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# MANIPULATION OF THE VORTEX CHARGE IN A CASCADE SYSTEM OF GLASSES SUBJECTED TO BENDING STRESS

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**Abstract.** It has been experimentally shown for the first time that orbital angular momentum can be manipulated using a two-cascade system of glass plates subjected to bending stress. We have demonstrated that doubling the vortex charge is possible when the incident optical beams on each cascade have the same sign of circular polarization. Otherwise, when the signs of these polarizations are opposite, the outgoing beam is a Gaussian, vortex-free beam; i.e., the OAM of the generated vortices is opposite, leading to annihilation of the OVs. It has been shown that the proposed method for multiplying the OAM can be used in optical communication.

**Keywords**: piezooptic effect, bending deformation, multi-cascade system, optical vortex, orbital angular momentum, multiplication of the vortex charge
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## 1. Introduction

Optical vortices (OV) carrying orbital angular momentum (OAM) have attracted researchers' attention for more than 30 years [1]. These physical objects are of interest for their applications in emerging areas of optics, such as microparticle manipulation [2], quantum information processing [3], optical microscopy beyond the diffraction limit [4], etc. To date, methods for generating OVs are well developed and include: spiral phase plates [5], q-plates [6], computer-synthesized holograms [7], spatial light modulators or metasurfaces [8-11], OV lasers [12], anisotropic crystals [13], and other methods not listed here. Recently, we have shown that OV generation can be achieved using parametric optical effects, i.e., electro- and piezo-optics, which allow one to operate the efficiency of spin-to-orbit conversion at the working element by applying a non-homogeneous field of a certain configuration [14-17]. From the perspective of materials optical science, operation via the piezo-optic effect is particularly attractive because it does not require crystalline materials and can generate OVs even in isotropic glasses by applying bending stress [18,19].

Branches such as quantum information processing and singular optics telecommunications encourage the use of vortex beams with different OAM, which allow encoding a certain amount of information in each beam with a defined OAM. These lead to an increase in data transmission capacity [20]. Vortex charge multiplication can be achieved using cascade systems of spiral phase plates [21,22], q-plates [23-25], and metasurfaces [26]. The spiral phase plates are rigid elements that cannot be operated. Q-plates can be tuned in a small range by an electric field [27]. Liquid crystal metasurfaces, or spatial light modulators,

are programmable, high-tech devices. Recently, we have theoretically shown that a multistage system of crystalline elements subjected to torsion stresses can multiply the OV charge and control it with applied bending stress [28]. The bending-stressed elements must produce the same OV charge multiplication as the multistage system of elements subjected to torsion stress, since torsion and bending stresses generate single-charged OVs. The experimental verification of the single-stage bending system has also been demonstrated, which produced an almost canonical single-charged vortex [29]. Therefore, the present work is aimed at the experimental verification of the possibility of multiplication of OAM using multistage bent glass elements.

## 2. Experimental method and results

To demonstrate vortex charge multiplication or compensation, we carried out our experiment with a Mach-Zehnder interferometer. The He-Ne laser (λ = 632.8 nm) served as the light source. In our experiment, we used a two-cascade system of bent glass plates. A long-focal-length lens is placed in the reference arm to create a beam with a spherical wavefront.

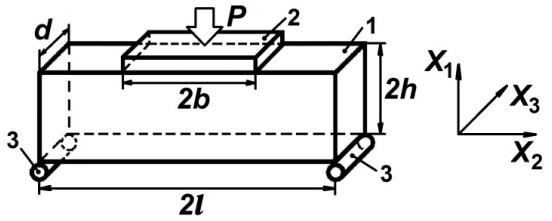



**Fig. 1.** Scheme of application of load $P$ distributed over the rectangular region $2b \times d$ on the upper surface of the glass element in the shape of a rectangular parallelepiped: 1 – sample; 2 – punch; 3 – support; the $X_3$ axis of the rectangular coordinate system ($X_1$, $X_2$, $X_3$) indicates the direction of light propagation.

For our experimental studies, the bending-stressed glass elements with geometric parameters $d$ = 41 mm, $2h$ = 5 mm, $2b$ = 5 mm and $2l$ = 36 mm, made of flint F2 glass (in SCHOTT classification), were used (Fig. 1). For this glass, the refractive index in the unstressed state $n_0 = 1.6169$ and the stress optical coefficient $K = 0.5 n_0^3 (\pi_{11} - \pi_{12}) = 2.95 \times 10^{-12}$ m$^2$ / N ($\pi_{11}$, $\pi_{12}$ are the components of the piezo-optical tensor) at the wavelength λ = 550 nm [30]. For this aim, we designed and fabricated a special setup for applying bending stress. The working area of the bending-stressed glass elements was limited to the load-application region.

The bending-stressed glass element (BSGE) is described by a Jones matrix $J_S$ of the linear phase retarder [31]

$$J_S = \begin{bmatrix} \cos(\pi d\Delta n/\lambda) + i\sin(\pi d\Delta n/\lambda)\cos(2\theta) & i\sin(\pi d\Delta n/\lambda)\sin(2\theta) \\ i\sin(\pi d\Delta n/\lambda)\sin(2\theta) & \cos(\pi d\Delta n/\lambda) - i\sin(\pi d\Delta n/\lambda)\cos(2\theta) \end{bmatrix}, \quad (1)$$

where $\Delta n = K(\sigma_{22}^2 + 4\sigma_{12}^2)^{1/2}$ is the birefringence; $\theta$ is the angle of rotation of the optical indicatrix about the $X_3$ axis; $\sigma_{12} = -\dfrac{3PX_2(h^2 - X_1^2)}{8bdh^3}$ and $\sigma_{22} = \dfrac{3PX_1(2lb - b^2 - X_2^2)}{8bdh^3}$ are the shear stress and normal stress, respectively, within the working area of the BSGE.

Let a light beam of radius $R$ pass through the BSGE along the $X_3$ axis within the working area. If polar coordinates $r$ and $\varphi$ within the cross-section of this light beam are used, $X_1 = r\cos\varphi$ and $X_2 = r\sin\varphi$. Then, given values of $l$, $h$, $b$, and $R$ for which the equality $\theta = q\varphi$ (where $q$ = 1/2) holds fairly accurately, the Jones matrix of the BSGE is expressed as

$$J_S = \begin{bmatrix} \cos(APr) + i\sin(APr)\cos(2q\varphi) & i\sin(APr)\sin(2q\varphi) \\ i\sin(APr)\sin(2q\varphi) & \cos(APr) - i\sin(APr)\cos(2q\varphi) \end{bmatrix}, \quad (2)$$

where the quantity $A$ is a design parameter of the BSGE – that is, it is determined by the set of its geometric and physical parameters:

$$A = \frac{3\pi K}{8\lambda b h^3}\left(\frac{1}{2}\left(2lb - b^2 - \frac{R^2}{6}\right)^2 + 2\left(h^2 - \frac{R^2}{6}\right)^2\right)^{1/2}. \quad (3)$$

For our experimental studies, we used the one-cascade system to generate a single-charged optical vortex, the two-cascade system to generate a double-charged optical vortex, and the two-cascade system for optical vortex charge compensation. The optical schemes of these systems are presented in Fig. 2.

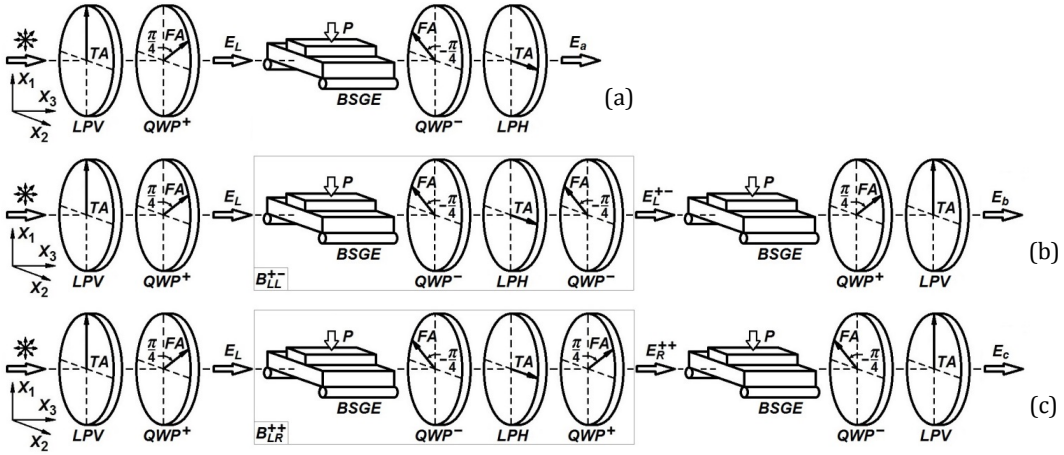



**Fig. 2.** The optical schemes of one-cascade system for generating a single-charged optical vortex (a), two-cascade system for generating a double-charged optical vortex (b) and two-cascade system for optical vortex charge compensation (c): *QWP*+ and *QWP*– are the quarter-wave plates, the fast axes (*FA*) of which, respectively, form angles of +π/4, –π/4 with the $X_1$ axis; *LPV* is the linear polarizer, the transmission axis (*TA*) of which is parallel to the $X_1$ axis; *LPH* is the linear polarizer, the transmission axis (*TA*) of which is parallel to the $X_2$ axis; $E_L$ and $E_R$ are the Jones vectors of the electric field of the left (incident) and right circularly polarized optical waves, respectively; $E_L^{+-}$ and $E_R^{++}$ are the Jones vectors of the electric field of the optical waves at the output of the elementary (single) cascades $B_{LL}^{+-}$ and $B_{LR}^{++}$, respectively [32]; $E_a$, $E_b$, $E_c$ are the Jones vectors of the electric field of the outgoing optical waves for the one-cascade system for generating a single-charged optical vortex, two-cascade system for generating a double-charged optical vortex and two-cascade system for optical vortex charge compensation, respectively.

The Jones vector $E_L$, $E_R$ and the Jones matrices $J_{QWP+}$, $J_{QWP-}$, $J_{LPV}$, $J_{LPH}$ of the optical elements *QWP*+, *QWP*–, *LPV*, *LPH* are defined by the following relations:

$$E_L = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ i \end{bmatrix};\ E_R = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -i \end{bmatrix};\ J_{QWP+} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix};$$

$$J_{QWP-} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -i \\ -i & 1 \end{bmatrix};\ J_{LPV} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix};\ J_{LPH} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}. \quad (4)$$

As a result of the calculations, the following values for the Jones vectors $E_a$, $E_L^{+-}$, $E_b$, $E_R^{++}$ and $E_c$ were obtained:

a) one-cascade system for generating a single-charged optical vortex:

$$E_a = J_{LPH} J_{QWP^-} J_S E_L = \sin(APr)\exp(i(2q\varphi))\begin{bmatrix}0\\1\end{bmatrix}. \quad (5)$$

b) two-cascade system for generating a double-charged optical vortex:

$$E_L^{+-} = J_{QWP^-} J_{LPH} J_{QWP^-} J_S E_L = \sin(APr)\exp(i(2q\varphi - \pi/2))E_L, \quad (6)$$

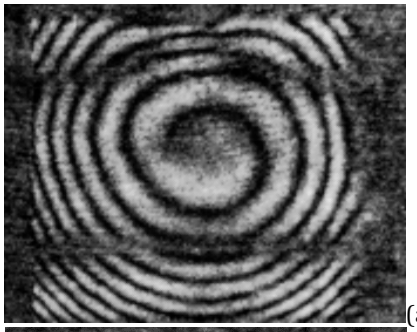
$$E_b = J_{LPV} J_{QWP^+} J_S E_L^{+-} = \sin^2(APr)\exp(i(4q\varphi - \pi/2))\begin{bmatrix}1\\0\end{bmatrix}. \quad (7)$$

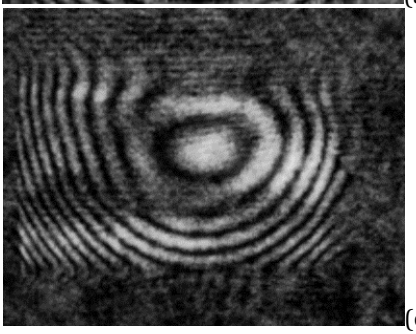
c) two-cascade system for optical vortex charge compensation:

$$E_R^{++} = J_{QWP^+} J_{LPH} J_{QWP^-} J_S E_L = \sin(APr)\exp(i(2q\varphi + \pi/2))E_R, \quad (8)$$

$$E_c = J_{LPV} J_{QWP^-} J_S E_R^{++} = \sin^2(APr)\exp(i(-\pi/2))\begin{bmatrix}1\\0\end{bmatrix}. \quad (9)$$

The interference patterns obtained for the above-mentioned systems are shown in Fig. 3.


(a)


(c)

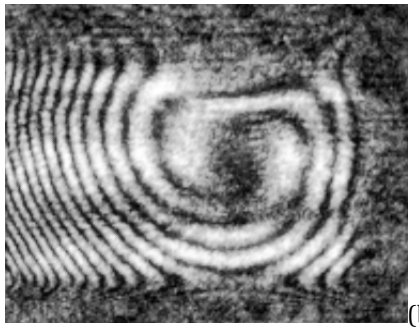

(b)

**Fig. 3.** Spiral interference patterns that appear at the bend stress application to a glass plate loaded by 5 kg ($P$=111.5 N at a value of leverage ratio equal to 2.274): (a) – the one-cascade system for generating a single-charged optical vortex; (b) – the two-cascade system for generating a double-charged optical vortex (b); (c) – the two-cascade system for optical vortex charge compensation.

As one can see (Fig. 3a), when using a one-cascade system, clear one-arm interference spiral patterns are formed that suggest the appearance of the single-charged OV in the object beam of the interferometer. Adding a second cascade and aligning its incident circular polarization to the first cascade's incident wave in the same sign produces two-arm spiral interference patterns (Fig. 3b). This unambiguously indicates that one observes double-charged OV in the interferometer's outgoing beam. The third experiment concerns a two-cascade system in which the incident optical beams on each cascade possess opposite signs of circular polarization. As shown in Fig. 3c, the Gaussian, vortex-free beam emerges from the interferometer, indicating that the vortex charges are compensated.

Consider the experimental scheme in which, after the first BSGE, the $QWP^-$, *LPH*, and $QWP^+$ are removed (Fig. 2b). Instead of these elements, we will introduce the half-wave plate (*HVP*), the function of which is to invert two circularly polarized modes (Gaussian and doughnut) that emerge from the first BSGE into modes with opposite circular polarization. The second BSGE then converts these modes into a coaxial multiple-vortex beam, as shown in Fig. 4.

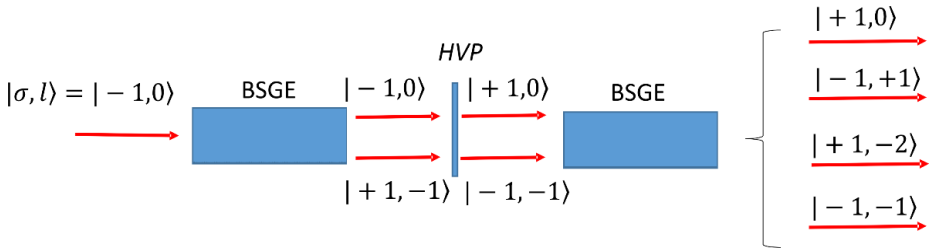



**Fig. 4.** Scheme for creating the coaxial multiple-vortex beam using a two-cascade BSGE. $|\sigma,l\rangle$ is the photon quantum state where $\sigma$ and $l$ correspond to the spin and orbital momentum, respectively.

As one can see (Fig. 4), using such a simple system configuration, which can be changed depending on needs, one can realize the conversion of a circularly polarized beam with the photon's state $|-1,0\rangle$ into multiple vortex beams with three states $|-1,+1\rangle$, $|+1,-2\rangle$, and $|-1,-1\rangle$. This method can be used in optical communication, i.e., in OAM mode-division multiplexing.

## 3. Conclusions

In this work, we experimentally demonstrate, for the first time, the feasibility of operating the OAM using a two-cascade system of glass plates subjected to bending stress. We show that multiplication (doubling) of the vortex charge is possible when the incident optical beams on each cascade have the same sign of circular polarization. When the signs of these polarizations are opposite, the outgoing beam is a Gaussian, vortex-free beam; i.e., the OAM of the generated vortices is opposite, leading to annihilation of the OVs. In the example of a simple optical scheme, it has been shown that the proposed method for multiplying the OAM can be used in optical communication.

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**Conflict of interest**. The authors declare no conflicts of interest.

**Authors' contributions**. Adamenko D. – design of the setup for bending stress application, paper draft writing, results discussion; Krupych O. – paper draft writing, performing experimental research, results discussion; Skab I. – project management, results discussion, paper draft writing; Vlokh R. – formulation of the study aim, paper writing, results discussion.

## References

1. Allen, L., Beijersbergen, M. W., Spreeuw, R. J. C., & Woerdman, J. P. (1992). Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes. *Physical Review A, 45*(11), 8185–8189.
2. He, H., Friese, M. E. J., Heckenberg, N. R., & Rubinsztein-Dunlop, H. (1995). Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity. *Physical Review Letters, 75*(5), 826–829.
3. Mafu, M., Dudley, A., Goyal, S., Giovannini, D., McLaren, M., Padgett, M. J., Konrad, T., Petruccione, F., Lütkenhaus, N., & Forbes, A. (2013). Higher-dimensional orbital-angular-momentum-based quantum key distribution with mutually unbiased bases. *Physical Review A, 88*(3), Article 032305.
4. Ritsch-Marte, M. (2017). Orbital angular momentum light in microscopy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 375*(2087), Article 20150437.
5. Sueda, K., Miyaji, G., Miyanaga, N., & Nakatsuka, M. (2004). Laguerre–Gaussian beam generated with a multilevel spiral phase plate for high intensity laser pulses. *Optics Express, 12*(15), 3548–3553.
6. Marrucci, L. (2013). The q-plate and its future. *Journal of Nanophotonics, 7*, Article 078598.

7. Bazhenov, V. Y., Soskin, M. S., & Vasnetsov, M. V. (1992). Screw dislocations in light wavefronts. *Journal of Modern Optics, 39*(5), 985–990.
8. Bentley, J. B., Davis, J. A., Bandres, M. A., & Gutiérrez-Vega, J. C. (2006). Generation of helical Ince–Gaussian beams with a liquid-crystal display. *Optics Letters, 31*(5), 649–651.
9. Ahmed, H., Kim, H., Zhang, Y., Intaravanne, Y., Jang, J., Rho, J., Chen, S., & Chen, X. (2022). Optical metasurfaces for generating and manipulating optical vortex beams. *Nanophotonics, 11*(5), 941–956.
10. Du, J., & Wang, J. (2018). Dielectric metasurfaces enabling twisted light generation/detection/(de)multiplexing for data information transfer. *Optics Express, 26*(10), 13183–13194.
11. Ostrovsky, A. S., Rickenstorff-Parrao, C., & Arrizón, V. (2013). Generation of the "perfect" optical vortex using a liquid-crystal spatial light modulator. *Optics Letters, 38*(4), 534–536.
12. Qiao, Z., Xie, G., Wu, Y., Yuan, P., Ma, J., Qian, L., & Fan, D. (2018). Generating high-charge optical vortices directly from laser up to 288th order. *Laser & Photonics Reviews, 12*, Article 1800019.
13. Volyar, A., Shvedov, V., Fadeyeva, T., Desyatnikov, A. S., Neshev, D. N., Krolikowski, W., & Kivshar, Y. S. (2006). Generation of single-charge optical vortices with an uniaxial crystal. *Optics Express, 14*(9), 3724–3729.
14. Skab, I., Vasylkiv, Y., Smaga, I., & Vlokh, R. (2011). Spin-to-orbital momentum conversion via electro-optic Pockels effect in crystals. *Physical Review A, 84*(4), Article 043815.
15. Vasylkiv, Y., Skab, I., & Vlokh, R. (2014). Generation of double-charged optical vortices on the basis of electro-optic Kerr effect. *Applied Optics, 53*(10), B60–B73.
16. Skab, I., Vasylkiv, Y., Savaryn, V., & Vlokh, R. (2011). Optical anisotropy induced by torsion stresses in $LiNbO_3$ crystals: Appearance of an optical vortex. *Journal of the Optical Society of America A, 28*(4), 633–640.
17. Skab, I., Vasylkiv, Y., Zapeka, B., Savaryn, V., & Vlokh, R. (2011). Appearance of singularities of optical fields under torsion of crystals containing threefold symmetry axes. *Journal of the Optical Society of America A, 28*(7), 1331–1340.
18. Skab, I., Vasylkiv, Y., & Vlokh, R. (2012). Induction of optical vortex in the crystals subjected to bending stresses. *Applied Optics, 51*(24), 5797–5805.
19. Vasylkiv, Y., Smaga, I., Skab, I., & Vlokh, R. (2013). Efficient materials for spin-to-orbit angular momentum conversion using bending technique. *Ukrainian Journal of Physical Optics, 14*(4), 200–209.
20. Wang, J., Yang, J.-Y., Fazal, I. M., Ahmed, N., Yan, Y., Huang, H., Ren, Y., Yue, Y., Dolinar, S., Tur, M., & Willner, A. E. (2012). Terabit free-space data transmission employing orbital angular momentum multiplexing. *Nature Photonics, 6*(7), 488–496.
21. Zhou, Z., Li, P., Ma, J., Zhang, S., & Gu, Y. (2022). Generation and detection of optical vortices with multiple cascaded spiral phase plates. *Photonics, 9*(5), Article 354.
22. Wang, C., Liu, T., Ren, Y., Shao, Q., & Dong, H. (2018). Generating optical vortex with large topological charges by spiral phase plates in cascaded and double-pass configuration. *Optik, 171*, 404–412.
23. Marrucci, L., Manzo, C., & Paparo, D. (2006). Pancharatnam–Berry phase optical elements for wave front shaping in the visible domain: Switchable helical mode generation. *Applied Physics Letters, 88*(22), Article 221102.
24. Cardano, F., Massa, F., Qassim, H., Karimi, E., Slussarenko, S., Paparo, D., de Lisio, C., Sciarrino, F., Santamato, E., Boyd, R. W., & Marrucci, L. (2015). Quantum walks and wavepacket dynamics on a lattice with twisted photons. *Science Advances, 1*(2), Article e1500087.
25. Rubano, A., Cardano, F., Piccirillo, B., & Marrucci, L. (2019). Q-plate technology: A progress review. *Journal of the Optical Society of America B, 36*(5), D70–D87.
26. He, Y., Ye, H., Liu, J., Xie, Z., Zhang, X., Xiang, Y., Chen, S., Li, Y., & Fan, D. (2017). Order-controllable cylindrical vector vortex beam generation by using spatial light modulator and cascaded metasurfaces. *IEEE Photonics Journal, 9*(5), Article 6501810.
27. Slussarenko, S., Murauski, A., Du, T., Chigrinov, V., Marrucci, L., & Santamato, E. (2011). Tunable liquid crystal q-plates with arbitrary topological charge. *Optics Express, 19*(5), 4085–4090.
28. Adamenko, D., Kryvyy, T., Skab, I., & Vlokh, R. (2024). Optical vortices generated in multi-cascade optical systems with torsion-stressed $LiNbO_3$ crystalline elements. *Ukrainian Journal of Physical Optics, 25*(2), 02099–02108.
29. Krupych, O., Adamenko, D., Dudok, T., Skab, I., & Vlokh, R. (2026). Optical vortex generation using a glass plate bent by a load distributed over a finite distance. *Ukrainian Journal of Physical Optics, 27*(1), 01102–01109.
30. State Standard 13659-78. (1978). *Colourless optical glass: Physical and chemical properties. Basic parameters*.
31. Gil, J. J., & Bernabeu, E. (1987). Obtainment of the polarizing and retardation parameters of a non-depolarizing optical system from the polar decomposition of its Mueller matrix. *Optik, 76*(2), 67–71.
32. Adamenko, D., Skab, I., & Vlokh, R. (2025). Optical vortices generation in multi-stage optical elements stressed by bending. *Proceedings of SPIE, 13813*, Article 138131L.

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***Анотація.*** *Експериментально показано, що орбітальним кутовим моментом можна керувати за допомогою двокаскадної системи скляних пластин, які зазнають деформації згину. Ми продемонстрували, що подвоєння заряду вихору можна отримати, якщо оптичні пучки, що падають на кожен із каскадів, мають однаковий знак кругової поляризації. В іншому випадку — коли знаки поляризації протилежні — вихідний пучок стає гауссовим і не містить вихорів; це пояснюється тим, що орбітальні кутові моменти (ОКМ) утворених вихорів мають протилежні знаки, що призводить до анігіляції оптичних вихорів.*

***Ключові слова:*** *п'єзооптичний ефект, деформація згину, багатокаскадна система, оптичний вихор, орбітальний кутовий момент, множення вихрового заряду*