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GENERATION OF AN ARRAY OF VECTOR BOTTLE BEAMS

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In present work an experimental method of formation of an bottle beam array by focusing an array of N uniformly-polarized Gaussian beams passed uniaxial crystal is considered.
Keywords: uniaxial crystal, array of bottle beams.

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INTRODUCTION

The possibility of manipulation of micro particles with the help of light [1] is one of the most topical researches in modern optics. Optical tweezers manipulate colloidal microscopic particles, life cells, nano- and microparticles, single molecules and atoms, which find wide applications in modern microbiology and micro engineering. For creating an optical potential well and achieve fully three dimensional trapping, the so-called *optical bottle beam* have been proposed, i.e. beams with a finite axial region of low intensity surrounded in all dimensions by area of high light intensity [2, 3]. In works [4, 5] it was shown, that the speckle pattern of a coherent beam from the surface of diffuser could be used for trapping of a great number of micron sized particles in air. However this type of multi tweezers is sensible to any shift of the diffuse screen, so it's not possible to realize changes of trapped particles position.

In present work the method of generating an array of bottle beams using an uniaxial crystal is demonstrated.

1. FORMATION OF SINGLE BOTTLE BEAM BY UNIAXIAL CRYSTAL

The main feature of bottle beams is closed 3D area of low intensity inside light focus. An uniaxial crystal could serve as basic element for realization of practical generation of such beams [6, 7, 8]. In works of Chiatonni, prof. Volyar, prof. Fadeyeva, prof. Shvedov it has been shown theoretically and experimentally that the propagation of circularly polarized beam along the axis of an uniaxial crystal in an orthogonal with respect to the initial circularly polarized component optical vortex is born, its topological charge differs from the charge of the initial beam in two units. In the basis of the formation of an optical vortex in this case is the law of conservation of the projection of the total flux of angular momentum of the beam to the optical axis of the crystal [9].

Consider the case when initial beam on crystal is the circular polarized Gaussian beam. Circularly polarized Gaussian beam in crystal could be described as superposition of ordinary and extraordinary beams, which have different beam waists [6, 8].

As the result of focusing of the beam exit uniaxial crystal there are clearly observed two focuses with different polarization distributions separated by the region of low intensity, i.e. bottle beam [8]. Computer modulation of longitudinal and transverse intensity distributions is shown in Fig. 1 (a, b). The distance between two waists in such beam is defined as: $2\delta = d(n_o^2 - n_e^2)/(n_e^2 n_o)$, where n_o and n_e are ordinary and extraordinary refractive indices, d is the thickness of the crystal. Thus the distance between beam waists depends not only on birefringence properties of the crystal but and on its thickness. I.e., it is possible to change the properties of the formed bottle beam by changing geometrical parameters of optical system for its generation.

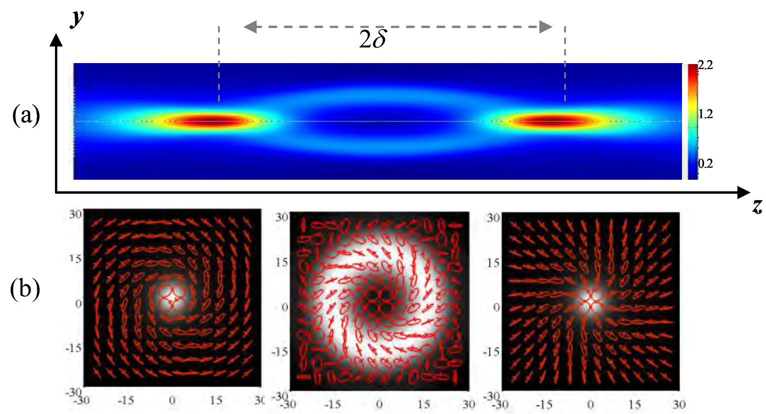

Fig. 1. Theoretical calculation (a), (b) of longitudinal and transverse intensity distributions in bottle beam. On (b) are presented pictures of polarization distribution in the areas of the beam waists.

Let us answer the question, is it possible to form an array of bottle beams in the following manner.

2. GENERATION OF AN ARRAY OF 3-DIMENSION BOTTLE BEAMS

The computer generated diffraction element, constituted screen with N regularly arranged pinholes, allows to split initial laser coherent beam into N Gaussian beams.

An equation for the general wave function of an array in free space can be presented in the following way:

$$\Psi = \sum_{n=1}^{N} \Psi_n \qquad (1)$$

where N – number of the local beams in array, n – index of each beam.

As it was shown in [10] the incline of the paraxial beam axis at a small angle is equivalent to the shift of the y-axis of the beam to the imaginary part on the distance $i\alpha z_0$.

Thus the wave function of the *n*-th inclined beam in an array could be written as the following expression:

$$\Psi_n = \frac{1}{\sigma}\exp(-k\frac{\alpha^2 z_0}{2})\exp(-\frac{x_{n'}^2 + (y_{n'} + i\alpha z_0)^2}{\omega_0^2 \sigma})\exp(-ikz) \tag{2}$$

Coordinates of *n*-the beam are written the following way:

$$\begin{cases} x_{n'} = x_n \cos\varphi_n + y_n \sin\varphi_n + r_0 \\ y_{n'} = y_n \cos\varphi_n - x_n \sin\varphi_n \end{cases} \tag{3}$$

where $\varphi_n = \frac{2\pi}{N} n$, $z_0 = k\rho^2 / 2$, $k = 2\pi/\lambda$ is wave number, λ is wave length, $\sigma = 1 - i\frac{z}{z_0}$.

We work in paraxial regime, so we consider $\sin\alpha \approx \alpha$, α is the inclination angle of the beam axis to the optical axis of the hole system.

Let's consider propagation of an array of Gaussian beams (1) in crystal. In work [10] it was shown, that for a given crystal length there is an optimal inclination angle α when the output beam contains an isolated single charge vortex on its axis as in the case of on-axis propagation of circularly polarized Gaussian beam. So for small inclination angle the ordinary and extraordinary polarized beam components propagate together along the optical axis of the inclined beam, and the conservation law is done. Thus for a small inclination angle of each beam in an array the focusing of the crystal-propagating beam array can shape an array of isolated "bottle beams".

For experimental study of the beam array evolution and formation of bottle beam array we have used an experimental setup shown in Fig. 2.

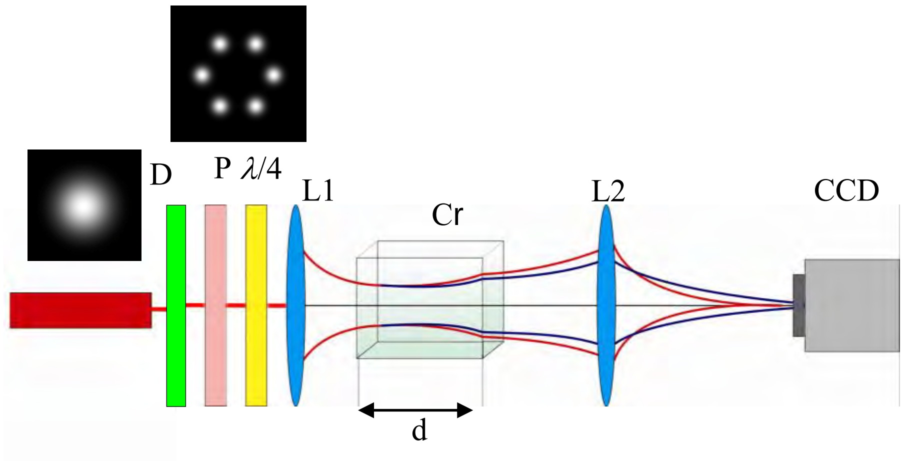

Fig. 2. Experimental set-up: laser with the wave length $\lambda = 634$ nm; D – amplitude screen; P – polarizer; λ/4 – quarter wave plate; Cr – uniaxial crystal; L1, L2 – focusing lenses.

The polarization filter, consisting the polarizer and quarter wave plate transforms initial Gaussian beam array after amplitude screen (with N pinholes) into circularly polarized. The circularly polarized array is focused by the lens L1 into the uniaxial crystal, and the propagation axis of the whole array of Gaussian beams coincides with the optical axis of the crystal.

As in previous case each circularly polarized Gaussian beam of an emerged array after crystal could be described as superposition of ordinary and extraordinary beams, which focuses are situated in different distances from the focusing lens L2. Experimental results are shown in Fig. 3 (transverse intensity distributions of an array of bottle beams) are presented in Fig. 3.

(a)
(b)
(c)

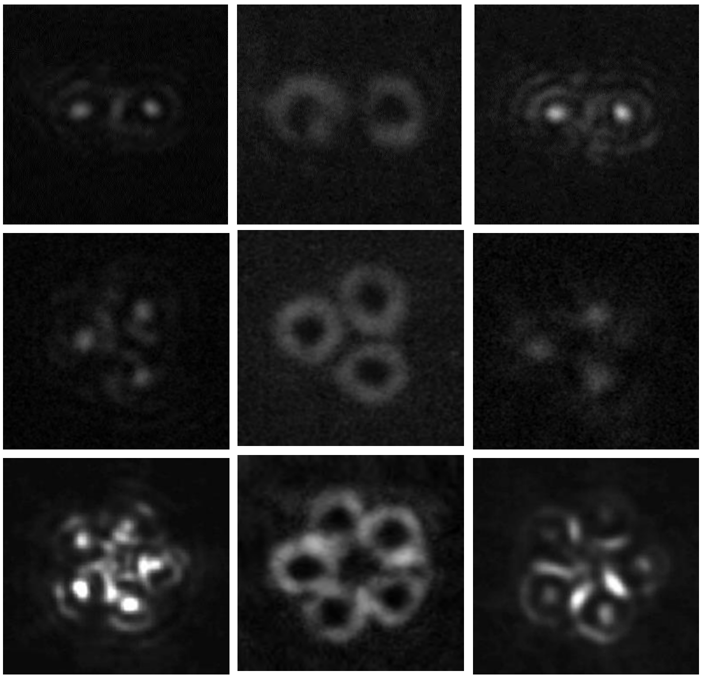

Fig. 3. Experimental transverse intensity distribution of array with $N = 2$ bottle beams (a), array with $N = 3$ bottle beams (b) and array with $N = 5$ bottle beams (c).

As it could be seen the result of focusing of Gaussian beam array exit uniaxial crystal is the formation of an array of bottle beams.

CONCLUSION

In this work is suggested an experimental method of generation bottle beam array by using uniaxial crystal. Such structures of the vector beams could be used in various applications of optical trapping and manipulation of microparticles. This method could be used both with coherent and temporarily coherent laser beams.

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Шостка Н. В. Генерація масиву векторних пляшкових пучків / Н. В. Шостка, В. І. Шостка, М. Іванов // Вчені записки Таврійського національного університету імені В. І. Вернадського. Серія : Фізико-математичні науки. – 2014. – Т. 27 (66), № 2. – С. 23-28.
У роботі представлено експериментальний метод формування масивів пляшкових пучків в ході фокусування масиву N гаусівських пучків, які пройшли уздовж оптичної осі одновісного кристалу. Подобні структури векторних пучків можуть бути використані в різноманітних сферах оптичного захоплювання та маніпулювання частками мікронного розміру. Основна особливість представленого методу є те, що він може бути застосований як для когерентного так й для частково-когерентного лазерного випромінювання.
Ключові слова: одновісний кристал, масив пляшкових пучків.

Шостка Н. В. Генерация массива векторных бутылочных пучков / Н. В. Шостка, В. И. Шостка, М. Иванов // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия : Физико-математические науки. – 2014. – Т. 27 (66), № 2. – С. 23-28.
В работе представлен экспериментальный метод формирования массива бутылочных пучков при фокусировке массива N Гауссовых пучков, прошедших одноосный кристалл вдоль его оптической оси. Подобные структуры векторних пучков могут бать использованы в различных сферах оптического захвата и манипулирования частицами мікронного размера. Основной особенностью представленного метода является то, что он может бать прменен как для когерентного так и частино-когерентного лазерного излучения.
Ключевые слова: одноосный кристалл, массив бутылочных пучков.

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