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OPTICAL TRAPPING AND OPTICAL BINDING USING CYLINDRICAL VECTOR BEAMS

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(Invited paper)

ABSTRACT. We report on the use of cylindrical vector beams for optical manipulation of micron and sub-micron sized particles using the methods of a single-beam gradient force trap (optical tweezers) and an evanescent-field surface trap (optical binding). We have demonstrated a stable interferometric method for the synthesis of cylindrical vector beams (CVBs), and present measurements demonstrating polarization-controlled focal volume shaping using CVBs in an optical tweezers. Furthermore we show how appropriate combinations of CVBs corresponding to superpositions of optical fibre modes can be used for controlled trapping and trafficking of micro- and nanoparticles along a tapered optical fibre.

1. Introduction

Cylindrical vector beams (CVBs) are the family of solutions to the vector wave equation in the paraxial limit [1]. The lowest-order members of the set are the beams with radially or azimuthally directed polarization, that is the polarization is everywhere linear but changing in direction, such that the polarization vector makes one complete rotation on a trajectory about the beam axis. These beams have a 'doughnut' shaped intensity profile with a zero of electric field on axis due to the polarization vortex. Higher-order azimuthal modes have more than one rotation of the polarization vector, whereas higher radial modes have a number of radial nodes in the electric field, and thus appear as a series of concentric rings. Such laser beams that possess a non-uniform polarization direction are attracting considerable interest for a variety of novel applications. Here we concentrate on two particular properties with potentially useful applications for optical manipulation of micron and sub-micron scale material, namely the behaviour of such beams in the limit of high numerical aperture (NA) focusing [2, 3], and the similarity of the polarization distribution of these beams to those of the higher modes of a cylindrical dielectric waveguide (optical fibre) [4, 5].

2. Synthesis of cylindrical vector beams

A number of methods of producing CVBs exist, such as liquid crystal devices [6], segmented waveplates [7] and interferometric techniques [8]. Of these, interferometry is particularly attractive as it allows the production of both higher order (multi-ring) radial modes [9], and higher order azimuthal modes where the polarization direction makes a number of rotations about the beam axis [10]. We have demonstrated a method for synthesizing CVBs that uses a Sagnac interferometer which includes a device for helical phase modulation of a laser beam [11]. The Sagnac interferometer presents advantages over other techniques as the two interfering beams cover the same physical path, making it insensitive to relative phase fluctuations. We use this flexible interferometric method for synthesizing CVBs with a polarization directed at an arbitrary angle to the beam radius, and thus continuously variable from the radially polarized beam through arbitrary superpositions to the azimuthally polarized beam. We have used the output of the interferometer as the trapping beam in an optical tweezers in order to investigate the sensitivity of the optical trap to polarization state, and to implement polarization controlled shaping of the optical potential for sub-micron sized particles.

3. Applications to optical tweezers

An optical tweezers is a device for the non-contact trapping and manipulation of microparticles using a single, strongly focused laser beam. The device exploits the strong gradient in intensity across the waist produced by a high NA lens to confine particles in three dimensions in an approximately harmonic potential, characterized by a spring constant related to the curvature of the potential. While simple models for predicting optical trapping parameters based on ray-optics (for large particles) or point dipoles (for small particles) have long been used, it is only very recently that a full electromagnetic scattering description of optical trapping providing quantitative agreement between experiment and theory has been achieved [12]. In such a model the polarization state of the trapping beam plays a significant role in determining the shape of the the optical potential. The vast majority of experimental realizations of optical tweezers to date use a trapping laser beam with a spatially homogeneous state of polarization, however spatial modulation of the polarization of the trapping beam has the potential to add a further degree of control to the field distribution in the region of the focus [13], and hence the optical trapping parameters thus permitting further optimization of the trap for certain particle types [14, 15]. Furthermore due to symmetries in the polarization components, the time-averaged axial component of the Poynting vector is zero and thus the scattering force vanishes, making the CVB optical tweezer an ideal candidate for trapping nano-particles. We have investigated the effects of a spatially inhomogeneous beam on the trapping of a variety of particles, ranging from micrometre to sub micrometre in size by performing a three-dimensional tracking of the fluctuations in position of a trapped particle as it performs Brownian motion in an optical trap [16, 17]. We show that for sub-micron particles the additional degree of freedom present in a CVB allows us to control the optical trap strength and geometry by adjusting the polarization of the tapping beam only.

4. Applications to optical binding

‘Optical binding’ is the term applied to the self-organization of micron scale colloidal material into one- and two-dimensional periodic structures in an evanescent optical field [18]. Typically this is realized using a laser beam incident on an interface between relatively higher- and lower- refractive index media at an angle the slightly exceeds the critical angle for total internal reflection. In such a scenario, microparticles suspended in water can be held by an evanescent field in a ‘surface trap’ above a glass prism.

An alternative scheme for accessing evanescent wave interactions is to use a laser beam in an optical fibre that is tapered to a $\lesssim 1\mu\mathrm{m}$ diameter waist. In the region of the taper a large fraction of the optical power propagates in an evanescent field surrounding the remaining glass core [19]. Figure 1 shows optical binding to, and propulsion along such a tapered optical fibre of a 2 μm diameter polystyrene sphere. Here we present results on the experimental fabrication of tapered optical fibres for use in evanescent-wave optical binding by a ‘heat-and-pull’ method. We also present calculations of the evanescent field distributions in the region of the taper, demonstrating how appropriate superpositions of fibre modes (corresponding to superpositions of cylindrical vector beams) can be used to produce optical binding sites at controlled locations around the circumference of the tapered fibre. We further calculate the optical potential for metallic nanoparticles in the tapered fibre evanescent field, and suggest configurations of fibre modes for two-colour (bichromatic) stable trapping or directed trafficking of nanoparticles that exploits the enhanced optical forces for wavelengths close to the nanoparticle’s plasmon resonance wavelength.

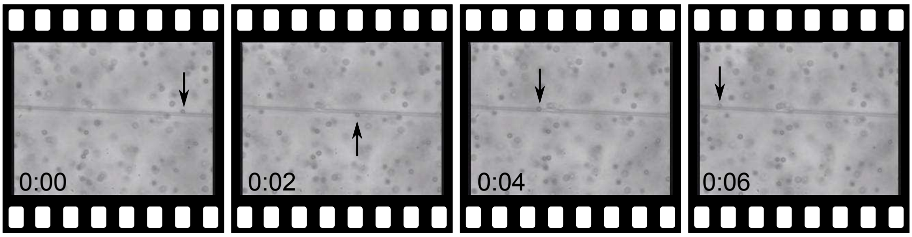

Figure 1. Sequence of frames taken from a movie at intervals of 2 s showing optical binding and propulsion of a 2 μm diameter polystyrene sphere (indicated by the back arrow) in the evanescent field surrounding a tapered optical fibre.

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References

[1] D. G. Hall, “Vector-beam solutions of Maxwells wave equation”, *Opt. Lett.* **21**, 9–11 (1996).

[2] R. Dorn, S. Quabis and G. Leuchs, “Sharper focus for a radially polarized light beam”, *Phys. Rev. Lett.* **91**, 233901 (2003).

[3] L. Novotny and B. Hecht, *Principles of Nano-Optics*, Edition (Cambridge University Press, Cambridge, United Kingdom, 2006)

[4] K. Kawano and T. Kitoh, *Introduction to Optical Waveguide Analysis*, Edition (John Wiley & Sons, New York, USA, 2001)

[5] F. Gori, “Polarization basis for vortex beams”, *J. Opt. Soc. Am. A* **18**, 1612–17 (2001).

[6] M. Stalder and M. Schadt, “Linearly polarized light with axial symmetry generated by liquid-crystal polarization converters”, *Opt. Lett.* **21**, 1948-1950 (1996).

[7] G. Machavariani, Y. Lumer, I. Moshe, A. Meir and S. Jackel, “Efficient extracavity generation of radially and azimuthally polarized beams”, *Opt. Lett.* **32**, 1468-1470 (2007).

[8] V. G. Niziev, R. S. Chang and A. V. Nesterov, “Generation of inhomogeneously polarized laser beams by use of a Sagnac interferometer”, *Appl. Opt.* **45**, 8393 (2006).

[9] X.-L. Wang, J. Ding, W.-J. Ni, C.-S. Guo and H.-T. Wang, “Generation of arbitrary vector beams with a spatial light modulator and a common path interferometric arrangement”, *Opt. Lett.* **32**, 3549 (2007).

[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).

[11] P. H. Jones, M. Rashid, M. Makita and O. M. Maragò, “Sagnac interferometer method for synthesis of fractional polarization vortices”, *Opt. Lett.* **34**, 2560-2562 (2009)

[12] F. Borghese, P. Denti, R. Saija and M. A. Iatí, “Optical trapping of non-spherical particles in the T-matrix formalism”, *Opt. Express* **15**, 11984-11998 (2007)

[13] M. Rashid, O. M. Maragò and P. H. Jones, “Focusing of high order cylindrical vector beams”, *J. Opt. A: Pure. Appl. Opt.* **11**, 065204 (2009).

[14] Q. Zhan, “Optical radiation forces on a dielectric sphere produced by highly focused cylindrical vector beams”, *J. Opt. A, Pure Appl. Opt.* **5**, 229-232 (2003).

[15] H. Kawauchi, K. Yonezawa, Y. Kozawa and S. Sato, “Calculation of optical trapping forces on a dielectric sphere in the ray optics regime produced by a radially polarized laser beam”, *Opt. Lett.* **32**, 1839-1841 (2007).

[16] O. M. Maragò, P. H. Jones, F. Bonaccorso, V. Scardaci, P. G. Gucciardi, A. Rozhin and A. C. Ferrari, “Femtonewton Force Sensing with Optically Trapped Nanotubes”, *Nano Letters* **8**, 3211–3216 (2008).

[17] O. M. Maragò, F. Bonaccorso, R. Saija, G. Privitera, P. G. Gucciardi, M. A. Iatí, G. Calogero, P. H. Jones, F. Borghese, P. Denti, V. Nicolosi and A. C. Ferrari, “Brownian motion of graphene”, *ACS Nano* **4** 7515–7523 (2010).

[18] C. D. Mellor and C. D. Bain, “Array formation in evanescent waves”, *ChemPhysChem* **7**, 329–332 (2006).

[19] F. L. Kien, J. Q. Liang, K. Hakuta and V. I. Balykin, “Field intensity distributions and polarization orientations in a vacuum-clad subwavelength-diameter optical fiber ”, *Opt. Commun.* **242**, 445–455 (2004).

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