DIGITAL SORTING OF STRUCTURED VECTOR LG BEAMS BY THE MOMENT OF INTENSITY METHOD

S.I. Khalilov*, M.V. Bretsko, Ya.E. Akimova, A.V. Volyar, A.O. Ivakhnenko

Physics and Technology Institute of V.I. Vernadsky Crimean Federal University, Simferopol, Republic of Crimea, 295007, Russia

**e-mail: server.khalilov.94@mail.ru*

INTRODUCTION

Polarization is one of the important properties of light. The vector nature and its ability to interact with matter makes it possible for many optical devices and systems to exist. The propagation and interaction of polarization with materials has been extensively studied in metrology, imaging technologies, data storage, optical communications, materials science and astronomy, and biological research. Most of the studies dealt with spatially uniform polarizations, i.e. the polarization parameters are the same at all points of the laser beam cross section.

Of particular interest are beams with axial symmetry of all parameters of laser radiation, including polarization, for example, beams with radial and azimuth polarization [1]. Cylindrical axially symmetric vector beams have many applications, including microscopy, lithography, electron acceleration, material processing, high resolution metrology, microellipsometry, and spectroscopy [1].

There are two groups of methods for obtaining cylindrical vector beams: intracavity and extracavity. In the first case, polarization-selective optical elements are used in the resonator. This method is preferable for high-power lasers, which have a high gain of the active medium, a low-quality factor of the resonator, and a relatively low quality of radiation [2, 3].

The main advantage of out-of-cavity methods for the formation of polarization-inhomogeneous modes is their versatility. Most often, extracavity methods are based on a coherent superposition of a pair of ordinary modes, for example, using an interferometer. Any type of cylindrical vector beams can be formed in this way, and, in principle, this method is applicable to any wavelength. In addition to interference methods, schemes are known using low-mode optical fibers and nematic liquid-crystal extended light modulators [4-6].

In our article, we theoretically and experimentally consider the formation of vector sLG beams by the interferometric method and, using the method of intensity moments, analyze the scalar fields [7] after their demultiplexing.

SINGULAR VECTOR BEAMS

According to the Ref. [8], a structured scalar LG [9] beam is specified in the basis of Hermite-Gaussian (HG) beams by the complex amplitude:

$$sLG_{n,\ell}\left(\mathbf{r}|\varepsilon,\theta\right)=\frac{(-1)^n}{2^{2n+3\ell/2}n!}\sum_{k=0}^{2n+\ell}(2i)^k\,\varepsilon_k(\varepsilon,\theta)P_k^{(n+\ell-k,n-k)}(0)HG_{2n+\ell-k,k}(\mathbf{r}), \qquad (1)$$

where $\mathbf{r}=(x,y)$, $P_k^{(m-k,\,n-k)}(\bullet)$ is a Jacobi polynomial, $HG_{n,m}(\mathbf{r})$ stands for a complex amplitude of the HG mode, $\varepsilon_k(\varepsilon,\theta)=1+\varepsilon_k\exp(ik\theta)$ is an excitation function with a the amplitude ε and phase θ control parameters, n and ℓ are the radial and azimuthal number, respectively, of the LG mode with $\varepsilon=0$. A structured LG beam (1) can be treated as a representation of the LG mode in the basis of HG modes, each of which has acquired an amplitude ε and a multiple phase $k\theta$. The representation of the structured LG beam in the LG mode basis is given by Eq. (7) in Ref. [8]. When the amplitude parameter LG beam (1) equal zero (ε=0), then sLG beams corresponds to the standard LG mode with the $TC=\ell$, if we want create LG beam (also for sLG beam) with a negative TC<0, it is sufficiently to change the sign of the complex unit $i\to -i$ in Eq. (1).

The vector structured beam $\mathbf{sLG}_{n,\ell}(r|\varepsilon,\theta)$ will be shaped as a superposition of the sLG beam with right-handed circular (RH) polarization with a unit vector $\mathbf{e}_+$ and positive TC >0 in Eq.(1), while the left-handed circular (LH) polarization with a unit vector $\mathbf{e}_-$ has a complex amplitude (1), but with TC<0 as is shown in Fig.1.

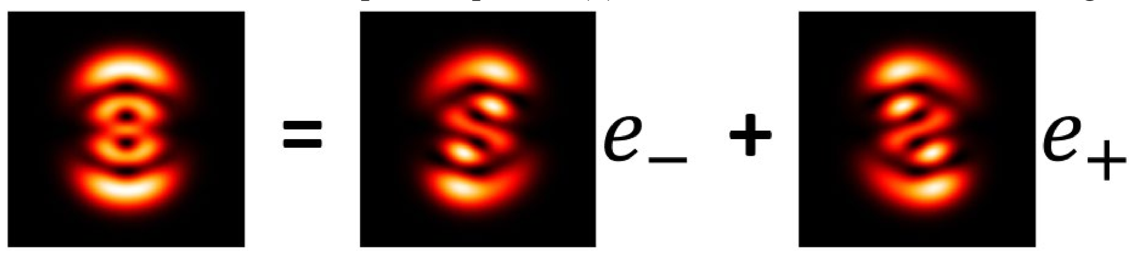

Fig. 1. *Sketch of shaping the* $\mathbf{sLG}_{1,2}$ *beam field with amplitude ε=1 and phase θ=π/4 parameters.*

Its complex amplitude is described by

$$\mathbf{sLG}_{n,\ell}\left(\mathbf{r}|\varepsilon,\theta\right)=\frac{(-1)^n}{2^{2n+3\ell/2}n!}\sum_{k=0}^{2n+\ell}\left[\mathbf{e}_+(2i)^k+\mathbf{e}_-(-2i)^k\right]\varepsilon_k(\varepsilon,\theta)P_k^{(n+\ell-k,n-k)}(0)HG_{2n+\ell-k,k}(\mathbf{r}), \qquad (2)$$

The polarization matrix (coherence matrix ($J_{\nu,\mu}$, (ν, μ)=(x, y)) or Stokes matrix (S_i, i=0,1,2,3) [11]) J is a 2×2 hermitian matrix defined by its components

$$J=\begin{pmatrix}J_{xx} & J_{xy}\\ J_{yx} & J_{yy}\end{pmatrix}=\frac{1}{2}\begin{pmatrix}S_0+S_1 & S_2+iS_3\\ S_2-iS_3 & S_0-S_1\end{pmatrix}, \qquad (3)$$

and they are given by

$$\begin{aligned}S_0&=|\psi_R|^2+|\psi_L|^2=|E_x|^2+|E_y|^2\\ S_1&=2\operatorname{Re}\left(\psi_R^*\psi_L\right)=|E_x|^2-|E_y|^2\\ S_2&=2\operatorname{Im}\left(\psi_R^*\psi_L\right)=2\operatorname{Re}\left(E_x^*E_y\right)\\ S_3&=|\psi_R|^2-|\psi_L|^2=2\operatorname{Im}\left(E_x^*E_y\right)\end{aligned} \qquad (4)$$

where Ψ_R and Ψ_L are circular and, E_x and E_y are linear components of the field. Expression (4) can be rewritten as:

$$\begin{aligned}S_0&=I(0;0)+I(90;0);\\ S_1&=I(0;0)-I(90;0);\\ S_2&=I(45;0)-I(135;0);\\ S_3&=I(45;45)-I(135;45),\end{aligned} \qquad (5)$$

here, $I(\theta;\varepsilon)$ is the intensity of light vibrations in the direction at the angle of θ to the Ox-axis, while their y-component is delayed value of ε with respect to the x-component. The ellipticity Q and the angle of inclination Ψ of the major semiaxis to the axis of the laboratory coordinate system are calculated by the formulas (6) and (7), respectively (Fig.2, 3):

$$Q=\tan\left(\frac{1}{2}\arcsin\left(\frac{S_3}{S_0}\right)\right) \qquad (6)$$

$$\Psi=\frac{1}{2}\arctan\left(\frac{S_2}{S_1}\right) \qquad (7)$$

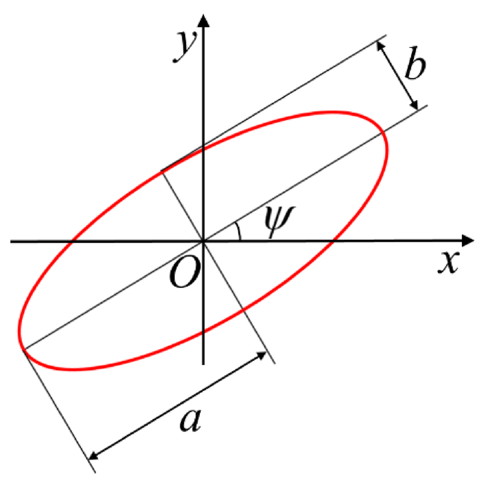

Fig. 2. *Polarization ellipse.*

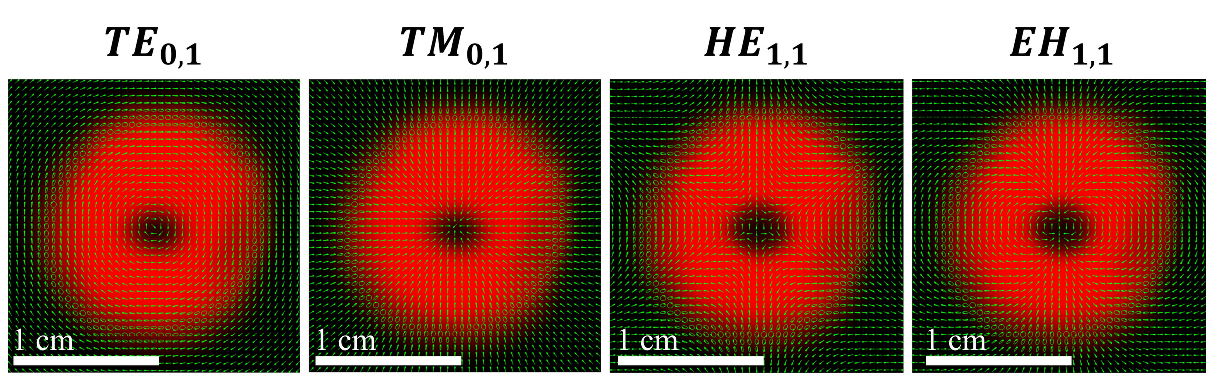

Fig. 3. *Experimentally obtained space variant lineally polarized modes of the lowest order* TE_{01}, TM_{01}, HE_{21}, EH_{11}. *The scale of patterns presented in centimeters.*

EXPERIMENTAL SETUP

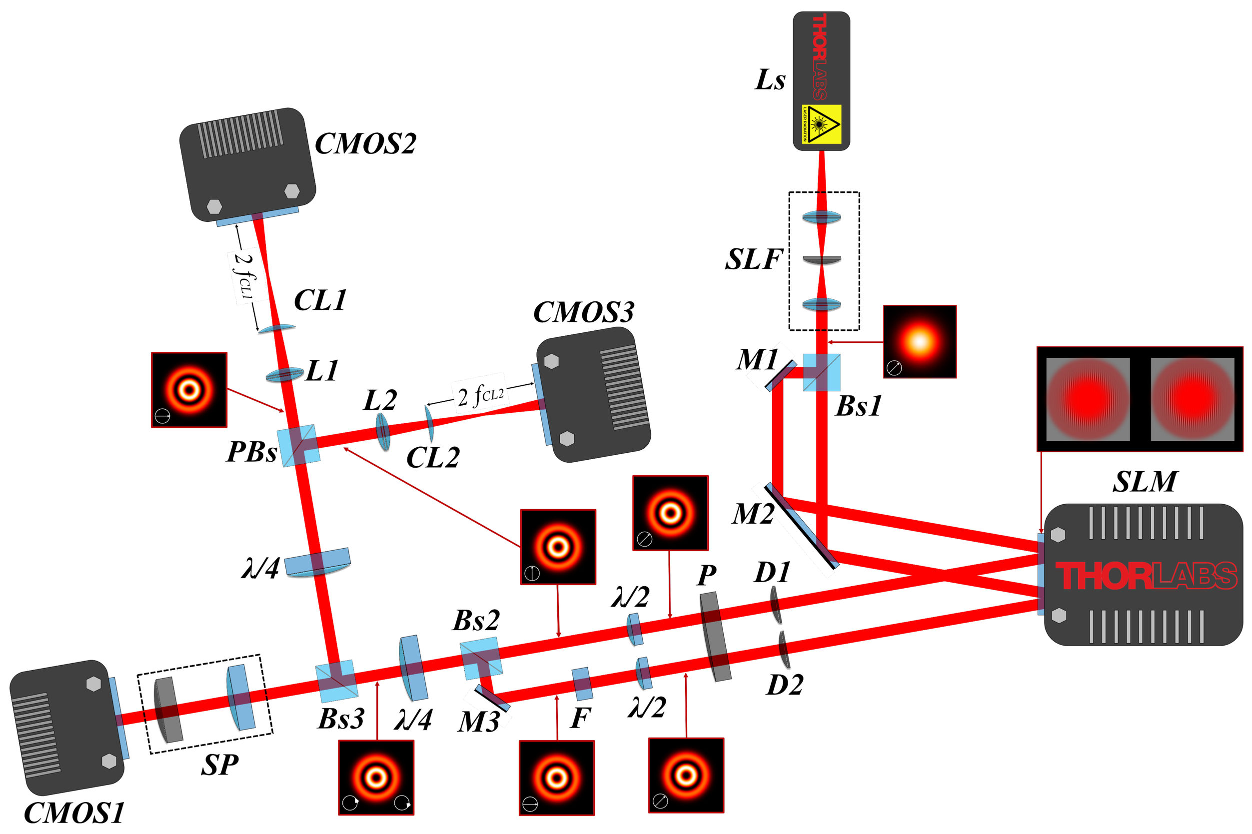

Fig. 4. *The experimental setup sketch: Ls – He-Ne laser (λ=633 nm), SLM – spatial light modulator, SLF – spatial filter, Bs – beam splitter, M- mirror, D- aperture, P- polarizer, λ/2 – half wave plate, λ/4- quarter wave plate, PBs – polarized beam splitter, L -spherical lens, Cl – cylindrical lens, F- light filter, SP- Stokes polarimeter, CMOS – camera.*

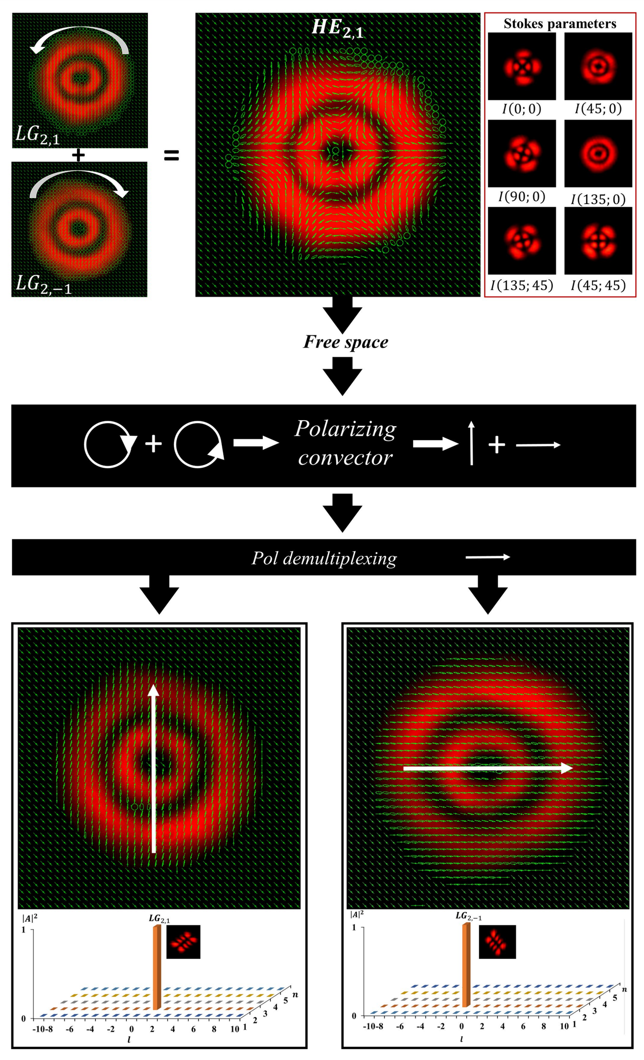

Fig. 5. *Scheme of formation of a vector sLG beam by the interferometric method and measurement of the vortex spectrum by the method of intensity moments.*

CONCLUSIONS

In the experiment, we used the intensity moments technique for the first time to measure the spectrum of vector modes and their digital multiplexing of a simple vector $\mathbf{sLG}_{21}$ beam. The amplitude and phase spectra were measured in each linear polarized component of the space-variant polarization field. Then scalar fields of the polarization components were formed, which was the digital demultiplexing of the vector **sLG** field. The combination of the vector modes made it possible to restore the vector **sLG** beam again, that is the digital multiplexing the vector field.

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