Biaxial crystal-based optical tweezers

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Abstract

We suggest an optical tweezer setup based on an optically biaxial crystal. To control movements of opaque particles, we use shifts. The results of experimental studies are reported which are concerned with this laser tweezer setup. We demonstrate a movement of microparticles of toner using a singular-optical trap, rotation of particles due to orbital angular momentum of the field, and converging or diverging of two different traps when changing transmission plane of polariser at the input of our polarisation interferometer.

Keywords: optical tweezers, biaxial crystals, shift polarisation interferometer, singular-optical trap

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1. Introduction

Since the introduction, in 1986, by A. Ashkin and his collaborators of a first optical trap keeping microparticles in space [1], many kinds of optical tweezers have been developed, and numerous areas for application of those devices have been revealed [2–5]. There are, first of all, gradient traps based on a focused Gaussian laser beam mode T_{00}. The use of Bessel beams has facilitated much larger intensity gradients in the transverse cross section of the beam and construction of so-called diffraction light pipes for transporting microscopic objects at larger distances [6]. Holographic schemes are the most usual for arranging optical traps [7–9]. Using a generalised contrast technique [10] or spatial light modulators [11, 12], one can form several individual beams for manipulating of microparticles.

Gradient traps capture transparent micro- and nanoparticles with large refractive indices. Ring-like light traps are more efficient for particles with high optical reflectivity or with the refractive index close to unity. Ashkin [13] has developed the concept of single-beam laser tweezers based on higher-order laser modes, such as Hermite-Gaussian (TEM_{xy}), Laguerre-Gaussian (LG, TEM_{pl}) and Bessel (J_n) beams. Laser tweezers based on the Laguerre-Gaussian beams with optical singularities reveal unique features while trapping particles. Besides, the Laguerre-Gaussian beams possess an angular momentum, which can be used for rotating microparticles [14].

Investigation of the behaviour of electromagnetic fields in the vicinity of singular points (referred to also as amplitude zeroes, vortices or wave-front dislocations) is of great interest [15, 16]. It is, in part, stimulated by significant progress in nanotechnologies. If an opaque particle is placed in the centre of a scalar vortex, it is caught by the vortex and can rotate due to different pressures of light at the centre and at the periphery [17]. These traps are formed by focusing the beams generated by computer-synthesised holograms [18]. However, tweezers based on simple singular beams have an important limitation, *viz.* one cannot make several microobjects converge using such the devices. In order to facilitate this feature, it is necessary to overcome the intensity barrier of the bright ring surrounding the vortex centre. Notice that the limitation is absent in self-converging tweezers [19]. In this paper we represent a new version of these optical tweezers.

In brief, we have designed our optical tweezers using a biaxial crystal. To control the motion of an opaque particle, we use polarisation shift interferometer. By changing the azimuth of linear polarisation at the interferometer output, one can make two traps converge or diverge. Changes in the optical path difference between eigenmode beams propagating in the interferometer result in displacement of a trap. Finally, utilisation of a divergent beam at the input of polarisation interferometer results in multiplication of the number of traps.

2. Theoretical basis and experimental setup

Let us consider a plane-parallel plate of an optically biaxial crystal, with its surfaces perpendicular to the plane of optic axes. In this case, the phase velocities of orthogonal waves propagating in a crystal along the direction, which make the angles ϑ_1 and ϑ_2 with the optic axes of the crystal, are linked via the relation [20]

$$(\upsilon_p^{/})^2-(\upsilon_p^{//})^2=(\upsilon_x^2-\upsilon_y^2)\sin\vartheta_1\sin\vartheta_2\,, \quad (1)$$

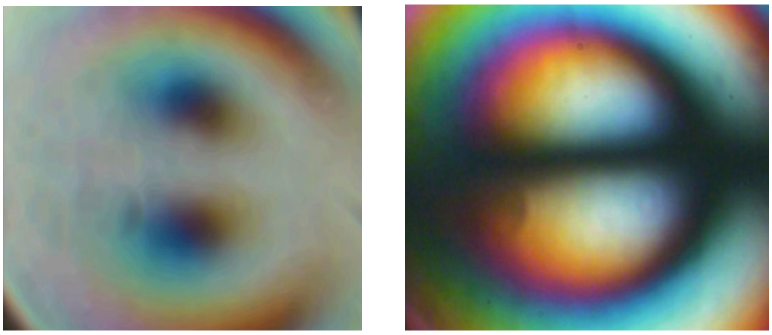
where $\upsilon_p^{/}$ and $\upsilon_p^{//}$ are the phase velocities sought for, and υ_x and υ_y the phase velocities referred respectively to the principal crystal axes x and y,

Putting $\upsilon_p=c/n$ and $\upsilon_{x,y}=c/n_{x,y}$ (with n_x and n_y being the refractive indices for the principal axes x and y), one can rewrite Eq. (1) in the following form:

$$\left(\frac{1}{(n^{/})^2}\right)-\left(\frac{1}{(n^{//})^2}\right)=\left(\frac{1}{n_x^2}-\frac{1}{n_y^2}\right)\sin\vartheta_1\sin\vartheta_2\,, \quad (2)$$

where $n^{/}$ and $n^{//}$ denote the refractive indices for the orthogonal eigenmode beams. Issuing from Eq. (2), one can determine the optical path difference between those beams and obtain a conoscopic pattern for the biaxial crystal placed between two polarisers.

Theoretical and experimental aspects of formation of singularities in biaxial crystals have been considered elsewhere [21–23]. A possibility for formation of optical traps has been demonstrated with the experimental setup shown in Fig. 1. It is feasible even in the case a white light used [24]. Here we use a film of polyethylene terephthalate, which represents a biaxial crystal. It has been prepared so that the bisector of the two optic axes is orthogonal to the film surface. The film thickness is equal to 74 µm and the birefringence is 0.085 [24]. Fig. 1a and Fig. 1b show the field distributions obtained respectively for the matched and crossed polariser–analyser systems.



a b

Fig. 1. Conoscopic patterns obtained for the geometries of parallel (a) and crossed (b) polarisers, respectively.

Using the interference diagnostics, the authors have shown that two wave dislocations of the opposite signs are in fact present in Fig. 1a [24–26]. To control the traps, we use a polarisation shift interferometer [27]. The latter permits us moving the traps, multiplexing them, and making two or more traps converge or divergence.

The polarisation interferometer setup is shown in Fig. 2. It consists of two identical birefringent wedges, forming a plane-parallel plate, which are placed between crossed polarisers [27]. The principal optic axes of those wedges, 2 and 3, make the angle of 45^0 with respect to the polarisation planes of polarisers 1 and 5. The optical paths of the eigenmode beams, "1" and "2", in this scheme are shown in Fig. 2, too. The two beams are spatially separated at the output of the first wedge 3. A longitudinal shift of the mentioned beams is compensated by a plane-parallel plate 2. It is made of the same material as the wedges. Its thickness is equal to the total thickness of those wedges and the orientation of its principal optic axis is kept orthogonal with respect to the orientation of the wedge axes.

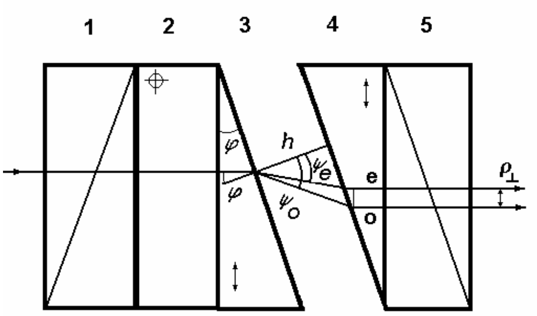


Fig. 2. Optical scheme of our polarisation interferometer: 1 and 5 – polarisers; 2 – calcite plate; 3 and 4 – calcite wedges.

The optical arrangement aimed at practical realisation of the tweezers based on biaxial crystals is shown in Fig. 3. A quarter-wave plate 2 makes the incident radiation of a

He-Ne laser (the wavelength λ = 0.6328 μm and the optical power 20 mW) circularly polarised. Then the beam is expanded by a special system 4 and directed by an objective 5 towards a polymer crystalline plate 6. An objective 7 forms a plane wave incident on the polarisation interferometer (calcite wedges 8 and a polariser 9). A polarisation cube 10 totally reflects the laser beam, and a 40^x microobjective 11 focuses it at particles 12 under test, which are placed in the immersion oil between glass substrates. One can observe particles in the white light, using an illuminator (items 13–15 in Fig. 3) and a CCD-camera 17. A very small portion of the reflected laser radiation (about 0.2%) is reflected by a glass substrate and also hits the CCD-camera. That is why we can observe a trap formed in the laser beam.

Trapping of a particle is implemented in the following way. If the laser channel forming the trap is turned off, then the centre of a grid cross in the visualisation channel, which is aligned with the centre of the trap, is combined with the particle. If the laser channel is turned on, a particle appears at the centre of the ring trap.

A displacement of the particle within the distance of 5 μm occurs owing to changing path difference between the eigenmode beams in the polarisation interferometer. In its turn, this is achieved via movements of one of the two wedges 8. Larger displacements could be provided by the polarisation cube 10, using a precisely controlled mechanical system. It is possible to move a table at which the sample 12 is mounted, when the trapped particle remains fixed.

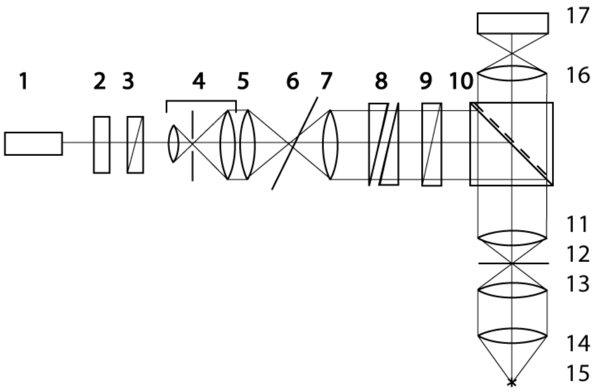


Fig. 3. Optical arrangement of a tweezer based on biaxial crystal: 1 – laser; 2 – quarter-wave plate; 3 and 9 – polarisers; 4 – beam expander with spatial filter; 5, 7, 11, 13, 14 and 16 – microobjectives; 6 – biaxial crystal plate (polyethylene terephthalate film); 8 – calcite wedges; 10 – polarisation cube; 12 – sample under study; 15 – white-light source; 17 – CCD-camera.

3. Results

The results of experimental studies for the functioning of the laser tweezers are shown in Fig. 4 to Fig. 8. In particular, Fig. 4 shows a change in the conoscopic pattern obtained in a beam propagating along one of the two optic axes of the biaxial crystal when the transmission plane of the polariser is rotated. Two phase singularities of the opposite signs are nucleated for the matched polariser and analyser. Depending on a problem being solved, one can use one (for displacement of a particle) or two (for bringing two particles together) singularities.

Fig. 5 demonstrates how to make two traps converge. Rotation of the polariser 3 in Fig. 3 yields in annihilation of the two singularities. When these singularities trap two microparticles, the latter can be converged or diverged.

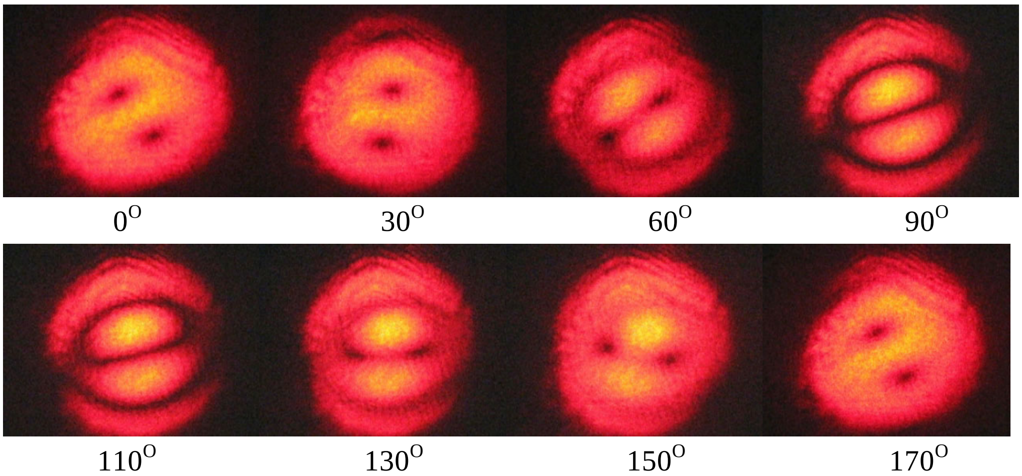


Fig. 4. Conversion of two traps when changing the plane of polariser (movie 4).

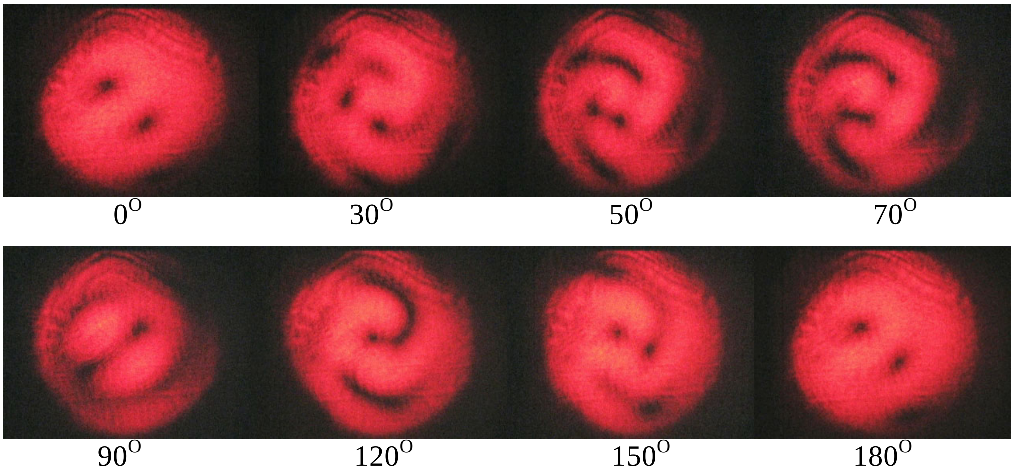


Fig. 5. Convergence of two traps when changing the angle between the polarisers 3 and 9 (movie 5).

Fig. 6 demonstrates how a microparticle of toner, with the linear size of 8 μm and the mass about 0.25 μg, moves in the immersion oil (the oil DIFFELEN used for diffusion pumps, with the density of 0.87 g/ml) using a singular-optical trap. The microparticle is trapped by the tweezer based on the phase singularity and is retained under displacement of the table with the sample. The force affecting the particle is about 5 pN. It provides the maximal velocity of about 50μm/s for the linear displacement of microparticles. Due to the orbital momentum, about 10^{-18} Nm, the trap can also rotate the particle (see Fig. 7).

Finally, Fig. 8 shows converging of three particles. One of them is kept by the singular trap (red ring), and the other two are led towards it by the self-converging trap, as shown in Fig. 5. This trap is not seen in the figure, since it is formed by the laser beam propagating at some angle with respect to the first trap and remains out of the microobjective aperture.

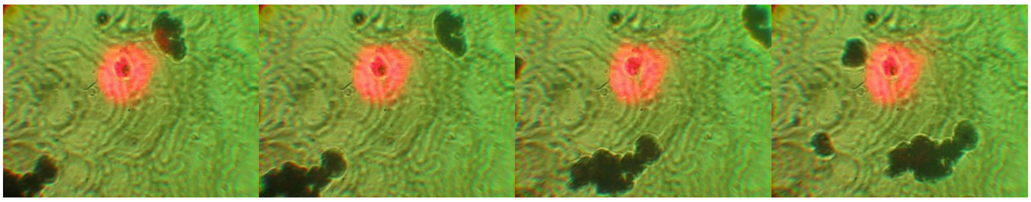


Fig. 6. Movement of a microparticle (movie 6).

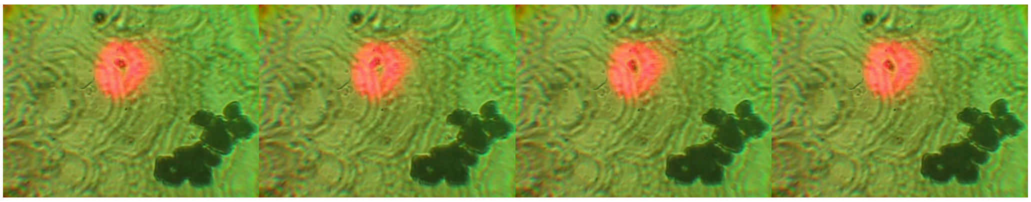


Fig. 7. Rotation of a particle due to orbital momentum (movie 7).

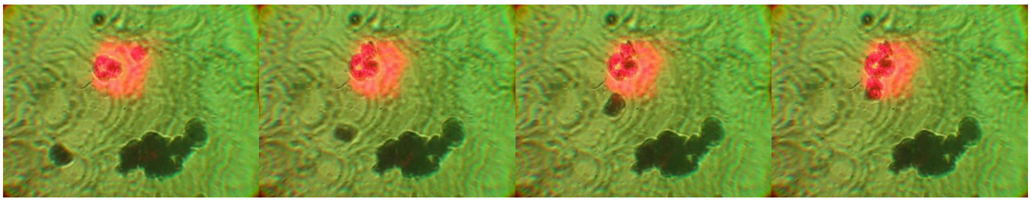


Fig. 8. Convergence of three particles (movie 8).

4. Conclusion

Let us summarise the results. The main advantage of the optical tweezers designed here consists in their potential for converging and diverging microparticles. Besides, the formation of self-converging optical traps based on the biaxial crystals provides an evident advantage concerned with energy consumption. In fact, one can utilise more that 50% of the laser power.

The optical tweezers elaborated by us can also operate with the white light. However, in this case one must provide precise compensation of the optical path difference of the eigenmode beams in the polarisation interferometer, using the calcite plate 2 shown in Fig. 2.

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Анотація. *Запропоновано схему оптичного пінцета, що базується на використанні двовісних кристалів. Для керування рухом непрозорих частинок використано поляризаційний інтерферометр зсуву. Наведено результати експериментального дослідження можливостей цієї схеми пінцета. За допомогою сингулярного-оптичної пастки продемонстровано рух мікрочастинок тонера, обертання частинок, зумовлене орбітальним кутовим моментом поля та зведення двох пасток при повороті лінійного поляризатора на виході поляризаційного інтерферометра.*