Generation of the trapping light structures based on vector fields

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Abstract. The paper discusses the main mechanisms for the formation of arrays of singular beams with non-uniform polarization for capture and particle control. The article considers a new system of vector beams with an ideal dark area, suitable for trapping and manipulating light-absorbing particles in the air. In this case, the trapping properties in the light structure can be controlled. For this purpose, the mechanism of the formation of light structures based on a single-axis crystal scheme was considered in detail. The obtained results provide a new way for creating and controlling the properties of beams suitable for trapping and will expand the possibilities of micromanipulation of absorbing particles. Besides the possibility of generating multidimensional lattices of polaritons are considered.

1. Introduction

Researches pay great attention to trapping and manipulation of particles with optical tweezers because of broad areas of their practical applications [1-9]. Usually optical tweezers manipulate microscopic objects in planar geometry, and the particles are limited by a thin layer determined by the focal region of the beam, but to create an optical potential well and achieve a fully three-dimensional capture, a so-called «optical bottle» was proposed [1]. The term «optical bottle beam» describes a beam with a finite axial region of low intensity surrounded in all dimensions by light [1-4]. Once in such a light construction, the absorbing particle is held in its axial region and under certain conditions cannot penetrate through the light walls [10]. Any shift of a particle leads to a heating of that part of it that is farther from the centre of the beam. The resulting pressure difference on the cold part of the particle close to the centre of the beam and the hot peripheral one returns the particle to a position of stable equilibrium inside the optical "bottle". A number of different techniques has been proposed to generate bottle beams such as mechanical angular scanning of a laser beam [2] and the use of optical diffractive elements such as holograms and phase plates to form a desired hollow axial structure [3].

Most of realizations of optical tweezers and bottle beams employ coherent light, however it was shown, that the light with partial spatial and temporal coherence could be used for realization bottle beams. For example, it was shown that focusing of the spatially partially incoherent light beam by an axicon leads to the formation of a bottle beam [4, 5]. A great number of researches in this area was developed for trapping particles in liquids. However stable trapping of absorbing particles in air has been achieved only recently in a new trap created by two counter-propagating optical vortex beams [6]. Generated after uniaxial crystal vector beams could create intensity distribution as in bottle beam [7-9, 11].
In this paper, we consider the formation of 3D trap arrays when a Gaussian beam array and arrays of singular optical beams pass along the crystal axis, when the axis of each beam in the array will be inclined at a small angle relative to the propagation axis and we show method of generation periodical incoherent and coherent bottle beams created by using periodical diffractive screen, and controlled shaping of bottle beams with uniaxial crystal.

From another hand, polariton models allow us to describe the dynamics of the generation and propagation of linear and nonlinear waves in different media over a wide frequency range. Depending on the parameters of the initial polariton wave, the form of the system of equations changes. In the case of linear polarization, a single spatial soliton (one polariton flow) or a cnoidal wave (several streams) forms depending on the beam width: for a narrow beam with a width on the order of the wavelength, one stream is formed, and for a broad beam with a thickness of several tens of wavelengths, multiple threads [12,13]. It was considered the process of propagation of an array of polariton waves in dependence on the polarization of the incoming wave. As a result, a significant increase in signal power was obtained, which makes it possible to use such arrays in various communication devices.

2. Bottle beam structures

Consider the model of formation bottle beams by uniaxial crystal. The main advantage of the method based on using inhomogeneous medium is the possibility of highly efficient generation of a number of practically important optical beams, whose power is limited only by the threshold for the destruction of glass elements. Also, an anisotropic medium makes it possible to form not only a grid of phase and polarization singularities in the beam, but also to control their shape and mutual position [14].

The problem of generating necessary beam structures in this method reduces to the following scheme. Primarily will describe the properties of the beam array consisting of the $N$ paraxial local gaussian beams. The array is simultaneously a complex beam that propagates along the crystal axis and a superposition of individual beams propagating at an angle to the optical axis [15]. The axis of the single beam is shifted by the distance $r_i$ relative to the center of the array and is tilted at the small angle to the $z$-axis of the array. Without analysis, it is impossible to say whether the integrity of the optical bottle will be preserved when the beam is tilted, and also what pattern will be observed when the beam angle in the array is increased. In connection with this, in Ref. [16] it was shown experimentally and analytically the effect of focusing of a Gaussian beam propagated under small angle $\alpha$ with respect to the optical axis of a uniaxial crystal on the generation of a bottle beam. At $\alpha = 0^\circ$ two foci that correspond to ordinary and extraordinary parts of a beam form a closed 3D structure of a bottle beam. Starting from the value of $\alpha = \pm 2^\circ$ the closed 3D symmetric structure of a bottle beam breaks down.

We impose the following conditions on the initial array: each beam in the array should propagate at an angle to the crystal axis not exceeding two degrees, and the beams must be at the necessary distance from each other so that interference effects do not arise between them.

As it was shown in [17], the slope relatively to the propagation axis $z$ is displayed for small angles as $y \rightarrow y^\prime + i\alpha z_0$, where $\alpha$ – the angle between the optical axis of the crystal and the propagation direction (axis) of the beam in the array, $z_0 = \frac{k\omega_0^2}{2}$, $k$ – wave number.

To generate arrays of bottle beams we use the following experimental setup: initial Gaussian beam from He-Ne laser with a wavelength of $\lambda = 632.8$ nm is transformed into array by diaphragm D with N pinholes. With the lens system the formed array is focused into c-cut uniaxial crystal of $LiNbO_3$ with $n_e = 2.286$, $n_o = 2.203$. Due to the birefringence in the anisotropic medium of the crystal each Gaussian beam splits into ordinary and extraordinary beams with different radii of curvature. The light after crystal is focused by the lens with $f = 7$ cm. The foci points locate at the different positions $Z_e$ and $Z_o$, spaced by a distance $\delta = Z_e - Z_o$. Intensity patterns are presented on Figure 1 (a–d).
Figure 1 (a–d). Experimental (a, c) intensity distributions and theoretical calculation (b, d) in the formed array with N=3 and N=5 singular beams respectively

3. Vortex beam structures

Polarization of light can also affect the quality of capture, so the ability to control the polarization states of optical beams gives an additional degree of freedom in manipulating the trapped particles in space, which will allow more controlled change in the positions of trapped particles in the array.

Thus, at the present time, singular beams with a spatial variation of the polarization over the beam cross section are of particular interest. The simplest examples of such beams are radially and azimuthally polarized beams. Recently, a number of studies devoted to the generation of azimuthally and radially polarized beams have been presented in connection with the potential for wide application in microscopy, laser lithography, data storage, and capture devices. As it was shown, a single circularly polarized optical vortex with opposite signs of topological charge and polarization propagating along the optical axis of the crystal is a superposition of radially and azimuthally polarized beams [3]. In this work we form arrays with spatial variation of polarization similar to the previous case with one difference - at the entrance to the crystal an array of optical vortices is generated on the hologram.
Figure 2 (a–e). Theoretical calculation of intensity distribution (a, d) and polarization (c); (b) corresponds to experimental intensity patterns in the waist region of a vector beams array (N=3 and N=5 respectively) formed after uniaxial crystal.

Analysis of patterns of polarization distribution shows the following:
- with an increase of the number of beams in the array the effect of spherical aberration increases;
- when focusing an array with N>3 beams, the beams begin to overlap, destructive interference occurs between them, resulting in the polarization distribution patterns lose pure radial and azimuthal distributions.

4. Structured polariton flows
In a dielectric medium with cubic nonlinearity electromagnetic wave with a frequency lying in spectral gap can generate a plane polariton wave, which as a result of the stability transforms into a
spatial soliton. In such medium the polariton flux representing a wave with a plane wave front with linear polarization stratifies (splits into plane flows) as a result of self-focusing.

Polariton flow with a plane wave front
\[ \frac{d^2 e}{d\eta^2} + \alpha_2 e + \alpha_3 e^3 = 0 \], where \( \eta = (x + iy) \), \( \alpha_1 \) and \( \alpha_3 \) – medium coefficients.

We obtain the general solution for the vector polariton wave front \( e(\xi, \eta) \) depending on the right and left spirality coordinates \( (\xi, \eta) \), where \( \xi = \sqrt{|\alpha_1|} \), \( \eta = \sqrt{|\alpha_3|} \):

\[
e(\xi, \eta) = i \left[ \frac{1}{\sqrt{|\alpha_3|}} \tanh \left\{ C_1 + C_2 \xi + i \left[ C_3 (i+1) - (i-1 - i2C_2)^{1/2} \right] \eta \right\} \right].
\]

Figure 3 (a,b). Number of polariton flows of polariton wave with initial circular polarization

The constans \( C_1 \) and \( C_2 \) are determined by the boundary conditions at \( \xi = 0 \) and \( \eta = 0 \) for the polariton wave. For example, if the value of envelope at longitudinal axis \( z \) is

\[
e(0,0) = \text{Re} \left[ i \sqrt{|\alpha_1|/|\alpha_3|} \tanh(C_1) \right] = 0 ,
\]

it allows to determine the constant \( C_1 = 0 \) and \( C_2 = 1 \) and

\[
e(\xi, \eta) = i \left[ \frac{1}{\sqrt{|\alpha_3|}} \tanh \left\{ \xi + \frac{1}{2} \left[ i - 1 + \sqrt{i+1} \right] \eta \right\} \right].
\]

Figure 4 (a,b). Array of polariton flows at the scalar polariton wave with elliptical polarization
The weak intensity waves with the frequency lying in a spectrum gap don’t propagate through the linear medium. On the contrary the waves of new spectrum branches appear in the gap as the nonlinear periodic cnoidal waves or spatial solitons, depending on the sign of nonlinear susceptibility and value of wave perturbation. These nonlinear waves propagate through the medium. The given effects are similar to the nonlinear (self-induced) transparency for power wave or pulse with carrier frequency close to resonance transition of the medium atoms. This effect can be used for design and creation of the nonlinear filter that transforms the harmonic wave to nonlinear cnoidal wave or spatial soliton.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research and the government of the region of the Russian Federation grant № 17-42-92020 and partially supported by the V.I. Vernadsky Crimean Federal University Development Program for 2015 – 2024.

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