SECTORIAL PERTURBATION OF SPIRAL VORTEX BEAMS

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Abstract

This research presents studies of the structural stability of a spiral beam subjected to sectoral perturbation. Sector perturbation causes a change in the direction of circulation of streamlines of the Poynting vector in the area of perturbation, which are caused by the appearance of vortices with negative topological charges. However, such perturbations do not cause a change in the orbital angular momentum of the beam, despite the increase in the number of vortex modes, and the perturbed beam remains structurally stable.

Theoretical information

In our research, we considered the passage of a spiral beam (SB) of light in the form of a seven-quantized triangle through an opaque sector. The complex amplitude of such a beam [1] can be represented as:

$$\Psi_\Delta(X,Y,Z|\alpha)=\sum_{m=0}^{\infty}C_{3m+1}\sum_{n=-\infty}^{\infty}C_{3m+1,n}(\alpha)LG_{0,n}(X,Y,Z), \tag{1}$$

where C_{3m+1} – amplitude coefficients of Laguerre-Gaussian (LG) modes included in the composition of the SB, $C_{m,n}(\alpha)$ – amplitude coefficients of each perturbed LG mode by the sector, which are defined as

$$C_{m,n}(\alpha)=(-1)^{m-n}\,\Gamma\left(\frac{|m|+|n|}{2}+1\right)\frac{\sin\left[(m-n)(\pi-\alpha)\right]}{m-n}\Big/\left(\pi 2^{\frac{|m|-|n|}{2}}|n|!\right). \tag{2}$$

The construction of the streamlines of the Poynting vector contains fine details of the process of destruction of the singular structure of the beam and manifests itself in the form of a pattern of critical points of the energy flow. Unlike the phase distribution, streamlines outline complex trajectories in the vicinity of singular points. The shape of the streamlines is determined by the phase gradient of the SB beam $\nabla(\Phi_\Delta)$, $\nabla=\mathbf{i}\partial_x+\mathbf{j}\partial_y+\mathbf{k}\partial_z$ and is written as

$$\mathbf{J}_\Delta(\mathbf{r})=\mathrm{Im}\left(\Psi^*_\Delta\cdot\nabla\Psi_\Delta\right). \tag{3}$$

Orbital angular momentum defined as [3]

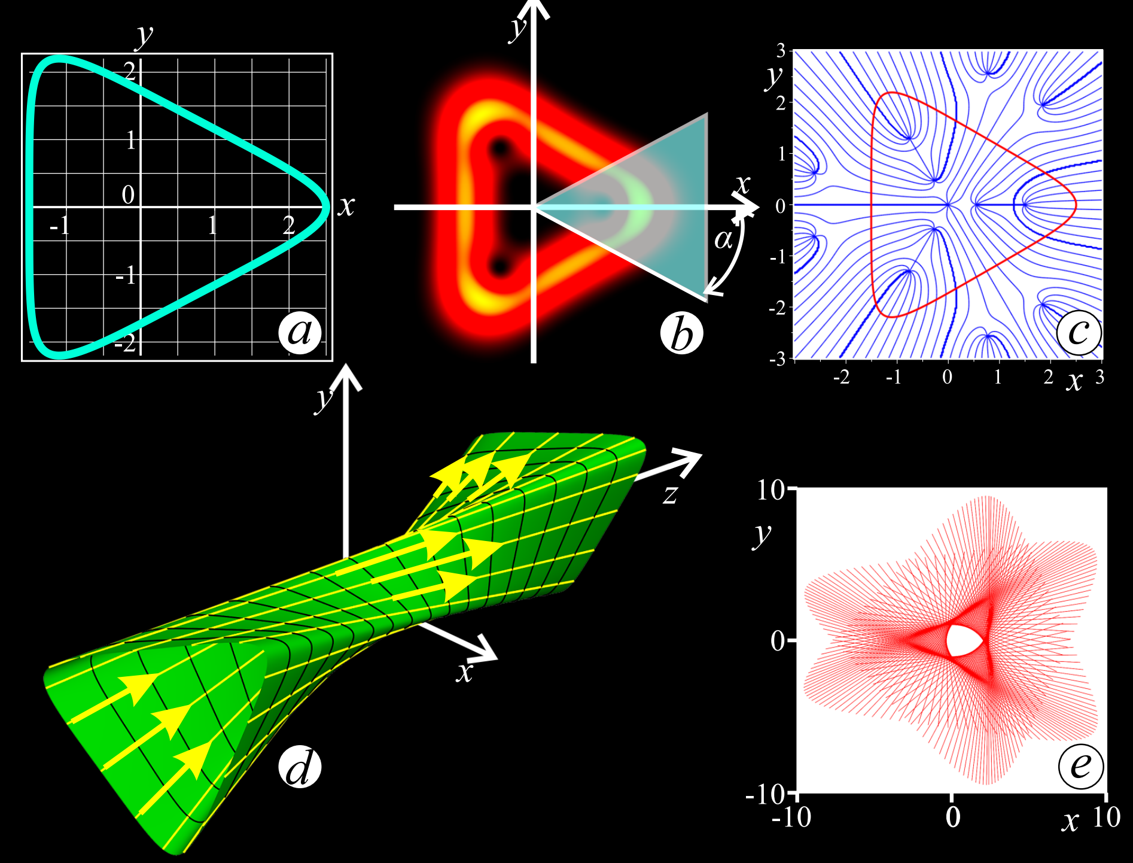
$$\ell_z=\sum_{m=0}^{N}\sum_{n=-M}^{M}n\bar{C}^2_{m,n} \tag{4}$$

and Informational Entropy [2]

$$H_I(\alpha)=-\sum_{m=0}^{N}\sum_{n=-M}^{M}\bar{C}^2_{m,n}(\alpha)\log_2\bar{C}^2_{m,n}(\alpha) \tag{5}$$

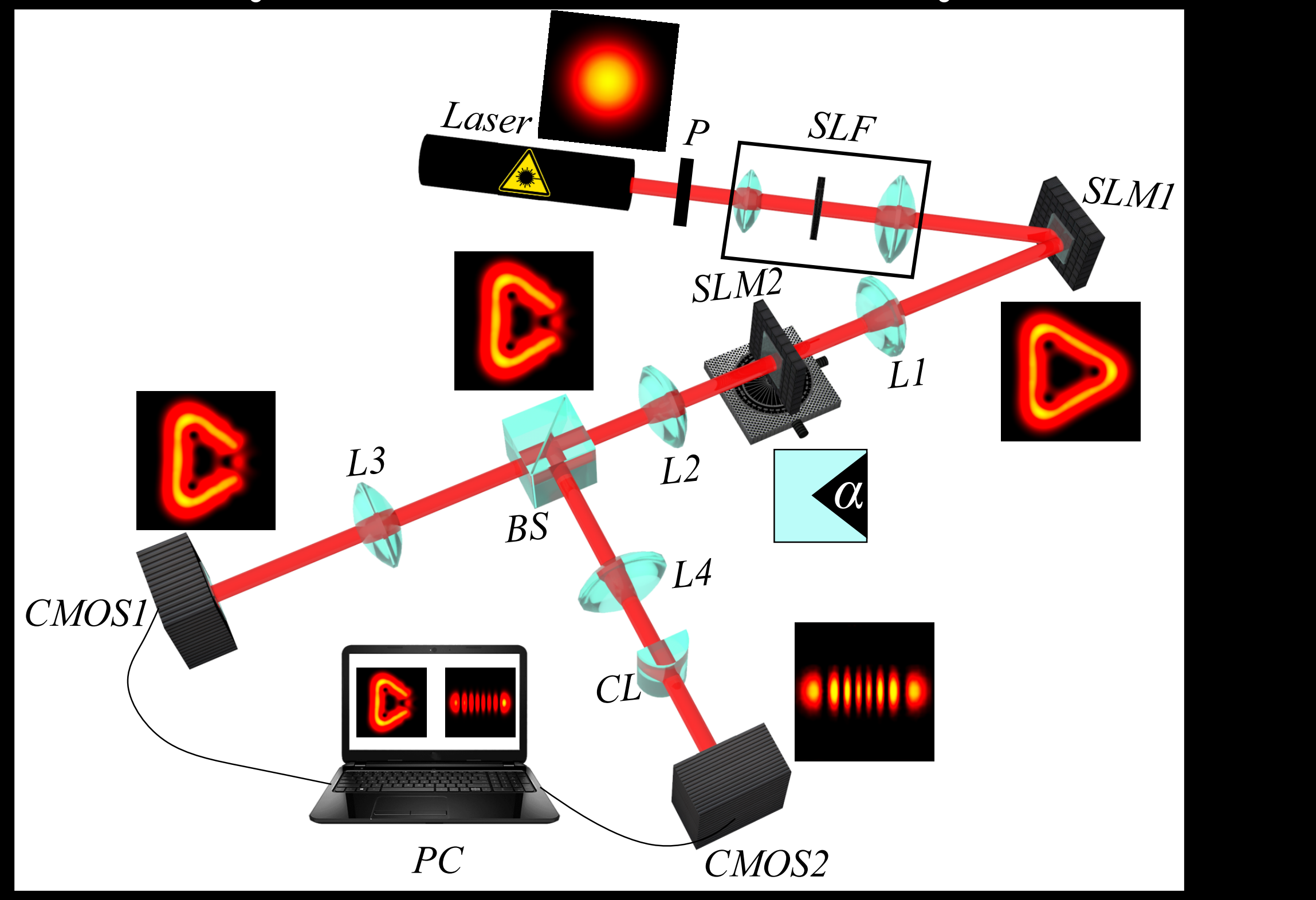
where $\bar{C}^2_{m,n}$ are normalized squared modes related to (2) modes by the relation $\bar{C}_{m,n}=C_{m,n}\sqrt{\pi 2^{-2-m}m!}$

Beam model



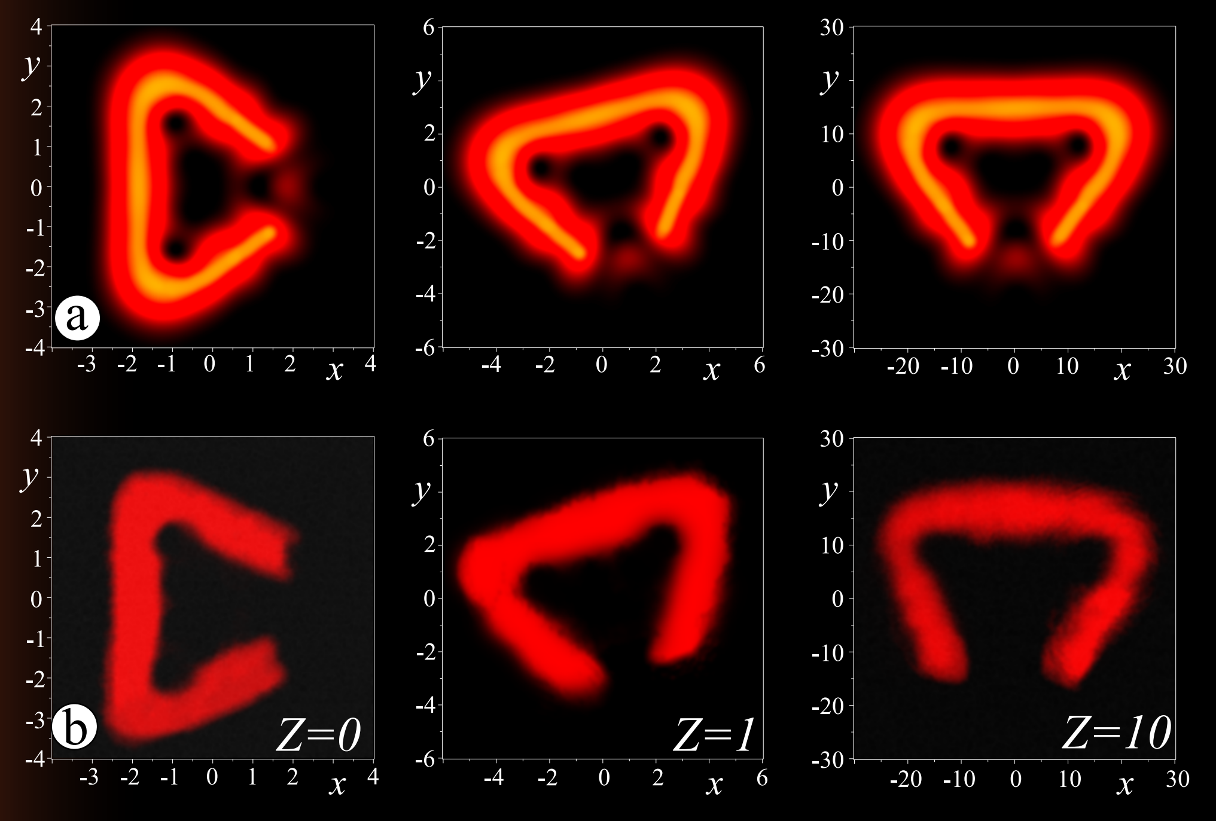
Triangular spiral vortex beam: (a) the triangular line on the complex plane, (b) intensity distribution of the spiral beam (bright triangular line corresponds to maxima intensity values), (c) the phase pattern with a triangular generatrix, (d) a surface outlined by the generatrix with straight rays on its surface, (e) projections of the ray trajectories onto the $z=0$ plane. The wedge inserted into the triangle image points out the sector perturbation.

Experimental setup

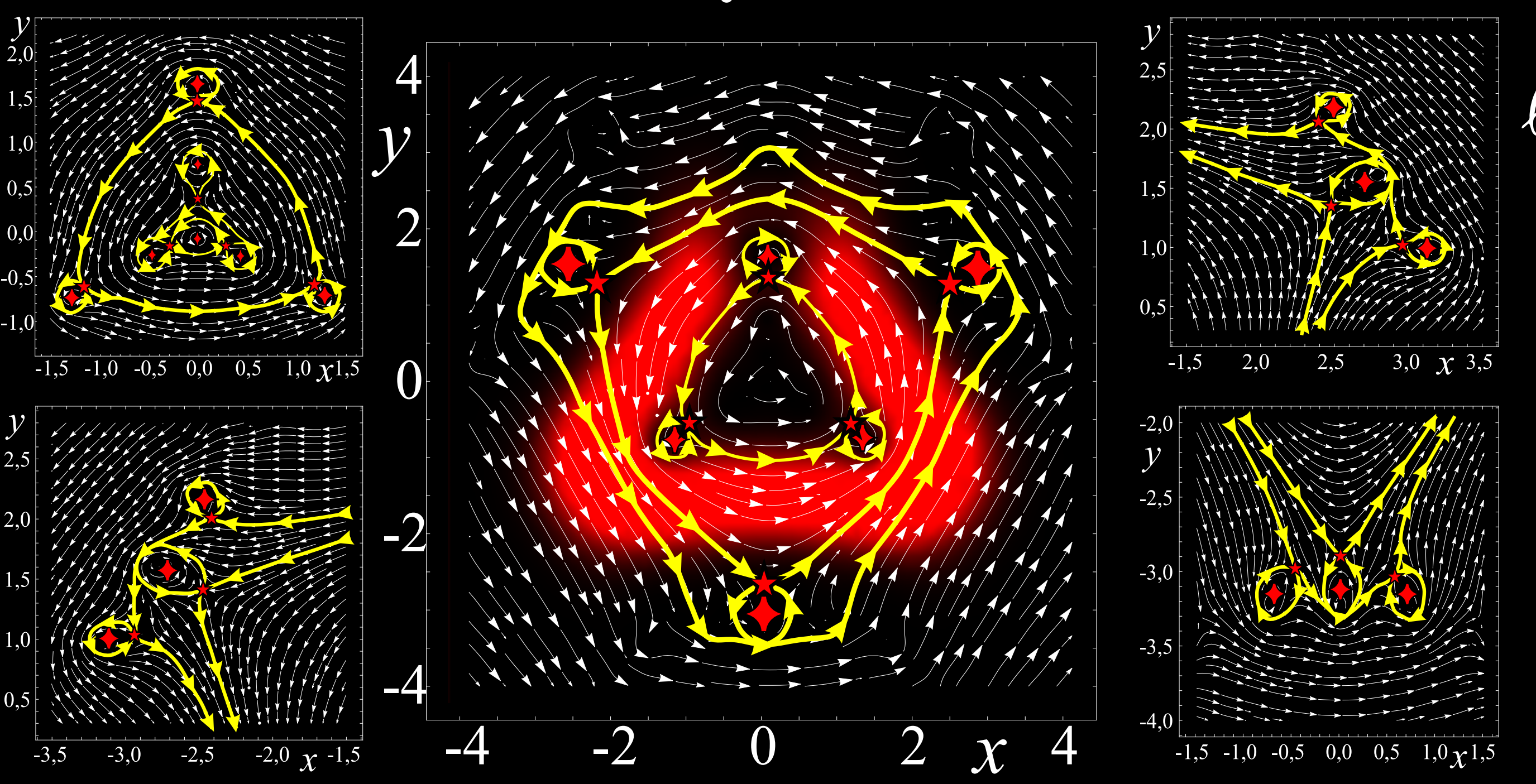


Experimental setup: laser 0.633 μm, *P*-polarizer, SLF – spatial light filter, L1-4 - lens, L3 lens has a focal length about *f=20cm*, CL – cylindrical lens (*f =25cm*), BS – beam splitter, SLM1,2 - spatial light modulator, CMOS1,2 – photodetector, PC - computer.

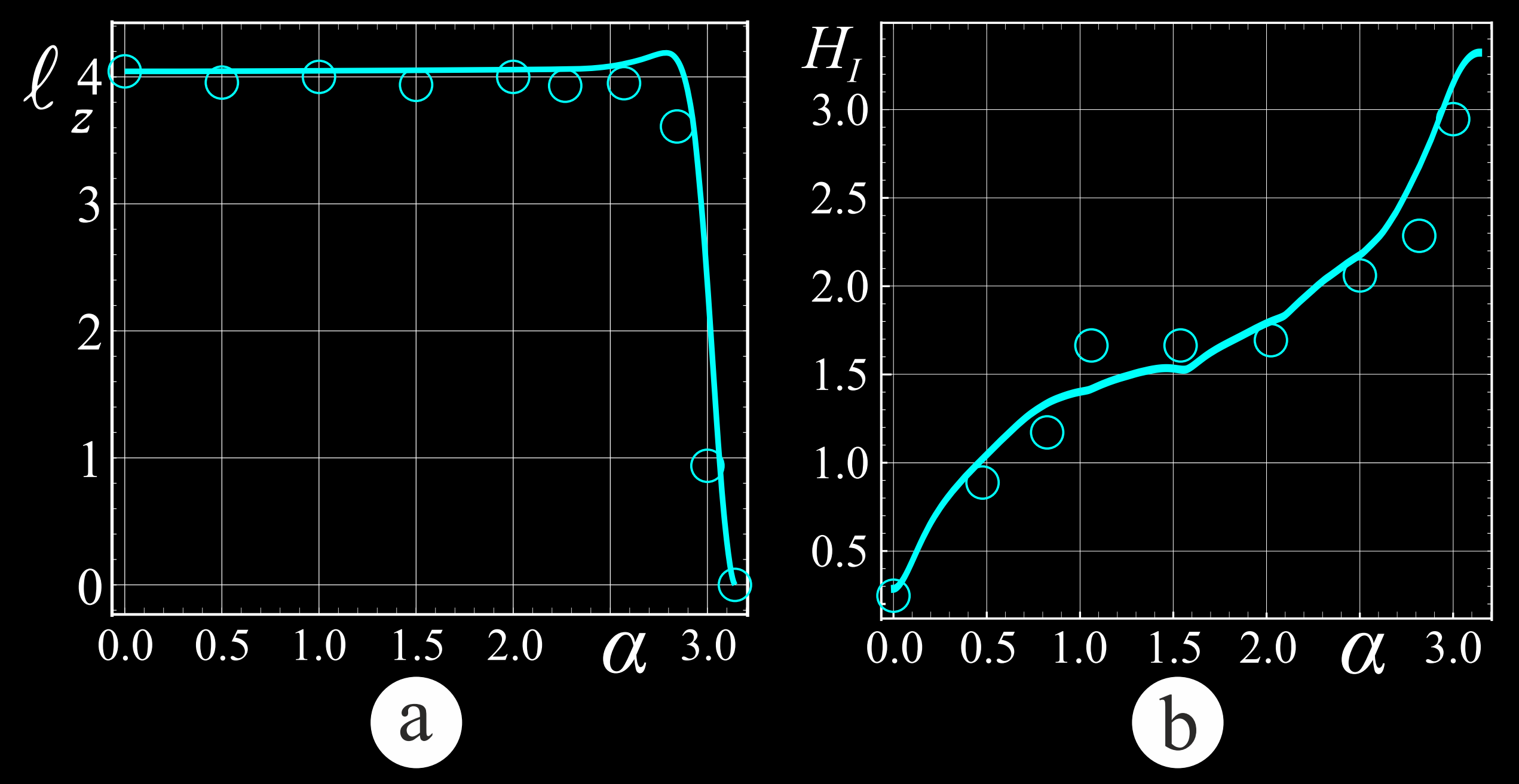
Experiment



In the figure, we see a good agreement between theory (a) and experiment (b). Intensity pattern when propagating from $Z=0$ to $Z=10$ does not change even in the perturbed region taking into account the beam expansion and angular rotation. In other words, the beam remains structurally stable.



Why the SB keeps stability without changing its perturbed structure despite removing several optical vortices and breaking partially the caustic? Our task is to trace the main features of the perturbed energy flows for angle π/10 of the sector perturbations and to point out inherent in their structural stability. In the center of figure there is a streamlines pattern of the entire triangular beam cross-section against a background of the flux density. Despite it breaks down the caustic line, cuts out two vortices at the vertex of the triangle and touches a vortex on the beam axis, does not significantly change the inner structure of the streamlines. In the vicinity of the vertex, three centers and three saddles were shaped, separated from each other and the inner region of the caustic by two separatrices, streamlines circulations around the critical points with opposite signs. The increased perturbation “attractes” vortices from distant regions to the caustic region.



We have deliberately expanded the range of perturbation angles in order to reveal the perturbation region where vortices with negative TC have a significant effect. In the full angular range the informational entropy (b) slowly increases, since the contribution of new LG states to the perturbed beam is increases. The OAM (a) remains unchanged over almost the entire range of perturbation angles, and only when the beam is practically overlapped does the OAM decrease to zero.

Conclusion

Using computer simulation methods and measurement of 3D mode spectra (amplitudes and phases), we investigated the property of triangular helical beams to maintain structural stability despite significant sector perturbations. It was found that the sector perturbation causes significant distortions in the pattern of streamlines in the region of the shadow of the sector diaphragm. However, they have the same direction of circulation over the entire cross-sectional area of the beam at small perturbation angles. At large angles of the sector diaphragm, wide sections of the beam cross section appear with opposite circulations of the streamlines. It turned out that the OAM remains unchanged over a wide range of perturbation angles, despite the rapid increase in the number of states, and only at sector angles of about 170° does the OAM drop sharply.

References

1 E. Abramochkin and V. Volostnikov, *Modern optics of Gaussian beams* (Moscow, Fizmatlit, 2010).
2 A. Volyar, M. Bretsko, Ya. Akimova, and Yu. Egorov, “Orbital angular momentum and informational entropy in perturbed vortex beams,” Opt. Lett. 44, 5687-5680 (2019).
3 A. Volyar, M. Bretsko, Ya. Akimova, and Yu. Egorov, "Measurement of the vortex and orbital angular momentum spectra with a single cylindrical lens," Appl. Opt. 58, 5748-5755 (2019).