum Electron. **6**(6), 841–856 (2000).
2. K. Dholakia, and P. Reece, "Optical micromanipulation takes hold," Nanotoday **1**(1), 18–27 (2006).
3. M. Woerdemann, S. Gläsener, F. Hörner, A. Devaux, L. De Cola, and C. Denz, "Dynamic and reversible organization of zeolite L crystals induced by holographic optical tweezers," Adv. Mater. (to be published).
4. F. Hörner, M. Woerdemann, S. Müller, B. Maier, and C. Denz, "Full 3D translational and rotational optical control of multiple rod-shaped bacteria," J. Biophoton. **3**(7), 468–475 (2010) http://onlinelibrary.wiley.com/doi/10.1002/adma.201001453/abstract.
5. D. Altman, H. L. Sweeney, and J. A. Spudich, "The mechanism of myosin VI translocation and its load-induced anchoring," Cell **116**(5), 737–749 (2004).
6. E. R. Dufresne, G. C. Spalding, M. T. Dearing, S. A. Sheets, and D. G. Grier, "Computer-generated holographic optical tweezer arrays," Rev. Sci. Instrum. **72**(3), 1810 (2001).
7. R. L. Eriksen, V. R. Daria, and J. Glückstad, "Fully dynamic multiple-beam optical tweezers," Opt. Express **10**(14), 597–602 (2002).
8. M. Woerdemann, F. Holtmann, and C. Denz, "Holographic phase contrast for dynamic multiple-beam optical tweezers," J. Opt. A, Pure Appl. Opt. **11**(3), 034010 (2009).
9. G. J. Brouhard, H. T. Schek, and A. J. Hunt, "Advanced optical tweezers for the study of cellular and molecular biomechanics," IEEE Trans. Biomed. Eng. **50**, 121 (2003).
10. K. Visscher, G. J. Brakenhoff, and J. J. Krol, "Micromanipulation by "multiple" optical traps created by a single fast scanning trap integrated with the bilateral confocal scanning laser microscope," Cytometry **14**(2), 105–114 (1993).
11. A. Ashkin, "Acceleration and Trapping of Particles by Radiation Pressure," Phys. Rev. Lett. **24**(4), 156–159 (1970).
12. M. Petrovic, M. Beli, C. Denz, and Y. S. Kivshar, "Counterpropagating optical beams and solitons," Laser Photon. Rev. (to be published).
13. A. Jonás, and P. Zemánek, "Light at work: the use of optical forces for particle manipulation, sorting, and analysis," Electrophoresis **29**(24), 4813–4851 (2008).
14. P. Zemánek, A. Jonás, L. Šrámek, and M. Liska, "Optical trapping of nanoparticles and microparticles by a Gaussian standing wave," Opt. Lett. **24**(21), 1448–1450 (1999).
15. J. S. Dam, P. J. Rodrigo, I. R. Perch-Nielsen, and J. Glückstad, "Fully automated beam-alignment and single stroke guided manual alignment of counter-propagating multi-beam based optical micromanipulation systems," Opt. Express **15**(13), 7968–7973 (2007).

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

16. P. J. Rodrigo, V. R. Daria, and J. Glückstad, "Four-dimensional optical manipulation of colloidal particles," Appl. Phys. Lett. **86**(7), 074103 (2005).
17. R. A. Fisher, ed., *Optical Phase Conjugation* (Academic Press, Inc., 1983).
18. W. Wang, A. E. Chiou, G. J. Sonek, and M. W. Berns, "Self-aligned dual-beam optical laser trap using photorefractive phase conjugation," J. Opt. Soc. Am. B **14**(4), 697 (1997).
19. G. S. He, "Optical phase conjugation: principles, techniques, and applications," Prog. Quantum Electron. **26**(3), 131–191 (2002).
20. J. Feinberg, and R. W. Hellwarth, "Phase-conjugating mirror with continuous-wave gain," Opt. Lett. **5**(12), 519 (1980).
21. M. Woerdemann, C. Alpmann, and C. Denz, "Self-pumped phase conjugation of light beams carrying orbital angular momentum," Opt. Express **17**(25), 22791–22799 (2009).
22. P. Xie, J. H. Dai, P. Y. Wang, and H. J. Zhang, "Self-pumped phase conjugation in photorefractive crystals: Reflectivity and spatial fidelity," Phys. Rev. A **55**(4), 3092–3100 (1997).
23. M. Cronin-Golomb, "Nonlinear optics and phase conjugation in photorefractive materials," J. Cryst. Growth **109**(1-4), 340 (1991).
24. E. L. Florin, A. Pralle, E. H. K. Stelzer, and J. K. H. Horber, "Photonic force microscope calibration by thermal noise analysis," Appl. Phys., A Mater. Sci. Process. **66**(7), S75–S78 (1998).
25. J. Liesener, M. Reicherter, T. Haist, and H. J. Tiziani, "Multi-functional optical tweezers using computer-generated holograms," Opt. Commun. **185**(1-3), 77–82 (2000).
26. K. C. Neuman, E. H. Chadd, G. F. Liou, K. Bergman, and S. M. Block, "Characterization of photodamage to escherichia coli in optical traps," Biophys. J. **77**(5), 2856–2863 (1999).
27. D. Rytz, R. R. Stephens, B. A. Wechsler, M. S. Keirstead, and T. M. Baer, "Efficient self-pumped phase conjugation at near-infrared wavelengths using cobalt-doped BaTiO3," Opt. Lett. **15**(22), 1279–1281 (1990).
28. E. Schonbrun, R. Piestun, P. Jordan, J. Cooper, K. D. Wulff, J. Courtial, and M. Padgett, "3D interferometric optical tweezers using a single spatial light modulator," Opt. Express **13**(10), 3777–3786 (2005).
29. V. Garcés-Chávez, D. McGloin, H. Melville, W. Sibbett, and K. Dholakia, "Simultaneous micromanipulation in multiple planes using a self-reconstructing light beam," Nature **419**(6903), 145–147 (2002).

1. Introduction

Optical trapping has revolutionized many fields of science and engineering since its discovery 40 years ago, including micro- and nano-structuring, biology and biophysics, atom physics and fundamental physics [1]. One particularly simple and still powerful implementation of optical traps is the *single-beam gradient force optical trap*, also commonly called *optical tweezers*. Here, one laser beam is tightly focused – usually through a microscope objective that is used for observation anyway – such that it can hold and trap microscopic particles without the aid of any other, counteracting forces. The simplicity and elegance of this approach has led to a vast number of applications of optical tweezers [2], but they also suffer from fundamental limitations. The requirement of a strongly focused laser beam inevitably results in extreme local intensities and the need for microscope objectives with a high numerical aperture. These objectives limit the available working distance between objective and specimen to a millimeter or less and make the use of immersion fluid unavoidable. Furthermore, the optical potential well is strongly asymmetric in axial direction with the weakest part being in beam propagation direction.

Single optical traps have a wide range of applications, but many scenarios require multiple traps. Examples are structuring of multiple microparticles [3], orientational control of non-spherical objects [4], and exploration of biophysical properties of molecular motors [5], to name just a few. An established concept for the flexible generation of multiple traps are *holographic optical tweezers* (HOT), where the phase front of a light field is structured with a spatial light modulator (SLM) in order to get a desired trapping configuration [6]. Along with other SLM-based methods [7,8] and time-sharing approaches [9,10], HOT can be considered as state-of-the-art technique if versatile optical trapping is required.

An interesting alternative to optical tweezers are *counter-propagating (CP) optical traps* where the scattering force in direction of beam propagation is counterbalanced by an opposed second beam [cf. Figure 1(a)]. Historically, this concept of an optical trap exists much longer than optical tweezers [11] and it has always been in focus of research for applications where high working distance, low light pollution, or axially symmetric trapping potentials are more important than a simple implementation. Utilization of CP beams, however, has much more fundamental implications [12]. The available solid angle of incident k-vectors at the focal plane is extended from 2π – the ideal case if one beam and one microscope objective is used –

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

to up to 4π. This enables, for example, the creation of standing light waves that are structured in axial direction and have exciting applications like optical sorting or a particularly strong axial confinement [13]. All but the simplest implementations of CP traps where a mirror is placed directly in the specimen plane [14] have in common that they are relatively complex, compared to optical tweezers, and accurate alignment can be complicated [15]. If typical state-of-the-art features like multiple traps and individual, flexible positioning in all three dimensions are required, the complexity even increases [16].

In this paper we present a method that utilizes optical phase-conjugation to realize CP optical traps. A photorefractive phase-conjugate mirror is used to create a back-propagating beam that automatically matches an arbitrary incident beam. This implementation is intrinsically self-aligning. We demonstrate that not only single optical traps can be generated by this means. The concept can be extended to multiple traps and even dynamically reconfigured traps are possible. By this means the versatility of HOT is transferred to CP optical traps, retaining their unique properties.

2. Counter-propagating optical traps using phase-conjugation

Perfect optical phase-conjugation (PC) exactly reflects a light field into itself, thereby reversing propagation direction and phase front [17]. This property led to the idea to use a phase-conjugate mirror (PCM) to create the back-propagating beam in a counter-propagating trap configuration [cf. Figure 1(b)] [18]. One compelling advantage over the conventional implementation with two separately prepared beams is the inherent ability of the PCM to adapt dynamically to any change in the input light field. This means that the initial fine adjustment as well as any further readjustment, e.g. necessitated by unavoidable thermal drift of components, is done automatically by the system itself.

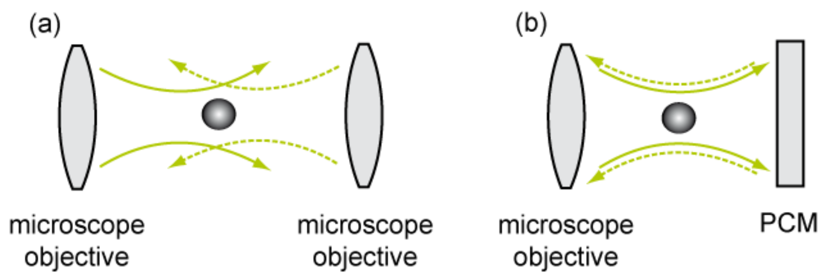

Fig. 1. (a) Commonly used counter-propagating trap configuration. (b) Principle idea of counter-propagating traps using optical phase-conjugation.

There are some fundamental differences of phase-conjugate CP traps compared with conventional CP traps. In the conventional implementation, the relative position of the beam waists can be chosen freely, while in the (ideal) phase-conjugate implementation, the beam waists overlap perfectly by definition. Furthermore, in the phase-conjugate implementation both CP beams usually are mutually coherent in contrast to the conventional case, where the beams can be mutually coherent or not. However, it should be possible to tune the degree of mutual coherence in the phase-conjugate implementation by changing the propagation distance of the light between the trap and the phase-conjugate mirror to values smaller or larger than the coherence length of the utilized laser source. In most cases, however, coherence is desired, as it is the prerequisite for standing light wave traps.

The properties of a phase-conjugate CP trap are strongly related to the properties of the actually used implementation of the optical PC. In reality, for example, a PCM will not react instantaneously to a change in the incident light field, but will need a finite time τ to adapt the change. It is obvious that the two extreme cases of an almost instantaneous and a relatively slow implementation of the PCM lead to two completely different situations as soon as dynamics like Brownian motion of the trapped particle or a change of the trapping configuration are considered.

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

Optical PC can be realized through various nonlinear optical processes, such as four-wave mixing, three-wave mixing, backward stimulated scattering, and others [19]. For our experiments we decided to use an implementation that relies on degenerate four-wave mixing in a photorefractive crystal. We use a variation that is self-pumped, utilizing beam fanning and internal reflection to provide the necessary beams for the four-wave mixing process inside the crystal [20,21]. This implementation has the advantage of being very easy to set up and providing high quality phase conjugation even with low light powers (in the order of milliwatts) [22]. Photorefractive PCMs feature relatively large time constants τ [23] in the order of seconds, which enables us to analyze the dynamics of the CP traps in detail.

A single optical trap implemented using optical PC is already interesting from the fundamental physics point of view as well as for applications in all fields that require counter-propagating optical light fields [18]. For state-of-the-art applications of optical trapping, however, it is important to have the possibility to use structured light fields like, for example, multiple traps and control them dynamically. In this contribution we develop the basic, elegant idea of CP traps using optical PC further towards these application driven needs.

3. Single counter-propagating trap

The setup for a single CP optical trap with optical PC is depicted in Fig. 2(a). We follow the basic concept of Wang et al. [18], introducing a couple of modifications that mainly aim at a setup that is as simple as possible in order to facilitate a broad range of applications. The laser source is a frequency doubled Nd:YAG solid-state laser, emitting at a wavelength of $\lambda = 532$ nm with maximal output power of $P_{max} = 300$ mW. After passing an optical isolator, the beam is variably split into the trap beam and a pump beam by means of a half-wave plate (HWP) and a polarizing beams splitter (PBS). Polarization of the trap beam is set (p-polarization) by another HWP and the trap beam is relayed and resized by a telescope and focused by microscope objective MO_1 with 40 x magnification and a numerical aperture NA = 0.65. After the specimen, the beam is collected by a second microscope objective (MO_2) with identical properties. The collected beam is loosely focused through lens L_{PCM} into a nominally undoped $BaTiO_3$ photorefractive crystal, which acts as the PCM. A pump beam, which is relayed by two mirrors (M), supplies the PCM with additional energy, thus enabling reflectivity of more than unity. With the current setup, maximal reflectivity of approximately $R_{max} = 280\%$ can be achieved.

The total transmittance of all components between specimen and PCM was measured to be T = 85%. In order to achieve equal power of the input beam and the back-propagating beam at the sample plane, the reflectivity thus should be set to approximately R = 152%, if the specimen has a transmission of $T_{sample} = 91\%$. The time constant of the PCM depends on the type of crystal, the total intensity incident on the crystal, the ratio of signal and pump beam and the exact geometry, i.e. overlap of the beams, incidence angles and position of the crystal. Typical time constants of the current setup are $\tau = (1.30)$ s. For the single CP trap experiments, a time constant of $\tau_0 = 10$ s was chosen.

An optical microscope is integrated by means of two dichroic mirrors (DM_1, DM_2). It consists of MO_1, acting as the observing microscope objective, an illumination, the tube lens L_T and a video camera. The illumination is provided by a red ($\lambda \approx 625$ nm) LED, a collimation lens LC and MO_2, acting as the condenser.

First evidence that the input beam is actually phase-conjugated rather than simply reflected is given by the observation that the beam exactly traces back its own path. It can be seen on the camera at the expected, correct position and even goes back into the laser, resulting in unstable operation of the laser, if the optical isolator is omitted.

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

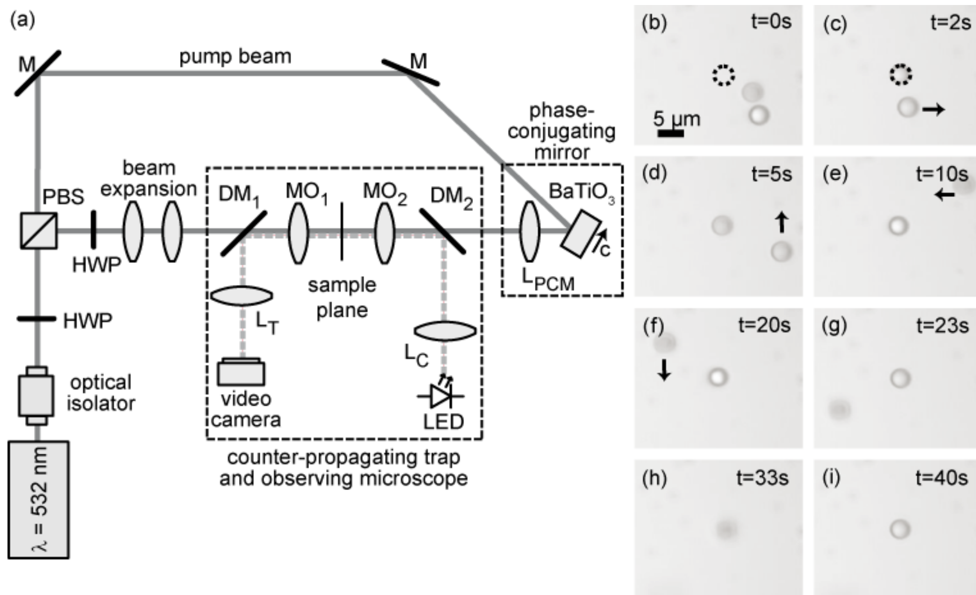

Fig. 2. (a) Experimental setup for a single counter-propagating trap. (b-i) Three dimensional trapping of a d = 4 µm polystyrene bead: the bead is trapped at the position of the dashed circle (b,c) and the sample plane is translated transversally (d-g) and axially (h,i), respectively. As the axial potential is relatively weak, the bead needs a few seconds to return to the trapping position in focus after axial displacement (Media 1).

With this configuration, stable three dimensional (3D) trapping of particles is possible. Typical values of laser power P = 4 mW (comprising both CP beams) in the trapping plane result in a transversal trap stiffness of k_t = 2 pN/µm for polystyrene beads with a diameter d of 4 µm. Values for the trap stiffness are determined using thermal noise analysis of the video data, utilizing Boltzman statistics [24]. A trapped bead remains confined in the trap, when the sample holder is translated in transversal or axial direction, respectively (cf. Figures 2b-2i). The axial stiffness was not measured by us, but from simple observation it can be concluded that it is significantly lower than the transversal stiffness. This is in agreement with the lower axial gradient forces, resulting from the low numerical aperture of the used microscope objectives. In contrast to single beam optical tweezers, 3D trapping is still possible in spite of the low NA (and hence high working distance) due to the compensated scattering forces.

4. Multiple counter-propagating traps

An extension of the concept of phase-conjugate CP trap to multiple-beam traps is required for many advanced applications. Two traps already extend the possible applications significantly [4,3]. In Fig. 3(a) the extended experimental setup for a dual CP trap is depicted. An interferometric part consisting of beamsplitter BS and two mirrors originates two beams which can be steered independently by the mirrors. The two beams usually have a small mutual angle, resulting in a corresponding interference pattern at the back aperture of the microscope objective MO_1. The interference pattern has a sinusoidal modulation [cf. inlets in Fig. 3(a) for images of the light intensities at the respective planes]. MO_1 performs an optical Fourier transformation of the incident light field and thus creates the desired two traps in the sample plane. The second microscope objective MO_2 performs an analogous reverse Fourier transformation and yields an interference pattern at the objective's back aperture that is similar to the pattern at the entrance of MO_1. This pattern is phase-conjugated and the phase-conjugate light field traces back the original. By this means, two CP traps are generated in the sample plane. Figure 3(b) demonstrates trapping of two 4 µm polystyrene bead simultaneously. This extension to two individually steerable traps already allows for many advanced operations.

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

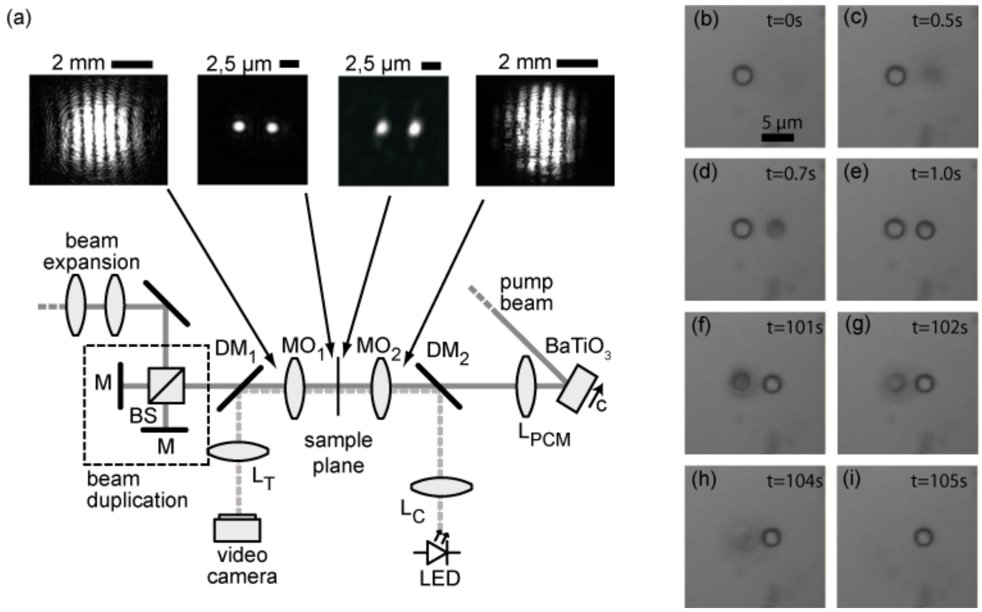

Fig. 3. (a) Experimental setup for a dual counter-propagating trap. Origin of trap and pump beams is omitted. Inlets show the measured intensity distribution at the indicated planes. (b-i) Trapping of two d = 4 µm beads simultaneously. At t = 0 only one trap is occupied (b). A second bead enters the other trap (c,d) and both are trapped in a stable way until the first bead is pushed out of the trap by another bead (f-i).

The concept of multiple traps originating in discrete splitting of one laser beam into multiple, independently steerable beams can in principle be extended to any desired number of traps by adding a corresponding number of beam splitters and mirrors. In practice, however, this approach is not feasible for more than a few traps and it is relatively inflexible. On the other hand it is simple to implement and thus the method of choice, if two or a few CP optical traps are required.

5. Dynamic counter-propagating traps

For a most versatile optical trapping system we aimed to combine the advantageous features of phase-conjugate CP traps with the formidable flexibility of light fields that are structured with SLMs. The extension of our setup towards SLM shaped input light fields is depicted in Fig. 4(a). The SLM is illuminated with an expanded beam and then imaged onto the back aperture of MO_1 by lenses L_1 and L_2, such that it exactly fits the back aperture area. By means of the optical Fourier transformation of MO_1 the desired trapping configuration is created, according to the calculated phase-pattern displayed on the SLM. After being recollected by MO_2, the light field is phase-conjugated by the PCM. In this configuration the advantages of PC become even more evident than in the configurations with one or a few beams. The PCM inverts any arbitrary, complex wave front that is created by the SLM without the need for any precise adjustment. Hence, any configuration from a single up to hundreds of traps can be used; the respective CP antagonists are always built up automatically.

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

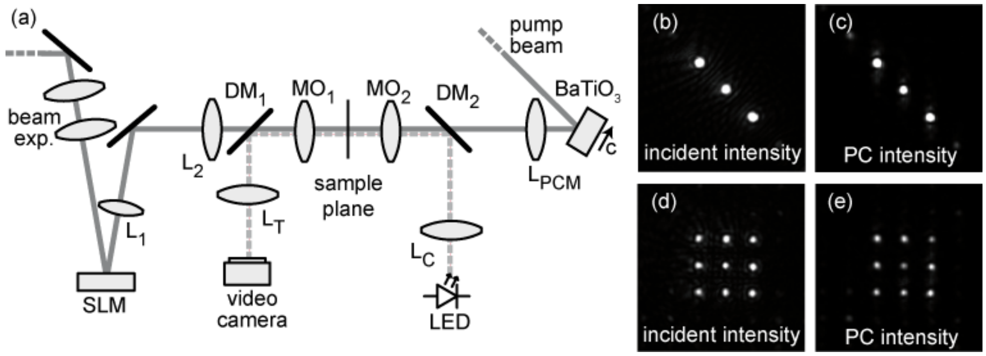

Fig. 4. (a) Experimental setup for a counter-propagating trap using an SLM. Origin of trap and pump beams is omitted. (b,d) Trapping configurations as created with the SLM and measured in the sample plane. (c,e) Corresponding phase-conjugate replicas.

The calculation of the phase-pattern on the SLM can be performed with many available algorithms. We decided to use a simple superposition of diffraction gratings and Fresnel lenses which is easy to implement and fast in calculation [25]. A few examples of possible trapping patterns are shown in Figs. 4(b) and 4(d). The bright spots indicate the positions of the optical traps that are reflected from an air-glass interface (cover slip) of the sample. The corresponding back-propagating light field is generated by the PCM, propagates through the sample and is directly imaged onto the camera [Figs. 4(c), 4(e)]. Corresponding patterns overlap exactly, indicating the correct function of the PCM. Figure 5(a) shows an example of two particles that are trapped simultaneously. The left trap is positioned in focus, while the other trap is displaced in axial (+ z) direction. Hence, the right particle is a few micrometers out of focus and barley visible. In Fig. 5(b) the situation is reversed: the left particle is displaced in axial (-z) direction, the other particle is in focus. This simple example clearly demonstrates the ability of the SLM based setup to trap and position multiple traps three dimensionally. Of course, also more than two particles can be trapped simultaneously. Figures 5(c)-5(e) show examples of multiple trapped particles. The trapping configuration can be changed by simply displaying a new phase-pattern on the SLM. After a time τ_{trap} which is directly related to τ, the new trapping configuration can be used. τ_{trap} usually is significantly smaller than τ, as the axial scattering forces are already sufficiently compensated even before both CP beams have reached equal intensities.

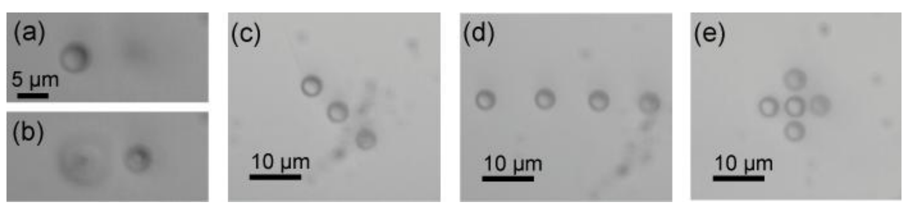

Fig. 5. Examples of trapping d = 4 µm beads with more complex configurations. (a,b) Two beads in different axial planes. (c-e) Increasing number of beads in various trapping configurations (Media 2).

Multiple optical traps reach their ultimate versatility if the traps – and thus the trapped particles – can be translated interactively and in real-time. It is obvious that the time constant of the PCM τ has a direct influence on the dynamics of the system. For many applications it is of interest, how fast a particle with given properties can be moved from its initial position A to a destination B. Moving a particle with holographic optical traps always means a step-by-step motion, with a minimal step size resulting from the SLM's pixelation. Consequently, there are two parameters that can be changed in order to increase the mean velocity: step-size and step-frequency. The diagram in Fig. 6 shows a study with a d = 4 µm particle for which both parameters were varied, using P_T = 240 µW of trap power and P_P = 16 mW for the pump

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

beam. This configuration results in time constant τ_0 in the order of 10 seconds. For each set of parameters, the probe particle was 10 times translated along the same trajectory from A to B with a length of d = 10 µm and it was documented, if the particle reached the final position or not. Parameter sets with 50% or more successful translations are considered suitable (black dots in the figure).

If only the time constant of the PCM were the limiting factor, the maximal steps per second should be independent from the step size: it takes the PCM always the same time τ_{trap} to build up a new trap, independent from the distance between the old and the new trap. Figure 6, however, shows a clearly decreasing maximal step frequency with increasing step size. To gain insight into the reasons, we recall what happens when the position of a trap is changed. The old trap is switched off, the new trap is switched on; directly after switching, however, at the old trap's position there still is a back-propagating beam from the PCM. At the new position only the incident beam exists, but no CP antagonist. It takes a time τ_{trap} until the CP trap at the new position is established and the trap at the old position has vanished. During the reconfiguration, the incident beam at the new position and the back-propagating beam at the old position need to compensate for each other's scattering force. This works the more efficient the closer the new trapping position is to the old position; hence smaller step sizes are favored and allow for a higher step frequency. Furthermore, refraction by the particle can increase the temporary spatial mismatch. Our reasoning is supported by the observation that step sizes larger than the particle diameter cannot be used at all; in this case the separated CP beams cannot compensate for each other's scattering forces and the particle is pushed out of the trap before the CP traps are properly reinstalled.

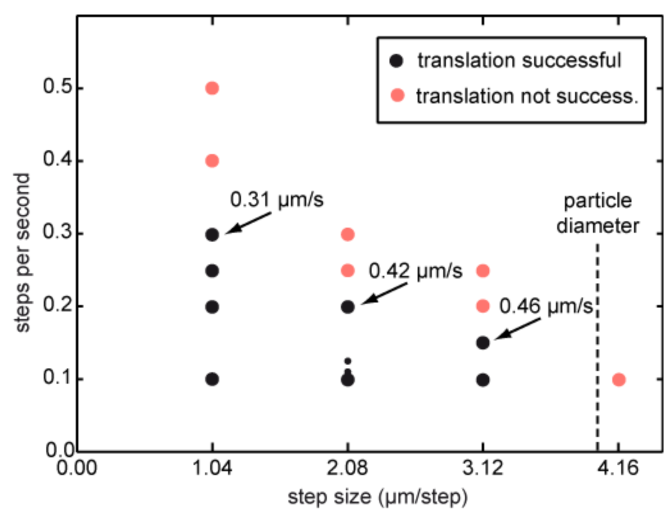

Fig. 6. A d = 4 µm polystyrene bead is translated with various step sizes and step frequencies. Each data point represents the majority vote of 10 single measurements (5 and 6 measurements for the small points, respectively). The maximal velocity is indicated for each step size (Media 3).

With the intention to translate a given particle as fast as possible, therefore a larger step size – but still below the particle diameter – is preferable. In the example this choice enables us to move a d = 4 µm polystyrene bead with v_{max} = (0.46 ± 0.06) µm/s with a step size of (3.12 ± 0.4) µm and 0.15 steps per second.

The time τ_{trap} it takes to build up a trap still is the limiting factor, once the step-size is chosen optimally. If τ_{trap} is given for some reason, the maximal velocity still can be increased if the trajectory is known in advance. With this knowledge, the next steps can be prepared by setting up a few traps along the trajectory, just in front of the particle. These traps have time to fully establish CP traps. In order to translate the particle, the trap on the particle's old position and the trap directly behind that position are switched off. The particle will take one step.

With this approach of "paving the way", utilizing 5 traps (P_T = 670 µW total), we are able to move a d = 4 µm particle with a velocity up to v_{max} = (2.72 ± 0.88) µm/s. The achievable velocity is thus significantly higher than in the single trap mode, although the used power per trap is less than half.

6. Discussion

The resulting system is somewhat complex from the physical point of view. It is, for example, not trivial and highly interesting how the particle interacts with the light field. In the case of an infinitesimally small particle, we can assume that the incident light field is unaltered and reflected by the PCM as illustrated in Fig. 1(b). A particle of a few micrometers on the other hand certainly does interact with the incident light field by scattering. Consequences are that not all scattered light might be recollected after passing through the particle and the light field that reaches the PCM is additionally modified, e.g. by focusing effects of the particle. Depending on the strength of the influence and thus on the size and refractive index of the particle, this can results in an axially not perfectly symmetric trapping potential.

The response time of the system is not significantly influenced by a trapped particle, as it basically depends on the total intensity in the four-wave mixing interaction area, which is dominated by the reference beam (so-called undepleted pump configuration), and not by the signal beam that passes the particle. Furthermore, the particle is not still, even if it is not translated intentionally, but vibrates in the trap because of Brownian motion. The power spectrum of this vibration (depending on the trap stiffness and temperature) yields characteristic time constants τ_{vib} that can be compared to τ. In our concrete implementation, the PCM has time constants τ in the order of seconds which is very large compared to typical values of τ_{vib}. Hence, the PCM reflects an averaged light field.

The response time of the PCM also limits the maximal possible velocity with which a particle can be translated. The faster the PCM responds the higher velocities can be achieved. With the current setup, velocities up to about 3µm/s are accessible. We decided to use a photorefractive implementation of a PCM which is not only known for its high fidelity and the low required light intensities, but also has a very long response time compared to most other ways to realize optical PC [19]. It thus should be easy to decrease the time constant τ by many orders of magnitude. Then, the PCM is no longer the limiting factor in translation speed, but other factors, like the available optical force and the viscosity of the medium that surrounds the particle.

Many applications of optical traps involve trapping of biological cells. The demonstrated setup uses green (λ = 532 nm) light, which is a good choice for manipulation of artificial objects, but causes serious photo damage in living cells. Better suited wavelengths are in the near infrared (NIR), with 830 nm and 970 nm being optimal in many cases [26]. It should be straightforward to extend the presented concept to NIR wavelengths, as there are photorefractive materials available that provide high reflectivity in this wavelength regime (e.g. cobalt-doped $BaTiO_3$ [27]).

7. Conclusion

We have demonstrated that CP optical traps that utilize optical PC can be a versatile tool in optical micromanipulation. On the one hand they inherit most desired features, in particular low possible numerical apertures and thus high working distances, increased axial symmetry of the optical potentials and reduced intensities compared to single beam optical tweezers. On the other hand they are self-aligning and adapt automatically to any arbitrary input trap configuration. The concept of a single CP trap was developed towards multiple, dynamic traps, paving the way towards advanced applications. The dynamic capabilities include reconfigurable traps and 3D translation of the trapped particles in real-time. Having demonstrated that SLMs can be used with PC optical traps, it is possible to use almost any complex, structured light field as the basis for novel trapping configurations. Exciting examples are interference patterns of multiple plane waves [28], vortex beams that carry orbital angular momentum [21], or nondiffracting beams [29].

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010

Acknowledgements

The authors gratefully acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG) (TRR61) and from European Cooperation in Science and Technology (COST) (Action MP0604).

#132420 - $15.00 USD Received 28 Jul 2010; revised 27 Aug 2010; accepted 28 Aug 2010; published 7 Oct 2010
