Preece, D., Keen, S., Botvinick, E., Bowman, R. , Padgett, M. , and Leach, J. (2008) *Independent polarisation control of multiple optical traps*. Optics Express, 16 (20). pp. 15897-15902. ISSN 1094-4087 (doi:10.1364/OE.16.015897)

Independent polarisation control of multiple optical traps

Daryl Preece[1], **Stephen Keen**[1], **Elliot Botvinick**[2], **Richard Bowman**[1,3],
Miles Padgett[1] **and Jonathan Leach**[1]

[1]*Department of Physics & Astronomy, Kelvin Building, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

[2]*Beckman Laser Institute, Biomedical Engineering, Irvine, CA 92697-1475, USA*

[3]*Department of Physics, University of Cambridge, CB3 0HE, United Kingdom*
d.preece@physics.gla.ac.uk

Abstract: We present a system which uses a single spatial light modulator to control the spin angular momentum of multiple optical traps. These traps may be independently controlled both in terms of spatial location and in terms of their spin angular momentum content. The system relies on a spatial light modulator used in a "split-screen" configuration to generate beams of orthogonal polarisation states which are subsequently combined at a polarising beam splitter. Defining the phase difference between the beams with the spatial light modulator enables control of the polarisation state of the light. We demonstrate the functionality of the system by controlling the rotation and orientation of birefringent vaterite crystals within holographic optical tweezers.

OCIS codes: (230.6120) Spatial light modulators; (140.7010) Laser trapping

References and links

1. A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," Opt. Lett. **11**, 288–290 (1986).
2. G. Knoner, S. Parkin, N. Heckenberg, and H. Rubinsztein-Dunlop, "Microrheology using dual beam optical tweezers and ultrasensitive force measurements," Proc. Soc. Photo-Opt. Instrumentation Engineers **5736**, 73–80 (2005).
3. D. Grier, "Optical tweezers in colloid and interface science," Curr. Opin. Colloid Interface Sci. **2**, 264–270 (1997).
4. J. Leach, H. Mushfique, R. di Leonardo, M. Padgett, and J. Cooper, "An optically driven pump for microfluidics," Lab on a Chip **6**, 735–739 (2006).
5. J. Scrimgeour, E. Eriksson, and M. Goksor, "Laser surgery and optical trapping in a laser scanning microscope," Laser Manipulation Of Cells And Tissues **82**, 629–646 (2007).
6. 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**, 105–114 (1993).
7. K. Vermeulen, J. van Mameren, G. Stienen, E. Peterman, G. Wuite, and C. Schmidt, "Calibrating bead displacements in optical tweezers using acousto-optic deflectors," Rev. of Sci. Instrum. **77** (2006).
8. E. Dufresne, G. Spalding, M. Dearing, S. Sheets, and D. Grier, "Computer-generated holographic optical tweezers arrays," Rev. Sci. Instrum. **72**, 1820–1816 (2001).
9. J. Liesener, M. Reicherter, T. Haist, and H. J. Tiziani, "Multi-functional optical tweezers using computer-generated holograms," Opt. Commun. **185**, 77–82 (2000).
10. C. Maurer, A. Jesacher, S. Fürhapter, S. Bernet, and M. Ritsch-Marte, "Tailoring of arbitrary optical vector beams," New J. Phys. **9**, 78 (2007).

#99337 - $15.00 USD Received 25 Jul 2008; revised 10 Sep 2008; accepted 16 Sep 2008; published 22 Sep 2008

11. J. Leach, G. Sinclair, P. Jordan, M. J. P. J. Courtial, J. Cooper, and z. J. Laczik, “3D manipulation of particles into crystal structures using holographic optical tweezers,” Opt. Express. **12**, 220–226 (2004).
12. G. Sinclair, P. Jordan, J. Courtial, M. Padgett, J. Cooper, and Z. Laczik, “Assembly of 3-dimentional structures using programmable holographic optical tweezers,” Opt. Express **12**, 5475–5480 (2004).
13. Y. Roichman and D. Grier, “Holographic assembly of quasicrystalline photonic heterostructures,” Opt. Express **13**(14), 5434–5439 (2005).
14. S. Sato, M. Ishigure, and H. Inaba, “Optical trapping and rotational manipulation of microscopic particles and biological cells,” Electron. Lett. **27**, 831–1832 (1991).
15. A. O’Neil and M. J. Padgett, “Rotational control within optical tweezers by use of a rotating aperture,” Opt.Lett **27**, 743–745 (2002).
16. L. Paterson, M. MacDonald, J.Arlt, W. Sibbett, P. Bryant, and K. Dholakia, “Controlled rotation of optically trapped microscopic particles,” Science **292**, 912–914 (2001).
17. V. Bingelyte, J. Leach, J. Courtial, and M. Padgett, “Optically controlled three-dimensional rotation of microscopic objects,” Appl. Phys. Lett. **82**, 829–831 (2003).
18. L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, “Orbital angular momentum of light and the transformation of Laguerre-Gaussian modes,” Phys. Rev. A **45**, 8185–8189 (1992).
19. M. Padgett, J. Courtial, and L. Allen, “Light’s Orbital Angular Momentum,” Physics Today **57**, 35–40 (2004).
20. H. He, M. Friese, N. Heckenberg, and H. Rubinsztein-Dunlop, “Observation of transfer of angular momentum to absorptive particles from laser beam with a phase singularity.” Phys. Rev. Lett. **75**, 826–829 (1995).
21. M. E. J. Friese, T. A. Nieminen, N. R. Heckenberg, and H. Rubinsztein-Dunlop, “Optical alignment and spinning of laser-trapped microscopic particles,” Nature **394**, 348–350 (1998).
22. K. Ladavac and D. Grier, “Microoptomechanical pumps assembled and driven by holographic optical vortex arrays,” Opt. Express **12**, 1144–1149 (2004).
23. A. Jesacher, S. Fürhapter, C. Maurer, S. Bernet, and M. Ritsch-Marte, “Holographic optical tweezers for object manipulations at an air-liquid surface,” Opt. Express **14**, 6342–6352 (2006).
24. J. Leach, M. Dennis, J. Courtial, and M. J. Padgett, “Laser beams - Knotted threads of darkness,” Nature **432**, 165 (2004).
25. A. I. Bishop, T. A. .Nieminen, N. R. Heckenberg, and H. Rubinsztein-Dunlop, “Optical Microrheology using rotating laser trapped particles,” Phys Rev Lett **92**, 198,104 (2004).
26. G. Knoner, S. Parkin, N. Hekenberg, and H. Rubinsztein-Dunlop, “Characterization of optically driven fluid stress fields with optical tweezers,” Phys. Rev. **72**, 031,507 (2005).

---

1. Introduction

Recent years have seen the growth in the development and use of optical tweezers as a means of manipulating micron sized objects [1]. This interaction has allowed research into a diverse range of subject matter including rheology, microbiology, microfluidics, and colloidal systems [2, 3, 4, 5]. These systems utilize the trapping force created when light is incident on a high refractive index particle in a lower refractive index medium. 3D trapping however requires high numerical aperture objectives to produce strongly focused trapping beams.

Multiple optical traps can be produced in many ways including scanning mirrors [6] and acousto-optic modulators [7]. Both of these methods are time sharing techniques where a single optical trap is rapidly scanned to multiple locations in a 2D plane. A complimentary method to these is to generate multiple optical beams through diffractive optics [8], a technique named holographic optical tweezers. Often, a spatial light modulator (SLM) displaying a computer generated hologram is used to modify the phase and/or intensity of an incident light beam [9, 10]. This allows independent position control of multiple optical traps such that complex 3D structures can be manipulated in real-time [11, 12, 13].

Since the first demonstration of the controlled rotation of an optically trapped object [14], a number of different techniques to induce rotation have been investigated. To induce rotation, one must transfer angular momentum to the trapped object. This can be achieved in a number of ways, either rotating a structured intensity pattern in the trapping plane (for example, rotating a fixed aperture in the optical train[15] or using a rotating interference pattern[16]) or using a spatial light modulator to produce traps revolving around each other [17], The trapping beam properties can also be used to transfer angular momentum to the object. The spin angular momentum content of an optical beam is determined by the polarisation state of the light whereas

#99337 - $15.00 USD Received 25 Jul 2008; revised 10 Sep 2008; accepted 16 Sep 2008; published 22 Sep 2008

the orbital angular momentum content of the light is governed by the phase structure. A left, or right handed circularly polarised beam contains $\pm\hbar$ of angular momentum per photon and a beam with an $\exp(i\ell\phi)$ phase structure contains $\ell\hbar$ of angular momentum per photon [18, 19]. Either, or both of these forms of angular momentum can be transferred to appropriately trapped objects [20, 21].

It is possible to generate multiple optical traps and control the orbital angular momentum of the individual traps by use of holographic optical tweezers with an appropriately designed hologram [22, 23]. It is also possible to generate multiple optical traps with spin angular momentum with the use of polarising beam splitters [4] but controlling the polarisation state of each trap independently has not hitherto been achieved. Here we report a system whereby a single spatial light modulator used in a "split-screen" configuration can generate and control the spin angular momentum content of multiple optical traps.

2. Polarisation control of multiple optical traps

The electric field corresponding to the trapping light can be written as a vector field where the total field is the sum of the orthogonal components. It is useful to use the Jones vector convention to represent different polarisation states,

$$\mathbf{E} = \begin{bmatrix} E_x e^{i\phi_x} \\ E_y e^{i\phi_y} \end{bmatrix} = e^{i\phi_x} \begin{bmatrix} E_x \\ E_y e^{i\delta} \end{bmatrix}. \tag{1}$$

One can see here that controlling the phase difference between the two components δ, determines the polarisation state of the outgoing light. As stated before, δ can be controlled by an appropriately adjusted quarter-wave plate and in our experiment, we choose to control the phase difference with a spatial light modulator.

A spatial light modulator is a computer controlled diffractive optical element which can be used to control the phase $\Phi(x,\ y)$, and amplitude $\mathrm{A}(x,\ y)$, of light [24]. It can be used to simulate simple optical components such as lens, prisms and gratings and for more complex operations such as generating multiple beams. The simplest algorithm to calculate holograms which generate multiple beams relies on the complex addition of the individual beams that are desired. If the complex field distributions of the beams are known, $E_n(x,\ y) = A(x,\ y)e^{i\Phi(x,\ y)}$, the phase of the hologram that is required is given by [9],

$$\phi(x,\ y) = \arg\left(\sum_{n=1}^{N} E_n(x,\ y)\right). \tag{2}$$

The resultant hologram is a superposition of orthogonally orientated diffraction gratings combined with Fresnel lenses. We call this algorithm gratings and lenses [9]. In addition, the phase of the reflected light can be controlled by multiplying the hologram by a constant phase factor $\exp(i\delta)$. This technique for controlling the phase of the reflected light was used by, Maurer *et. al.* [10] who used a spatial light modulator in a "split-screen" configuration to generate a number of different vector beams. The two halves of the spatial light modulator were independently controlled to generate beams of orthogonal polarisations that were subsequently combined but with a well defined phase difference δ between them. Adjusting the phase difference between the beams allowed them to control the polarisation state of the resulting superposition.

In our experiment, we generate multiple optical traps with independent polarisation control through a combination of a gratings and lenses algorithm [9] and the use of the split screen SLM, see Fig. 1. As has been stated, by using two holograms with an overall phase difference of $\pi/2$ we can create a circularly polarised output, where as with 0 phase difference the output will be linearly polarised light. Since multiple traps may be produced by combining differing

#99337 - $15.00 USD Received 25 Jul 2008; revised 10 Sep 2008; accepted 16 Sep 2008; published 22 Sep 2008

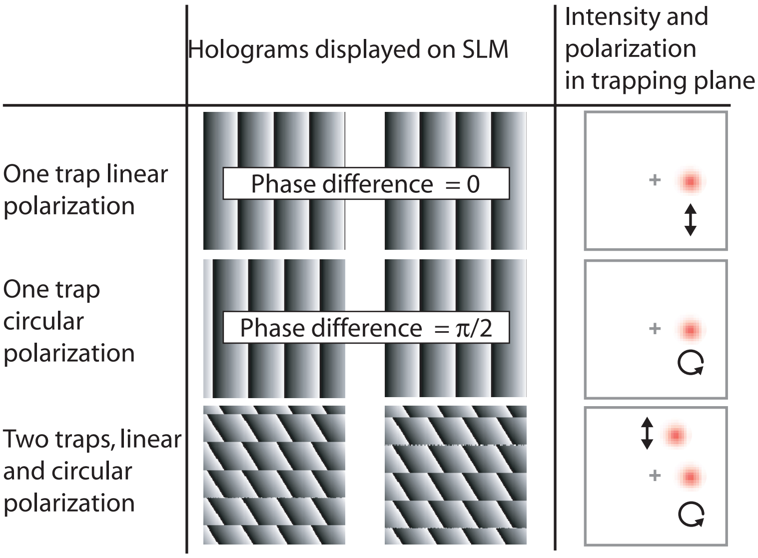

Fig. 1. Illustration of the holograms used to generate beams with independent polarisation control. To produce a single, linearly polarised trap the phase difference between the two holograms on the SLM is 0. To produce a single, circularly polarised trap the phase difference between the two holograms on the SLM is $\pi/2$.

gratings if we adjust the phase difference between the individual gratings on each side of the SLM we can then control the polarisation of individual traps independently.

3. Experiment

The experimental setup is shown in Fig. 2. A 532nm laser (Laser Quantum, Opus) was passed through a $\lambda/2$ wave plate so that the polarisation state of the light was matched to the orientation of the liquid crystal in the spatial light modulator (Holoeye, LCR 3000). The beam was then magnified and collimated via a telescope and split into two beams on passing through a non-polarising beam splitter. Each resulting beam was then incident onto one half of the wide screen spatial light modulator. The polarisation state of each reflected beam was then rotated to so that they could be combined on a polarising beam splitter with orthogonal polarisation. The composite beam was passed to a conventional optical tweezers setup. The tweezers system uses a beam steering mirror, 160mm focusing lenses and an infinity corrected microscope objective (Zeiss, 100x 1.3 NA). A slide sample was illuminated by a standard halogen lamp and imaged onto a CMOS camera (Prosilica, EC1280). A dichroic mirror was used to separate laser light from the illumination light.

The software and hardware interfacing was implemented in the LabVIEW programming environment. Mouse actions were used to define the coordinate system and the polarisation state of the optical traps. The holograms for the SLM that corresponded to these traps positions were generated using the algorithm first reported by Liesener [9], see Eq. 2. The 8 bit grayscale images that were produced were displayed via an extended desktop directly onto the SLM where they where converted into phase holograms.

To calibrate the system, a single birefringent vaterite crystal [25] of a few microns in diameter was trapped in the first diffraction order of the SLM. The crystal will rotate about the optical axis if the trapping light is circularly or elliptically polarised and align itself with the axis of polarisation if the state is linear. It should be noted at this point that each half of the SLM

#99337 - $15.00 USD Received 25 Jul 2008; revised 10 Sep 2008; accepted 16 Sep 2008; published 22 Sep 2008

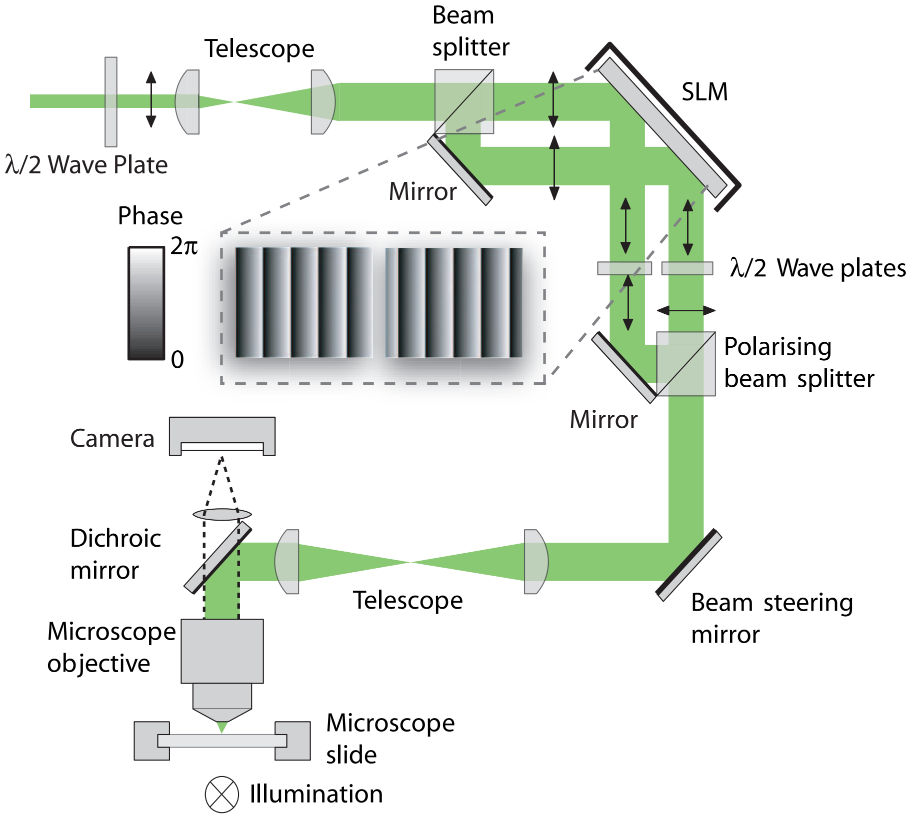

Fig. 2. Experimental set up showing the addition of kinoforms of different gratings to produce variously polarised diffraction orders.

contributes equally to the power in this optical trap. The polarisation state of this trapping beam is therefore defined by the phase difference δ between the beams origination from each side of the SLM. The phase difference between each of these beams was controlled by adding a constant phase offset to one half of the SLM. This was adjusted until the polarisation state was linear and the vaterite crystal did not rotate and was aligned to this axis. From this point, adding a constant phase of $\delta = \pi/2, 3\pi/2$, or π to one half of the SLM allowed us to generate either a circular polarisation state or an orthogonal linear state.

4. Results

To illustrate the functionality and some of the potential applications of our holographic polarisation control we report the controlled manipulation, orientation and rotation of birefringent micro-particles. These particles are single crystals of vaterite, which exhibit a variety of sizes, shapes and birefringence which is highly dependent upon each individual crystal.

When circularly polarised light is incident upon a particle of arbitrary birefringence and orientation, the light transmitted will, in general, no longer be circularly polarised. Consequently, irrespective of the particle the torque will be in the same direction. Hence the direction of rotation is therefore determined only by the handedness of the incident circular polarisation.

When illuminated by linearly polarised light, the transmitted polarisation and hence angular momentum exchange depends upon both the thickness and orientation of the particle. The

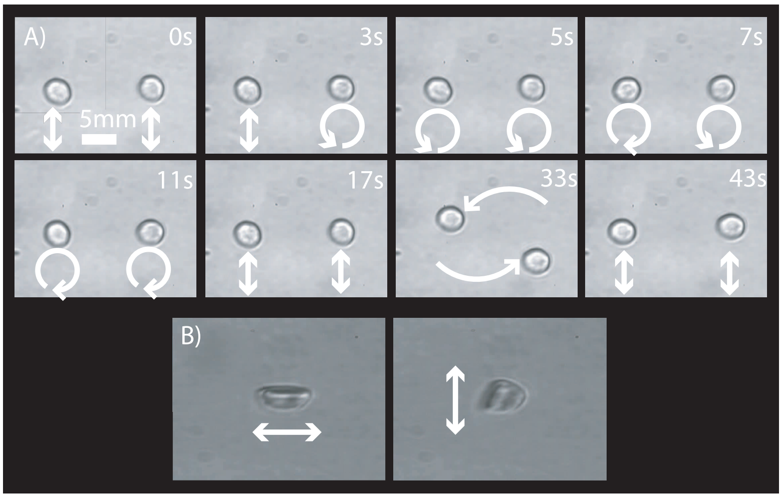

Fig. 3. (a) Image sequence of two birefringent vaterite crystals independently rotated in a holographic optical tweezers. Showing the current polarisation state of the incident light and the translation of the optical traps. (Media 1) 1.2MB (b) Change in particle orientation due to change in polarisation state. (Media 2) 325KB

resulting torque varies in both magnitude and sign such that the particle will always rotate to a stable position aligned to the polarisation direction. Consequently, it is both possible to continuously spin or rotate the particle to a specific orientation by illumination with circularly or linearly polarised light respectively. Because our holographic technique allows both the position and polarisation of the multiple traps to be set independently of each other it has significantly greater flexibility than any system yet reported. We demonstrate the technique for 2 particles as is shown though we believe the technique is extendable to higher numbers based on our preliminary results. This would of course be dependant on laser power, the trap spacing which is limited by the number of pixels on the halved SLM as well as on the quality and number of vaterite particles produced.

Figure 3(a) shows an image sequence illustrating the changing position and rotational sense of two vaterite particles being controlled with the system. At various times in the image sequence each of the particles is set into either clockwise or anticlockwise rotation, by trapping with circularly polarised light, or fixed in orientation by linearly polarised light. Figure 3(b) shows a trapped particle being finely rotated. This is done by changing the polarisation direction of the light.

5. Discussion and conclusions

We have demonstrated the system by independently controlling the rotation and orientation of multiple birefringent vaterite crystals in water. We were able to create multiple traps and dynamically control the position and spin angular momentum content of individual traps. Multiple vaterite particles could be trapped, moved and rotated. The speed of rotation was dependent on the power of the incident beam, however we were regularly able to reach rotation speeds of >30 Hz. The system is particularly useful in the generation of complex flow patterns where the ability to control the spin of multiple particles may prove useful in fields ranging from microfuidics to cell biology as well as microrheology where spinning micro-particles are useful as local probes [26].

#99337 - $15.00 USD Received 25 Jul 2008; revised 10 Sep 2008; accepted 16 Sep 2008; published 22 Sep 2008