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Singular Beams Transmitted Gyroanisotropic Crystals

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***Abstract*— In this work, studies were carried out in the field of singular beams, in the case of the passage of light beams through gyroanisotropic media. It has been experimentally shown that when Gaussian light beams pass through a system of two gyroanisotropic crystals with opposite values of the gyration coefficient, singular beams with a helical intensity distribution are formed. Using computer simulation of the process of light propagation through two gyroanisotropic crystals, it is shown that such a system is capable of generating optical vortices with a double topological charge in one of the components of circular polarization.**

***Keywords*— singular optics, topological charge, gyro anisotropic crystal.**

I. Introduction

Recently, a large cycle of experimental studies [1, 2] on solving optical problems for the paraxial wave equation [3] in the analysis of various types of singular beams has been published in leading scientific journals, which in due time open up new theoretical prospects for further scientific research. Particular attention is paid to methods for creating and analyzing phase masks [4–12] for structurally stable singular beams with a helical intensity distribution. But as you know, artificially created phase masks must be made with high precision and are associated with high production costs.

On the other hand, anisotropic crystals are of great interest for creating various types of optical singular beams. Both uniaxial and biaxial crystals can serve as the main elements for generating various types of optical singular beams [13]. One of the surprising features of optical crystals is their ability to generate polychromatic vortices in one of the components with a high degree of efficiency. Modern studies show that optical crystals, in contrast to computer-synthesized holograms [14–16], can generate polychromatic structurally stable singular beams with a helical intensity distribution.

The purpose of this article is to consider another method that allows one to generate singular beams carrying screw edge dislocations and optical vortices using two gyroanisotropic crystals.

II. Simple gyrotropic crystals

Let us ask ourselves how it is possible to obtain a structurally stable singular beam with a helical intensity distribution from a beam that has passed through an anisotropic medium.

As experimental data have shown, it is necessary to pass a beam of linearly polarized light through a gyroanisotropic medium. Figure 1 shows such beams or so-called. Airy spirals. These studies are used in crystallography to determine the right and left-handed anisotropic optical crystals.

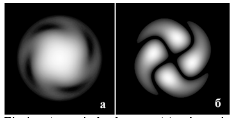

Fig.1 A spiral beam (a) intensity distribution E_x, (b) intensity distribution E_y

Under the condition that the beam waist ρ at the input face of the crystal is equal $\rho \approx \lambda$, almost perfect matching of the beams is observed in the entire cross-sectional region, when the waist is approximately equal to the wavelength. Moreover, such matching is typical for Laguerre-Gauss beams. In this case, the contribution of the energy flux with ring dislocations is negligibly small, and the field forms a helical beam. It should also be noted that this gives us the technical ability to generate polychromatic helical beams. To do this, you just need to focus polychromatic light into a crystal.

As an example of the generation of polychromatic structurally stable singular beams with a helical intensity distribution, we present the intensity distribution patterns shown in Figure 2. We regard a light source to be similar to an absolutely black body while the beam to have the only beam radius for all wavelengths. This means that our rays are spatially coherent.

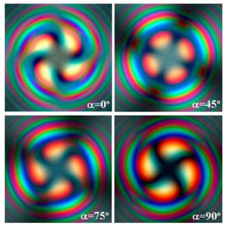

Fig.2 Polychromatic spiral beam obtained at different angles relative to the polarizer axes.

III. Double gyrotropic crystal

As we showed earlier, one gyroanisotropic crystal makes it possible to generate polychromatic structurally stable singular beams with a helical intensity distribution in the same way as two consecutively located gyroanisotropic crystals, but with different gyration values.

The rest of the crystal parameters remain the same. For this case, it is necessary to multiply two matrices for each crystal with the difference $\gamma_1 = -\gamma_2 = \gamma$. Where $\gamma = k\Delta n_C\sqrt{r^2+d^2}$ - full rotation (gyration) of the electric vector, r - radius of the first ring dislocation, d - crystal length. After applying linear algebra, we have

$$D\hat{G} = \begin{pmatrix} C_{11} & C_{12} \\ -C_{12}^* & C_{11}^* \end{pmatrix} \tag{1}$$

$$\begin{aligned} C_{11} &= \cos^2\Lambda + \left(\gamma^2+\delta^2/4\right)\frac{\sin^2\Lambda}{\Lambda^2} + \\ &+ i\frac{\delta}{\Lambda}\sin\Lambda\left(\cos\Lambda\cos 2\phi - \frac{\gamma}{\Lambda}\sin\Lambda\sin 2\phi\right), \end{aligned} \tag{2}$$

$$C_{12} = i\frac{\delta}{\Lambda}\sin\Lambda\left(\cos\Lambda\sin 2\phi + \frac{\gamma}{\Lambda}\sin\Lambda\cos 2\phi\right). \tag{3}$$

Since the eigenmodes included in the linearly polarized beam propagate with different phase velocities, the field amplitude will oscillate along the crystal with a period $\Lambda^2 = \gamma^2 - (\delta/2)^2$, β - propagation constant of a non-diffracting beam. $\delta = k\,\Delta n_L \frac{r^2}{\sqrt{r^2+d^2}}$ is a phase difference between ordinary $E^{(o)}$ and extraordinary $E^{(e)}$ ray components at the total crystal length d, $\Delta n_L = n^e - n^o$ is a linear birefringence, n^o and n^e stand for ordinary and extraordinary refractive indices, k is a wavenumber. The eigenvalues η of matrix (1) have the form

$$\eta = \cos^2\Lambda + \left(\gamma^2+\delta^2/4\right)\frac{\sin^2\Lambda}{\Lambda^2} \pm i\frac{\delta}{\Lambda}\sin\Lambda\sqrt{\cos^2\Lambda + \frac{\gamma^2}{\Lambda^2}\sin^2\Lambda} \tag{4}$$

Thus, the eigenvectors can be represented as:

$$\left|\mathbf{TE}\right\rangle^{ps} = \begin{pmatrix} -C_{12} \\ C_{11}-\eta \end{pmatrix}, \quad \left|\mathbf{TM}\right\rangle^{ps} = \begin{pmatrix} C_{22}-\eta \\ -C_{21} \end{pmatrix}. \tag{5}$$

Let's plot the polarization distribution (Figure 3) for the pseudo-TE and pseudo-TM modes (5):

As we can see, the intensity distribution near the optical axis during the passage of two gyroanisotropic crystals is similar to the classical TE and TM modes that are formed in an anisotropic crystal. But at the periphery of the optical beam, we can observe significant differences, which we will call pseudo-TE and pseudo-TM modes.

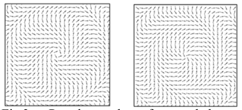

Fig.3 Pseudo modes of natural beam polarization in a gyrotropic crystal: (a) TE mode $\left|\mathbf{TE}\right\rangle^{ps}$ and (b) TM mode $\left|\mathbf{TM}\right\rangle^{ps}$.

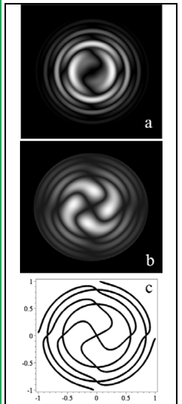

Fig.4 P Beams passing through two gyrotropic crystals: components (a) - E_x components, (b) - E_y components, (c) - phase.

Figure 4 shows examples of the intensity distribution of a beam passing through two gyroanisotropic crystals for various components. As we can see, the E_x component (Figure 4(a)) has no features other than zero intensity on the beam axis. At the same time, a new phase feature is being formed in the E_y component (Figure 4(b)) - this is the so-called double screw edge dislocation. Consider the condition for the phase singularity,

$$\tan 2\phi = -\frac{\gamma\left(r^2\right)}{\Lambda\left(r^2\right)}\tan\Lambda\left(r^2\right); \quad \sin\Lambda\left(r^2\right) = 0 \tag{6}$$

The first expression describes the double helix, while the second describes the distribution at the periphery. This complex spiral is shown in Figure 5.

$$D\hat{G}\begin{pmatrix} 1 \\ \pm i \end{pmatrix} = \begin{pmatrix} C_{11} \pm iC_{12} \\ C_{12} \pm iC_{11}^* \end{pmatrix} = \tag{7}$$

$$= \begin{pmatrix} \cos^2\Lambda + \left(\gamma^2+\frac{\delta^2}{4}\right)\frac{\sin^2\Lambda}{\Lambda^2} + i\frac{\delta}{\Lambda}\left(\cos\Lambda + i\frac{\gamma}{\Lambda}\sin\Lambda\right)\exp\left(\pm i\,2\,\phi\right) \\ i\left[\cos^2\Lambda + \left(\gamma^2+\frac{\delta^2}{4}\right)\frac{\sin^2\Lambda}{\Lambda^2} - \frac{\delta}{\Lambda}\left(\cos\Lambda + i\frac{\gamma}{\Lambda}\sin\Lambda\right)\exp\left(\pm i\,2\,\phi\right)\right] \end{pmatrix}$$

After passing through a quarter-wave plate, the field will take the form:

$$\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} D\hat{G}\begin{pmatrix} 1 \\ \pm i \end{pmatrix} = 2i\begin{pmatrix} \frac{\delta}{\Lambda}\left(\cos\Lambda + i\frac{\gamma}{\Lambda}\sin\Lambda\right)\exp\left(\pm i\,2\,\phi\right) \\ \cos^2\Lambda + \left(\gamma^2+\frac{\delta^2}{4}\right)\frac{\sin^2\Lambda}{\Lambda^2} \end{pmatrix} \tag{8}$$

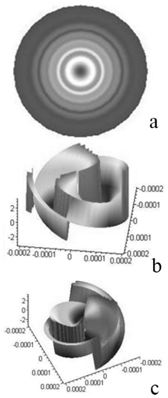

Fig.5 Intensity distribution in the E(-) left circularly polarized component and phase distribution for the left circularly and right circularly polarized components.

The polarizer cuts out the E_y - component from the vortex field. Intensity distribution shown in Figure 6.

In fact, we have obtained an ordinary vortex with a double charge, similar to those that can be obtained on a simple anisotropic crystal [17,18]. We know that the vortices obtained in anisotropic crystals are surrounded by numerous ring dislocations, while in our case these dislocations are almost not observed. The degree of splitting of dislocations depends on the coefficient γ/Λ. The greater the gyration of the crystal, the less the dislocations are noticeable, but at the same time the coefficient $\int\left|E_x\right|^2 dS / \int\left|E_y\right|^2 dS$ decreases, so that in the final analysis the dislocations can disappear under the condition $\Delta n_C >> \Delta n_L$ that the circular birefringence is much greater than the linear one.

IV. Experiment

More and more scientific publications appear in which the authors use not monochromatic, but polychromatic singular beams, this is obvious. The transmission capacity of any communication channel directly depends on the degrees of freedom, and it is the wavelength that becomes an additional degree of freedom. In this regard, we have concentrated on the study of polychromatic singular beams transmitted for a gyroanisotropic crystal.

Consider an experimental setup (Figure 7) for studying polychromatic singular beams transmitted for a gyroanisotropic crystal. One of the main conditions for the generation of polychromatic singular beams is the radiation source. We opted for a halogen lamp with a spherical mirror and an angular beam divergence of less than 4 degrees. Subsequently, such a beam becomes linearly polarized due to the passage of a polarizer.

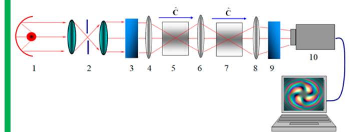

Fig.7 Scheme of the experimental setup: 1 - halogen lamp, 2 - spatial lens filter, 3,9 - polarizers, 4,6,8 - lenses, 5 - LiNbO3 crystal, 7 - SiO2 crystal, 10 - CCD camera, - $\hat{\mathbf{C}}$ unit vector of optical axes

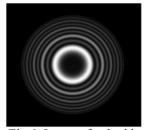

Fig.6 Image of a double charged vortex

Subsequently, such a linearly polarized beam is focused by a system of lenses for the passage of two successively located anisotropic crystals - a LiNbO3 crystal and a SiO2 crystal. It should be immediately noted that the optical axes of these two crystals are codirectional. The resulting beam passes through the polarizer and then hits the CCD camera array.

As our studies have shown, the intensity distribution of the resulting singular beam directly depends on the polarizer rotation angle (Figure 8) and at an angle of $\alpha = 90^0$ polarizer axes, an intensity carina arises corresponding to a purely helical dislocation.

It should be noted a special property of polychromatic beams that have passed through two successively located anisotropic crystals - the dislocations of the wave front are not smeared, and clear spiral lines are visible, which form four branches. The method of generation of polychromatic beams during the passage of two successively located anisotropic crystals, described in this article, can be used by other researchers to analyze the properties of spin and orbital angular momentum in free space [19,20].

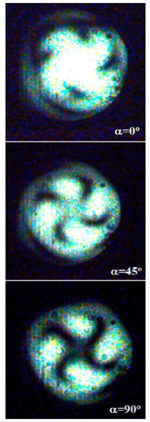

Fig.8 Experimentally obtained spiral beams under different directions of polarizer axes .

V. Conclusion

As our studies show, polychromatic singular beams carrying screw edge dislocations and optical vortices can be created using gyroanisotropic crystals.

As we have shown, two gyrotropic crystals with opposite signs of the gyration coefficients make it possible to create spiral edge dislocations from a beam of linearly polarized polychromatic light. The equations presented in this paper make it possible to analyze the propagation of polychromatic singular beams in various cases.

The use of two anisotropic crystals and a halogen lamp as a source of radiation. showed that in one of the beam components it is possible to create a polychromatic phase feature with a clearly defined central helical line.

References

1. G. Rodriguez-Morales, S. Chaves-Cerda, "Exact nonparaxial beams of scalar Helmholtz equation,", Opt. Lett, Vol. 29, P. 430-432. March 2004. https://doi.org/10.1364/ol.29.000430
2. J.G. Gutierrez-Vega, M.A. Baudres, "Helmholtz-Gauss waves,", J. Opt. Soc. Am, Vol. 22, pp. 289-298, February 2005. https://doi.org/10.1364/JOSAA.22.000289
3. A.P. Kiselev, "New structures in paraxial Gaussian beams,", Optics and Spectroscopy, Vol. 96. pp. 479-481. January 2004. https://doi.org/10.1134/1.1719131
4. V.V. Kotlyar, E.G. Abramochkin, A.A. Kovalev, A.G Nalimov, "Astigmatic transformation of a fractional-order edge dislocation," Computer Optics, 2022, 46(4), pp. 522-530. DOI: https://doi.org/10.18287/2412-6179-CO-1084.
5. V.V. Kotlyar, A.A. Kovalev, A.A.Savelyeva, "Coherent superposition of the Laguerre-Gaussian beams with different wavelengths: colored optical vortices," Computer Optics, 2022, 46(5), pp. 692-700. https://doi.org/10.18287/2412-6179-CO-1106.
6. S.V. Karpeev, V.V. Podlipnov, N.A. Ivliev, S.N. Khonina, "High-speed format 1000BASE-SX / LX transmission through the atmosphere by vortex beams near IR range with help modified SFP-transmers DEM-310GT," Computer Optics, 2020, 44(4), pp. 578-581. https://doi.org/10.18287/2412-6179-CO-772.
7. A.A.Kovalev, "Optical vortex beams with an infinite number of screw dislocations," Computer Optics, 2021, 45(4), 497-505. https://doi.org/10.18287/2412-6179-CO-866.
8. V.V. Kotlyar, A.A. Kovalev, D.S. Kalinkina, E.S.Kozlova, "Fourier-Bessel beams of finite energy," Computer Optics, 2021, 45(4), pp. 506-511. https://doi.org/10.18287/2412-6179-CO-864.
9. V.V. Kotlyar, A.A. Kovalev, E.S. Kozlova, A.P. Porfirev, "Spiral phase plate with multiple singularity centers," Computer Optics, 2020, 44(6), pp. 901-908. https://doi.org/10.18287/2412-6179-CO-774.
10. V.V. Kotlyar, "Optical beams with an infinite number of vortices," Computer Optics, 2021, 45(4), pp. 490-496. https://doi.org/10.18287/2412-6179-CO-858.
11. A.G. Nalimov, V.V.Kotlyar, "Topological charge of optical vortices in the far field with an initial fractional charge: optical "dipoles"," Computer Optics, 2022, 46(2), pp. 189-195. https://doi.org/10.18287/2412-6179-CO-1073.
12. E.V. Barshak, B.P. Lapin, D.V. Vikulin, S.S. Alieva, C.N. Alexeyev, M.A. Yavorsky, "All fiber SWAP-CNOT gate for optical vortices," Computer Optics, 2021, 45(6), pp. 853-859. https://doi.org/10.18287/2412-6179-CO-938.
13. V. Kotlyar, A. Kovalev and A. Porfirev, Vortex Laser Beams. New York: Taylor & Francis Groop, August 2018. ISBN: 978-135-1009607.
14. A. Volyar, T. Fadeeva and Y. Egorov, "Vector singularities of Gaussian beams in uniaxial crystals: Optical vortex generation," Technical Physics Letters, vol. 28, issue 11, pp. 958–961, November 2002. DOI: https://doi.org/10.1134/1.1526896.
15. V.A. Soifer, M.A. Golub, Laser beam mode selection by computer-generated holograms. Boca Raton: CRC Press., - 1994. ISBN: 0-8493-2476-9.
16. J. Leach and M.J. Padgett, "Observation of chromatic effects near a white-light vortex," New Journal of Physics, 2003, Vol. 5, pp. 154.1-154.7, March 2004. 10.1051/epn:2004207
17. A. Volyar, Y. Egorov, A. Rubass and T. Fadeeva, "Fine structure of white optical vortices in crystals," Technical Physics Letters, vol. 30, issue 8, pp. 701–704, August 2004. DOI: https://doi.org/10.1134/1.1792318
18. T. Fadeyeva, Y. Egorov, A. Rubass, G. Swartzlander and A. Volyar, "Indistinguishability limit for off-axis vortex beams in uniaxial crystals," Optics Letters, vol. 32, issue 21, pp. 3116–3118, November 2007. DOI: https://doi.org/10.1364/OL.32.003116.
19. A. V. Volyar, M. V. Bretsko, Ya. E. Akimova, Yu. A. Egorov, "Avalanche instability of the orbital angular momentum higher order optical vortices," Computer Optics, vol. 43(1), pp. 14-24, January 2019. https://doi.org/10.18287/2412-6179-2019-43-1-14-24
20. A. Volyar, M. Bretsko, Y. Akimova and Y. Egorov, "Digital sorting perturbed Laguerre-Gaussian beams by radial numbers" JOSA A, vol. 37, issue 6, pp. 959–968, June 2020. DOI: https://doi.org/10.1364/josaa.391153