Diffractive optical elements for capturing and controlled rotation of micro-objects

Ganchevskaya S.V., Skidanov R.V.

Image Processing Systems Institute, Russian Academy of Sciences,
Samara State Aerospace University

Abstract. A method is proposed for the controlled rotation of microobjects in non-ring vortex light fields generated by vortex axicons. In the real experiment, the rotation of the group of polystyrene microparticles with a diameter of 5 μm is carried out.

Keywords: light beams, vortex axicon, optical micromanipulation, rotation of particles.

Citation: Ganchevskaya S.V., Skidanov R.V. Diffractive optical elements for capturing and controlled rotation of micro-objects. Proceedings of Information Technology and Nanotechnology (ITNT-2015), CEUR Workshop Proceedings, 2015; 1490: 53-60. DOI: 10.18287/1613-0073-2015-1490-53-60

Introduction

Vortex light beams are used for transmission of information [1], in optical inspection systems [2], in optical micromanipulation [3, 4]. The presence of orbital angular momentum is determined by the use of optical vortex beams, especially for the rotation of microobjects. Most of the used vortex beams have a distinct ring structure. But there are light beams that have a more complex structure [5, 6], in the form of closed light lines. Optical actuator for micromechanical systems [7 – 12] is typically considered as the practical use of such light beams, but there are many other practical issues in the field of micromanipulation using vortex beams [13, 14].

1. Formation of the superposition of light fields by vortex axicons.

Diffractive helically-formed axicon is described by a function of complex transmission of the following form:

$$\tau(r,\phi) = \exp\left(i2\pi\nu r\right)\exp\left(in\phi\right), \tag{1}$$

where r, φ are polar coordinates in the plane of the DOE, υ is the spatial frequency of the lines of the axicon, n is the number of the helical component. When light passes through the axicon, a Bessel beam of the n-power is formed, $J_n(\alpha r)$, where $\alpha = k\cos(\upsilon\lambda)$ (k – wave number).

In accordance with one work [15], it is provided to generate Bessel beams using the DOE with a transmission function

$$\tau(r,\phi) = \operatorname{sgn}\left(J_n\left(\alpha r\right)\right)\exp\left(in\phi\right). \tag{2}$$

Helical DOE with the transmission (1) effectively forms a light field, the amplitude of which is proportional to the Bessel function $J_n(\alpha r)\exp(in\varphi)$, near the optical axis on the interval $0 < z < Rk/\alpha$, where R is the radius of the axicon.

If we consider the structure of the DOE with the function of the transmission (2) with regard to the geometrical arrangement of the zones, we can say that the DOE is a set of ring zones of approximately equal width in which the phase function is rotated by a azimuthal angle of $\phi_0 = \pi/n$, if the sign of the function $J_n(\alpha r)$ is negative.

Consider a diffractive optical element with the function of the transmission

$$\begin{aligned}\tau\left(r,\phi\right) &= \frac{1}{2}\left[\exp\left(im_1\phi\right)+\exp\left(im_2\phi\right)\right]+\\ &+\frac{1}{2}\left[\exp\left(im_2\phi\right)-\exp\left(im_1\phi\right)\right]\operatorname{sgn}\left[\cos\left(2\pi\nu r+n\phi\right)\right],\end{aligned} \tag{3}$$

where m_1, m_2 – numbers of additional vortex components, r, φ – polar coordinates, ν – spatial carrier frequency, n – topological charge of binary diffractive axicon, which is the basis of the structure of this DOE. In terms of the geometry, the DOE with such a function of the transmission looks like a binary diffractive axicon, in the ridges of which the vortex component of m_1 is recorded, and in the hollows – the vortex component of m_2, while the location of these zones is that a light field with topological charge n can also be formed in the near zone. Hereinafter the topological charge n will be called the topological charge of structure. In addition, if topological charge is the same in neighboring areas, some constant can be added to the phase in the whole area for the structural separation of these zones. It will look as rotation of the vortex phase at a certain angle. Let is say, for instance, about the phase shift of semiperiod, if this angle is π. The light fields formed in this DOE are notable for a great variety of intensity and phase distributions, that allows to say about their possible use in optical micromanipulation for a very wide range of tasks.

One of such tasks is the rotation of microobjects. In the present paper, a superposition of vortex beams with topological charges n = 6, m_1 = 2, (figure 1, a-c) and n = 0, m_1 = 7, m_2 = -5, (figure 1, d-f) is formed for this task.

Despite the complex shape of the beam in figure 1e, the motion of the particles takes place on the outer ring. However, light traps in figures 1b, e have many ways of application – the rotation of not only microparticles and bacteria, but more complex objects, for example, microturbines [16].

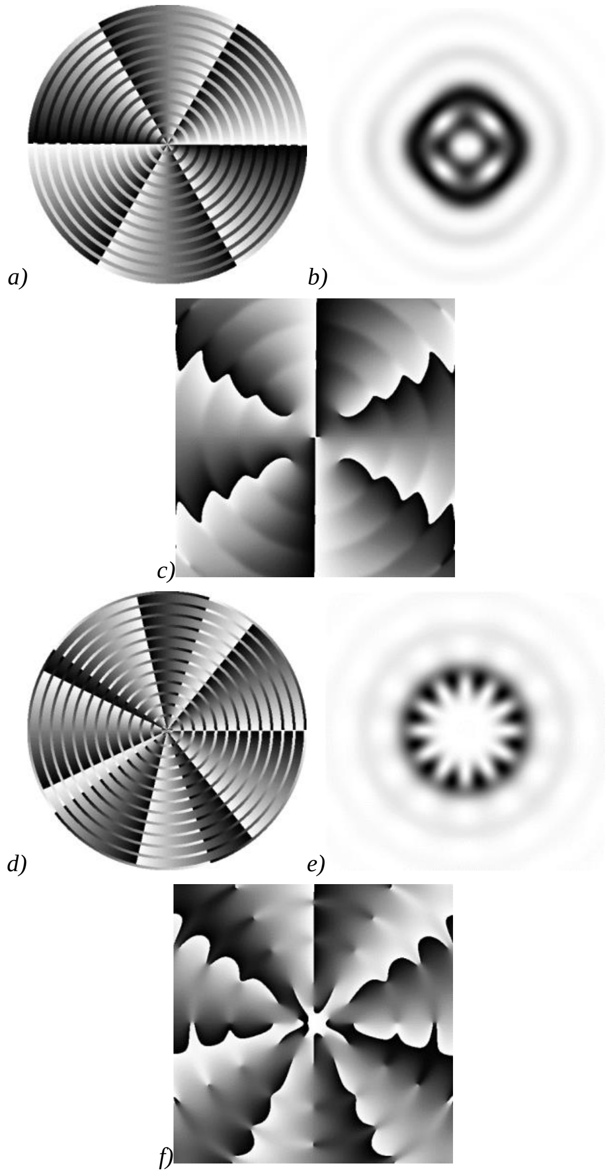

Fig. 1. – Phase function of the DOE (a, d), the intensity distribution in the far field of diffraction (b, e), the phase of the beam (c, f)

2. The experiments on the rotation of the agglomeration of the microparticles in the complex vortex beams

A series of experiments was conducted to check the possibility of rotation of microobjects in complex vortex beams. Figure 2 presents the scheme of the experimental setup. The beam was focused on the polystyrene microparticles with a diameter of 5μm located inside a drop of distilled water on the surface of the glass substrate. Two stepper motor system was used to move the platform with the installed cuvette, which allowed to move the platform with a step of 0.5 μm.

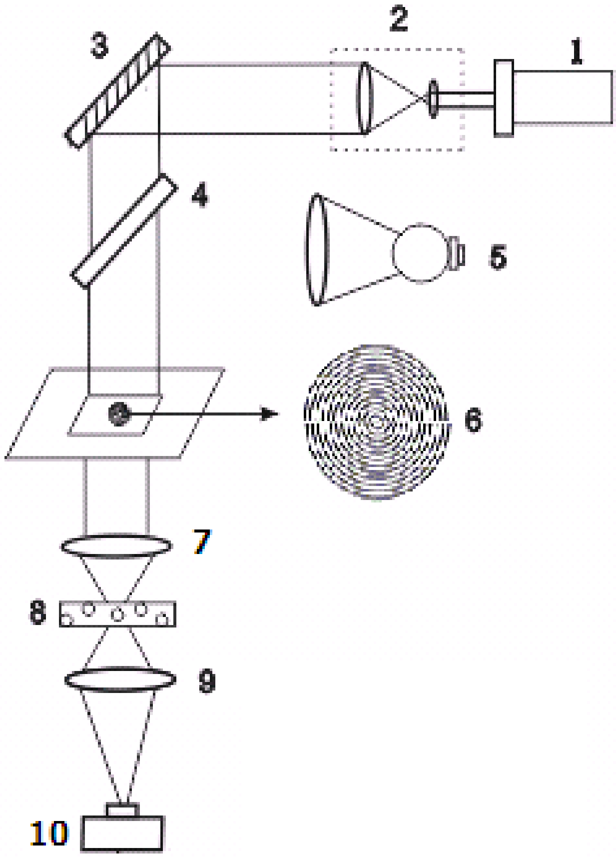

Fig. 2. – Optical scheme of the experiment on the capture of polystyrene microobjects in the beam: 1 – laser; 2 - collimator; 3, 4 – rotary mirrors; 5 – backlight; 6 – axicon; 7 – focusing microlens; 8 – substrate with microparticles; 9 – depicting microlens; 10 – CCD-camera

Figure 3 shows different stages of the movement process of the polystyrene particles in the beam, presented in figure 1b. At different focusing, microparticles get into the area corresponding to the different sign of the orbital angular momentum of the beam and rotate by a fixed angle before reaching the nearest maximum.

As a result of real experiment, capture of polystyrene particles was carried out and the rotation of the group of particles was initiated at the expense of focusing and defocusing of the light beam.

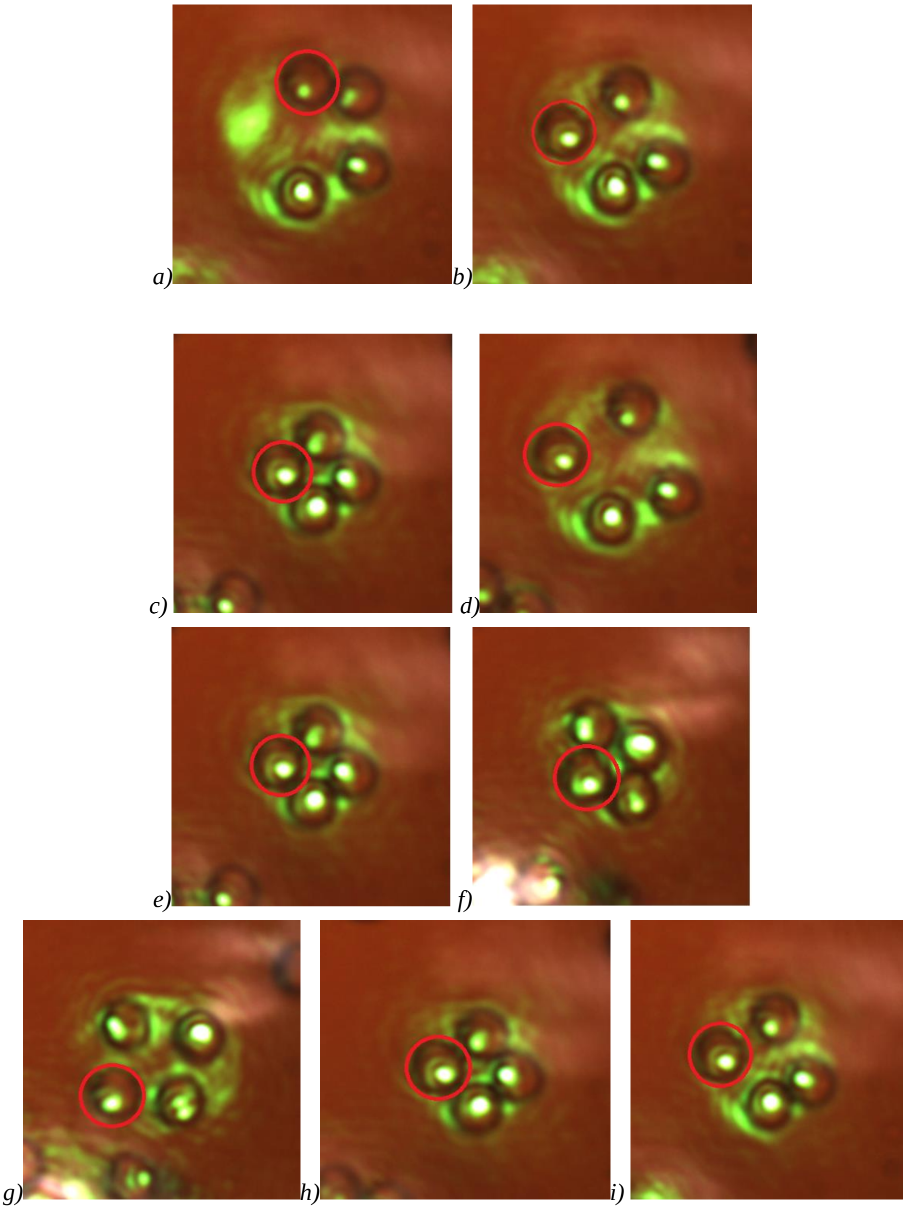

Fig. 3. – Stages of polystyrene microparticles rotation, taken with an interval of 2 seconds

Figure 4 shows the different stages of the movement process of polystyrene particles on a ring, taken with an interval of 2 sec.

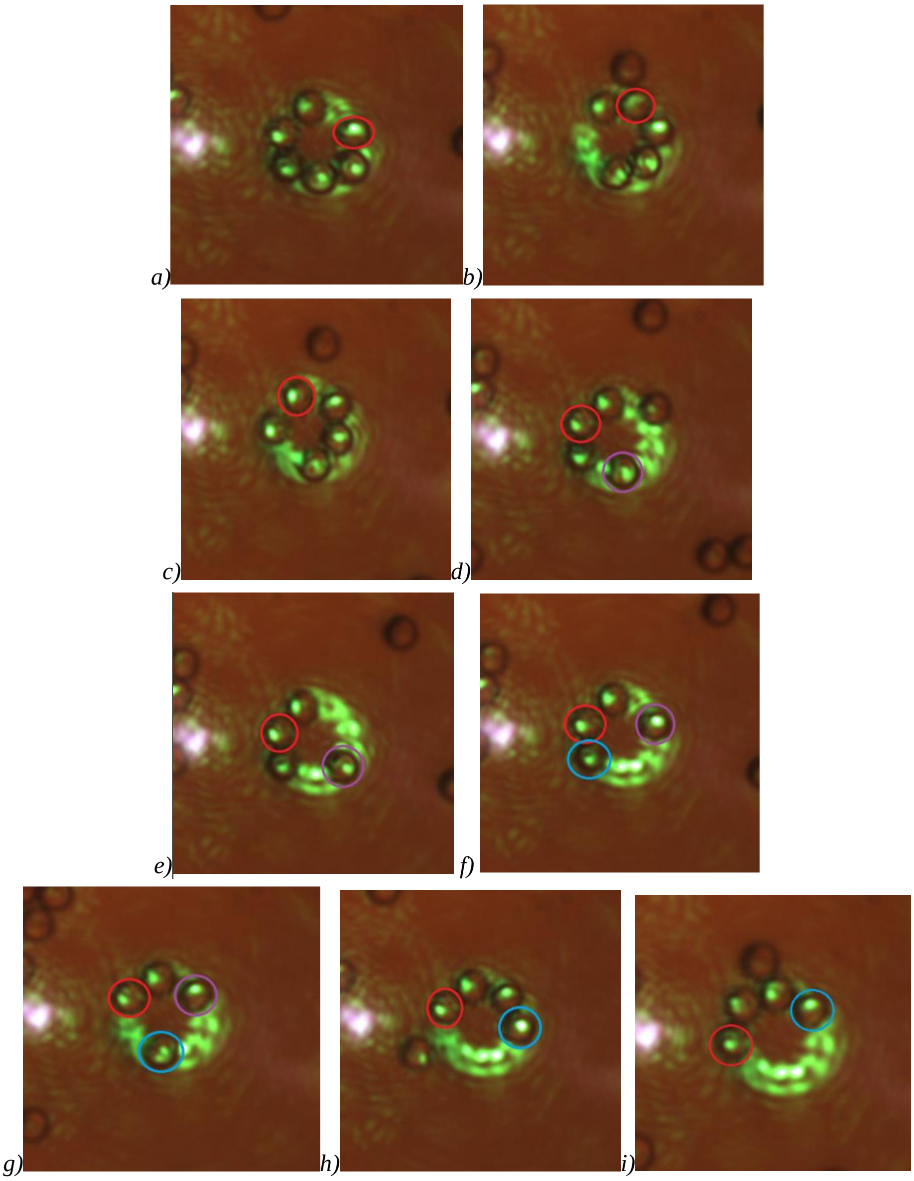

Fig. 4. – Stages of the micromanipulation process of polystyrene microparticles, taken with an interval of 2 seconds

As seen from figures 3, 4, there is rotation of microparticle group in the beams having substantially non-ring structure. Thus in figure 4, the rotation is performed in different directions, depending on the focus.

Conclusion

The light beams are described based on the superposition of vortex light beams with different topological charges. The presented results of experiments prove the possibility of controlled rotation of the group of microparticles in such light beams. It is shown that multidirectional rotation of the group of microparticles is possible with the superposition of vortex beams with a different sign of the topological charge, depending on the focus.

Funding Information

The work was funded RSF grant 14-19-00114.

References

1. **Bai N, Ezra Ip, Hang Y, Mateo E, Yaman F, Li M, Bickham S, Ten S, Liñares J, Montero C, Moreno V, Prieto X, Tse V, Chung K, Lau APT, Tam H, Lu C, Luo Y, Peng G, Li G, Wang T.** Mode-division multiplexed transmission with inline few-mode fiber amplifier. Optics Express, 2012; 20(3): 2668-2680.
2. **Kotlyar VV, Skidanov RV, Khonina SN.** Non-contact precision measurement of linear displacement with DOE forming fashion Bessel. Computer Optics, 2001; 21: 102-104. [in Russian]
3. **Skidanov RV, Khonina SN, Kotlyar VV, Soifer VA.** Experimental research of movement of dielectric spheres in light beams with angular harmonics of high orders. Computer Optics, 2007; 31(1): 14-21. [in Russian]
4. **Kotlyar VV, Kovalev AA, Skidanov RV, Moiseev OYu, Soifer VA.** Diffraction of a finite-radius plane wave and a gaussian beam by a helical axicon and a spiral phase. Journal of the Optical Society of America A: Optics and Image Science, and Vision, 2007; 24(7): 1955-1964.
5. **Abramochkin EG, Kotova S, Korobtsov A, Losevsky N, Mayorova A, Rakhmatulin M, Volostnikov V.** Microobject manipulations using laser beams with nonzero orbital angular momentum. Laser Physics, 2006; 16: 842-848.
6. **Abramochkin EG, Volostnikov VG.** Spiral light beams. Physics-Uspekhi, 2004; 47: 1177.
7. **Ladavac K, Grier D.** Microoptomechanical pumps assembled and driven by holographic optical vortex arrays. Optics Express, 2004; 12: 1144-1149.
8. **Lin X-F, Hu G-Q, Chen Q-D, Niu L-G, Li Q-S, Ostendorf A, Sun H-B.** A light-driven turbine-like micro-rotor and study on its light-to-mechanical power conversion efficiency. Applied Physics Letters, 2012; 101(11): 113901.
9. **Ukita H.** Rotation rate of a three-wing rotor illuminated by upward-directed focused beam in optical tweezers. Optical Review, 2008; 15: 97-104.
10. **Chaumet PC.** Coupled dipole method to compute optical torque: Application to a micropropeller. Journal Applied Physics, 2007; 101: 0231106.
11. **Maruo S.** Force-controllable, optically driven micromachines fabricated by single-step two-photon microstereolithography. Journal of Microelectromechanical Systems, 2003; 12: 533-539.
12. **Morozov AA, Skidanov RV.** Complex vortex beams for of rotation of micromechanical elements. Computer Optics. 2013; 37(1): 68-75. [in Russian]

13. **Burrow GM, Gaylord TK.** Multi-Beam Interference Advances and Applications: Nano-Electronics, Photonic Crystals, Metamaterials, Subwavelength Structures, Optical Trapping, and Biomedical Structures. Micromachines, 2011; 2: 221-257.
14. **McGloin D, Reid JP.** 40 years of optical manipulation. Optics & Photonics News, 2010; 21(3): 20-26.
15. **Fedotowsky A, Lehovec K.** Optimal filter design for annular imaging. Applies Optics, 1974; 13(12): 2919-2923.
16. **Morozov AA, Skidanov RV.** Rotation of microturbine in complex vortex beams. Computer Optics, 2013; 37(2): 203-207.