The method of polarization filtering for implementation of the optical manipulator

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Abstract. The ability to capture and transport micro-objects with the help of light is one of the topical studies in modern optics. Optical tweezers perform manipulations with colloidal and aerosol nano- and microparticles, living cells, individual molecules and atoms, which is widely used in modern science. Optical traps, created on the basis of singular beams, allow capturing live microorganisms for further study using optical microscopy. Such traps have important practical characteristics, such as maintaining a minimum of intensity on the beam axis, which allows to avoid unwanted overheating of the captured object, as well as to keep the object in transverse coordinates. On the other hand, for many practical purposes it is necessary to limit the transmission of the captured object in the longitudinal direction. Finding ways to generate such three-dimensional traps is currently one of the priorities of world optics. In presented work it is shown that polarized vector beams, formed after uniaxial crystal, create bottle beam with dark centre and by varying geometrical and polarization parameters of experimental set-up it is possible to control the bottle beam properties.

1. Introduction

One of the actively developing methods of optical diagnostics of various characteristics of single biological objects is the direction devoted to the study of the interaction of laser radiation with matter, as well as the principles of control of micro-objects and their agglomerates by means of optical traps. The principle of operation of optical tweezers, first demonstrated by Arthur Ashkin [1], formed the basis of modern optical instruments currently used in numerous biochemical and biophysical studies.

The classic type of light beams carrying optical vortices is Laguerre-Gaussian beams [4]. Due to the singular nature of the wavefront of the beam transporting the optical vortex, abrupt phase and amplitude changes in the light field occur in the vicinity of the singularity: the field amplitude vanishes and the phase becomes uncertain. This unique properties of optical vortices has opened up broad prospects for their practical application.

Optical tweezers based on singular beams allow to capture studied micro-objects, as well as to control their position in space. Moreover, a unique feature of the work of modern optical traps is that the capture of the object under study can be carried out directly in the medium, which allows one to study the object itself without taking into account the interaction with the substrate. To avoid overheating, hollow beams are used, which have a configuration with a minimum of intensity on the axis previously embedded in the structure of the light field, and, on the other hand, the researchers choose the wavelength of laser
radiation so that the matter of the captured objects and the environment does not absorb radiation of a
 certain wavelength.

 A special case of optical traps based on singular beams are “bottle” beams, the main characteristic
 of which is the existence of a closed three-dimensional region of low intensity inside the light focus.
 Once in such a beam, the absorbing particle is retained in its axial region, and under certain conditions
 cannot penetrate through the light walls. Any shift of a particle leads to the heating of its part that is
 farther from the center of the beam. The resulting pressure difference on the cold part of the particle
 closest to the center of the beam and the hot peripheral returns the particle to a position of stable
 equilibrium inside the optical “bottle”. Optical traps have been used in biological and medical research.

 Optical traps and manipulators are a suitable tool for manipulating living cells and can be applied in
 various fields [2,3]. For example, to study the mechanism of RNA polymerase movement during the
 synthesis of new DNA molecules [4]. The interaction of neutrophils with pathogens has been studied
 [5]. In work [6], infrared optical tweezers were used to capture and manipulate red blood cells inside the
 subcutaneous capillaries in live mice. Thus, a contactless micro-operation was implemented, which led
 to the cleaning of the blocked micro vessel. The results obtained during this study significantly expanded
 the use of optical tweezers to study the dynamics of living cells in animals. Separately, the use of laser
 tweezers and femtosecond scalpel manipulators for microsurgery of a shiny embryo shell should be
 emphasized [7].

 The actual task is the development of techniques that allow to realize multi-dimensional traps.
 Modern optics allows you to simultaneously create a large number of optical tweezers, using spatial
 light modulators (SLM), which allows to perform manipulations in real-time [8-10].

 However, such changes relate only to the transverse plane, in the longitudinal direction the position
 of the captured objects remains poorly controlled. In this paper, we consider the method of polarization
 filtering of the beam field after a medium of a uniaxial crystal, by means of which it is possible to
 control in real-time the position of trapped particle along the longitudinal coordinate.

 2. Experimental part

 Currently, in connection with a number of practical applications, special attention is paid to methods for
 generating non-uniformly polarized or so-called vector beams. The essence of these methods lies in the
 transformation of a spatially uniformly polarized beam specified by a laser (for example, a linearly or
 circularly polarized Gaussian beam) into a spatially inhomogeneously polarized vector beam in free
 space.

 The simplest process of mode transformation occurs in an uniaxial birefringent crystal, when the
 initial beam propagates along its optical axis. In this case, a field is formed with an inhomogeneous
 polarization distribution and, as a result, with different types of polarization singularities [11]. In
 particular, a circularly polarized Gaussian beam propagates along the axis of an uniaxial crystal, and an
 optical vortex is generated in the orthogonal relative to the initial circularly polarized component whose
 topological charge differs by 2 units from the charge in the original beam component. (The expression
 for the topological charge of the formed optical vortex in the orthogonal component of the beam:
 \( l' = l + 2\sigma \), where \( l \) is the topological charge of the beam focused into the crystal, corresponds to the
 direction of initial circulation of the beam) [12,13]. At the same time, using various polarization filters
 and selective excitation of a crystal, one or another type of vector or scalar singular beam can be
 distinguished. We note another advantage of this method – the possibility of converting high-power
 laser radiation, both in coherent and incoherent modes [14-15].

 Gaussian beam passing along an optical axis crystal presents a superposition of ordinary and
 extraordinary beams having different radii of curvature of the wave front:

 \[
 E_{z \lambda h} = \pm \frac{i}{2} \left( e^{i \theta} (G_{\lambda h} + G_{v h}) - e^{i \theta} r^{-2} \left( r^2 + \alpha_\beta \xi_{\lambda h} \right) G_{\lambda h} - \left( r^2 + \alpha_\beta \xi_{v h} \right) G_{v h} \right) \exp(\pm 2i\theta) \]  

 (1)
where \( G_{\|} = \left( E / \xi_{\|} \right) \exp \left( -r^2 / (\omega_{0\|}^2 \xi_{\|}) \right) \), \( G_{\perp} = \left( E / \xi_{\perp} \right) \exp \left( -r^2 / (\omega_{0\perp}^2 \xi_{\perp}) \right) \), \( \xi_{\|} = 1 + iz_0 n_{\|} / (\pi n_{\|}^2 \omega_0^2) \), \( \xi_{\perp} = 1 + iz_0 n_{\perp} / (\pi n_{\perp}^2 \omega_0^2) \), \( \omega_0 \) – the initial waist of the beam, \( n_{\|}\) и \( n_{\perp} \) – the refractive indices of the ordinary and extraordinary waves, respectively; \( \lambda \) – is the light wavelength in vacuum.

When outgoing beam is focused by a lens located at a certain distance from the exit face of the crystal, three focus areas will be formed: the first focus corresponds to the ordinary beam, the second - to the extraordinary one, and the zone between them corresponds to the field on the output face of the crystal. Such a structure has the form of a classic “bottle” beam with a minimum on the axis, evenly surrounded in all coordinates by a high intensity zone. The intensity difference from minimum to maximum is 80%.

In this case, the shape of the formed beam can be controlled by means of additional polarization elements. As can be seen from expression 1, the left side of the expression corresponds to the singular component, and the right side – to the non-singular component. So with the help of additional polarization elements (an additional quarter-wave plate and a polarizer located after the focusing lens), these beam components can be distinguished. The intensity distribution of the orthogonally circularly polarized components \( E_{\|} \) and \( E_{\perp} \) at the exit of the crystal show a similar structure in the region between the two focuses, but fundamentally different in the area of the waists of extraordinary and ordinary components. So in the case of a right circularly polarized initial Gaussian beam at the entrance to a crystal, in the waist areas the field of the right circular component is a Gaussian distribution with a maximum intensity at the center, while the field of the left circularly polarized component will contain a line of zero intensity along the beam axis. By choosing the right or left-polarized component of the field at the exit of the crystal, it is possible to form either a fully closed 3-dimensional trap or the optical structure allowing the particle to move along the longitudinal direction.

The distance between the focus areas of ordinary and extraordinary beams:
\[
2\delta = 2d(n_{e}^2 - n_{o}^2) / (n_{o}^2 n_{e})
\]
depends on the birefringent properties of the crystal and its thickness \( d \) along the direction of propagation of the optical beam.

If, however, the angle of inclination of the Gaussian beam is changed with respect to the optical axis of the crystal, the patterns of the intensity and polarization distributions begin to noticeably change [16]. Let us consider the effect of focusing a Gaussian beam propagating at a small angle to the optical axis of an uniaxial crystal on the formation of a bottle beam. The distance between two foci will depend in this case on the orientation of the optical axis of the crystal and the direction of beam propagation \( \phi = d \sin^2\varphi(n_{e}^2 - n_{o}^2) / (n_{o}^2 n_{e}) \). Positions of foci are given in a clockwise direction by \( z_o \) and \( z_e \) that corresponds to \( o \) and \( e \) beams respectively. To obtain experimental dependence of distance \( \delta \) between focuses on angle of the tilt of crystal \( \varphi \), the crystal were rotated with the step of 0.35 deg. Position of the focuses were registered by CCD camera.

An experimental study was conducted on an experimental setup, shown schematically in figure 1. From the intensity distribution maps shown in figure 2 it can be seen that at \( \varphi = 0 \) deg two focus form a closed three-dimensional structure of the bottle bundle. An increase in the angle leads to a change in the intensity and distribution of the polarization of the formed beam. Starting from the angle \( \varphi = \pm 2 \) degs, the axisymmetric structure of the bottle beam opens in the xy plane. And with the values of angle \( \varphi = \pm 5 \) degs, ordinary and extraordinary beams are focused in one transverse plane, while their polarization becomes linear. So by changing the angle \( \varphi \) it is possible to control the form of the formed bottle beam and “open” it for some purposes.
Figure 1. The Experimental set-up scheme for “bottle” beam generation.

Figure 2. Computer simulated and experimental intensity distributions for the following angles: a) $\varphi=0$ degrees; b) $\varphi \sim 3^\circ$; c) $\varphi \sim 5,5^\circ$.

Thus, the nature of the intensity distribution in the "bottle" beam can be changed: a) by changing the polarization state: choosing the left or right circular field components at the crystal output b) tilting the original Gaussian beam relative to the optical axis of the crystal at a small angle, or turning the crystal itself, which is equivalent.

The advantage of the proposed method is the possibility of changing the field distribution in the capture region without a fundamental change in the experimental scheme.

Acknowledgments
The reported research was partially supported by the V. I. Vernadsky Crimean Federal University Development Program for 2015 – 2024 and was funded by RFBR and Council of Ministers of the Republic of Crimea according to the research project № 19-42-910010.
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