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EVOLUTION OF SYMMETRIC AND ASYMMETRIC OPTICAL BEAM ARRAYS PASSING ALONG OPTICAL AXIS OF UNIAXIAL CRYSTAL

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We built theoretical model of evolution of intensity of asymmetric and symmetric arrays of singular beams passing along optical axis of uniaxial crystal ($LiNbO_3$) for arrays consisting different number of beams. We compared theoretical and experimental evolution of intensity distribution and dependence of angular rotation of an asymmetric and symmetric singular beam arrays on the inclination angle of corresponding arrays of singular beams passing along optical axis of uniaxial crystal for arrays consisting different number of beams.
Keywords: optical vortex, array, asymmetric.

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INTRODUCTION

At present time properties of optical beam arrays attract quiet big attention because of their unique properties [1, 2]. Possibility to carry big value of orbital angular momentum by such a systems give us an opportunity for trapping and transportation of microparticles and also for optical encoding and carrying information.

1. VORTEX-BEAM ARRAY PASSES THOUGH UNIAXIAL CRYSTAL

We consider the set of the beams that are placed symmetrically on the circular hyperboloid [3]. Such an array contains N beams with topological charge l that are shifted from a centre at the distance r_0 and inclined in azimuthal direction y_n at the angle α_i (Fig. 1 a, b). The initial array has the angle between the beams $\varphi_n = 2\pi/N$. Moreover, each partial beam has an additional phase $m\varphi_n$ at the initial plane that produces the central optical vortex with topological charge m. The shape of the beam array can be synthesized by a computer-synthesized hologram. We have the beam array recorded on the hologram for the order $l = +1$ in the diffracted beam. The lens system launches the array with the initial circular polarization to the uniaxial crystal along its optical axis. The output lens collimates the array while the quarter wave plate together with the polarizer enable us to separate the right or left circular polarized beam component. The circular polarized components of the beam array can be presented as a superposition of N beams (N for symmetric array, $N-1$ for asymmetric array) that are tilted at the different angles for the ordinary and the extraordinary beams relative to the optical axis.

Coordinates of the *n-th* beam are represented by

$$\begin{aligned} x_n &= x\cos\varphi_n + y\sin\varphi_n - r_0; \\ y_n &= (-x\sin\varphi_n + y\cos\varphi_n)\cos\alpha - z\sin\alpha; \\ z_n &= (-x\sin\varphi_n + y\cos\varphi_n)\sin\alpha + z\cos\alpha. \end{aligned} \quad (1)$$

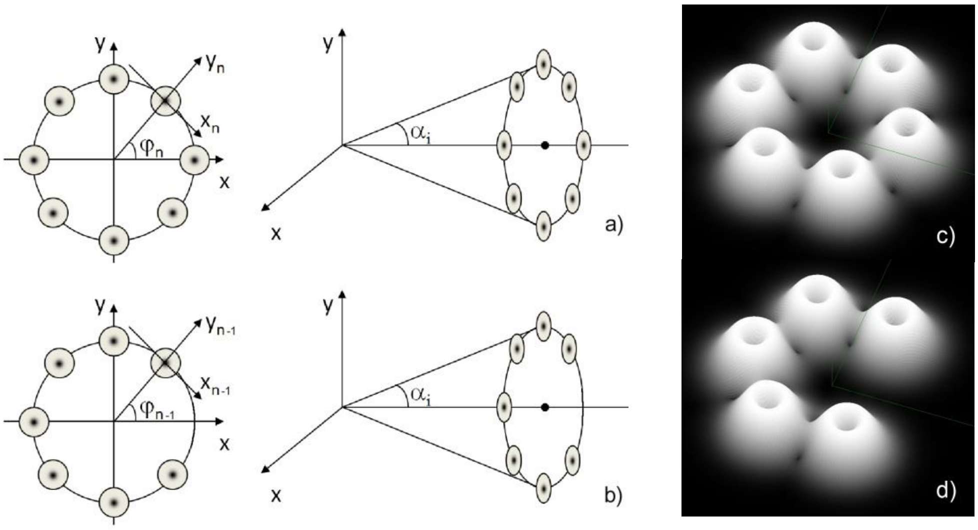

Fig. 1. Scheme of symmetric (a) and asymmetric (b) optical beam array and theoretical intensity distributions of symmetric array consisting 6 (c) and asymmetric array consisting 6-1 (d) beams with $l = 1$, $m = 1$, $z = 0$ cm, $r_0 = 0{,}65$ mm, $w = 2\times10^{-4}$m, $\alpha = 1{,}14$ deg.

The field of single n-th beam in the array can be represented in form of

$$\Psi_n = \left(\frac{r_n}{w_n}\right)^{|l|} \exp\left(-\frac{r_n}{w_n}\right)^2 \exp\left(-ik\left[\frac{z_n r_n^2}{2R_n} - \left(|l|+1\right)\arctan\left(\frac{z_n}{z_0}\right) + l\varphi_n\right]\right), \qquad (2)$$

where l – charge of vortex, r,φ,z – cylindrical coordinates, k – wave number, w – waist of the beam, $w_n = \rho_n\sqrt{1+\left(\frac{z_n}{z_0}\right)^2}$, ρ – waist of the beam in the focus, R – radius of curvature of the beam, $R_n = z_n\left(1+\left(\frac{z_n}{z_0}\right)^2\right)$, z_0 – Rayleigh length, $z_0 = \frac{k\rho_n^2}{2}$.

Then total field of

the symmetric array: $\Psi = \sum_{n=1}^{N}\Psi_n$ and

of the asymmetric array: $\Psi = \sum_{n=1}^{N-1}\Psi_n$. (3)

Modeling intensity distributions of symmetric and asymmetric arrays are represented in Fig. 1 (c, d).

2. ANGLE OF ROTATION

Average value of the rotation angle of the center of gravity of separate beams in array between right and left circular polarized components is connected with changing of orbital angular momentum (OAM) (Fig. 2). The value of the rotation angle has been calculated by Eqs. (4) – (7). We calculated the center of gravity of separate beams in array in right and left circular polarized components and the average angle between them. Calculation has been proceed numerically by using programming language – Delphi. In an area where beams separated in space the value of angle of rotation is reached the constant value $\Delta\varphi = -s / k_0\alpha_0\alpha_m z$ [4].

$$x_{n,right(left)}(y_{n,right(left)}) = \frac{\int_{\varphi_{n-1}}^{\varphi_n} d\varphi \int_0^\infty x(y) I_{right(left)} r dr}{\int_{\varphi_{n-1}}^{\varphi_n} d\varphi \int_0^\infty I_{right(left)} r dr}, \quad (4)$$

$$\varphi_{n,right(left)} = \arctan\frac{y_{n,right(left)}}{x_{n,right(left)}}, \quad (5)$$

$$\varphi_n = \varphi_{n,right} - \varphi_{n,left}, \quad (6)$$

$$\Delta\varphi = <\varphi_n>. \quad (7)$$

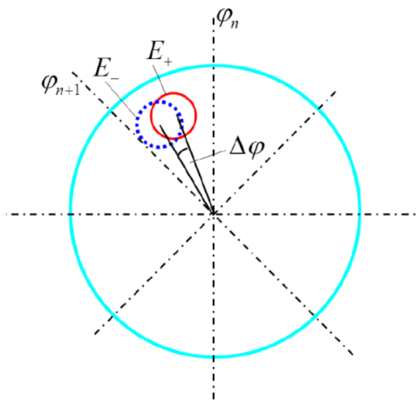

Fig. 2. Rotation of the beam array.

3. EXPERIMENTAL RESULTS

For experimental study of the optical beam array evolution we used the experimental set-up [5] that pictured at Fig. 3. Initial linearly polarized Gaussian beam from He-Ne laser with wavelength λ = 0.6328 μm is transformed to circularly polarized beam by the polarization filter consisting of the polarizer P and quarter-wave plate λ/4.The spatial computer-generated phase modulator D forms the optical beam array of vortices (we choose first order of diffraction). The lens system L1, L2 with known focus distances enables us to control shape and focusing of the beam array with defined inclination angle and the waist of the beam at input face of the $LiNbO_3$ crystal (length of the crystal $z = 2$ cm). Output beam is directed through the polarization filter λ/4, P to the CCD camera by the lens L3. The last mentioned polarization filter allows us to capture pictures in certain polarization states to define Stokes parameters.

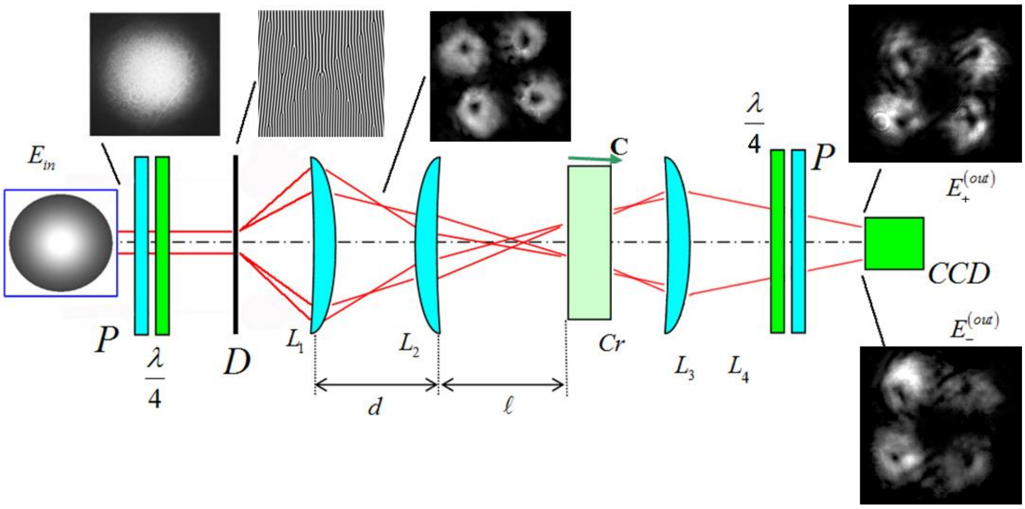

Fig. 3. Experimental set-up.

Rotations of the symmetric and asymmetric arrays while propagation are presented at Fig. 4 and 5, respectively. We reached good accordance of modeling and experimental results of intensity distribution of symmetric and asymmentric arrays while propagation along z axis.

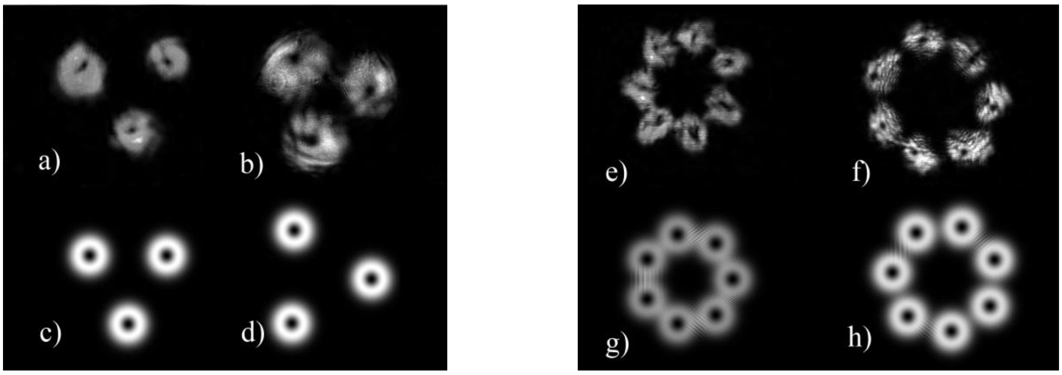

Fig. 4. Experimental (a, b, e, f) and theoretical (c, d, g, h) intensity distributions of symmetric array consisting 3 (a, b, c, d) and 7 (e, f, g, h) beams passing along optical axis of uniaxial crystal $LiNbO_3$ with $l = 1$, $m = 1$, $n_o = 2{,}2$, $n_e = 2{,}3$, $z = 2$ cm, $r_0 = 0{,}65$ mm, $w = 2\times10^{-4}$ m, $\alpha = 1{,}14$ deg (a, c, e, g), $\alpha = 5{,}21$ deg (b, d, f, h).

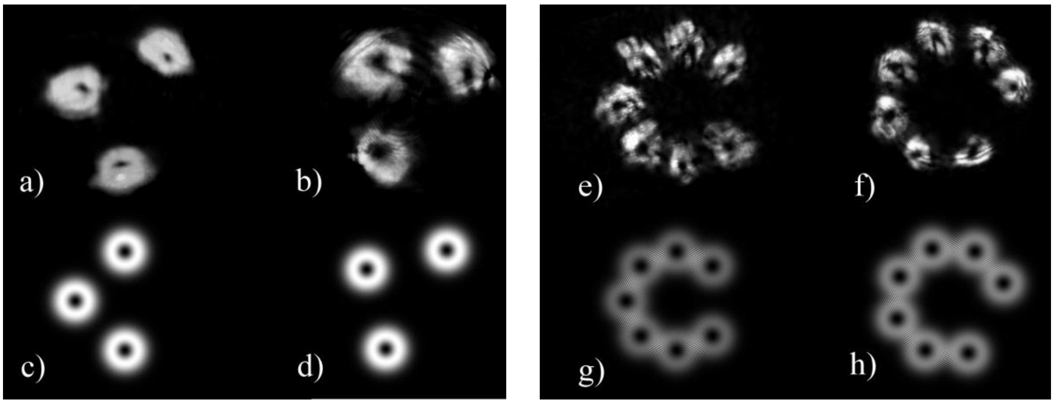

Fig. 5. Experimental (a, b, e, f) and theoretical (c, d, g, h) intensity distribution of asymmetric array consisting 4 – 1(a, b, c, d) and 8 – 1 (e, f, g, h) beams passing along optical axis of uniaxial crystal $LiNbO_3$ with $l = 1$, $m = 1$, $n_o = 2{,}2$, $n_e = 2{,}3$, $z = 2$ cm, $r_0 = 0{,}65$ mm, $w = 2\times10^{-4}$ m, $\alpha = 1{,}14$ deg (a, c, e, g), $\alpha = 5{,}21$ deg (b, d, f, h).

We can notice the peak down of angle of rotation φ in the area from 3,5 till 4,5 deg of inclination angle α for both types of arrays (Fig. 6). Such splash of value of rotation angle leads to change in flux of orbital angular momentum of the arrays in this area.

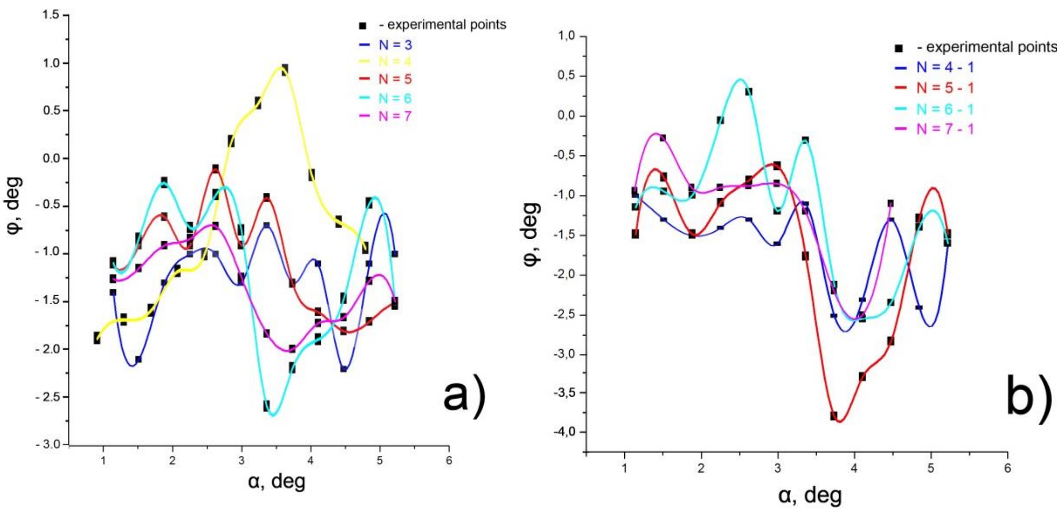

Fig. 6. Dependence of angular rotation of an asymmetric (b) and symmetric (a) singular beam arrays on the inclination angle of corresponding arrays of singular beams passing along optical axis of uniaxial crystal with $LiNbO_3$ with $l = 1$, $m = 1$, $n_o = 2{,}2$, $n_e = 2{,}3$, $z = 2$ cm, $r_0 = 0{,}65$ mm, $w = 2\times10^{-4}$ m.

CONCLUSIONS

Rotation of the symmetric and asymmetric arrays were registered while propagation.

In area of 4 deg of inclination angle α splash of angle of rotation φ results in energy conversion between orbital and spin angular momentum flux in both symmetric and asymmetric optical beam arrays.

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Фадєєва Т. А. Еволюція симетричних та асиметричних масивів оптичних пучків що пройши вздовж вісі одновісьового кристалу / Т. А. Фадєєва, М. О. Іванов, Х. В. Борисова, А. Г. Борисов, О. Ф. Рибась // Вчені записки Таврійського національного університету імені В. И. Вернадського. Серія : Фізико-математичні науки. – 2013. – Т. 26 (65), № 2. – С. 7-12.
Ми побудували теоретичну модель еволюції інтенсивності асиметричного та симетричного масивів сингулярних пучків що пройшли вздовж оптичної вісі одновісьового кристалу ($LiNbO_3$) для масивів що містять різну кількість пучків. Ми розглянули теоретичну та експериментальну залежність кутового обертання асиметричного та симетричного масивів сингулярних пучків від кута нахилу відповідних масивів сингулярних пучків що пройшли вздовж вісі одновісьового кристалу для масивів що містять різну кількість пучків.

Ключові слова: оптичний вихор, масив, асиметрія.

Фадеева Т. А. Эволюция симметрического и асимметрического оптических пучков прошедших вдоль оптической оси одноосного кристалла / Т. А. Фадеева, М. О. Иванов, К. В. Борисова, А. Г. Борисов, А. Ф. Рыбась // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия : Физико-математические науки. – 2013. – Т. 26 (65), № 2. – С. 7-12.
Мы построили теоретическую модель эволюции интенсивности асимметричного и симметричного массивов сингулярных пучков прошедших вдоль оптической оси одноосного кристалла ($LiNbO_3$) для массивов включающих разное количество пучков. Мы рассмотрели теоретическую и экспериментальную эволюцию распределения интенсивности и зависимость углового вращения асимметричного и симметричного массивов сингулярных пучков от угла наклона соответствующих массивов сингулярных пучков прошедших вдоль оси одноосного кристалла для массивов содержащих разное количество пучков.

Ключевые слова: оптический вихрь, массив, асимметрия.

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