Transfer of orbital angular momentum from a super-continuum, white-light beam

Amanda J Wright[1*], John M Girkin[1], Graham M Gibson[2], Jonathan Leach[2] and Miles J Padgett[2]

[1] *Institute of Photonics, SUPA, University of Strathclyde, Glasgow G4 0NW, UK.*

[2] *Department of Physics and Astronomy, SUPA, University of Glasgow, Glasgow G12 8QQ, UK.*

[*] *a.wright@strath.ac.uk*

Abstract: Beams with helical phasefronts described by $\exp(i\ell\phi)$ carry an orbital angular momentum equivalent to $\ell\hbar$ per photon. Using diffractive optics this helical phase structure can be applied to every spectral component of the beam such that a spatially coherent white-light beam can carry orbital angular momentum without any chromatic distortion. This achromatic property can be hard to achieve in spin angular momentum where pure circular polarization is difficult to maintain across a finite spectral bandwidth. We illustrate the achromatic, helical phase structure of a white-light beam by observing the transfer of its orbital angular momentum to particles held in optical tweezers.

OCIS codes: (050.4865) Optical vortices; (260.6042) Singular optics; (230.6120) Spatial light modulators.

References and links

1. J. H. Poynting, "The wave motion of a revolving shaft, and a suggestion as to the angular momentum in a beam of circularly polarised light," Proc. R. Soc. Lond. Ser. A **82**, 560–567 (1909).
2. R. A. Beth, "Mechanical detection and measurement of the angular momentum of light," Phys. Rev. **50**, 115–125 (1936).
3. 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**, 8185–8190 (1992).
4. H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, "Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity," Phys. Rev. Lett. **75**, 826–829 (1995).
5. M. E. J. Friese, J. Enger, H. Rubinsztein-Dunlop, and N. R. Heckenberg, "Optical angular-momentum transfer to trapped absorbing particles," Phys. Rev. A **54**, 1593–1596 (1996).
6. N. B. Simpson, K. Dholakia, L. Allen, and M. J. Padgett, "The mechanical equivalence of the spin and orbital angular momentum of light: an optical spanner," Opt. Lett. **22**, 52–54 (1997).
7. A. T. O'Neil, I. MacVicar, L. Allen, and M. J. Padgett, "Intrinsic and extrinsic nature of the orbital angular momentum of a light beam," Phys. Rev. Lett. **88**, 053601 (2002).
8. V. Y. Bazhenov, M. V. Vastnetsov, and M. S. Soskin, "Laser-beams with screw dislocations in their wave-fronts," JETP Lett. **52**, 429–431 (1990).
9. L. Allen, S. M. Barnett, and M. J. Padgett, *Optical Angular Momentum* (Institute of Physics Publishing, 2003).
10. M. Padgett, J. Courtial, and L. Allen, "Light's orbital angular momentum," Phys. Today **57**, 35–40 (2004).
11. J. Leach, J. Courtial, K. Skeldon, S. M. Barnett, S. Franke-Arnold, and M. Padgett, "Interferometric methods to measure orbital and spin, or the total angular momentum of a single photon," Phys. Rev. Lett. **92**, 013601 (2004).
12. J. Leach and M. J. Padgett, "Observation of chromatic effects near a white-light vortex," New J. Phys. **5**, 154 (2003).

#95133 - $15.00 USD Received 17 Apr 2008; revised 2 Jun 2008; accepted 6 Jun 2008; published 12 Jun 2008

13. I. Mariyenko, J. Strohaber, and C. Uiterwaal, “Creation of optical vortices in femtosecond pulses,” Opt. Express **3**, 7599–7608 (2005).
14. J. E. Curtis and D. G. Grier, “Structure of optical vortices,” Phys. Rev. Lett. **90**, 133901 (2003).
15. J. Leach, G. M. Gibson, M. J. Padgett, E. Esposito, G. McConnell, A. J. Wright, and J. M. Girkin, “Generation of achromatic Bessel beams using a compensated spatial light modulator,” Opt. Express **14**, 5581–5587 (2006).
16. Y. Roichman, B. Sun, Y. Roichman, J. Amato-Grill, and D. G. Grier, “Optical forces arising from phase gradients,” Phys. Rev. Lett. **100**, 013602 (2008).
17. A. Jesacher, C. Maurer, A. Schwaighofer, S. Bernet, and M. Ritsch-Mart, “Full phase and amplitude control of holographic optical tweezers with high efficiency,” Opt. Express **16**, 4479–4486 (2008).
18. Y. Roichman, D. G. Grier, and G. Zaslavsky, “Anomalous collective dynamics in optically driven colloidal rings,” Phys. Rev. E **75**, 020401 (2007).
19. S. Franke-Arnold, J. Leach, M. J. Padgett, V. Lembessis, A. Arnold, A. J. Wright, and J. M. Girkin, “Optical ferris wheel for ultracold atoms,” Opt. Express. **15**, 8619–8625 (2007).

1. Introduction

It is now widely recognized that in addition to linear momentum of $\hbar k_0$, light carries both spin and orbital angular momentum (OAM) of $\sigma\hbar$ and $\ell\hbar$ per photon respectively, where $\sigma = \pm 1$ for left and right circular polarization and $\exp(i\ell\phi)$ describes the helical phase cross-section of the light beam. The spin angular momentum of light and its link to polarization has been known since the time of Poynting [1] and was first transferred from light to matter in the 1930s by Beth [2]. However, although it was recognized that light’s linear momentum acting about a radius vector constituted an OAM it was not until the seminal work of Allen and co-workers in 1992 [3] that it was appreciated that OAM could be a property of laser beams created within a laboratory. The transfer of this OAM to matter came about three years later when Rubinsztein-Dunlop and colleagues observed the optically induced rotation of particles in optical tweezers using a Laguerre-Gaussian laser mode for the trapping beam[4]. Other work followed showing that the spin and OAM components could either add or subtract to make the trapped particle either speed up or slow down [5, 6]. In 2002 it was shown that for beam diameters larger than the trapped particle, the spin angular momentum would cause a birefringent particle to spin about its own axis, whereas the orbital component caused a scattering particle to orbit around the axis of the beam [7].

Prior to a recognition of its momentum properties, helically phased light had been produced as first-order beams, diffracted from a diffraction grating containing a fork dislocation coincident with the beam axis [8]. Such diffraction gratings (holograms) have since been used widely for the generation of beams carrying orbital angular momentum, in experiments ranging from those in optical tweezers, quantum optics and classical beam studies, e.g. see collected papers [9, 10].

Neither the spin nor OAM is a property restricted to monochromatic light. However, the use of forked diffraction gratings to produce broad-bandwidth helically phased beams has a similar problem to that encountered with the use of quarter wave plates to produce circularly polarized light. Although most quarter wave plates are fabricated from a single birefringent material with a thickness set to provide the required phase retardation at one optical wavelength, approximately achromatic waveplates can be made from combining different materials, or Fresnel Rombs and other specialist prisms [11]. In the case of forked diffraction gratings, the diffraction angle depends upon the wavelength of the light, meaning that under normal use, a broad bandwidth beam will be spectrally dispersed. However, in 2003 a white-light vortex beam was produced by imaging the plane of the diffraction grating onto a prism, selected such that the angular dispersion of the grating was negated by the prism whilst leaving the helical nature of each spectral component intact [12]. In an alternative configuration, rather than using a prism, it is also possible to use a second grating [13] to correct for the angular chromatic dispersion.

In this work we show that the OAM from a white-light vortex beam can be transferred to mi-

#95133 - $15.00 USD Received 17 Apr 2008; revised 2 Jun 2008; accepted 6 Jun 2008; published 12 Jun 2008

croscopic particles causing them to orbit around the beam axis. To confirm that the phasefronts are truly helical, and not significantly perturbed by problems associated with dispersion correction, we measure the dependence of rotation rate with the azimuthal index, ℓ, of the beam, relating our results to earlier work by Curtis and Grier [14].

2. Experimental configuration

Figure 1 shows a schematic representation of the experiment. The output from a modelocked Ti:sapphire laser (Spectra Physics Mai Tai) was coupled into a photonic crystal fibre, the non-linear action of which created a spatially coherent beam with a broad spectrum 475-600nm [15] (see fig. 2). This near white-light output from the fibre was collimated using an achromatic microscope objective (Nikon, 20x 0.5NA Plan Fluor) and then made incident upon a spatial light modulator (SLM) (HoloEye, LC-R 2500) which was programmed to display a forked hologram. The first-order diffracted beams with helically phased wavefronts were now angularly dispersed, meaning that the various spectral components were laterally displaced in the focal plane of the transform lens. This dispersion was corrected by imaging the plane of the hologram onto a small angle prism, specified to negate the angular chromatic dispersion. Thus, immediately after the prism, all the spectral components were helically phased, collimated and co-linear. This white-light beam was then coupled into the tweezers system using a second 4f lens arrangement to image the prism on to the back aperture of the microscope objective. The tweezers were based around an inverted microscope (Nikon TE2000) using a 100x 1.3NA Plan Fluor objective lens to both focus the white-light trapping beam and view the resulting motion of the particles. In order to view the trapped particles, a narrow-band filter was placed in the collimated portion of the white-light beam to remove light at 514nm. A filter that transmitted light at 514nm was then placed in front of the viewing camera such that the particles could be viewed using the 514nm component of the illumination source for the microscope without the white-light super-continuum saturating the camera. Unlike conventional tweezers, where the tightly focused Gaussian trapping beam ensures trapping of the particle in 3-dimensions, the extended cross-section of the vortex beam means that the particles were only confined laterally by the annular intensity distribution of the beam. If the particles were simply suspended in the bulk fluid then they would be subjected to a recoil force, propelling them rapidly along the axis of the beam and out of the image plane of the microscope. To axially confine the 1μm diameter polystyrene particles we prepared the sample cell as a thin ($< 100\mu$m) water layer between a microscope slide and cover slip. In this way the particles were held in the image plane but responded to the transverse forces associated with the both annular intensity gradient and the OAM (i.e. phase gradient [16, 17]). The particle motion was imaged using a CCD (QImaging, Retiga Exi) with a firewire interface to a desktop PC so that the individual images could be acquired and the particle motion analyzed.

3. Orbiting of microscopic particles in a helically phased beam

Helically phased beams are typified by the Laguerre-Gaussian laser modes. In their simplest form, with a radial mode index $p = 0$, they comprise single bright annular rings with an azimuthal phase term of $\exp(i\ell\phi)$. The peak intensity radius of the ring is given by $r_{max} = w\sqrt{\ell/2}$. The azimuthal phase term means that the local direction of the Poynting and wavevectors are skewed with respect to the optical axis of the beam by an angle $\alpha = \ell/kr$, where $k = 2\pi/\lambda$ and r is the radius from the beam axis. Any particle within the annular ring of light will scatter light and assuming it is larger than the width of the annular ring will experience a recoil force, with an azimuthal component, F_{recoil}, given by

$$F_{recoil} \propto \frac{P}{2\pi r}\frac{\ell}{kr} \tag{1}$$

#95133 - $15.00 USD Received 17 Apr 2008; revised 2 Jun 2008; accepted 6 Jun 2008; published 12 Jun 2008

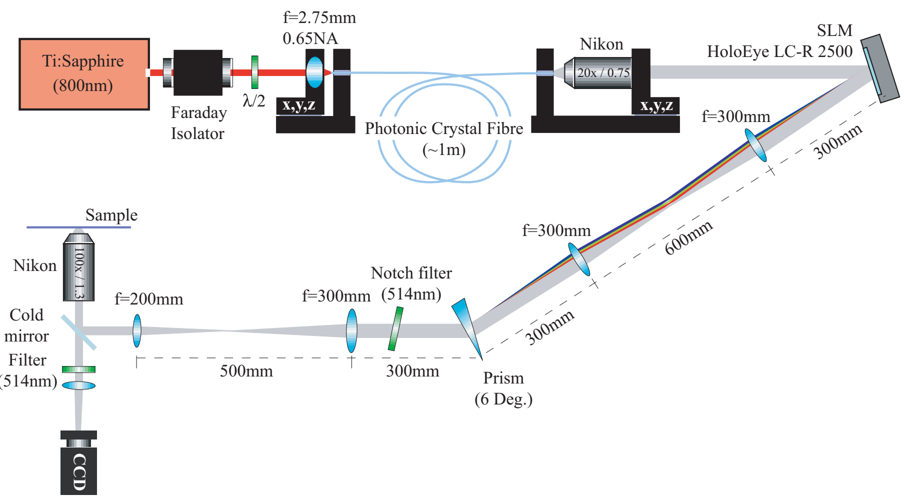

Fig. 1. Schematic representation of the experimental setup. A short pulsed Ti:Sapphire laser beam of 800nm was coupled into a photonic crystal fibre with a zero dispersion at 750nm to produce a white-light super-continuum. The beam was then incident on a SLM displaying a forked hologram to generate a Laguerre-Gaussian beam. A 6 degree prism corrected for the angular chromatic dispersion in the positive first-order beam and this was re-imaged onto the back aperture of a high numerical aperture microscope objective. A notch filter at 514nm was placed in the white-light super-continuum and a narrow pass 514nm filter was placed in front on the CCD camera, this allowed the sample to be viewed using the normal microscope illumination system without the white-light super-continuum saturating the camera.

If the particle is also confined to the ring by the intensity gradient force it will orbit around the beam axis at a speed such that the recoil force is balanced by the Stoke's drag force. The recoil force would also be expected to scale with the optical power incident on the particle. Thus for a ring of radius, r, we have a rotation rate, R, given by [14]

$$R \propto \frac{P}{2\pi r^2} \frac{\ell}{kr} \tag{2}$$

where P is the optical power of the annular beam.

It is intuitive to simplify this relationship by expressing the radius in terms of ℓ but as discussed in reference [14] this is problematic since in a real optical system, of finite aperture, the radius of maximum intensity cannot scale indefinitely with $\sqrt{\ell}$. Consequently, within our experiments we measure directly from the images the radius at which the particles are orbiting. The dependence of rotation rate on ℓ and r is a stringent test of the helical nature of the produced beam and its OAM content.

4. Results

Figure 3 shows images of the positive first-order diffracted beam and the negative first-order. The effect of the dispersion correction is clear, namely that the various spectral components of the positive first-order overlap and are collinear. Figure 4 is a series of images showing the orbiting of micron sized polystyrene particles around the beam axis for two different values of ℓ. In addition to the strength of the azimuthal recoil force, the rotation rate depends upon the number of particles confined within the ring. The equilibrium speed of a particle orbiting within

#95133 - $15.00 USD Received 17 Apr 2008; revised 2 Jun 2008; accepted 6 Jun 2008; published 12 Jun 2008

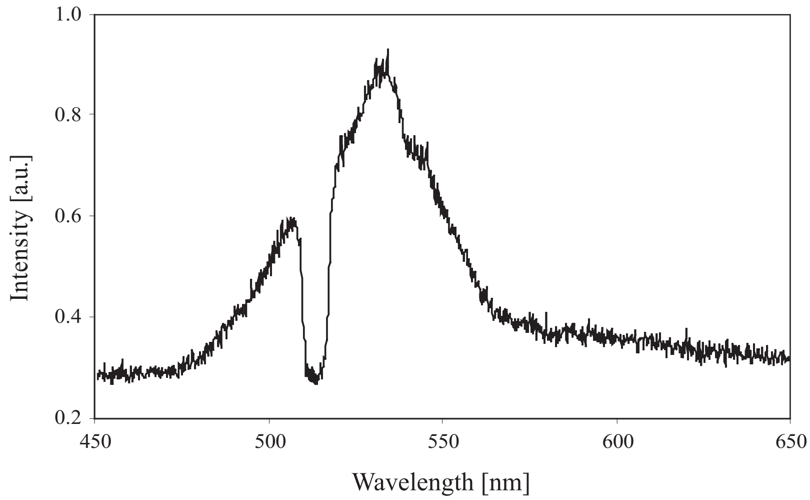

Fig. 2. Near white-light output from photonic crystal fibre. A filter is used to block out component at 514nm.

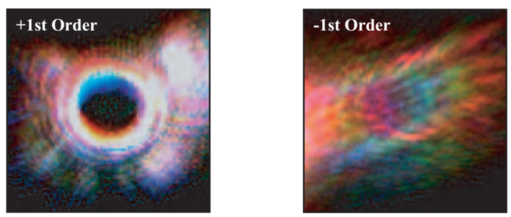

Fig. 3. Images of both the positive and negative first diffraction orders at the focus of the microscope objective. The prism angle was selected to correct for chromatic dispersion in the positive first-order beam and, as a result, the chromatic dispersion in the negative first-order beam was increased.

the ring depends upon Stoke's drag force, which is modified by the proximity of any neighboring particles. For example, two particles traveling together will always catch one particle on its own. Consequently, if multiple particles are circulating within a ring the tendency is that they orbit as a continuous chain [18]. Therefore, as ℓ is varied it is important to keep the number of particles in the ring a constant. In this work we found that three particles were an optimum number. Three is small enough so that even at low ℓ-values (i.e. low circumference) the lead particle is still separated from the trailing one, yet the use of multiple particles increases the scattering force so that there is a significant rotation rate even for the lower powers obtainable from our white-light super-continuum beam. Figure 5 shows the measured size of the annular ring and the rotation rate for three particles orbiting around the beam axis as a function of azimuthal mode index ℓ. We note that this relationship is in close agreement with equ. 2, confirming the helical nature of our white-light super-continuum beam.

5. Discussion and conclusions

The work of [14] also reported an interesting effect related to intensity modulations within the ring that arise from imperfections of the SLM. The kinoform used in that work was an on-axis hologram where the various diffraction orders are collinear. In that case one relies explicitly on the quality of the SLM diffracting the light as intended and suppressing the intensity of

#95133 - $15.00 USD Received 17 Apr 2008; revised 2 Jun 2008; accepted 6 Jun 2008; published 12 Jun 2008

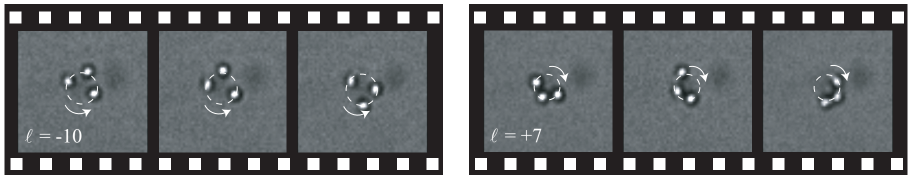

Fig. 4. Series of images showing the micron sized particles orbiting around the beam axis, illustrating that the rotation direction changes according to the sign of ℓ.

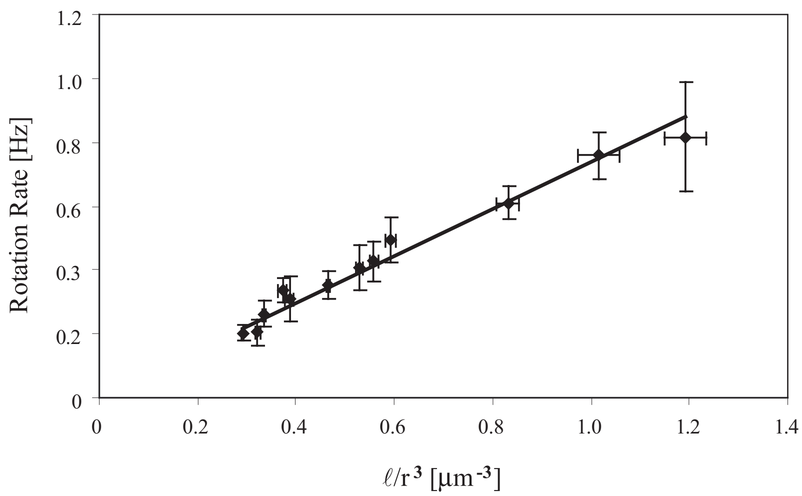

Fig. 5. Plot of ℓ/r^3 against the rotation rate for three particles orbiting around the beam axis, where r is the measured radius of the annular ring and ℓ is the azimuthal mode index.

the unwanted, but overlapping, orders. Should the SLM be imperfect then this will not be the case and the zero-order beam results in an on-axis intensity maximum. The negative first-order produces a beam with the opposite value of ℓ which overlaps, and interferes, with the positive first-order giving an annular ring with $2|\ell|$ intensity maxima, the contrast being determined by the relative intensity of the positive and negative diffraction orders [19]. This intensity modulation around the ring can cause particles to become fixed within a local intensity maxima, preventing a smooth orbital motion. These interference effects between diffraction orders are eliminated by using an off-axis kinoform, e.g. the forked hologram which spatially separates the various orders. However, as demonstrated here, if used with a wide bandwidth source this of axis kinoform requires dispersion compensation.

We have established that by using a prism to compensate for the chromatic dispersion inherent to a diffractive optical component it is possible to create a helically phased beam with sufficient fidelity that its OAM is not compromised. Our results for the orbiting of multiple particles around the annular ring of the helically phased beam are similar to those previously reported [14] for monochromatic light, showing the same dependence on both azimuthal mode index of the helically phased beam and radius of the annular ring.

Acknowledgments

This work was supported by the EPSRC, AJW is supported by the Royal Academy of Engineering/EPSRC.