System of optical traps for controlled three-dimensional shifting

N.V. Shostka[2], **O.S. Karakchieva**[1,2], **B.V. Sokolenko**[1,2], **V.I. Shostka**[1]

[1]Institute of Physics and Technology, V.I. Vernadsky Crimean Federal University, Vernadsky Avenue 4, Simferopol, Russia, 295007
[2]Scientific Department, V.I. Vernadsky Crimean Federal University, Vernadsky Avenue 4, Simferopol, Russia, 295007

Abstract. Optical traps created on the basis of singular beams allow capturing living cells and microorganisms for their further study by optical microscopy. Such traps have important practical characteristics, such as the preservation of the minimum intensity on the beam axis, which avoids unwanted overheating of the captured object, as well as to keep the object in transverse coordinates. On the other hand, in many practical purposes it is necessary to restrict the shifting of the captured object and in the longitudinal direction. Finding ways to generate such three-dimensional traps is currently one of the priorities of world optics. In recent years, a number of papers have been published on capturing and transmitting both single particles and whole arrays of light absorbing particles in the air. However, the issue of control over the structure of an array of particles and of the position of individual elements in it is only beginning to be considered by the world scientific community. The practical realization is directly related to the formation of optical beams with the necessary three-dimensional configuration of the intensity of the light field and given polarization properties. This project proposes the development of a method of microparticles capturing and controlled real-time changing in their positions in three coordinates.

1. Introduction

The ability to capture and transport micro-objects using light is one of the topical studies in modern optics. Optical tweezers perform manipulations with colloidal microparticles, living cells, nano- and microparticles, individual molecules and atoms, which are widely used in modern science. Despite the large number of studies on the capture of micro- and nanoparticles by optical methods, only very recently it was shown for the first time the controlled capture of light-absorbing particles in a gaseous medium. To create an optical potential well and implement a full three-dimensional capture of micro-objects, it was proposed to use so-called “bottle beams”, i.e. beams or three-dimensional optical traps, in which there is an isolated zero intensity in the waist area surrounded by a zone of high light intensity [2]. The key role in creating such an optical structure is played by a singular beam with a minimum of intensity on the axis. The potential contained in the unique properties of such beams is still far from exhausted, and further research in this direction makes it possible to improve the mechanism of capture and manipulation of particles using singular optical beams.

It has been shown in [3, 4] that generation of three-dimensional optical trap can be applied by uniaxial crystal. The incident field of circularly polarized Gaussian beam inside a uniaxial crystal is transformed into a superposition of the ordinary and extraordinary beams, whose radii of curvature is different. Lens, placed after the crystal, will focus beams at two different focus spots [3, 4]. First waist corresponds to the ordinary, second – to the extraordinary beam in a crystal. At the same time, Ciatonni [5] and Volyar [6] have showed that focusing of circularly polarized Gaussian beam into a uniaxial crystal leads to formation of optical vortex in the orthogonal circular polarized component of the beam. Generally speaking, uniaxial crystal behaves as a vector mode converter that transforms any homogeneously polarized beam into a superposition of vector singular beams. That means that each ordinary and extraordinary beam carry (phase and/or polarization) singularity. Its superposition after focusing allows formation of minimum of intensity at the axis between two foci of a bottle-beam, in such a way closed three-dimensional optical trap is formed. [4]

2. Array of three-dimensional traps

In the proposed work, the formation of an array of three-dimensional traps during the passage of the set of Gaussian beams along the crystal axis is considered. The axis of each beam in the array is inclined at a small angle relative to the optical axis of the crystal. In paper [7] it was shown, that the structure of intensity of bottle-beam in case of initially circularly polarized light experience dramatical changes with increasing value of inclination angle φ. At the value $\varphi = 0^0$, beam has highly symmetric structure. However, starting from φ equal 2^0, the symmetry of a bottle beam starts to break down, and at $\varphi \sim 3^0$ closed three-dimensional structure of the light completely “opens”. Further increasing of the angle φ leads to absolute destruction of symmetry of the beam.

So, we work in paraxial regime with the inclination angle of each beam in the array not exceeding 2^0. As it was shown in [6], the distance between the waists of a single bottle-beam depends not only on the birefringent properties of the crystal, but also on its length. In the case of the generation of an array consisting of N beams, the dependence of the distance between the waists along the longitudinal coordinate remains the same, therefore, on the one hand, it becomes possible to control the properties of the formed array of bottle beams by changing the geometrical parameters of the optical system. [6,7].

From another hand, the character of intensity distribution can be changed by changing polarization state: by selecting the field component with right- or left-handed polarization at the crystal output, it is possible to form an array of either fully closed optical traps or those allowing a trapped particle to move in the longitudinal direction. However, the field distribution control can be implemented for the entire array as a whole.

In addition, the use of SLM for the generation of various optical beams and their systems will allow real-time manipulation of the position of captured micron-sized object. Such translations in the transverse direction in conjunction with the previously noted properties of the proposed “open” and “closed” traps in the longitudinal direction will allow control over the position of objects in all three coordinates (Figures 1 and 2).

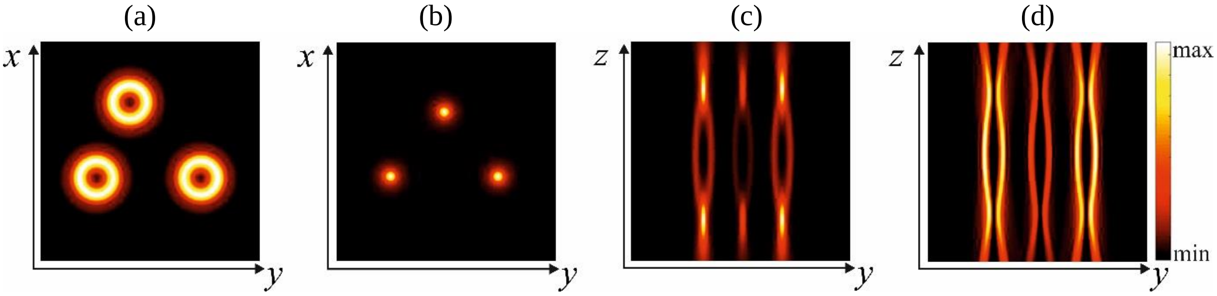

Figure 1. Intensity distributions in N = 3 array of optical traps. (a) and (b) shows transverse intensity distribution in the beam waists. The longitudinal intensity distribution is presented for fully “closed” optical trap (c) and “opened” in z-direction (d).

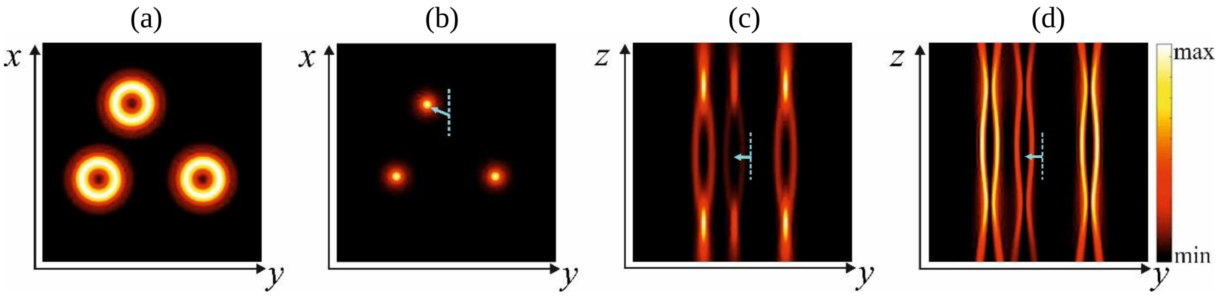

Figure 2. An example of an array of optical traps with a shifted single element. The arrow indicates the direction and distance of the shift relative to the original location shown in Figure 1.

3. References

[1] Sinjab, F. Holographic optical trapping Raman micro-spectroscopy for non-invasive measurement and manipulation of live cells / D. Awuah, G. Gibson, M. Padgett, F. Sinjab // Optics Express. – 2018. – Vol. 26(19). – P. 25211-25225.

[2] Arlt, J. Generation of a beam with a dark focus surrounded by regions of higher intensity: the optical bottle beam / J. Arlt, M.J. Padgett // Opt. Lett. – 2000. – Vol. 25. – P. 191-193.

[3] Rubass, A.F. The Focusing of Coherent Laguerre-Gaussian Beams after Uniaxial Crystals / A.F. Rubass, Yu.A. Egorov, T.A. Fadeyeva, A.V. Volyar // Proc. of SPIE. – 2005. – Vol. 6023. – P. 230-238.

[4] Shvedov, V.G. Generation of vector bottle beams with a uniaxial crystal / V.G. Shvedov, C. Hnatovsky, N. Shostka, W. Krolikowski // JOSA B. – 2013. – Vol. 30(1). – P. 1-6.

[5] Ciattoni, A. Circularly polarized beams and vortex generation in uniaxial media / A. Ciattoni, G. Cincotti, C. Palma // J. Opt. Soc. Am. A. – 2003. – Vol. 20. – P. 163-171.

[6] Volyar, A.V. Generation of singular beams in uniaxial crystals" / A.V. Volyar, T.A. Fadeyeva // Optics and Spectroscopy. – 2003. – Vol. 94(2). – P. 235-244.

[7] Ivanov, M.O. Focusing of Gaussian beam passed under small angle to optical axis of uniaxial crystal / M.O. Ivanov, N. Shostka // J. Opt. – 2016. – Vol. 18. – P. 075603 (6 pp.).

Acknowledgments

This work was funded by RFBR and the government of Crimean Republic to the research project № 18-42-910013 and partially supported by the V. I. Vernadsky Crimean Federal University Development Program for 2015 – 2024.